



## Spatial characteristics of ecosystem respiration in three tundra ecosystems of Alaska



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### ABSTRACT

Ecosystem respiration (ER) is a significant source in estimating terrestrial carbon budget under climate change. Here, we report on the assessment of spatial characteristics of ER, using manual chamber over three tundra ecosystems of Alaska. Annual simulated ER was 254–307 g CO<sub>2</sub> m<sup>-2</sup> based on *in-situ* air temperature and 212–305 g CO<sub>2</sub> m<sup>-2</sup> based on soil temperature, at Council, North Slope, and Arctic National Wildlife Refuge (ANWR) sites of Alaska. Growing-season ERs correspond to 79–92% (air temperature) and 81–86% (soil temperature) of simulated annual ER. Hence, soil temperature is a significant driver in modulating ER over tundra, suggesting soil temperature elucidates more than 80% of air temperature. At Council, between 31 and 84 sampling points during the growing season were required to attain spatial representativeness for ER, falling within ±10% of the full sample mean, with a 95% confidence level. At North Slope and ANWR sites, the number of sampling points was chosen to yield results within at least ±20%, with a 90% confidence level. These findings suggest that larger-size chamber and its measurement frequency can overcome logistical constraints and determine mean ER at tundra sites for the quantitative assessment of the tundra carbon budget in response to drastically changing Arctic environment and climate.

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## 1. Introduction

Ecosystem respiration (ER)—the sum of soil microbe- and plant-respired carbon dioxide (CO<sub>2</sub>) from the soil surface to the atmosphere—represents the second-largest source of carbon emissions between the atmosphere and the terrestrial ecosystem on a global scale (Schlesinger and Andrews, 2000; Bond-Lamberty and Thomson, 2010). Respiration in the tundra ecosystem depends on both the distribution of vegetation and the content of soil organic matter (SOM), with bioclimate and environmental gradients (Ping et al., 2008), all of which determine the spatial variability of respiration. Oechel et al. (1997) and Grogan and Chapin (2000) demonstrated that CO<sub>2</sub> exchange in tussock community was an order of magnitude greater than in wet sedge in the Arctic tundra

ecosystem of Alaska. In other words, according to vegetation distribution, CO<sub>2</sub> production rate depends on different decomposition rates of SOM (Phillips et al., 2011), as well as on differences in environmental elements such as soil temperature and soil moisture. Further, it is widely observed that soil temperature and soil moisture play significant roles in determining respiration rates in the terrestrial ecosystem (Lloyd and Taylor, 1994; Davidson and Janssens, 2006; Bond-Lamberty and Thomson, 2010; Kim et al., 2013).

Tussock cotton grass (*Eriophorum vaginatum*) inhabits flat to moderate (up to about 27% (15°)) slopes underlain by permafrost (Wein, 1973; Alpert and Oechel, 1984; Kummerow et al., 1988). Tussock cotton grass communities occur in lowlands, coastal plains, patterned ground resulting from geomorphic and freeze-thaw processes (e.g., tops of high-centered polygons, rims of low-centered polygons, edges of frost boils), rolling uplands, gentle foothill slopes, flat summits, plateaus, and boreal zones (Hulten, 1968; Bliss et al., 1973; Chapin, 1974; Peterson and Billings, 1980; Kummerow et al., 1988). Gently sloping (<5%)

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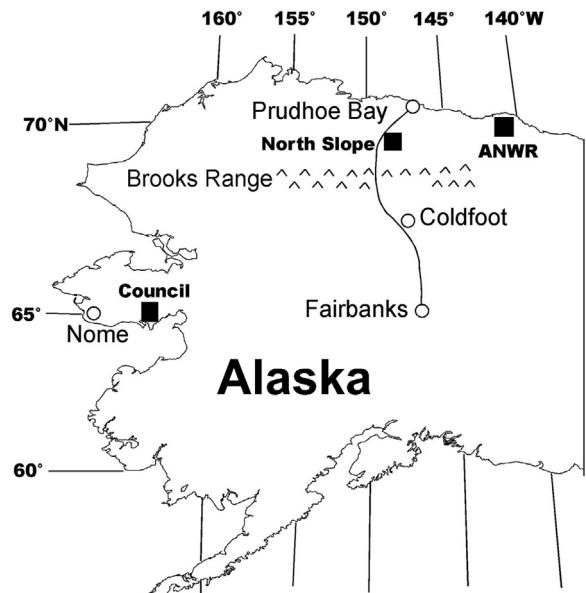
areas of tussock cotton grass tundra cover wide expanses of northern Alaska, Canada, and Russia (Wein, 1973). Hence, tussock represents both widely distributed and typical vegetation in Arctic tundra and boreal forest ecosystems of the pan-Arctic region (Miller et al., 1983; Oechel et al., 1997; Whalen and Reeburgh, 1988; Walker et al., 2008; Kim et al., 2013). Tussock tundra in Alaska is also a well-known source of carbon efflux to the atmosphere (Oechel et al., 1997; Kim et al., 2013). In two tundra sites across the North–South transect during the growing seasons of 2006–2010, Kim et al. (2013) noted that mean soil CO<sub>2</sub> effluxes from tussock and non-tussock (e.g., moss and lichen) regimes were  $29.7 \pm 6.8$  and  $8.8 \pm 6.6$  mgCO<sub>2</sub> m<sup>-2</sup> min<sup>-1</sup>, respectively. This suggests that soil-originated CO<sub>2</sub> emissions in tussock were much higher than in non-tussock vegetation, as well as a significant source of atmospheric CO<sub>2</sub> in the Alaska ecosystem. Further, Oechel et al. (1997) reported that even winter CO<sub>2</sub> efflux within tussock was a significant CO<sub>2</sub> source, and was much greater than in wet sedge on the Arctic coastal tundra plain of Barrow, Alaska. Our study provides understanding of spatial ecosystem respiration (ER) at three different tundra sites, generating evaluations of carbon budgets on local, regional, and Arctic scales.

Estimated levels of ER can be affected by the measurement methods used, due to factors such as chamber size (e.g., active cross-section), measurement frequency (e.g., hourly, weekly, seasonal, and annual), and efflux-measuring system type (e.g., manual or automated chamber). The spatial variability of ER within a constant area can be described by the coefficient of variance (CV, %), and the number of measuring points required for estimating a statistically significant mean ER can be obtained from this CV value. Manual chamber systems can more easily capture the spatial heterogeneity of a site; on the other hand, an automated chamber system offers greater measurement frequency during snow-free periods (Davidson et al., 2002; Hutchinson and Livingston, 2002; Savage and Davidson, 2003). As this study also intends to focus on the spatial heterogeneity of ER at each site, we used a manual chamber system to examine the spatial variability of ecosystem respiration, within three different tundra environments of Alaska. For example, Yim et al. (2003) calculated that the CV for spatial variability in soil respiration across 50 sampling points within a 30 × 30-m plot was 28%, using a small active area chamber (0.0125 m<sup>2</sup>) within a larch plantation of Hokkaido, Japan in late August 2000. Average numbers for sampling points required for estimating soil respiration within 10% and 20% of its true mean, at the 95% confidence level, were estimated as 26 and 6, respectively. Therefore, the objectives of this study were to 1) evaluate the dependence of temperature on ecosystem respiration within different tundra ecosystems, and 2) assess the spatial characteristics of ecosystem respiration using a manual chamber system within a constant plot at three distinct environmental locations in Alaska (e.g., Council, North Slope, and ANWR), all of which are remote, extremely difficult to access, and require permitting for the investigation from the Alaska Department of Fish and Game and the Bureau of Land Management (BLM) of the Department of Interior.

## 2. Material and methods

### 2.1. Research site

The three research sites observed in Alaska are remotely isolated, managed, and protected by federal and/or state government, representing a relatively undisturbed tundra ecosystem. Council, the North Slope, and ANWR are located in western, northern, and northeastern Alaska, respectively (Fig. 1). Table 1 lists the geographical features of each site, showing distinct differences in weather patterns and dominant plant species among the sites,



**Fig. 1.** Site locations: Council on the Seward Peninsula, the North Slope, and ANWR (Arctic National Wildlife Refuge), Alaska.

indicating differences in latitudinal and longitudinal distributions. Annual average air temperature and precipitation for these three sites were calculated from 6-, 25-, and 40-year measured data (National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA)). Fig. 2 shows daily mean soil temperature monitored at 5 cm depth below the soil surface at each site. Mean (and range) for observed soil temperatures at Council (2011), North Slope (2011), and ANWR (2008) were  $-0.6$  ( $-15.4$  to  $15.7$ ) °C,  $-6.4$  ( $-21.0$  to  $13.8$ ) °C, and  $-5.8$  ( $-22.3$  to  $11.5$ ) °C, respectively, while daily mean (and range) air temperatures were  $-2.8$  ( $-33$  to  $16.7$ ) °C,  $-13.7$  ( $-46.6$  to  $27.2$ ) °C, and  $-10.2$  ( $-35.6$  to  $11.7$ ) °C. Experimental plot size was 40 × 40 m (total 81 points; 5-m interval) at Council, 30 × 30 m (49 points; 5-m interval) at North Slope, and 40 × 100 m (55 points; 10-m interval) at ANWR. We performed ER observations at each point during the given growing season. At Council, I have measured two-time ERs for seven days a month at 81 points. Considering the constraints of accessibility and weather conditions, I conducted ER once for two days at 49 points at the North Slope site, and once for a week at 55 points at the ANWR site. Further, daytime (11am–6 pm) ER measurement was conducted at each Alaska site during summer. Summer in Alaska includes three months of sunlight throughout most of the day and night.

The thickness of organic matter layer is 22, 30, and 20 cm in Council, North Slope, and ANWR (Watanabe et al., 2012), respectively.

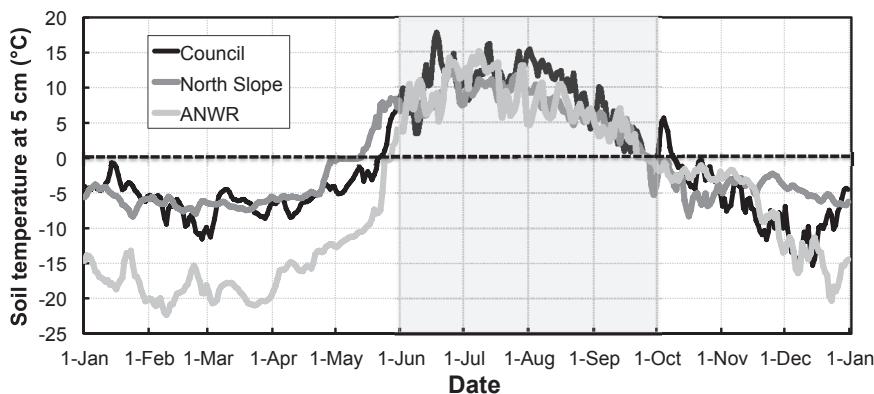
### 2.2. Ecosystem respiration (ER)

The system consisted of a chamber (24-cm diameter; 17-cm height), pump (flow rate: 1.0 L min<sup>-1</sup>; CM-15-12, Enomoto Micro Pump Co., Japan), NDIR (non-dispersive infra-red) CO<sub>2</sub> analyzer (Licor-820, Licor Inc., USA), commercial 12-V battery, a Gelman filter and Mg(ClO<sub>4</sub>)<sub>2</sub> column for removal of dust and water vapor, and a laptop computer running efflux calculation software (Savage and Davidson, 2003; Kim et al., 2013). After insertion of the stainless steel chamber base (24-cm diameter; 10-cm height; active cross section of 0.045 m<sup>2</sup>) into the soil surface, we measured ER using the manual chamber system at each site after several days of

**Table 1**

Summary of site characteristics in the tundra ecosystem of Alaska.

Site	Council	North slope (upland)	ANWR (Arctic National Wildlife Refuge)
Latitude (degree)	64°51'38" N	68°54'17" N	69°43'24" N
Longitude (degree)	163°42'39" W	148°52'33" W	143°38'12" W
Elevation (m.a.s.l.)	45	440	152
Aspect	SW	SE	SW
Thickness of organic layer (cm)	22	30	20
Ecosystem type	Coastal plain	Subarctic upland	Coastal plain
Dominant species	<i>Sphagnum</i> spp., <i>Thuidium abietinum</i> , <i>Cladonia</i> spp., <i>Eriophorum vaginatum</i>	<i>Eriophorum vaginatum</i> , <i>Ledum palustre</i> , <i>Betula glandulosa</i> , <i>Vaccinium vitis-idaea</i>	<i>Carex aquatilis</i> , <i>Ledum palustre</i> , <i>Vaccinium vitis-idaea</i> , <i>Sphagnum</i> spp.
Observation period	June–September, 2011 and 2012	June–July 2011 –7.2	July–August 2008 –12.8
Annual air temperature (°C)	–2.1		
Annual precipitation (mm)	485	252	153
Sampling frequency	81	49	55
Plot surface (m <sup>2</sup> )	1600	900	4000
Interval (m)	5	5	10

**Fig. 2.** Seasonal variations of in-situ daily mean soil temperature at 5 cm below the surface at Council (2009), North Slope (2011), and ANWR (2008) sites.

the base deployment.

ER measuring time was 5–10 min, depending on weather and soil surface conditions; we calculated efflux from the equation

$$ER_{CO_2} = (\Delta C / \Delta t) \times (V/A), \quad (1)$$

where  $\Delta C$  (ppmv) is the change in  $CO_2$  concentration during the measurement period ( $\Delta t$ , min),  $V$  is chamber volume, and  $A$  is surface area (cross section = 0.045 m<sup>2</sup>). The pump was kept at a flow rate of 1.0 L min<sup>-1</sup> to avoid underestimation or overestimation of ecosystem respiration due to under-/over-pressurization, as well as restrictions in flow and air circulation in the chamber (Davidson et al., 2002). Soil temperature, in parallel with the measurement of ecosystem respiration, was measured at 5 and 10 cm below the soil surface, using a portable probe thermometer (Model 8402-20, Cole-Palmer, USA). We determined the dependency of measured ER on temperature by fitting the following equation over soil temperatures, which are much lower in Alaska, at 5-cm depth rather than 10 cm (see Fig. 4; Kim et al., 2013). Hence we discuss the response of ER to soil temperature at 5-cm depth hereafter:

$$ER_{CO_2} = \beta_0 \times e^{\beta_1 \times T}, \quad (2)$$

where  $ER_{CO_2}$  is measured ecosystem respiration (mg  $CO_2$  m<sup>-2</sup> min<sup>-1</sup>),  $T$  is soil temperature (°C) at 5-cm depth, and  $\beta_0$  and  $\beta_1$  are constants. This exponential relationship is commonly used to represent ecosystem respiration and soil carbon efflux as

functions of temperature (Davidson et al., 1998; Kim et al., 2013, 2014).  $Q_{10}$  is a measure of the change in reaction rate at intervals of 10 °C, and is based on Van't Hoff's empirical rule (Lloyd and Taylor, 1994).  $Q_{10}$  was calculated as in Davidson et al. (1998) and Davidson and Janssens (2006):

$$Q_{10} = e^{\beta_1 \times 10}. \quad (3)$$

A reference value for  $R_{10}$  (ecosystem respiration normalized to air temperature of 10 °C; Bergeron et al., 2007; Kim et al., 2014) for comparing ER from the three sites was then calculated as

$$R_i = R_{10} Q_{10}^{(T-10)/10}, \quad (4)$$

where  $R_i$  is simulated ecosystem respiration (mg  $CO_2$  m<sup>-2</sup> min<sup>-1</sup>) and  $T$  is air temperature and soil temperature (°C) observed at each site. Using calculated values for  $Q_{10}$  and  $R_{10}$ , simulated ecosystem respiration at each site was simulated on the basis of in-situ air temperature and soil temperature (Kim et al., 2014). This method was applied to meet the homoscedasticity condition (i.e., equal variance around the regression line for all values of the independent variable), which is required to perform regression using the  $Q_{10}$  function (Humphrey et al., 2006), as in equation (4).

Soil temperature at 5 cm below the surface was measured in conjunction with ER at each site with a portable thermometer (model 8402-20, Cole-Palmer, USA). For additional measurements of soil temperature, hourly temperatures at 5 cm below the surface

at tussock and non-tussock (HOBO data logger U-12 and sensor TMC6-HD, Onsetcomp, USA) were monitored at each site.

We performed a one-way ANOVA (95% confidence level) for this data, using Microsoft Excel Data Analysis software for covariance analysis. We used regression analysis to examine the relationship between ecosystem respiration and soil temperature at a depth of 5 cm, which is more sensitive than at 10 cm (Kim et al., 2014).

### 3. Results and discussion

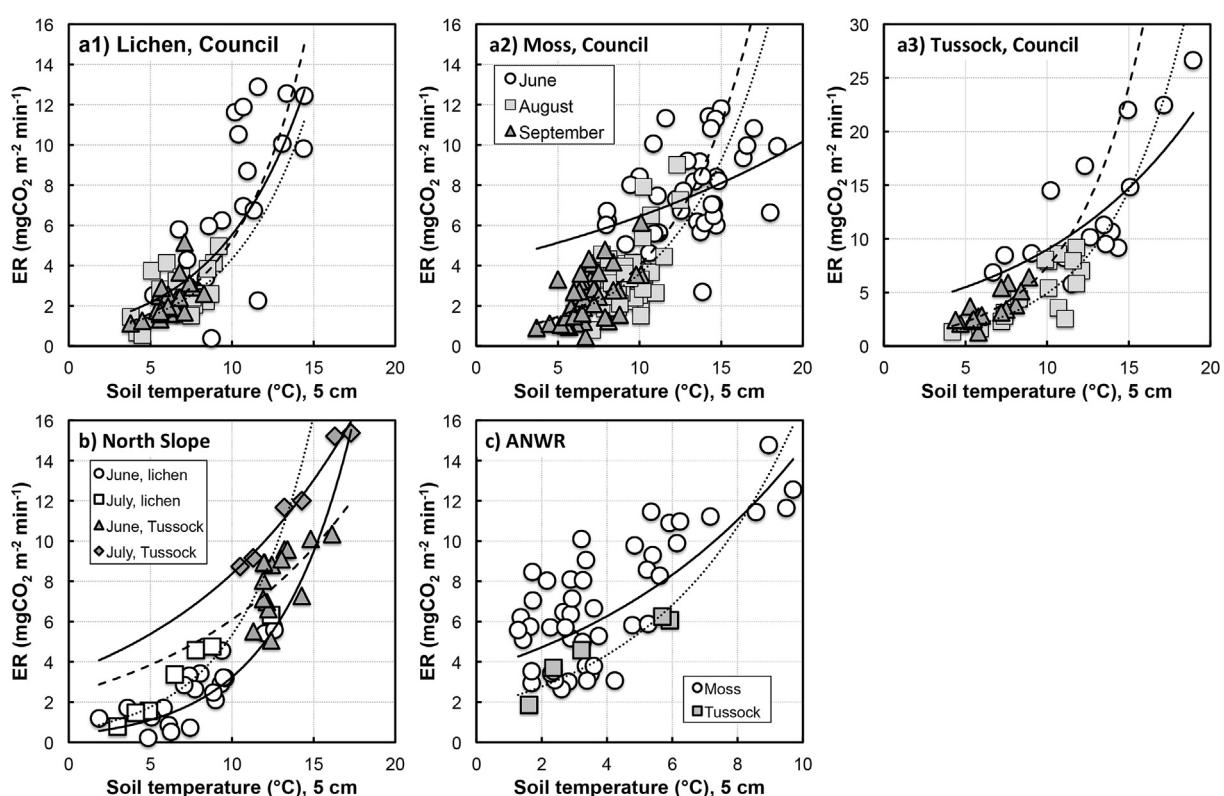
#### 3.1. Soil temperature regulating ecosystem respiration

At the Council and North Slope sites, ER showed seasonal variability and tended to decrease with time during the growing season, suggesting sensitivity to temperature when determining ER, as shown in Fig. 3a–c. ER in tussock tundra (Fig. 3a3) was twofold higher than in lichen and moss previously observed in Arctic tundra and boreal forest ecosystems (Miller et al., 1983; Oechel et al., 1997; Whalen and Reeburgh, 1988; Kim et al., 2013).

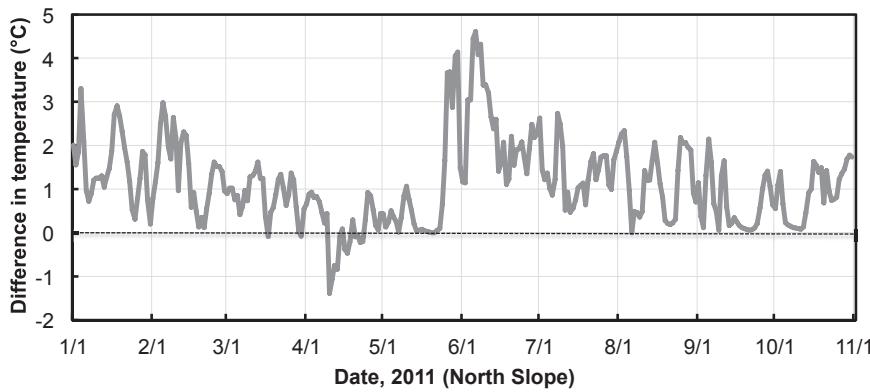
Mean ecosystem respiration rates from tussock tundra and non-tussock (e.g., lichen (*Cladonia* spp.) and moss (*Sphagnum* spp.)) regimes were  $7.2 \pm 2.9$  and  $4.5 \pm 2.9 \text{ mg CO}_2 \text{ m}^{-2} \text{ min}^{-1}$ , respectively, at Council, and  $7.3 \pm 5.1$  in tussock and  $4.9 \pm 3.2 \text{ mg CO}_2 \text{ m}^{-2} \text{ min}^{-1}$  in lichen at the North Slope site. ER observed in tussock was 1.5 times higher than in non-tussock, as reported by both Oechel et al. (1997) and Kim et al. (2013). This may result from 1) a distinct difference in temperature between tussock and non-tussock, reflecting the temperature difference ( $-1.39\text{--}4.61^\circ\text{C}$ ; Fig. 4) at the North Slope site from January 1 to October 31, 2011, and subsequently, 2) differences in microbial and plant respiration between tussock and non-tussock. Hence, higher temperature in tussock plays an important role in stimulating ER compared to that

of non-tussock, and leads to higher ER at the North Slope site. The reversal in temperature for both on April 9–10 may be due to a change in local weather, indicating that temperature in tussock, covered by thin snow depth, is vulnerable to colder air temperature; meanwhile, temperature in non-tussock is relatively stable and warm. After seasonal snowpack disappeared, tussock temperature was much higher than in non-tussock in mid-June (Fig. 4). Therefore, tussock tundra represents a significant atmospheric  $\text{CO}_2$  source across this widely distributed tundra ecosystem. Oechel et al. (1997) estimated that winter  $\text{CO}_2$  efflux in tussock was an important carbon source through the snowpack to the atmosphere—even ten times that of efflux in the wet sedge of the Barrow Arctic coastal tundra plain during the seasonal snow-covered season. Furthermore, tussock tundra covers a pan-Arctic region equivalent to  $9 \times 10^{11} \text{ m}^2$  (Miller et al., 1983)—and  $6.5 \times 10^{12} \text{ m}^2$  if moss is included (Whalen and Reeburgh, 1988)—yielding a quantitative understanding of atmospheric  $\text{CO}_2$  emissions from the Arctic tundra terrestrial ecosystem in response to the drastic climate change in the Arctic.

On the other hand, at the ANWR site, mean ecosystem respiration in tussock and non-tussock (dominant sphagnum) was  $4.5 \pm 1.8$  and  $6.9 \pm 3.1 \text{ mg CO}_2 \text{ m}^{-2} \text{ min}^{-1}$ , respectively, as shown in Fig. 3c, indicating lower ecosystem respiration in tussock. This may be due to shallower thaw depth ( $28.9 \pm 7.5 \text{ cm}$ ) at the ANWR site (Watanabe et al., 2012), reflecting a much slower decomposition rate of soil organic carbon from nearly saturated soil moisture, as compared to the Council ( $40.0 \pm 6.7 \text{ cm}$ ) and North Slope ( $35.5 \pm 7.1 \text{ cm}$ ) sites. Across the three sites,  $Q_{10}$  values ranged from 1.58 in moss to 10.7 in tussock at the Council site, compared to a narrow-range soil temperature ( $-1.0$  to  $0.0^\circ\text{C}$ ), which tends to result in much higher  $Q_{10}$  values ( $105\text{--}1.25 \times 10^6$ ; Monson et al., 2006), as shown in Table 2. Kim et al. (2013) described mean  $Q_{10}$



**Fig. 3.** Responses from ecosystem respiration rates to soil temperature at 5-cm depth at Council (a1–a3), North Slope (b), and ANWR (c) sites. Solid, grey, and open circles denote Council, North Slope, and ANWR. Exponential curve shows the relationship between ecosystem respiration and soil temperature for each month at each site.



**Fig. 4.** Temporal variation in difference in temperature between tussock and non-tussock (e.g., lichen) at North Slope site from January 1 to October 31, 2011.

**Table 2**

$Q_{10}$  values and correlation coefficient between ecosystem respiration and soil temperature at 5-cm depth at tundra sites during the growing season, based on a one-way ANOVA at the 95% confidence level\*.

Site	Month	Species	Soil temperature 5 cm				
			$Q_{10}$	$R^2$	$p$		
Council	June	Lichen	6.50	0.32	<0.001		
		Moss	1.58	0.19	0.124		
		Tussock	2.68	0.53	<0.001		
	August	Lichen	8.58	0.34	<0.001		
		Moss	6.59	0.39	<0.001		
		Tussock	8.66	0.67	<0.001		
	September	Lichen	10.59	0.43	<0.001		
		Moss	7.54	0.27	<0.001		
		Tussock	10.74	0.57	<0.001		
Upland	Total		5.83	0.58	<0.001		
	June	Lichen	8.56	0.50	<0.001		
		Tussock	2.52	0.32	<0.001		
	July	Lichen	9.27	0.86	<0.001		
		Tussock	2.45	0.67	<0.001		
	Total		9.32	0.75	<0.001		
ANWR	July–August		Moss	4.13	0.42		
			Tussock	9.58	0.79		
Total				4.40	0.42		
					<0.001		

\* These data are based on Fig. 3 and calculated by the equation (3).

value as higher for tundra sites than boreal forest sites, reflecting ecosystem respiration's different temperature dependency between the two ecosystems. Therefore, soil temperature is well known as a significant driver in determining ecosystem respiration, despite the different geological distributions and environmental controls across the sites, and can elucidate 58, 75, and 42% of ecosystem respiration at Council, North Slope, and ANWR, respectively.

### 3.2. Simulated ecosystem respiration

Based on our equation (4), the exponential curve between ecosystem respiration and soil temperature at 5 cm during a whole deployment period at each site, ecosystem respiration ( $R_{10}$ ), *in-situ* daily mean air temperature, and soil temperature at 5 cm below the surface at Council, the North Slope, and ANWR, simulated monthly ecosystem is shown in Table 3. Though we did monitor air/soil temperature at each site, we did not do it at each plant of each site. As a result, we assumed observed temperature to be representative at each site.

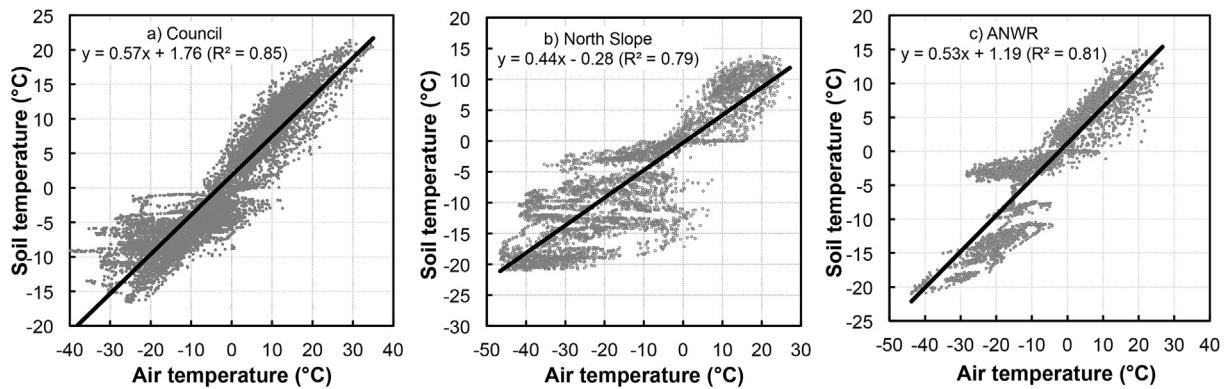
Annual simulated ecosystem respiration rates based on *in-situ* daily mean air temperature were 307, 266, and 254 g CO<sub>2</sub> m<sup>-2</sup> for the Council, North Slope, and ANWR sites, respectively, and

**Table 3**

Monthly ecosystem respiration simulated by our equation (4) and the exponential equation between *in-situ* ecosystem respiration and soil temperature, and *in-situ* daily mean temperature at each site.

Month/Site	Estimated ecosystem respiration (gC m <sup>-2</sup> )					
	Air temperature (°C)			Soil temperature (°C), 5 cm		
	Council	North slope	ANWR	Council	North slope	ANWR
January	3.7	0.5	1.2	5.3	2.6	2.3
February	1.8	0.3	1.2	2.4	1.8	1.6
March	2.3	0.1	1.6	3.2	2.0	1.6
April	5.4	0.3	8.5	3.6	3.4	2.8
May	35.1	18.6	29.7	12.0	25.1	8.8
June	68.4	91.0	75.7	79.0	62.0	48.9
July	65.1	94.3	65.4	89.1	84.6	63.0
August	63.3	50.2	43.2	74.9	46.0	38.9
September	47.0	10.0	16.9	21.2	18.6	21.4
October	10.1	0.7	5.3	10.0	3.9	12.5
November	1.8	0.1	3.4	2.8	4.0	8.2
December	2.8	0.2	2.4	2.0	2.7	2.9
Annual	307.0	266.3	254.4	305.5	256.7	212.9

growing season ERs (e.g., June 1 to September 30) represented 79, 92, and 79% of the sites' annual ecosystem respiration rates. Based on  $Q_{10}$  value during the observation period, together with our equation (4), we also calculated simulated daily ecosystem respiration based on *in-situ* daily mean soil temperature, yielding simulated ecosystem respirations of 305, 256, and 212 g CO<sub>2</sub> m<sup>-2</sup> for Council, North Slope, and ANWR, respectively, with growing season ERs representing 86, 82, and 81% of the sites' annual ecosystem respiration rates. Soil temperature further explained 85, 79, and 81% of air temperatures at the Council, North Slope, and ANWR sites, based on the relationship between both measured soil temperature and air temperature at each site (Fig. 5). Most ecosystem carbon models have used air temperature rather than soil temperature due to the constraint from soil temperature measurements over the estimation of the carbon budget at local and regional scales. Annual ecosystem respiration simulated at these three tundra sites was similar to the mean soil respiration over tundra (220 ± 22 gCO m<sup>-2</sup> yr<sup>-1</sup>; Raich and Schlesinger, 1992), considering the mean and standard deviation of 267 ± 36 gCO m<sup>-2</sup> yr<sup>-1</sup>. However, additional year-round monitoring of soil CO<sub>2</sub> efflux-measurement (e.g., ecosystem respiration and soil respiration) will be required to quantitatively estimate annual respiration at each site in response to recent warming Arctic.



**Fig. 5.** Responses from soil temperature at 5 cm below the soil surface to air temperature monitored at (a) Council, (b) North Slope, and (c) ANWR sites, suggesting that soil temperature explains more than 80% of air temperature.

### 3.3. Spatial variability of ecosystem respiration

Spatial variability of ecosystem respiration is related to the size of the vegetation communities, pockets of fine root proliferation, and the remnants of decomposing organic matter (Davidson et al., 2002). In this study, the CV (coefficient of variance, %) for measured ecosystem respiration ranged from 20% to 63% and averaged 48%. The surface area covered by a chamber influences the number of chambers required for estimating the representativeness of ecosystem respiration at each site. To estimate the number of sampling points required for each approach at various degrees of precision and at a specific confidence level, we used an equation from Savage and Davidson (2003), Yim et al. (2003), and Liang et al. (2004):

$$n = [ts/D]^2, \quad (5)$$

where  $n$  is the number of sampling points required,  $t$  is the t-statistic for a given confidence level and degrees of freedom,  $s$  is the standard deviation of all sample measurements within each sampling period, and  $D$  is the desired interval for the full sample mean, within which a smaller experimental mean is expected to fall.

The results in Table 4 demonstrate that 64, 50, and 31 sampling points for June, August, and September are required at the Council site for our 81-point manual chamber system to gain an experimental average within  $\pm 10\%$  of the full sample average and a 95% confidence level. 20 sampling points each for both June and July at the North Slope site and 21 sampling points at the ANWR site were required to achieve  $\pm 20\%$  with a 95% confidence level.

On the other hand, the number of sampling points required for each vegetation species at the Council, North Slope, and ANWR sites were 3–17, 2–22, and 8–9, respectively, to satisfy at least  $\pm 20\%$  with an 80% confidence level. This type of intensive study can help researchers guide in determining how many efflux measurements are routinely needed per site and date, depending on what spatial or temporal differences the study is attempting to identify, as well as the level of statistical confidence (Davidson et al., 2002). While large numbers of efflux measurements are ideal, logistical constraints on labor and time often limit the number of measurements that are feasible. In Japanese larch forest sites, Yim et al. (2003) showed that the CV for spatial variability of soil respiration across 50 sampling points within a  $30 \times 30$ -m plot was 28%. Average numbers for sampling points required to estimate soil  $\text{CO}_2$  efflux within 10% and 20% of its true mean, at the 95% confidence level, were estimated as 26 and 6, respectively. The required number of sampling points may depend on a chamber's active

cross-section; Yim et al.'s (2003) chamber had an area of  $0.0125 \text{ m}^2$ , which is much smaller than those used in this study. Using a different efflux-measuring technique, Liang et al. (2004) noted the average frequency of sampling points required to evaluate soil respiration within 10% of its true mean with an automated chamber (90 cm long, 90 cm wide, 40 cm high) at a 95% confidence level, and with 20% open-top and LI-6400 methods at the 90% confidence level. At a Harvard forest, Savage and Davidson (2003) indicated 20% with manual (25-cm diameter) and automated (30.5-cm diameter) systems at 95% and 80% confidence levels, respectively. Hence, a larger chamber size may require fewer sampling points, while a smaller chamber may require more. The differences in chamber size and measuring frequency in tundra ecosystems may result from differences in the accumulation rate of soil organic matter and environmental parameters such as thaw–freeze cycle, dominant vegetation community, soil temperature, and soil moisture. We suggest a measuring frequency for ecosystem respiration or soil respiration rate at representative points, after the determination of spatial representativeness at a sampling site, using a manual chamber system.

These findings suggest that the use of a larger-volume chamber (e.g., larger active cross section) and/or its measurement frequency at many sampling points will overcome logistical constraints, and that a manual chamber system will help in determining the spatial representativeness of the research site. Therefore, our outcomes have been to 1) perform ecosystem respiration or soil respiration measurement with a large cross-section chamber and its measuring frequency, and subsequently, 2) monitor the year-round soil carbon efflux such as with a Forced Diffusion  $\text{CO}_2$  chamber system (Risk et al., 2011) or automated chamber system (Savage and Davidson, 2003; Liang et al., 2004) at the mean ecosystem respiration point for the selected tundra site, for additional study in response to recently abruptly changing environment and climate in the Arctic.

### 4. Summary and conclusions

Ecosystem respiration in the tundra ecosystem is a significant carbon source and provides critical information on the carbon budget in response to the recently abruptly changing environment and climate in the Arctic. For this reason, ecosystem respiration should be quantitatively evaluated at a representative site. Here, we selected three different tundra sites—Council on the Seward Peninsula, the North Slope of the Brooks Mountain Ranges, and the Arctic National Wildlife Refuge (ANWR)—in Alaska. Ecosystem respiration in cotton grass tussock was 1.5-fold higher than in

**Table 4**

Number of required sampling points at different tundra ecosystems to achieve different degrees of precision (within  $\pm 10\%$  or  $20\%$  of full sample mean) with 80, 90, and 95% confidence levels.

Site	Season	Chamber type	Species	Frequency	80%		90%		95%			
					$\pm 10\%$	$\pm 20\%$	$\pm 10\%$	$\pm 20\%$	$\pm 10\%$	$\pm 20\%$		
Council	June	Manual	Lichen	22	70	17	118	30	173	43		
			Moss	43	13	3	22	5	31	8		
			Tussock	16	42	10	71	18	105	26		
			Total	81	28	7	45	11	64	16		
	August	Manual	Lichen	23	40	10	68	17	99	25		
			Moss	43	44	11	72	18	102	25		
			Tussock	15	51	13	87	22	129	32		
			Total	81	21	5	35	9	50	13		
	September	Manual	Lichen	23	27	7	45	11	66	16		
			Moss	43	38	9	62	16	89	22		
			Tussock	15	33	8	57	14	85	21		
			Total	81	13	3	22	6	31	8		
North Slope	June	Manual	Lichen	21	88	22	149	37	218	55		
			Tussock	16	9	2	16	4	23	6		
			Total	36	33	8	55	14	79	20		
	July	Manual	Lichen	21	38	10	65	16	95	24		
			Tussock	16	21	5	35	9	52	13		
			Total	36	33	8	55	14	80	20		
ANWR	July – August		Manual	Moss	50	33	8	55	14	78	19	
				Tussock	5	38	9	72	18	123	31	
				Total	55	13	3	60	15	85	21	
Yim et al. (2003) Liang et al. (2004)	August	Manual	Larch forest	50	11	3	18	5	26	6		
	June – October	Automated	Japanese larch forest	16	5	1	8	2	11	3		
Savage and Davidson (2003)	June	Manual	Harvard forest	12	8	2	13	3	20	5		
	July	Manual		12	7	2	13	3	19	5		
	August	Manual		12	9	2	16	4	25	6		
	June	Automated	Harvard forest	3	6	2	15	4	33	8		
	July	Automated		3	5	1	12	3	27	7		
	August	Automated		3	26	6	61	15	133	33		
Kim et al. (2013)	Growing season	Manual	Tundra	36	81	20	135	34	194	49		
		Manual	Tundra	36	61	15	103	26	148	37		
		Manual	Ecotone	36	24	6	40	10	57	14		
		Manual	Boreal forest	36	53	13	88	22	127	32		
		Manual	Boreal forest	36	33	8	55	14	79	20		

lichen and moss regimes at the Council and North Slope sites, suggesting tussock as an importantly atmospheric carbon source. Considering the geological distribution of tussock and the drastic climate change in the Arctic, tussock-originated carbon emission should not be overlooked.

The response of ecosystem respiration to soil temperature at 5 cm below the soil surface denotes a exponential curve across the three sites, demonstrating that soil temperature is a significant driver in determining ecosystem respiration, and explains >80% of air temperature, based on the relationship between *in-situ* temperature of air and soil. Monthly ecosystem respiration was simulated on the basis of *in-situ* daily mean air temperature and soil temperature at 5 cm below the surface. Annual simulated ecosystem respiration ranged from, 254–307 g CO<sub>2</sub> m<sup>-2</sup> for normalized air temperature, and 212–305 g CO<sub>2</sub> m<sup>-2</sup> for *in-situ* soil temperature, indicating there is no significant difference in ecosystem respiration between air temperature and soil temperature at the 95% confidence level. Simulated ecosystem respiration over a short growing season (June–September) dominates at 79–92% for normalized air temperature, and 81–86% for soil temperature. This finding suggests understory tundra plants have a much more active metabolism compared to the soil respiration produced by soil microbes and roots of plants.

In order to assess the spatial representativeness of the ecosystem, we suggest the following specific procedures: 1) experimental plot size is selected in a tundra ecosystem; 2) monthly efflux measurement using a manual chamber is conducted

at each point within the plot during the growing season; 3) monthly mean ecosystem respiration is estimated for sampling frequency required on the basis of equation (5); and subsequently, 4) the chamber size and sampling frequency is determined at a given confidence level. Finally, year-round monitoring of ecosystem or soil respiration should be performed using an automated chamber system at a representative point for the quantitative assessment of tundra carbon dynamics and budget in response to the abruptly changing Arctic and Subarctic climate system.

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