

# Summertime CO<sub>2</sub> fluxes from tundra of Ny-Ålesund in the High Arctic

LI Fangfang<sup>1</sup>, ZHU Renbin<sup>1,2\*</sup>, BAO Tao<sup>1</sup>, WANG Qing<sup>1</sup> & XU Hua<sup>2</sup>

<sup>1</sup> Anhui Province key Laboratory of Polar Environment and Global Change, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230036, China;

<sup>2</sup> State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China

Received 20 October 2016; accepted 15 February 2017

**Abstract** The Arctic ecosystem, especially High Arctic tundra, plays a unique role in the global carbon cycle because of amplified warming in the region. However, relatively little research has been conducted in High Arctic tundra compared with other global ecosystems. In the present work, summertime net ecosystem exchange (NEE), ecosystem respiration (ER), and photosynthesis were investigated at six tundra sites (DM1–DM6) on Ny-Ålesund in the High Arctic. NEE at the tundra sites varied between a weak sink and strong source (−3.3 to 19.0 mg CO<sub>2</sub>·m<sup>−2</sup>·h<sup>−1</sup>). ER and gross photosynthesis were 42.8 to 92.9 mg CO<sub>2</sub>·m<sup>−2</sup>·h<sup>−1</sup> and 54.7 to 108.7 mg CO<sub>2</sub>·m<sup>−2</sup>·h<sup>−1</sup>, respectively. The NEE variations showed a significant correlation with photosynthesis rates, whereas no significant correlation was found with ecosystem respiration, indicating that NEE variations across the region were controlled by differences in net uptake of CO<sub>2</sub> owing to photosynthesis, rather than by variations in ER. A  $Q_{10}$  value of 1.80 indicated weak temperature sensitivity of tundra ER and its response to future global warming. NEE and gross photosynthesis also showed relatively strong correlations with C/N ratio. The tundra ER, NEE, and gross photosynthesis showed variations over slightly waterlogged wetland tundra, mesic and dry tundra. Overall, soil temperature, nutrients and moisture can be key effects on CO<sub>2</sub> fluxes, ecosystem respiration, and NEE in the High Arctic.

**Keywords** CO<sub>2</sub> fluxes, net ecosystem exchange (NEE), ecosystem respiration (ER), gross photosynthesis, Arctic region

**Citation:** Li F F, Zhu R B, Bao T, et al. Summertime CO<sub>2</sub> fluxes from tundra of Ny-Ålesund in the High Arctic. *Adv Polar Sci*, 2017, 28(1): 50-60, doi: 10.13679/j.advps.2017.1.00050

## 1 Introduction

CO<sub>2</sub> is a major active radiative greenhouse gas (GHG) (Rasogi et al., 2002; Chen et al., 2012), and its increase in concentration and contribution to global warming has become a serious concern during the past few decades (IPCC, 2013). CO<sub>2</sub> fluxes in temperate and tropical regions, wetland ecosystems, and boreal tundra in the Northern Hemisphere have been extensively investigated (Oechel et al., 2000; Corradi et al., 2005; Jungkunst and Fiedler, 2007;

Ullah and Moore, 2011). Arctic tundra ecosystems are predicted to be more susceptible than other global regions to the responses of CO<sub>2</sub> flux dynamics to climate change, and CO<sub>2</sub> emissions have a special role in global carbon cycles because of amplified warming in the region (Oechel et al., 2000; Serreze et al., 2000; ACIA, 2005; Corradi et al., 2005; Davidson and Janssens, 2006; Oberbauer et al., 2007). Warming is predicted to be faster having a greater extent than in other areas of the globe during the coming century (IPCC, 2007; Trenberth et al., 2007). This rapid warming is expected to continue in the future, with >6°C warming expected throughout the 21st century under some scenarios

\* Corresponding author, E-mail: zhurb@ustc.edu.cn

(ACIA, 2004). Climate change could alter C cycling and energy exchange in the Arctic and produce positive or negative feedbacks, depending on changes in rates and balances of C sequestration and decomposition (Oechel and Vourlitis, 1994; Chapin et al., 2005). Nevertheless, there has been relatively little research of High Arctic tundra compared with other global ecosystems (Groendahl et al., 2007).

To better understand relationships of CO<sub>2</sub> emissions to environmental parameters, CO<sub>2</sub> fluxes have been measured at a number of boreal or Arctic sites for the past two decades (Welker et al., 2004; Lafleur and Humphreys, 2007; Poyatos et al., 2014). Temperature, vegetation cover and water table are important influences on the processes of photosynthesis and ecosystem respiration (ER), thereby affecting CO<sub>2</sub> budgets. Higher temperatures may increase ER (Dorrepaal et al., 2009) and even lead to greater carbon availability through increased thawing of the permafrost (Schoor et al., 2009), potentially offsetting any productivity increases. Vegetation cover in high-latitude regions causes marked spatial variability of net ecosystem exchange (NEE) and its flux components, associated with microtopography, local hydrology (Heikkinen et al., 2004; Nobrega and Grogan, 2008; Pelletier et al., 2011) and community composition (Riutta et al., 2007). An increase in soil moisture is likely to have a major impact on C and N mineralization or flux rates (Borken and Matzner, 2009), producing strong biological effects (Davis, 1981; Robinson et al., 2003; Convey and Smith, 2006) that in turn influence photosynthesis rates (Davey and Rothery, 1997). Nevertheless, there is still much uncertainty about the driving forces of CO<sub>2</sub> fluxes, ER, and NEE from tundra ecosystems in the Arctic.

The underlying cause of NEE variations remains ambiguous in tundra ecosystems. For example, differences of NEE in a subarctic fen were reported to be driven more by variations in productivity rather than respiration (Griffis and Rouse, 2001; McFadden et al., 2003). In contrast, NEE variations in Alaskan tussock tundra were driven largely by changes in ER (Vourlitis and Oechel, 1999). However, the underlying cause of NEE variations in High Arctic tundra has received little attention.

During summer 2014, we selected as a study area the coastal tundra ecosystems on Ny-Ålesund, Svalbard, a Norwegian archipelago in the High Arctic. We investigated tundra NEE and ER rates to test the hypothesis that NEE variations were driven largely by changes in photosynthesis rates rather than respiration. The aims of this study were to: (1) investigate spatial and temporal variation in tundra NEE, ER and gross photosynthesis; (2) study the effects of environmental variables on tundra NEE, gross photosynthesis, and ER; (3) compare with other measurements and investigate regional implications. This is an important evaluation of tundra CO<sub>2</sub> budgets in the High Arctic for

increasing the tundra dataset and reasonably estimating the carbon budget there.

## 2 Materials and methods

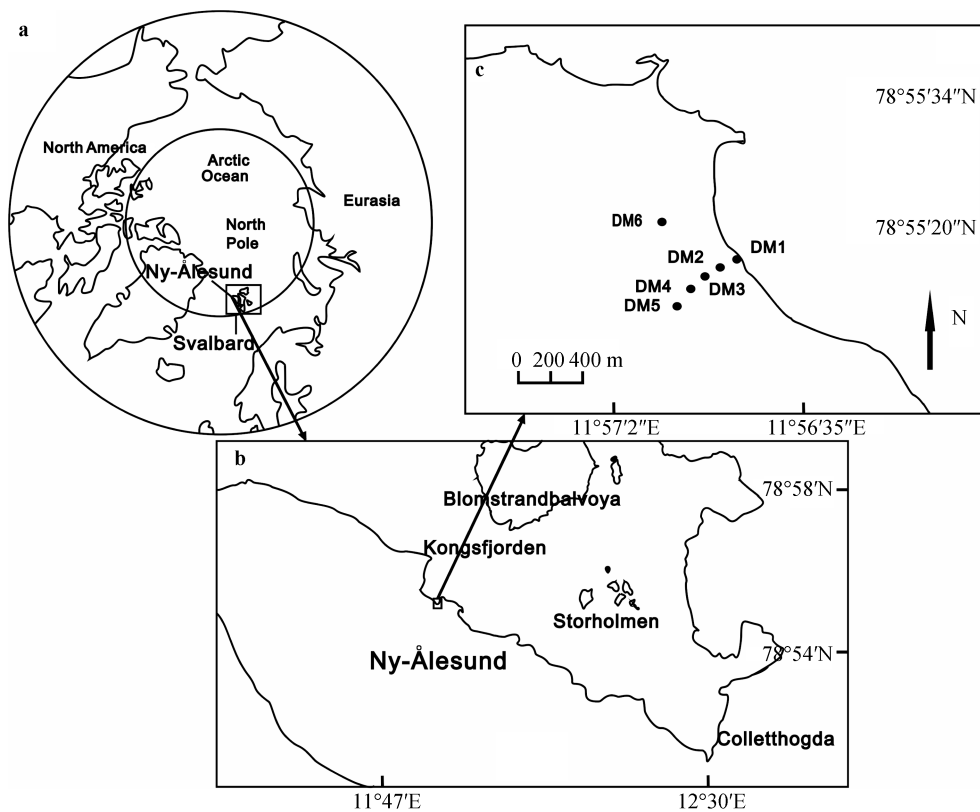
### 2.1 Study area

Our study area was the tundra ecosystem of Ny-Ålesund (78°55'N, 11°56'E) on the western coast of Spitsbergen, Svalbard, in the High Arctic. It has an Arctic maritime climate with annual mean air temperature and precipitation about -5.8°C and 400 mm, respectively. The tundra around Ny-Ålesund has a short growing season (June to August), when the temperature typically rises only a few degrees above freezing (Winther et al., 2002). The study area has silty clay and sandy gray soil that has a thin organic soil cover (Zhu et al., 2012; Chen et al., 2014). Soil thaw begins in early June, and thaw depths maximize (1.6–2.0 m) at the beginning of September and remain constant until at least the middle of the month, corresponding to active layer thickness (Westermann et al., 2010). The study area includes a slightly waterlogged wetland tundra, mesic and dry tundra (Zhu et al., 2012). Plant species are relatively simple, mainly including polar tundra and polar desert flora, such as mosses (*Salix polaris*, *Cerastium arcticum* and *Drepanocladus* spp), lichens (*Luzula confuse*), and sedges (*L. arctica* and *Saxifraga oppositifolia*) (Sun et al., 2004).

Selected observation sites are shown in Figure 1. Simple mapping of the flux measurement sites indicated that 52% of the vegetation was moss or lichen, 25% was vascular plants, 20% was bare soil, and 3% was stones. In total, the six flux observation sites (called DM1–DM6) were established along transect from the coastal tundra inland, with increasing elevation.

### 2.2 Measurements of net ecosystem exchange and ecosystem respiration

NEE was measured at each tundra site using transparent chambers (Hutchinson and Mosier, 1981; Zhu et al., 2008; Zhu et al., 2010). Open-bottom transparent Plexiglas chambers (50 cm×50 cm×25 cm) were placed on PVC collars, which were inserted in the soil to depth ~5 cm at the measurement sites, covering an area ~0.25 m<sup>2</sup>. Two collars were installed at each site, and CO<sub>2</sub> fluxes were measured at roughly the same time. The PVC collars allowed the same observation site to be measured repetitively, minimized site disturbance, and ensured that the chambers were well sealed, because those chambers fit into a water-filled notch in the collars. The mean height of all chambers was 20 cm above ground, which was the minimum required without influencing gas diffusion patterns under normal atmospheric pressure (Hutchinson and Mosier, 1981). ER was measured immediately following CO<sub>2</sub> flux measurements by the same procedure, in opaque chambers covered by three layers of thick black cloth during summer 2014 (Zhu et al., 2010).



**Figure 1** Study area and CO<sub>2</sub> flux observation sites. **a**, The black square indicates location of the investigation area in the High Arctic. **b**, Location of the sampling sites: Ny-Ålesund. **c**, The tundra flux observation sites. I: The six sites DM1-DM6 are shown in this figure. Note: The map was drawn using coreDRAW X7.

During CO<sub>2</sub> flux measurement, the chambers were inserted in the water-filled notch of the collars. Upon closure of these collars with the chambers, headspace gas samples were collected at 15-min intervals with a double-ended needle connected to pre-evacuated glass vials (17.5 mL) with butyl rubber septa. For each flux measurement, three samples (at 0, 15 and 30 min) were withdrawn from each chamber. Internal air temperature inside the chamber (i.e., chamber temperature) was simultaneously measured (at 0, 15 and 30 min) using a thermometer installed inside each chamber. Mean chamber temperatures were used for flux calculation and statistical analysis. NEE and ER were determined between 9:00–11:00 local time, once every one or two days at all sites. There were two replicate measurements at each site, and the order of measurement was varied to ensure that the measurement time did not bias the results. During the summer of 2014, NEE and ER were measured six times at the observation sites in the coastal tundra between 3 and 12 July. We also used chambers to investigate diurnal NEE and ER at tundra site DM6 in six periods (12:00–12:30, 16:00–16:30, 20:00–20:30, 0:00–0:30, 4:00–4:30 and 8:00–8:30) within a 20 h period on 13–14 July 2014. According to our previous studies, the flux measurements in the six periods can approximately represent diurnal variations of NEE and ER in the local tundra environment

(Chen et al., 2014).

### 2.3 Determination of gas concentration and flux calculation

The CO<sub>2</sub> concentration measurement and gas flux calculation have been described in our previous papers (Zhu et al., 2010, 2014a). Briefly, the CO<sub>2</sub> concentrations were analyzed using gas chromatography equipped with a thermal conductivity detector (Shimadzu GC-14B, Japan). Net gas fluxes were calculated using a linear least squares fit to three points in the concentration time series, with an average chamber temperature for each flux. Least squares regression lines of headspace CO<sub>2</sub> concentration versus time were visually inspected for abrupt changes in flux direction resulting from disturbances such as chamber leakage or of tundra soils during sampling. Zero or near-zero fluxes were retained to avoid biasing the results when CO<sub>2</sub> concentration had no evident increase or decrease in the chamber headspace over a 30-min period. For all fluxes, positive values indicate net emission to the atmosphere, and negative values represent net uptake from the atmosphere. During the flux measurement phase, CO<sub>2</sub> concentration generally rose or fell linearly with time. Gross photosynthesis was calculated as the difference between NEE and dark respiration (Ström and Christensen, 2007).

## 2.4 Environmental variables, soil sampling and analysis

Related meteorological data were collected at the Ny-Ålesund weather station near our observation sites. When flux measurement ended each time, the 0, 5, and 10 cm soil temperatures at each site were immediately measured by the thermometers, which had been inserted at corresponding depths just before flux measurement start. These temperatures approximately reflected soil temperatures during the flux observation period.

The soil samples were collected from the tundra sites with a 6-cm diameter PVC tube after the CO<sub>2</sub> flux measurements ended, and then stored at 4°C until analysis. The samples were homogenized manually and organic and mineral layers were mixed for analysis. Soil gravimetric water content was determined by oven-drying 10–15 g of fresh soil for 48 h at 105°C. Total carbon (TC), total nitrogen (TN), and total sulfur (TS) were measured by a CNS Elemental Analyzer (Elementar Vario EL, Hanau, Germany) (Zhu et al., 2014a). NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N contents in the soils were analyzed using the colorimetric indophenols blue method and Griess-Ilosvay colorimetric method (Keeney and Nelson, 1982).

## 2.5 Statistical analyses

Statistical analysis was done using Origin 8, SPSS Statistics 17.0, and Microsoft Excel 2007. For each site, we used standard deviation (SD) to estimate uncertainty of the mean flux. During the observation period, individual fluxes at each site (DM1–DM6) in the coastal tundra and their associated uncertainties were then averaged. Differences in mean GHG fluxes between the sites were tested using one-way repeated analysis of variance with multiple comparisons using a least significant difference test with  $p \leq 0.05$ , and letters (a, b and c) were used to indicate statistically significant spatial differences. The 0, 5, and 10 cm soil temperatures and mean chamber temperatures were used for each tundra site to analyze relationships between CO<sub>2</sub> fluxes and soil and chamber temperatures. Relationships of CO<sub>2</sub> fluxes with soil chemical properties (TC, TN, NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N and C/N) were tested using Pearson correlation to elucidate the effects of soil chemical properties on NEE, ER, and gross photosynthesis. Actual  $p$ -values were used in the statistical analyses. A univariate exponential function model was fit for the relationship between ER and soil temperature, i.e.,  $ER = \beta_0 e^{\beta_1 T}$ , where ER has units mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>,  $T$  is mean soil temperature (°C), and  $\beta_0$  and  $\beta_1$  are constants fitted using the least squares method.  $Q_{10}$  was calculated by  $Q_{10} = e^{10\beta_1}$  (Zhu et al., 2014b).

## 3 Results

### 3.1 Environmental variables

Daily air temperatures in summer 2014 varied from 4.8°C

to 7.2°C. The 0, 5 and 10 cm soil temperatures showed similar variation at tundra sites DM1–DM5, within 2.0°C–12.0°C, and temperatures decreased with soil depth from 0 to 10 cm (Figure 2). Physiochemical properties of the coastal tundra soils are summarized in Table 1. Soil moisture decreased in the coastal tundra within the range 51.9%–99.7%. Soil TC, TN, NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N contents were highly variable along transect from the coastal tundra because of environmental heterogeneity. Mean TC and TN contents in the tundra soils were 5.26%–24.15% and 0.34%–1.76%, respectively (Table 1). Mean NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentrations in the soils increased from the slightly waterlogged wetland tundra to the dry tundra, and NH<sub>4</sub><sup>+</sup>-N contents were one to two orders of magnitude greater than NO<sub>3</sub><sup>-</sup>-N contents in the tundra soils.

**Table 1** Soil physiochemical properties at the observation sites of High Arctic tundra

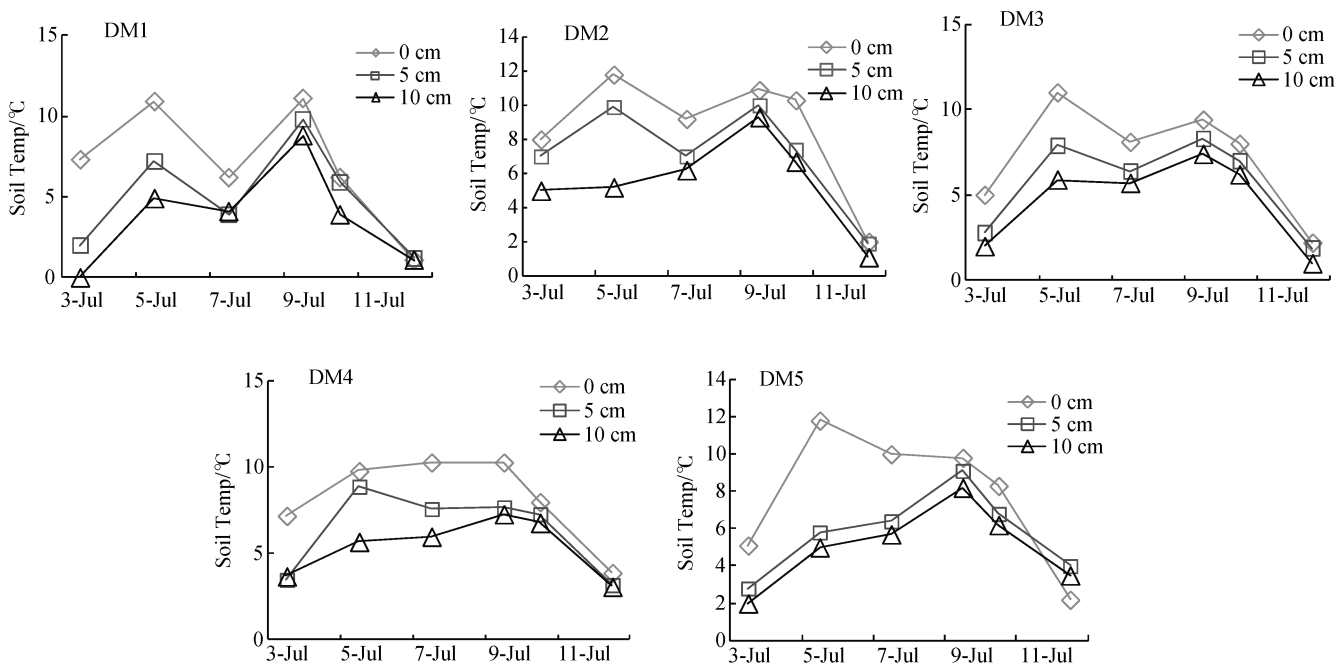
Site no.	Height /m	Soil properties					
		SM/%	TC/%	TN/%	NH <sub>4</sub> <sup>+</sup> -N /( $\mu\text{g}\cdot\text{g}^{-1}$ )	NO <sub>3</sub> <sup>-</sup> -N /( $\mu\text{g}\cdot\text{g}^{-1}$ )	C/N
DM1	0	88.9	21.03	1.54	0.28	0.11	13.7
DM2	7	99.5	5.26	0.39	1.00	0.27	13.5
DM3	8	89.8	7.55	0.34	18.74	0.81	22.2
DM4	10	59.3	24.15	1.49	10.23	0.70	16.2
DM5	15	51.9	19.29	1.55	19.16	1.16	12.5
DM6	22	74.1	24.03	1.76	12.60	1.19	13.7

Notes: SM, TC, TN, NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, and C/N indicate soil moisture, total carbon, total nitrogen and the ratios of soil carbon and nitrogen, respectively.

### 3.2 Summertime NEE, ER and gross photosynthesis in the High Arctic

The mean NEE at the tundra sites ranged from -3.3 to 19.0 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup> (Table 2). At sites DM1, DM2, DM3, and DM5, mean CO<sub>2</sub> fluxes exceeded 10 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup> over the observation period, indicating that the tundra overall was a net weak CO<sub>2</sub> source in the High Arctic. Net CO<sub>2</sub> fluxes showed strong temporal variation at the tundra sites. The greatest mean CO<sub>2</sub> uptake was at DM3 (-19.0±31.7 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>), followed by DM4 (-3.3±29.2 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>) (Table 2), but the difference in mean NEE among all the sites was not significant ( $p > 0.05$ ) (Figure 3). Mean ER and photosynthesis rates in the tundra varied from 42.8 to 92.9 and 54.7 to 108.7 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>, respectively.

Mean ER had no significant differences between DM1 (42.8±25.8 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>), DM2 (52.7±34.8 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>), DM3 (89.9±64.4 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>), DM4 (92.9±40.0 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>) and DM5 (53.6±50.2 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>) (Table 2) (Figure 3). Similarly, differences of gross photosynthesis between all the sites were not significant ( $p > 0.05$ ), indicating that tundra gross photosynthesis had no significant spatial variation (Figure 3). Mean NEE in the tundra showed a temporal trend consistent with photosynthesis rates (Figure 4). The

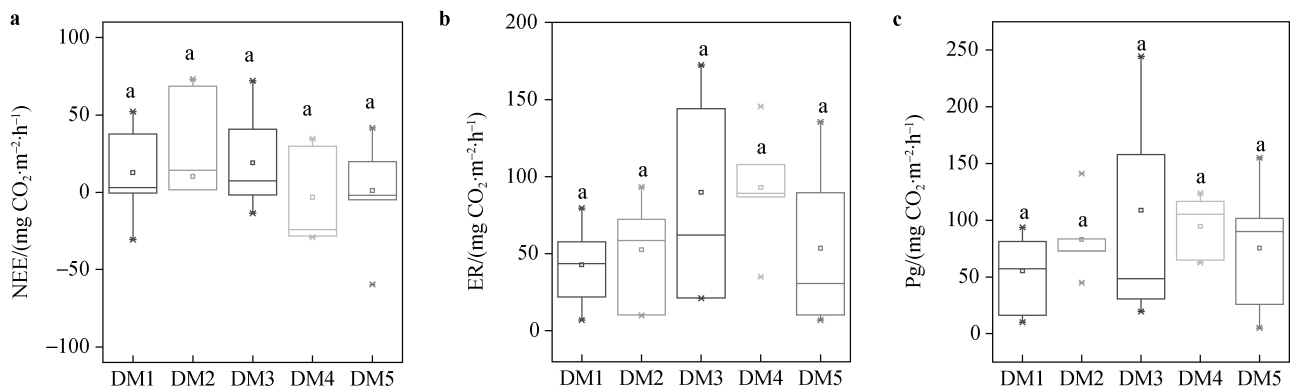


**Figure 2** Variations of soil temperatures measured at 0 cm, 5 cm and 10 cm depths at the flux observation sites DM1—DM5.

**Table 2** Comparisons of net ecosystem CO<sub>2</sub> exchange, ecosystem respiration and gross photosynthesis

Site no.	NEE/(mg CO <sub>2</sub> ·m <sup>-2</sup> ·h <sup>-1</sup> )		ER/(mg CO <sub>2</sub> ·m <sup>-2</sup> ·h <sup>-1</sup> )		Pg/(mg CO <sub>2</sub> ·m <sup>-2</sup> ·h <sup>-1</sup> )	
	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD
DM1	-30.7~52.2	12.6±29.5a	6.9~79.7	42.8±25.8a	10.0~93.7	55.4±34.9a
DM2	-131.5~73.2	10.2±75.0a	10.0~93.4	52.7±34.8a	-38.0~141.0	62.9±58.7a
DM3	-13.7~72.0	19.0±31.7a	21.2~172.5	89.8±64.4a	19.6~244.6	108.7±89.9a
DM4	-29.0~34.6	-3.3±29.2a	35.0~145.5	92.9±40.0a	62.6~123.8	89.6±29.0a
DM5	-59.7~41.6	1.1±34.2a	7.0~135.5	53.6±50.2a	-49.3~155.1	54.7±74.4a

Notes: Within the columns, the same suffix letters indicate that the mean fluxes between the sites have no significant difference (LSD,  $p > 0.05$ ). Pg indicates gross photosynthesis.



**Figure 3** a, Spatial variation of NEE among the tundra observation sites DM1-DM5. The spatial variation of ER and gross photosynthesis are shown in Figures b and c, respectively. The squares represent the mean fluxes and solid lines represent median values. Boxes enclose the interquartile range, whiskers show the full range. The same lowercase letters indicate statistically no significant differences among the observation sites DM1—DM5 (Fisher's LSD,  $p \leq 0.05$ ). Note: Pg indicates gross photosynthesis.

CO<sub>2</sub> budget was estimated at 237.5 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>. According to the Pearson correlation, NEE had a significant correlation ( $r=0.607$ ;  $p=0.000$ ) with photosynthesis rates, but there was no significant correlation ( $r=-0.662$ ;  $p=0.001$ ) with ER (Table 3). Correlations between NEE and gross photosynthesis and ER are shown in Figure 5. In accord with the results of Pearson correlation, mean NEE also showed a relatively strong positive correlation with photosynthesis rates (Figure 5). Thus, our results indicate that NEE is mainly controlled by photosynthesis rates rather than by ER in the High Arctic.

**Table 3** Pearson correlations among CO<sub>2</sub> fluxes, ecosystem respiration and photosynthesis measured at the sites and environmental variables in the tundra

Variables	NEE	ER	Pg
NEE	1	0.003	-0.662**
ER	-	1	0.747**
Pg	-	-	1
ST <sub>0</sub>	-0.244	0.072	-0.133
ST <sub>5</sub>	0.478	0.757	0.483
ST <sub>10</sub>	0.122	0.338	0.142
CT	0.151	0.302	0.504
SM	-0.158	-0.226	0.089
TC	-0.215	0.006	-0.250
TN	0.374	-0.234	-0.480
C/N	-0.891*	0.780	0.952*
NH <sub>4</sub> <sup>+</sup> -N	0.803	0.524	0.469
NO <sub>3</sub> <sup>-</sup> -N	0.622	0.419	0.267

Notes: NEE, ER and Pg indicate net ecosystem CO<sub>2</sub> exchange, ecosystem respiration and gross photosynthesis. ST<sub>0</sub>, ST<sub>5</sub>, ST<sub>10</sub>, CT and SM indicate 0 cm soil temperature, 5 cm soil temperature, 10 cm soil temperature, chamber temperature and soil moisture, respectively. Significant correlations are indicated by "\*" at the  $p<0.05$  level, and by "\*\*" at the  $p<0.01$  level.

### 3.3 Diurnal NEE, ER and gross photosynthesis in the High Arctic

Daily mean CO<sub>2</sub> fluxes (NEE) from tundra site DM6 ranged from -29.6 to 31.4 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>. Most fluxes exceeded 0.76 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>. NEE reached a maximum at midnight and a minimum at noon (Figure 6). ER continuously increased from midnight to noon, maximizing (85.3 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>) at noon. Daily photosynthesis rates were 16.2 to 95.9 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>. Almost half the fluxes exceeded 60 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup>, even reaching 95.9 mg CO<sub>2</sub>·m<sup>-2</sup>·h<sup>-1</sup> (Figure 6). Therefore, tundra soils in the High Arctic had relatively strong photosynthesis rates. Mean NEE in the tundra had a daily variation consistent with photosynthesis rates (Figure 6).

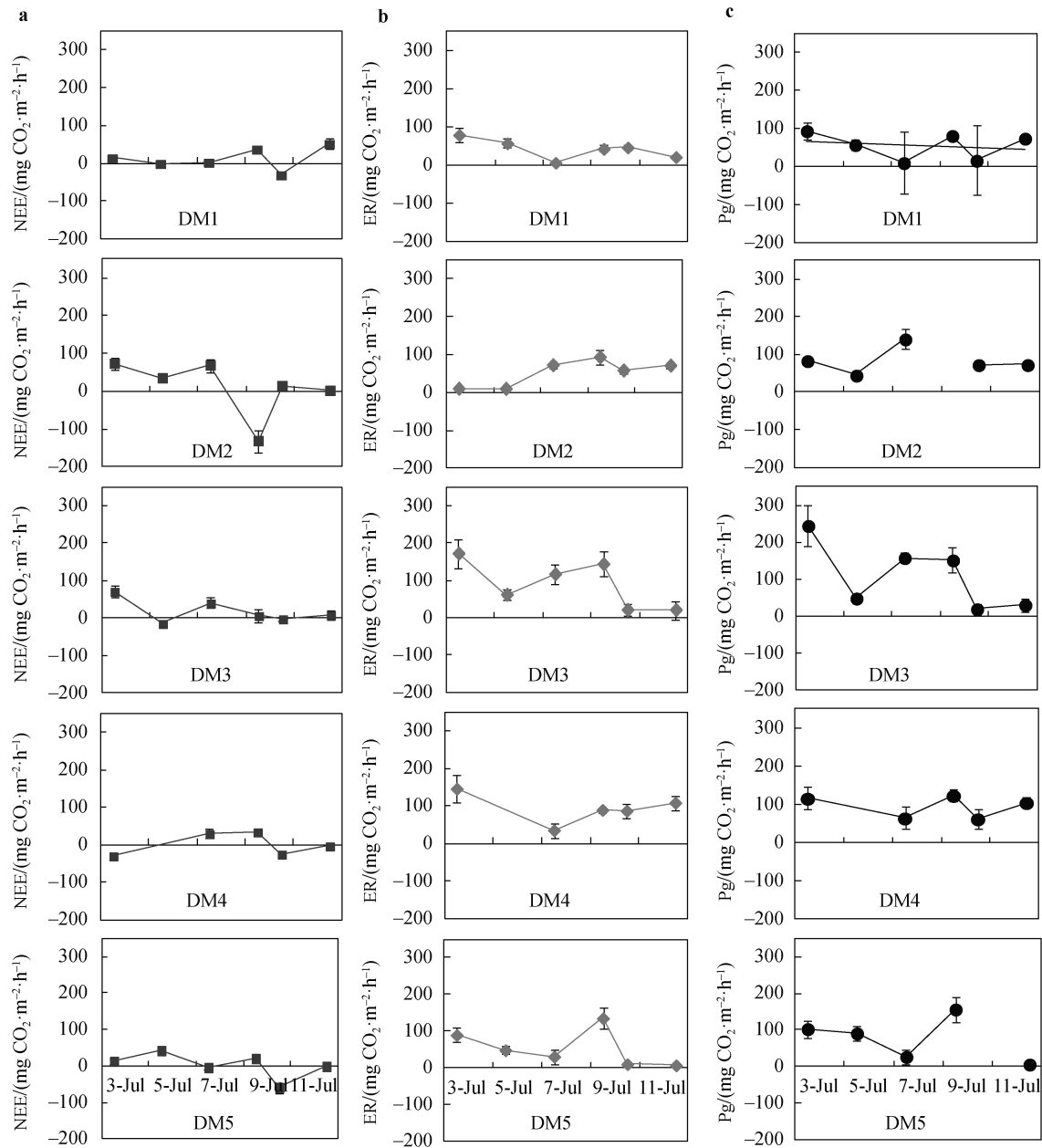
### 3.4 Correlation between CO<sub>2</sub> and environmental variables

As summarized in Table 3, mean NEE showed no significant correlation ( $p>0.05$ ) with 0–5 cm soil temperature (ST), chamber temperature (CT), soil moisture (SM), TC, TN, NH<sub>4</sub><sup>+</sup>-N or NO<sub>3</sub><sup>-</sup>-N contents when data at all tundra sites were combined. Mean NEE showed significant correlation with C/N ( $r=-0.891$ ,  $p=0.043$ ). Similarly, both gross photosynthesis and ER had no significant correlation ( $p>0.05$ ) with ST, CT, SM, NH<sub>4</sub><sup>+</sup>-N or NO<sub>3</sub><sup>-</sup>-N contents in the soils. However, the photosynthesis rates showed significant positive correlation with C/N ( $r=0.952$ ,  $p=0.013$ ) (Table 3). Correlations between ER, NEE, gross photosynthesis and soil chemical properties (0–10-cm mean ST, SM and soil C/N ratio) are shown in Figure 7. In accord with the results of Pearson correlation, mean CO<sub>2</sub> fluxes and photosynthesis rates had relatively strong positive correlations with the soil C/N ratio. Our results reveal that ER and gross photosynthesis in mesic tundra (DM3) were higher than those in slightly waterlogged wetland tundra (DM1–DM2). ER reached its largest value at DM4 and gross photosynthesis was maximum at DM3, and then decreased from the mesic tundra to dry tundra (DM5) (Table 2). We observed that slightly waterlogged wetland tundra acted as a CO<sub>2</sub> source. From the mesic to dry tundra with increasing elevation, the observation sites showed a switch from CO<sub>2</sub> source to sink. Mean NEE showed a relatively strong correlation with soil moisture ( $R^2=0.677$ ) (Figure 7). Overall among these environmental variables, the soil C/N ratio and soil moisture may be key effects on tundra mean NEE and photosynthesis rates.

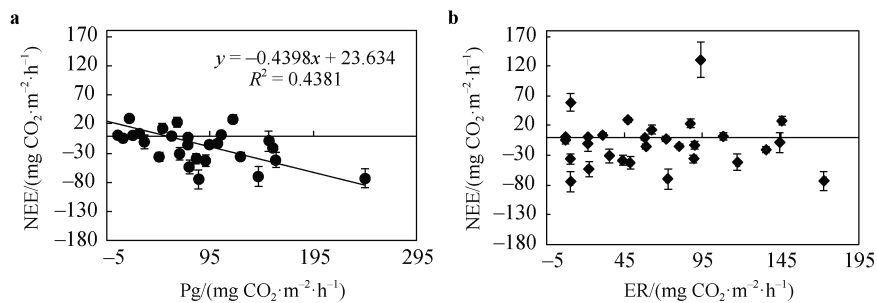
## 4 Discussion

### 4.1 Relationship between NEE and gross photosynthesis

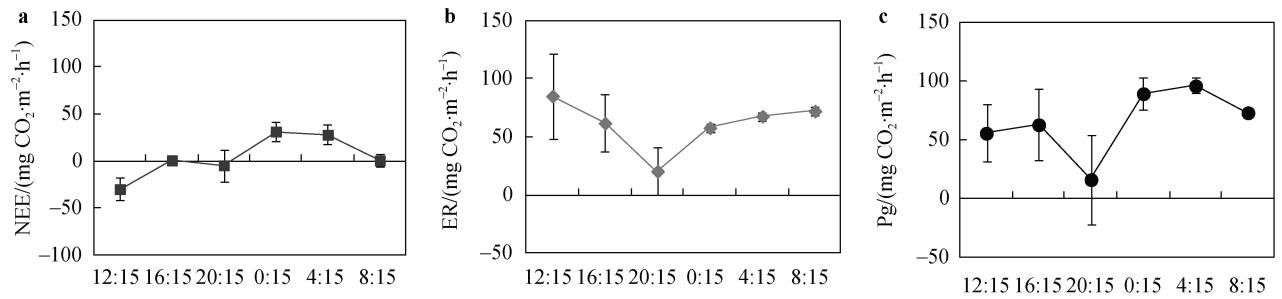
Results show that the observed NEE dynamics are probably linked to the processes of photosynthesis and tundra ER. Photosynthesis tends to dominate under light conditions, and vegetation respiration, microbial respiration and microbial decomposition of organic matter under dark conditions (Kuz'yakov and Gavrichkova, 2010; Jorgensen et al., 2011). In the present study, summertime NEE had significant correlation with photosynthesis ( $r=-0.662$ ;  $p=0.001$ ). However, no significant correlation was found between NEE and ER ( $r=-0.156$ ;  $p=0.418$ ). These results indicate that NEE variations at the tundra sites were largely driven by changes in photosynthesis rates rather than respiration. A similar pattern of NEE and gross photosynthesis has been found in other Arctic tundra, including that near Daring Lake in the Northwest Territories of Canada (McFadden et al., 2003) and along a transect from the Arctic coast to latitudinal treeline in



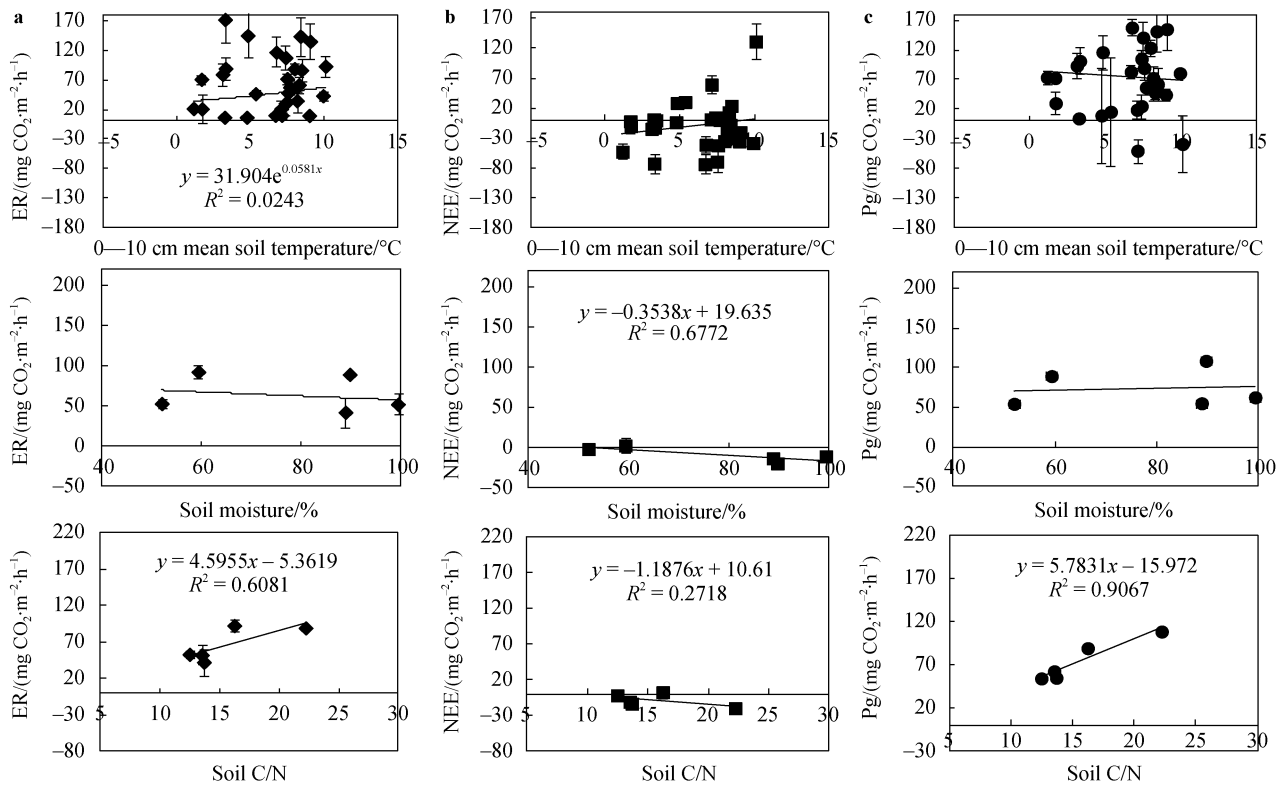
**Figure 4** Summertime NEE (a), ER (b) and gross photosynthesis (c) from tundra observation sites DM1—DM5. The lines with square indicate net ecosystem CO<sub>2</sub> exchange, the lines with diamond indicate ecosystem respiration and the lines with circle indicate photosynthesis rates. Pg indicates gross photosynthesis.



**Figure 5** a, The correlation between net ecosystem CO<sub>2</sub> exchange (NEE) and photosynthesis rates. b, The correlation between net ecosystem CO<sub>2</sub> exchange (NEE) and ecosystem respiration (ER) at the observation sites in the High Arctic.



**Figure 6** Comparisons of the daily net CO<sub>2</sub> fluxes (a), ecosystem respiration (b) and photosynthesis rates (c) from the tundra site DM6. The lines with square indicate net ecosystem CO<sub>2</sub> exchange, the lines with diamond indicate ecosystem respiration and the lines with circle indicate photosynthesis rates.



**Figure 7** Correlations between ER (a), NEE (b), gross photosynthesis and soil chemical properties (c, 0–10 mean soil temperature, soil moisture (SM) and C/N ratio) at the observation sites in the High Arctic. Pg indicates gross photosynthesis.

northern Alaska (Lafleur and Humphreys, 2007), plus in Antarctic tundra such as at Ardley Island (Zhu et al., 2014a). Tundra vegetation coverage may be more important to net CO<sub>2</sub> flux rather than bacterial respiration and the mineralization of organic matter (Ding et al., 2013). Therefore, tundra vegetation photosynthesis is the dominant influence on NEE in the High Arctic (Zhu et al., 2010). In contrast, differences in NEE of Alaskan tussock tundra were reported to be driven more by changes in ER (Vourlitis and Oechel, 1999). Thus, not all the tundra sites are the same, and predicting responses to climatic change requires knowledge of both the distribution of tundra type and ecophysiological functioning of various tundra types. A similar conclusion has been reported from plot-scale

chamber studies (Welker et al., 2004).

#### 4.2 Effects of environmental variables on tundra NEE, ER and gross photosynthesis

Higher soil organic carbon contents may support a more abundant soil bacterial component, resulting in more intense soil respiration responsible for higher CO<sub>2</sub> emissions (Ma et al., 2013). In our study, both mean NEE ( $r=-0.891$ ,  $p=0.043$ ) and photosynthesis rates ( $r=0.952$ ,  $p=0.013$ ) showed significant correlations with soil C/N ratio (Table 3). Therefore, substantial organic C and N at the tundra sites could significantly increase gross photosynthesis and NEE via the acceleration of mineralization rates in organic C in the High Arctic.



An increase in temperature could slightly reduce C gain by increasing respiratory loss (Nakatsubo, 2002; Gregorich et al., 2006; Park et al., 2007; Cannone et al., 2012). Davidson et al. (1998) observed that  $Q_{10}$  ranged from 3.4 to 5.6 in a temperate mixed hardwood forest. Xu and Qi (2001) found a  $Q_{10}$  range from 1.21 to 2.63 for a Sierra Nevada forest in California. The  $Q_{10}$  value of 1.80 in this study was near those reported by the above references, indicating a similar weak temperature sensitivity of tundra  $\text{CO}_2$  production. This is possibly associated with similar nutrient availability in the soil ecosystem. Analogously, the soil respiration response to temperature was stronger in nutrient-rich soils, and there were larger  $Q_{10}$  values in such soils (Paz-Ferreiro et al., 2012). Our study area included slightly waterlogged wetland tundra (DM1–DM2), mesic tundra (DM3), and dry tundra (DM4–DM5) along transect with increasing elevation from the coastal tundra (Zhu et al., 2012). The tundra ER and gross photosynthesis were maximally in the mesic tundra, and decreased to the dry tundra (Table 2). Soil moisture is generally considered to have a strong impact on C and N mineralization or flux rates, thereby affecting photosynthetic rates (Davey and Rothery, 1997; Borken and Matzer, 2009). Photosynthetic rates were also correlated with soil moisture in habitats vegetated by Antarctic bryophytes (Davey and Rothery). As shown in Figure 6, mean NEE had a relatively strong correlation with soil moisture ( $R^2=0.677$ ), indicating that lowering of the water table increased C loss from the tundra. Increases in soil water availability are likely to have strong biological effects in terrestrial ecosystems (Davis, 1981; Robinson et al., 2003; Convey and Smith, 2006). Overall, soil temperature, nutrients and moisture may be key influences on  $\text{CO}_2$  fluxes in the High Arctic.

### 4.3 Comparisons with other measurements and regional implications

The net mean NEE was  $-3.3$  to  $19.0 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ , and fluxes at most tundra sites exceeded  $10 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$  over the observation period. This indicates a net  $\text{CO}_2$  emission in the High Arctic. Most global ecosystems are net sinks for  $\text{CO}_2$  because of photosynthesis by vegetation (Dalal and Allen, 2008). Examples include an active bird area rich in vegetation at Ny-Ålesund ( $-107.6\pm 19.2 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ) and a marine animal colony with dense tundra vegetation in maritime Antarctica (Zhu et al., 2014a) ( $-37.2$  to  $5.2 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ). However, results from the tundra sites with sparse vegetation agreed with those from terrestrial ecosystems of the coastal Antarctic lacking vegetation (Zhu et al., 2009), and were well within the range of values for a moderate seabird activity area of Ny-Ålesund described by Chen et al. (2012) ( $21.7\pm 9.7 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ). Our results reveal that the High Arctic tundra was a weak  $\text{CO}_2$  emission source. Mean ER was  $42.8$  to  $92.9 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ , and photosynthesis rates were  $-40.3$  to  $-91.2 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ .

Our ER results were in accord with those from middle upland ( $-77.4\pm 16.0 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ) and western lowland tundra ( $-87.1\pm 18.1$ ) on Ardley Island (Zhu et al., 2014b). Our photosynthesis rates were lower than for a penguin colony ( $219.7\pm 34.5 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ), but were similar to those from penguin-free sites ( $128.6\pm 20.1 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ) on Ardley Island (Zhu et al., 2014b).

### 4.4 Uncertainty of $\text{CO}_2$ flux

The present study is limited by several uncertainties. First, uncertainties of mean NEE and ER may be caused by error associated with chamber measurement. This may be caused by: (i) lack of spatial representation, which might be attributable to the limited sampling points, effects of spatial variability in vegetation cover, community compositions and soil properties in the High Arctic, and inadequate measurement periods (Ding et al., 2013); (ii) changes of temperature under the transparent chambers (Zheng et al., 2008). These factors could have impacted our mean NEE and ER measurements.

Second, our observation gave a short, summertime mean NEE and ER in ice-free tundra of the High Arctic, and fluxes were measured only between 9:00 and 11:00 local time. Results from the Arctic tundra showed an even smaller summer budget (Oechel et al., 1997; Lafleur and Humphreys, 2007), and snow-cover season  $\text{CO}_2$  emissions and fluxes outside the measured period remain unknown. It is difficult to evaluate the importance of summertime C exchanges in the annual C budget of the High Arctic.

## 5 Conclusions

We documented summer NEE, ER and photosynthesis at six tundra sites (DM1–DM6) on Ny-Ålesund in the High Arctic, revealing relationships between NEE, gross photosynthesis and environmental variables for tundra NEE, photosynthesis rates and ER. Most NEE values at the tundra sites exceeded  $10 \text{ mg CO}_2\cdot\text{m}^{-2}\cdot\text{h}^{-1}$  over the observation period, indicating a net weak  $\text{CO}_2$  source in the High Arctic. Tundra NEE showed significant correlation with gross photosynthesis, but no significant correlation with ER was found. This suggests that variations in NEE were largely driven by change in photosynthesis rates at the tundra sites. Both mean NEE and the photosynthesis rates showed significant correlations with soil C/N ratio. Tundra ER, NEE and gross photosynthesis all showed variations between the slightly waterlogged tundra, mesic tundra and dry tundra, along transect inland from the coastal tundra. A  $Q_{10}$  value of 1.80 indicated weak temperature sensitivity of tundra ER and its response to future global warming. Thus, soil temperature, nutrients and moisture may be key influences on  $\text{CO}_2$  fluxes in the High Arctic.

**Acknowledgments** This work was supported by the National Natural Science Foundation of China (Grant nos. 41576181 and 41176171) and

Specialized Research Fund for the Doctoral Program of Higher Education (Grant no. 20123402110026). We thank Chinese Arctic and Antarctic Administration and members of the Chinese National Arctic Research Expedition for their support and assistance.

## References

- ACIA. 2004. Arctic climate impact assessment. Cambridge, UK: Cambridge University Press
- ACIA. 2005. Impacts of a warming arctic: arctic climate impact assessment. Cambridge, UK: Cambridge University Press
- Borken W, Matzner E. 2009. Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Glob Change Biol*, 15(4): 808–824
- Cannone N, Binelli G, Worland M R, et al. 2012. CO<sub>2</sub> fluxes among different vegetation types during the growing season in Marguerite Bay (Antarctic Peninsula). *Geoderma*, 189–190: 595–605
- Chapin III F S, Sturm M, Serreze M C, et al. 2005. Role of land-surface changes in arctic summer warming. *Science*, 310(5748): 657–660
- Chen Q Q, Zhu R B, Ding W, et al. 2012. Effects of seabird activity on carbon dioxide exchange between tundra and atmosphere in Ny-Ålesund, Arctic. *Chin J Polar Res*, 24(3): 254–265 (in Chinese)
- Chen Q Q, Zhu R B, Wang Q, et al. 2014. Methane and nitrous oxide fluxes from four tundra ecotopes in Ny-Ålesund of the High Arctic. *J Environ Sci*, 26(7): 1403–1410
- Convey P, Smith R I L. 2006. Responses of terrestrial Antarctic ecosystems to climate change. *Plant Ecol*, 182(1–2): 1–10
- Corradi C, Kolle O, Walter K, et al. 2005. Carbon dioxide and methane exchange of a North-East Siberian tussock tundra. *Glob Change Biol*, 11(11): 1910–1925
- Dalal R C, Allen D E. 2008. Greenhouse gas fluxes from natural ecosystems. *Aust J Bot*, 56(5): 369–407
- Davey M C, Rothery P. 1997. Interspecific variation in respiratory and photosynthetic parameters in Antarctic bryophytes. *New Phytol*, 137(2): 231–240
- Davidson E A, Belk E, Boone R D. 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Glob Change Biol*, 4(2): 217–227
- Davidson E A, Janssens I A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, 440(7081): 165–173
- Davis R C. 1981. Structure and function of two Antarctic terrestrial moss communities. *Ecol Monogr*, 51(2): 125–143
- Ding W, Zhu R B, Ma D W, et al. 2013. Summertime fluxes of N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> from the littoral zone of Lake Daming, East Antarctica: effects of environmental conditions. *Antarct Sci*, 25(6): 752–762
- Dorrepaal E, Toet S, Van Logtestijn R S P, et al. 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. *Nature*, 460(7255): 616–619
- Gregorich E G, Hopkins D W, Elberling B, et al. 2006. Emission of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from lakeshore soils in an Antarctic dry valley. *Soil Biol Biochem*, 38(10): 3120–3129
- Griffis T J, Rouse W R. 2001. Modelling the interannual variability of net ecosystem CO<sub>2</sub> exchange at a subarctic sedge fen. *Global Change Biol*, 7(5): 511–530
- Groendahl L, Friborg T, Soegaard H. 2007. Temperature and snow-melt controls on interannual variability in carbon exchange in the high Arctic. *Theor Appl Climatol*, 88(1–2): 111–125
- Heikkinen J E P, Virtanen T, Huttunen J T, et al. 2004. Carbon balance in East European tundra. *Glob Biogeochem Cycles*, 18(1): GB1023, doi: 10.1029/2003GB002054
- Hutchinson G L, Mosier A R. 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. *Soil Sci Soc Am J*, 45(2): 311–316
- IPCC. 2007. Climate change 2007: the physical science basis. Cambridge, New York: Cambridge University Press
- IPCC. 2013. Climate change 2013: the physical science basis: contribution of working group I to the fifth assessment report of the IPCC// Stocker T F, Qin D, Plattner G K, et al. Summary for policymakers. Cambridge, United Kingdom, New York: Cambridge University Press, 24–25
- Jørgensen C J, Struwe S, Elberling B. 2012. Temporal trends in N<sub>2</sub>O flux dynamics in a Danish wetland - effects of plant-mediated gas transport of N<sub>2</sub>O and O<sub>2</sub> following changes in water level and soil mineral-N availability. *Glob Change Biol*, 18(1): 210–222
- Jungkunst H F, Fiedler S. 2007. Latitudinal differentiated water table control of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes from hydromorphic soils: feedbacks to climate change. *Global Change Biol*, 13(12): 2668–2683
- Keeney D R, Nelson D W. 1982. Nitrogen-inorganic forms//Page A L, Miller R H, Keeney D R. Methods of soil analysis, Part 2: chemical and microbiological properties, 2nd edn. Madison WI: American Society of Agronomy, 643–698
- Kuzyakov Y, Gavrichkova O. 2010. Time lag between photosynthesis and carbon dioxide efflux from soil: a review of mechanisms and controls. *Glob Change Biol*, 16(12): 3386–3406
- Lafleur P M, Humphreys E R. 2007. Spring warming and carbon dioxide exchange over low Arctic tundra in central Canada. *Glob Change Biol*, 14(4): 740–756
- Ma D W, Zhu R B, Ding W, et al. 2013. Ex-situ enzyme activity and bacterial community diversity through soil depth profiles in penguin and seal colonies on Vestfold Hills, East Antarctica. *Polar Biol*, 36(9): 1347–1361
- McFadden J P, Eugster W, Chapin III F S. 2003. A regional study of the controls on water vapor and CO<sub>2</sub> exchange in arctic tundra. *Ecology*, 84(10): 2762–2776
- Nakatsubo T. 2002. Predicting the impact of climatic warming on the carbon balance of the moss *Sanionia uncinata* on a maritime Antarctic island. *J Plant Res*, 115(2): 99–106
- Nobrega S, Grogan P. 2008. Landscape and ecosystem-level controls on net carbon dioxide exchange along a natural moisture gradient in Canadian low arctic tundra. *Ecosystems*, 11(3): 377–396
- Oberbauer S F, Tweedie C E, Welker J M, et al. 2007. Tundra CO<sub>2</sub> fluxes in response to experimental warming across latitudinal and moisture gradients. *Ecol Monogr*, 77(2): 221–238
- Oechel W C, Vourlitis G L. 1994. The effects of climate change on land-atmosphere feedbacks in arctic tundra regions. *Trends Ecol Evol*, 9(9): 324–329
- Oechel W C, Vourlitis G, Hastings S J. 1997. Cold season CO<sub>2</sub> emission

- from arctic soils. *Glob Biogeochem Cycles*, 11(2): 163–172
- Oechel W C, Vourlitis G L, Hastings S J, et al. 2000. Acclimation of ecosystem CO<sub>2</sub> exchange in the Alaskan Arctic in response to decadal climate warming. *Nature*, 406(6799): 978–981
- Park J H, Day T A, Strauss S, et al. 2007. Biogeochemical pools and fluxes of carbon and nitrogen in a maritime tundra near penguin colonies along the Antarctic Peninsula. *Polar Biol*, 30(2): 199–207
- Paz-Ferreiro J, Medina-Roldán E, Ostle N J, et al. 2012. Grazing increases the temperature sensitivity of soil organic matter decomposition in a temperate grassland. *Environ Res Lett*, 7(1): 014027
- Pelletier L, Garneau M, Moore T R. 2011. Variation in CO<sub>2</sub> exchange over three summers at microform scale in a boreal bog, Eastmain region, Québec Canada. *J Geophys Res Biogeosci*, 116(G3): G03019
- Poyatos R, Heinemeyer A, Ineson P, et al. 2014. Environmental and vegetation drivers of seasonal CO<sub>2</sub> fluxes in a sub-arctic forest–mire ecotone. *Ecosystems*, 17(3): 377–393
- Rastogi M, Singh S, Pathak H. 2002. Emission of carbon dioxide from soil. *Current Sci*, 82(5): 510–517
- Riutta T, Laine J, Aurela M, et al. 2007. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem. *Tellus B*, 59(5): 838–852
- Robinson S A, Wasley J, Tobin A K. 2003. Living on the edge - plants and global change in continental and maritime Antarctica. *Glob Change Biol*, 9(12): 1681–1717
- Schuur E A G, Vogel J G, Crummer K G, et al. 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, 459(7246): 556–559
- Serreze M C, Walsh J E, Chapin III F S, et al. 2000. Observational evidence of recent change in the northern high-latitude environment. *Clim Change*, 46(1–2): 159–207
- Ström L, Christensen T R. 2007. Below ground carbon turnover and greenhouse gas exchanges in a sub-arctic wetland. *Soil Biol Biochem*, 39(7): 1689–1698
- Sun L G, Liu X D, Yin X B, et al. 2004. A 1500-year record of Antarctic seal populations in response to climate change. *Polar Biol*, 27(8): 495–501
- Trenberth K E, Jones P D, Ambenje P, et al. 2007. Observations: surface and atmospheric climate change//Solomon S, Qin D, Manning M, et al. *Climate Change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom, New York: Cambridge University Press, 235–336
- Ullah S, Moore T R. 2011. Biogeochemical controls on methane, nitrous oxide, and carbon dioxide fluxes from deciduous forest soils in eastern Canada. *J Geophys Res*, 116(G3): G03010
- Vourlitis G L, Oechel W C. 1999. Eddy covariance measurements of CO<sub>2</sub> and energy fluxes of an Alaskan tussock tundra ecosystem. *Ecology*, 80(2): 686–701
- Welker J M, Fahnestock J T, Henry G H R, et al. 2004. CO<sub>2</sub> exchange in three Canadian High Arctic ecosystems: response to long-term experimental warming. *Glob Change Biol*, 10(12): 1981–1995
- Westermann S, Wollschläger U, Boike J. 2010. Monitoring of active layer dynamics at a permafrost site on Svalbard using multi-channel ground-penetrating radar. *Cryosph*, 4(4): 475–487
- Winther J G, Godtlielsen F, Gerland S, et al. 2002. Surface albedo in Ny-Ålesund, Svalbard: variability and trends during 1981–1997. *Glob Planet Change*, 32(2–3): 127–139
- Xu M, Qi Y. 2001. Spatial and seasonal variations of Q<sub>10</sub> determined by soil respiration measurements at a Sierra Nevada forest. *Glob Biogeochem Cycles*, 15(3): 687–696
- Zheng X H, Xie B H, Liu C Y, et al. 2008. Quantifying net ecosystem carbon dioxide exchange of a short-plant cropland with intermittent chamber measurements. *Glob Biogeochem Cycles*, 22(3): GB3031
- Zhu R B, Liu Y S, Ma J, et al. 2008. Nitrous oxide flux to the atmosphere from two coastal tundra wetlands in eastern Antarctica. *Atmos Environ*, 42(10): 2437–2447
- Zhu R B, Liu Y S, Ma E D, et al. 2009. Nutrient compositions and potential greenhouse gas production in penguin guano, ornithogenic soils and seal colony soils in coastal Antarctica. *Antarct Sci*, 21(5): 427–438
- Zhu R B, Liu Y S, Xu H, et al. 2010. Carbon dioxide and methane fluxes in the littoral zones of two lakes, East Antarctica. *Atmos Environ*, 44(3): 304–311
- Zhu R B, Chen Q Q, Ding W, et al. 2012. Impact of seabird activity on nitrous oxide and methane fluxes from High Arctic tundra in Svalbard, Norway. *J Geophys Res*, 117(G4): G04015
- Zhu R B, Ma D W, Xu H. 2014a. Summertime N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> exchanges from a tundra marsh and an upland tundra in maritime Antarctica. *Atmos Environ*, 83: 269–281
- Zhu R B, Bao T, Wang Q, et al. 2014b. Summertime CO<sub>2</sub> fluxes and ecosystem respiration from marine animal colony tundra in maritime Antarctica. *Atmos Environ*, 98: 190–201