Science of the Total Environment 566–567 (2016) 175–184

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Continuous measurement of soil carbon efflux with Forced Diffusion (FD) chambers in a tundra ecosystem of Alaska

Yongwon Kim [a,*], Sang-Jong Park [b], Bang-Yong Lee [c,**], David Risk [d]

[a] International Arctic Research Center (IARC), University of Alaska Fairbanks (UAF), Fairbanks, AK 99775, USA
[b] Division of Polar Climate Research, Korea Polar Research Institute (KOPRI), Incheon 21990, Republic of Korea
[c] Arctic Research Center, Korea Polar Research Institute (KOPRI), Incheon 21990, Republic of Korea
[d] Department of Earth Sciences, St. Francis Xavier University, Nova Scotia, B2G 2W5, Canada

HIGHLIGHTS

- Continuous monitoring of soil CO_2 efflux is accommodated by a Forced Diffusion (FD) chamber system in all locations and weather conditions.
- Temperature and thaw depth are important parameters for influencing soil CO_2 emissions.
- Growing and non-growing season simulated soil carbon represent 75.7 and 24.3% of annual carbon emissions, respectively.
- Annual CO_2emission with FD chamber would be an effective for quantifying growing and non-growing seasons soil carbon budget in the Arctic.

ARTICLE INFO

Article history:
Received 1 February 2016
Received in revised form 26 April 2016
Accepted 8 May 2016
Available online xxxx

Editor: D. Barcelo

Keywords:
Soil CO_2 efflux
Forced Diffusion (FD) chamber system
Temperature
Thaw depth
Annual soil carbon budget
Alaska

ABSTRACT

Soil is a significant source of CO_2 emission to the atmosphere, and this process is accelerating at high latitudes due to rapidly changing climates. To investigate the sensitivity of soil CO_2 emissions to high temporal frequency variations in climate, we performed continuous monitoring of soil CO_2 efflux using Forced Diffusion (FD) chambers at half-hour intervals, across three representative Alaskan soil cover types with underlying permafrost. These sites were established during the growing season of 2015, on the Seward Peninsula of western Alaska. Our chamber system is conceptually similar to a dynamic chamber, though FD is more durable and water-resistant and consumes less power, lending itself to remote deployments. We first conducted methodological tests, testing different frequencies of measurement, and did not observe a significant difference between collecting data at 30-min and 10-min measurement intervals (averaged half-hourly) ($p < 0.001$).

Temperature and thaw depth, meanwhile, are important parameters in influencing soil carbon emission. At the study sites, we observed cumulative soil CO_2 emissions of 62.0, 126.3, and 133.5 gC m^{-2} for the growing period, in sphagnum, lichen, and tussock, respectively, corresponding to 83.8, 63.7, and 79.6% of annual carbon emissions. Growing season soil carbon emissions extrapolated over the region equated to 0.17 ± 0.06 MgC over the measurement period. This was 47% higher than previous estimates from coarse-resolution manual chamber sampling, presumably because it better captured high efflux events. This finding demonstrates how differences in measurement method and frequency can impact interpretations of seasonal and annual soil carbon budgets. We conclude that annual CO_2 efflux-measurements using FD chamber networks would be an effective means for quantifying growing and non-growing season soil carbon budgets, with optimal pairing with time-lapse imagery for tracking local and regional changes in environment and climate in a warming Arctic.

1. Introduction

Northern High Latitudes are currently experiencing climate and environment changes including increasing temperatures, degrading permafrost, changing snow cover extent, northward movement of shrub communities, and extended vegetative growing seasons (Sturm et al., 2001; ACIA, 2004; AMAP, 2011; Bhatt et al., 2013; Lawrence et al., 2015; Natali et al., 2015). For example, recent summer warming in Arctic Alaska has accelerated. The mean annual air temperature of Nome, western Alaska has increased by 0.73 °C over the last century (National Weather Service, NOAA), and 0.3–0.4 °C of this change has occurred during the past few decades (Chapin et al., 2005). Annual precipitation in Nome has also decreased by 14%, and snow depth has

* Correspondence to: Y. Kim, International Arctic Research Center (IARC), University of Alaska Fairbanks (UAF), Fairbanks, AK 99775-7335, U.S.A.
** Corresponding author.
E-mail addresses: kimyw@iarc.uaf.edu (Y. Kim), bylee@kopri.re.kr (B.-Y. Lee).

http://dx.doi.org/10.1016/j.scitotenv.2016.05.052

increased by 25% (National Weather Service, NOAA), which will translate to warmer soil temperatures via the insulating snow layer.

These changes influence the high-latitude terrestrial carbon cycle, via changes in vegetation productivity (Euskirchen et al., 2006; Barr et al., 2007) and decomposition of soil organic matter (Piao et al., 2007; Wu et al., 2012). Soil CO_2 efflux, produced through the decomposition of soil organic carbon and roots, signifies the second largest terrestrial carbon source on both time and space scales (Raich and Schlesinger, 1992; Schlesinger and Andrews, 2000). Of the changes documented in the Arctic, the increase in temperature is most important, as it drives positive feedbacks on regional and pan-Arctic scales (Chapin et al., 2000; ACIA, 2005; Chapin et al., 2005). Soil carbon dynamics in tundra and boreal forest ecosystems exhibit strong temperature dependence, and is characterized by Q_{10} value, which describes the increase in respiratory rate with a given 10 °C temperature change (Xu and Qi, 2001; Davidson and Janssens, 2006; Bond-Lamberty and Thomson, 2010; Mahecha et al., 2010; Kim et al., 2013, 2014a; Kim, 2014). Bond-Lamberty and Thomson (2010) estimated the global soil respiration rate at 98 ± 12 GtC (1 GtC = 10^{15} gC), indicating an increase of 0.1 GtC $year^{-1}$ over two decades. This rate of increase suggests a CO_2 emission response factor of 1.5 compared to air temperature, which is consistent with enhanced soil CO_2 emission response to a warming global climate.

In Alaska, soil temperature regulates seasonal variations in soil CO_2 efflux, and soil moisture has also been found to affect the inter-annual variation in soil CO_2 emission in a study of two growing seasons by Kim et al. (2014a). In that study, emissions during the wet growing season had been suppressed by 27% compared to the dry summer season, due to higher soil moisture from severe rain (Dunn et al., 2006; Kim et al., 2014a).

The interpreted rates of soil CO_2 efflux are affected, of course, by the spatiotemporal intensity of monitoring, and also by differences in measurement methodology. For example, methodological 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) may each affect emissions accounting (Davidson et al., 2002; Savage and Davidson, 2003). Normally, different methodologies are used for different purposes, and manual chamber systems are traditionally used to capture spatial heterogeneity, while automated chamber systems offer much improved measurement frequency during snow-free periods (Davidson et al., 2002; Savage and Davidson, 2003). The impact of temporal sampling frequency is particularly important in studies seeking to account for emissions across the year. Darenova et al. (2014) compared manual and continuous measurements of soil CO_2 efflux, and found that interpreted Q_{10} values were significantly different between datasets because of the difference in measurement frequency. They were able to demonstrate that total seasonal carbon emission simulated by continuous soil temperatures differed by as much as 7.2% from continuously measured data. Annual and/or seasonal soil carbon emissions have been estimated in several studies on the basis of manual measurements over periods as short as some days, and up to many months (Davidson et al., 1998; Epron et

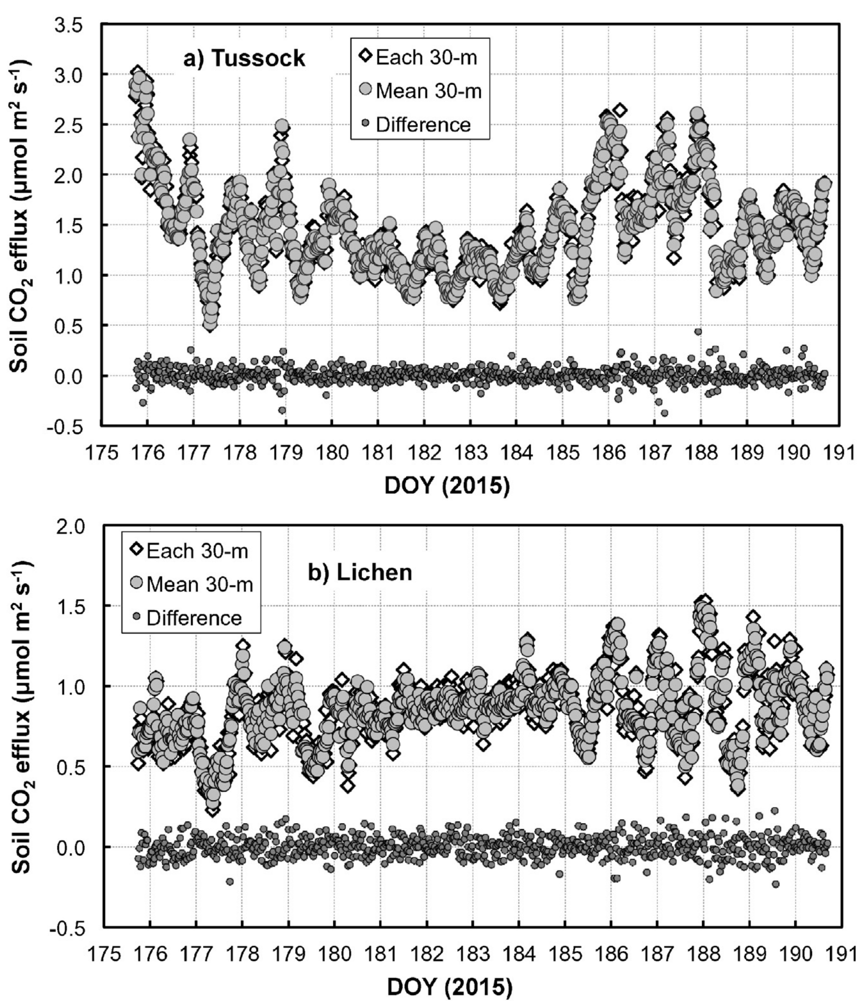

Fig. 1. Temporal variations in CO_2 effluxes at 30-min (diamonds) and 10-min (averaged half-hourly) (grey circles) measurement intervals in (a) tussock and (b) lichen over fifteen days. There is no difference (small circles) between the 30-min interval and mean 30-min at a 10-min interval, suggesting no significant difference based on a one-way ANOVA at the 95% confidence level ($p < 0.001$).

al., 2004; Khomik et al., 2006; Kim et al., 2014a). Presumably, the interval from which the extrapolations are made will be increasingly biased when duration is limited. For soil CO_2 efflux measurements, it is not uncommon to extrapolate to 24 hours, and then interpolate between measurement days (Savage and Davidson, 2003; Parkin and Kaspar, 2004; Savage et al., 2008). This will result in a bias of apparent emission toward whatever time of day the measurements are taken. As is well known, soil CO_2 efflux changes during diel cycles might be as high as the changes seen even over week timescales (Flanagan and Johnson, 2005). Overall, the degree to which measured fluxes are representative of reality depends on temporal frequency and spatial coverage. For both, higher is generally better, but monitoring at high latitudes is generally limited by weather and the availability of power, making it hard to achieve the desired level of spatiotemporal coverage.

The Forced Diffusion (FD) CO_2 efflux measurement technique was first developed for work in the boreal forest and Antarctica (Risk et al., 2011, 2013; Lavoie et al., 2012). This initial measurement technique has applicability to Arctic studies, for continuously monitoring soil CO_2 efflux measurements in tundra ecosystems underlain by permafrost. This study focused on the dynamics of soil carbon accounting near Council, on the Seward Peninsula of western Alaska, during the growing season of 2015. The objectives of this study were to 1) analyze environmental parameters in determining soil CO_2 efflux, 2) assess the level of agreement between manual chambers and FD soil CO_2 efflux chambers, when both measurements are extrapolated across the growing season, and lastly to 3) estimate simulated annual soil CO_2 efflux based on observed air temperature.

2. Materials and methods

2.1. Experimental site

The experimental study site is located within the tundra ecosystem near Council (64°51′38.3″ N; 163°42′39.7″ W; 45 m.a.s.l.), on the Seward Peninsula of Alaska, about 114 km northeast of Nome (Kim et al., 2014a). This site was selected for its relatively smooth transition from forest to tundra, and its underlying discontinuous permafrost regime. The annual average air temperature is −3.1 °C, as recorded at the Nome airport from 1949 to 2012. Temperatures ranged from −14.8 °C in January to 10.7 °C in July, and annual precipitation was 401 mm, including snowfall of 157 cm (Western Regional Climate Center). During the growing season (June to September) of 2015, average ambient temperature and precipitation were 9.5 ± 4.9 °C (CV, coefficient of variance: 51%), and 156.8 mm. The precipitation in July–August alone was 128 mm, corresponding to 82% of the entire summer. These recent conditions contrast with averages for the past 64 years, when summer temperature and precipitation was 8.7 ± 2.2 °C (CV: 25%) and 224.5 mm, respectively—or cooler, less variable, and much wetter. Hence, recent trends point toward hotter and drier weather than in past decades. These sites can only be accessed from May to early October, as the road leading inland from Nome is closed during the winter by the Alaska Department of Transportation.

Based on the observations of CO_2 efflux and environmental factors in three dominantly understory plants such as lichen, sphagnum moss, and tussock tundra microsites within a 40 m × 40 m plot (5-m interval; 81 points), we chose three representative microsites for monitoring CO_2 efflux with the FD chamber system (Risk et al., 2011, 2013; Lavoie et al., 2012). Within the 81-point area, dominantly understory plants were caribou lichen (*Cladonia mitis*, *Cladonia crispata*, and *Cladonia stellaris*); moss, such as sphagnum (*Sphagnum magellanicum*, *Sphagnum angustifolium*, and *Sphagnum fuscum*) and others (*Polytricum* spp., *Thuidium abietinum*, and *Calliergon* spp.); and cotton grass tussock tundra (*Eriophorum vaginatum*). Understory lichen, sphagnum moss, and tussock tundra occupied fractions of 27, 53, and 20% of the plot, respectively.

2.2. Forced Diffusion (FD) chamber

The FD soil CO_2 efflux autochamber (Eosense, Canada) is a soil CO_2 monitoring instrument conceptually similar to a dynamic chamber. The FD housing contains a single high accuracy CO_2 sensor, an internal data-logger, two valves, and a small diaphragm pump that operates only for short durations to bring air to the sensor. Otherwise, the dynamic CO_2 flow is regulated entirely without power (unlike a traditional dynamic chamber system), using waterproof breathable membranes of specific size and diffusivity. To perform flux measurements, the instrument takes the difference of CO_2 concentrations measured in two separate cavities, both of which are machined into a single high-density acetal housing. All flux solving is done internally based on manufacturer calibrations. These variants differ from the original Risk et al. (2011) system, by virtue of a single integrated housing (rather than two) and a single sensor (rather than two), to better measure the difference between cavity concentrations without appreciable sensitivity to long-term drift. The FD chamber can sample soil CO_2 flux at intervals from 5 min to 1440 min; we specified 30-min frequency for this study. Each FD chamber instrument consumes only 1.6 watts per hour at the highest measurement frequency. We powered our FD instruments with a cold-resistant external 12-V battery, a solar power charge converter, and a 140-W solar panel (KD140GX-LFBS, Kyocera Solar Inc., Japan). A standard 5-m power and data cable (SSC) plugs directly into the twelve-pin socket on the FD housing. Before deploying the FD chamber, the chamber was placed into a previously installed soil collar (7.5-cm ID; 9.0-cm OD; 5-cm length). For best results, we chose a flat soil surface clear of obstructions for inserting the chamber. Using an attached mounting ring and legs, the FD chamber was pegged and fixed to the soil surface. FD chambers were deployed on June 25, 2015 at the representative lichen, sphagnum moss, and tussock microsites.

We tested the difference in sampling rate between 30-min and 10-min interval (with 30-min averages). Soil CO_2 effluxes at 30-min interval and for mean 30-min at 10-min interval were 1.46 ± 0.44 and 1.45 ± 0.44 μmol m^2 s^{-1} for tussock, and 0.85 ± 0.21 and 0.85 ± 0.20 μmol m^2 s^{-1} in lichen, respectively, from DOY 175 to 190, showing no significant difference, based on a one-way ANOVA at the 95% confidence level (p < 0.001) (Fig. 1). As a result, we chose the 30-min

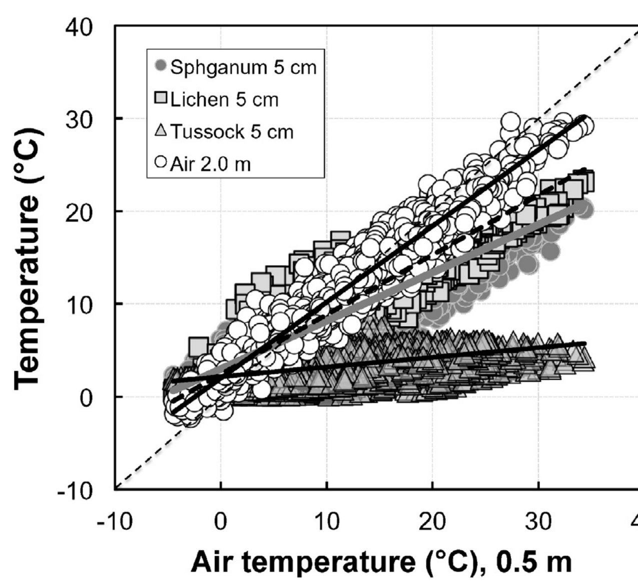

Fig. 2. Responses of soil temperature at 5-cm depth of sphagnum (grey solid circle), lichen (grey square), tussock (grey triangle), and air temperature at 2.0 m (open circle) to air temperature at 0.5 m at the site during the growing season of 2015. This suggests air temperature at 0.5 m is analogous to 2.0 m (R^2 = 0.94), and to soil temperature at 5 cm depth at sphagnum (R^2 = 0.73) and lichen (R^2 = 0.85). On the other hand, air temperature at 0.5 m is not well correlated with soil temperature 5 cm at tussock tundra (R^2 = 0.24). Dashed line denotes 1:1 line.

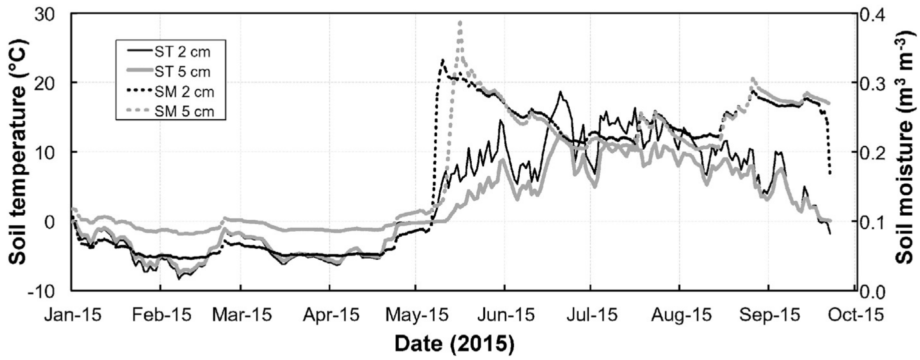

Fig. 3. Two peaks of mean daily soil moisture (SM) just after snow melting found at 2 cm (dotted black line) and 5 cm (dotted grey line) depths on May 10 and 15, 2016 in parallel to increase of soil temperature (ST) at 2 cm (solid line) and 5 cm (grey line) depths below the soil surface.

measurement frequency for the duration of the study, in order to keep power usage at a minimum.

2.3. Measurement of environmental parameters

Temperature was monitored at 0.5 m above soil surface, and at 2 and 5 cm below the surface using a logger with two probes (logger: U12-006; probe: TMC6-HD, Onset Computer, USA). Soil temperature at depths of 2 and 5 cm below the soil surface was measured within the sphagnum moss species, and soil temperature at a depth of 5 cm was monitored in lichen and tussock tundra communities. Air temperature at 0.5 and 2.0 m above the surface was also measured at the sites (Fig. 2). Soil moisture at 2 and 5 cm below the surface was measured with a logger (H21-002, Onsetcomp, USA) and sensor (SMD-M005 Onsetcomp, USA) in parallel to soil temperature, as shown in Fig. 3. Thaw depth was measured with a fiberglass tile probe (1.5 m long) in June, July, August, and September. A year-round time-lapse camera (GardenWatchCams, Brinno Inc., Taiwan) recorded at four-hour intervals, to help track snow depth and variations in understory phenology.

2.4. Simulated soil CO_2 efflux

Using data collected with the FD autochamber, we established the temperature sensitivity of soil CO_2 efflux by plotting its exponential relationship with air temperature, and with soil temperature at depths of 2 and 5 cm, by using the following equation:

$$SR = \beta_0\, e^{\beta 1 \times T}, \tag{1}$$

where SR is the measured soil CO_2 efflux (μmol m^2 s^{-1}), T is temperature (°C), and β_0 and β_1 are constants. This exponential relationship is commonly used to represent soil carbon flux as a function of temperature (Davidson et al., 1998; Davidson and Janssens, 2006; Gaumont-Guay et al., 2006; Lavigne et al., 1997; Rayment and Jarvis, 2000; Xu and Qi, 2001; Zhou et al., 2009; Kim et al., 2014b). Q_{10} temperature coefficient values were calculated as in Davidson et al. (1998), Davidson and Janssens (2006), and Kim et al. (2014a, 2014b):

$$Q_{10} = e^{\beta 1 \times 10}, \tag{2}$$

where Q_{10} is the change in reaction rate at intervals of 10 °C and is based on the Van't Hoff empirical rule that a rate increase on the order of two to three times occurs for every 10 °C rise in temperature (Lloyd and Taylor, 1994).

A reference value of R_{10} (i.e., soil CO_2 efflux normalized to air temperature of 10 °C) was then calculated as:

$$R_{10} = R_i \times Q_{10}{}^{[(10-T)/10]}, \tag{3}$$

where R_i is the simulated soil CO_2 efflux (μmol m^2 s^{-1}) at T temperatures in air (°C). Using the calculated values of Q_{10} and R_{10}, soil CO_2 efflux was simulated on the basis of the measured air temperature. Simulated soil CO_2 efflux values, R_i (μmol m^2 s^{-1}), were calculated as:

$$R_i = R_{10} \times Q_{10}{}^{[(T-10)/10]}. \tag{4}$$

The parameters of the nonrectangular hyperbola function were determined daily, using a fifteen-day moving window and the least-squares method. Soil CO_2 efflux (SR) was estimated using the following two models (Ueyama et al., 2014):

$$SR = R_0 \times Q_{10}{}^{(Ta/10)}, \tag{5}$$

$$SR = R_{ref} \times \left[\frac{E_0}{R_{gas}}\left(\frac{1}{T_k + T_{ref} - T_0} - \frac{1}{T_k + T_a - T_0}\right)\right], \tag{6}$$

where T_a is the air temperature at 2 m, R_o represents soil CO_2 efflux at 0 °C, and Q_{10} is the temperature sensitivity coefficient of soil CO_2

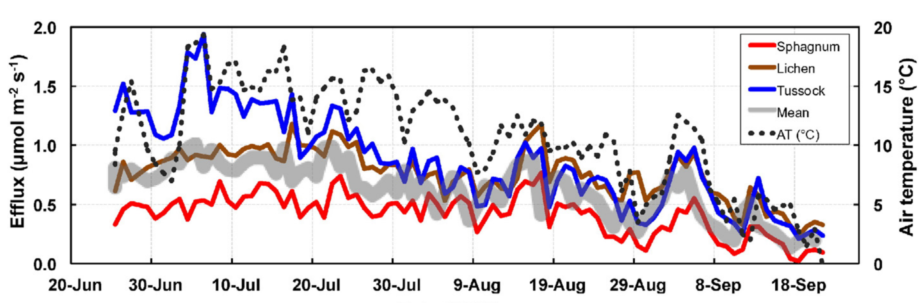

Fig. 4. Temporal variations in measured soil CO_2 efflux by forced diffusion (FD) chamber system at three sphagnum moss, lichen, and tussock tundra communities of Council, from June 24 to September 22, 2015. The grey thick line denotes mean and its 95% confidence level.

Table 1
Mean hourly rate (standard deviation), coefficient of variance (%)* for CO_2 efflux (μmol m^{-2} s^{-1}), and air temperature (°C), and soil temperature (°C) at depths of 2 and 5 cm in sphagnum, and 5 cm in lichen, and tussock of tundra ecosystem of Council, Alaska during the growing season.

		Temperature (°C)				Temperature (°C)		Temperature (°C)
Month 2015	Sphagnum (μmol m^{-2} s^{-1})	Air	Soil 2 cm	Soil 5 cm	Lichen (μmol m^{-2} s^{-1})	Soil 5 cm	Tussock (μmol m^{-2} s^{-1})	Soil 5 cm
June	0.45 (0.23)	10.7 (5.0)	10.5 (4.5)	7.5 (2.0)	0.76 (0.17)	9.5 (3.2)	1.38 (0.36)	2.8 (0.6)
25 to 30	52*	47	43	27	23	34	26	20
July	0.53 (0.28)	14.6 (5.6)	12.9 (4.6)	9.6 (2.4)	0.93 (0.23)	12.7 (3.8)	1.22 (0.40)	4.4 (1.0)
1 to 31	53	39	35	25	24	30	32	23
August	0.42 (0.26)	10.1 (4.8)	9.3 (4.2)	7.2 (2.3)	0.74 (0.22)	9.1 (3.7)	0.68 (0.29)	4.0 (0.9)
1 to 31	60	48	46	32	30	41	43	22
September	0.23 (0.20)	5.4 (5.3)	3.7 (4.2)	3.1 (2.5)	0.53 (0.24)	5.6 (3.9)	0.49 (0.28)	2.4 (0.9)
1 to 22	88	99	113	81	45	69	59	39
Total	0.41 (0.27)	10.6 (6.3)	9.3 (5.6)	7.1 (3.4)	0.76 (0.27)	9.9 (4.5)	0.87 (0.47)	3.8 (1.2)
($n = 2149$)	66	42	60	48	36	46	47	31

* Denotes the coefficient of variance (%).

efflux. R_{ref} is the soil CO_2 efflux at T_{ref}, E_0 is the activation energy, and R_{gas} is the ideal gas constant. T_k, T_0, and T_{ref} are 273.15 K, 227.13 K, and 283.15 K, respectively (Lloyd and Taylor, 1994). We used the conventional Q_{10} model to estimate soil CO_2 efflux, but used the Lloyd and Taylor model Eq. (6) for uncertainty estimates, as Q_{10} exhibited clear seasonal variations, whereas E_0 showed no discernable seasonal variation.

3. Results and discussion

3.1. Observed environmental parameters

Ambient air temperature at 0.5 and 2.0 m above the surface were measured at the site, and ranged from less than −30 °C to >20 °C. Differences between temperatures measured at these heights were not significant, based on a one-way ANOVA at the 95% confidence level ($p < 0.001$). Two peaks for soil moisture just after snowmelt were found at 2 and 5-cm depths on May 10 and 15, 2016, respectively, suggesting the thawing rate between the two depths was 0.5 cm day^{-1}. We also found the heat transfer rate for soil temperature between 2 and 5-cm depths during soil thaw on May 7 and 11, 2016, respectively, was 0.6 cm day^{-1}. These values were the same as the soil thawing rate during the growing season of 2015, indicating thaw depth equal to $0.495 \times DOY - 56.3$ ($R^2 = 0.991$), based on the thaw depth averaged at 81 points from June to September. During the growing seasons of 2011 to 2014, the mean thawing rate was 0.438 cm day^{-1}. These changes in snow accumulation and ablation were documented by time-lapse camera at a four-hour interval from September 17, 2014 to June 20, 2015, as shown in Appendix Fig. A1.

3.2. Seasonal variation in soil CO_2 efflux

30-min soil CO_2 efflux was measured with the FD chamber system at representative sphagnum moss, lichen, and tussock tundra communities from June 24 to September 22, 2015 as shown in Fig. 4. Seasonal variations in soil CO_2 effluxes at each plant community visually appear to follow the variations in air temperature (Fig. 4). Mean growing season soil temperature at 5-cm depth was 7.1 ± 3.4 °C (Coefficient of Variance, CV: 48%), 9.9 ± 4.5 °C (CV: 46%), and 3.8 ± 1.2 °C (CV: 31%) at sphagnum, lichen, and tussock plots, respectively. The seasonal variation in soil temperature at the tussock plot was much lower than for other species. Also, air temperature was a useful proxy for soil temperature, and showed good linear agreement with soil temperature at 5-cm depth at sphagnum and lichen, and for which the correlation coefficient (R^2) is over 0.73 during the growing season of 2015 (Fig. 2). Air temperature was not as well correlated with soil temperature at tussock tundra plot ($R^2 = 0.24$), which may be due to much slower heat transfer by the denser cotton grass community and rougher shape than other species.

Table 1 denotes hourly mean monthly soil CO_2 efflux, air temperature, and soil temperature at 2 and 5-cm depths below the surface at the three understory plants. The ranges for growing season soil CO_2 efflux were 0.02–0.76 μmol m^2 s^{-1} at sphagnum moss, 0.23–1.18 μmol m^2 s^{-1} at lichen, and 0.21–1.94 μmol m^2 s^{-1} at tussock tundra. The mean growing season air temperature was 10.7 ± 4.5 °C at range of −0.2-19.3 °C.

Mean growing season soil CO_2 efflux by FD chamber was 0.41 ± 0.27 (CV: 66%), 0.76 ± 0.21 (CV: 28%), and 0.87 ± 0.41 (CV: 47%) μmol m^2 s^{-1} at sphagnum moss, lichen, and tussock tundra. On the other hand, in the 2012 study, CO_2 efflux was somewhat higher at 1.17 ± 0.40 (CV: 34%), 1.54 ± 0.72 (CV: 36%), and 2.20 ± 1.25 (CV: 37%) μmol m^2 s^{-1}

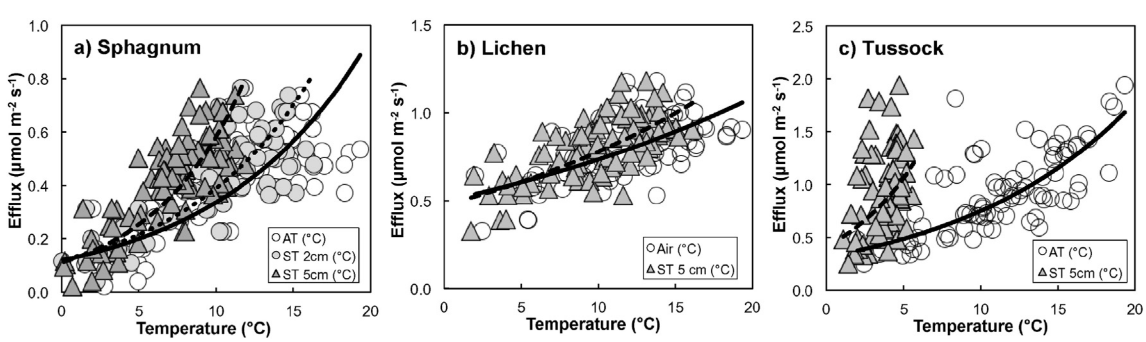

Fig. 5. Responses from mean daily soil CO_2 effluxes to air temperature (open circles), soil temperature at 2 cm (grey circles), and 5 cm (grey triangles) below the surface at (a) sphagnum, (b) lichen, and (c) tussock tundra in Council during the growing season of 2015. Correlation curves for air temperature, soil temperature at 2 cm, and soil temperature at 5 cm are shown by solid, dotted, and dashed lines, respectively.

Table 2
Q_{10} values and correlation coefficient between CO_2 efflux and air temperature (°C), and soil temperature (°C) at depths of 2 and 5 cm in sphagnum, and 5 cm in lichen, and tussock of tundra ecosystem, Seward Peninsula, Alaska from June 25 to September 22, 2015, based on a one-way ANOVA with 95% confidence level*.

Dominant plants	Temperature (°C)	b	Q_{10}	R^{2*}
Sphagnum	Air	0.059	1.81	0.54
	Soil 2 cm	0.118	3.25	0.63
	Soil 5 cm	**0.167**	5.30	0.63
Lichen	Air	0.039	1.48	0.40
	Soil 5 cm	0.050	1.64	0.49
Tussock	Air	0.087	2.38	0.60
	Soil 5 cm	0.189	6.63	0.21

* $p < 0.05$.

at sphagnum moss, lichen, and tussock tundra from June to September 2012 (Kim et al., 2014a). The higher emissions in 2012 may result from flux measurements being made by manual chamber only in the daylight hours—normally in the warm afternoon under sunny weather. Contrary to the weather conditions for the manual chamber, soil CO_2 efflux monitored by FD chamber captured data through the entirety of diel cycles, and even through poor weather conditions. Hence, although there is a somewhat higher difference between the FD and manual chamber methods, the soil CO_2 efflux according to FD chamber more likely reflects the true diel values. The manual chamber would have been far more likely to miss critical episodic and process-driven events. Accordingly, Darenova et al. (2014) found that 1) the time of day of CO_2 flux measurement influenced the estimate of the emitted carbon, and 2) the lowest bias of amount of emitted carbon from the soil was for measurements made between 10 am and 8 pm. These scheduling improvements were able to improve the temporal representation of the manual chamber method in that study. Further, Parkin and Kaspar (2004) applied a similar re-sampling technique to automated CO_2 flux measurements over a three month deployment, concluding that manual sampling every two days would bias the total emissions estimate by over 10%, while weekly sampling increases the deviation by up to 30%. Overall, we were not surprised by the departures in FD-observed effluxes as compared to manually observed fluxes in a previous year. We were also not surprised by the higher variance in FD-observed datasets, as the instrument would have captured the true highs and lows in soil CO_2 efflux within each diel period.

3.3. Dependence of soil CO_2 efflux on temperature and thaw depth

Fig. 5 shows the response of observed soil CO_2 effluxes at sphagnum, lichen, and tussock, to temperatures in air and to soil at 2 and 5-cm depths. Soil CO_2 efflux follows the normal exponential relation to temperature as in Eq. (1). However, we did observe a distinct difference in the response from soil CO_2 efflux to air and soil temperature, due to lower seasonal variation in soil temperature within the denser *Eriophorum* community. The Q_{10} values of the three species can be estimated by Eq. (2), as listed in Table 2. Q_{10} value increases with soil depth, reflecting the narrower ranges of soil temperature experienced at those depths (Mikan et al., 2002; Pavelka et al., 2007; Kim et al., 2014b). Interestingly, the Q_{10} value for the snow-covering and melting seasons were very high relative to other seasons. Recorded values for Q_{10} have reached as high as 1.25×10^6 at a subalpine forest within the Colorado Front Range of the Rocky Mountains (Monson et al., 2006), and 4.2×10^6 in the exposed tussock tundra and cryoturbed soils of tundra sites (Kim, 2014). These highest Q_{10} tundra values reflected a dramatic rise in soil CO_2 efflux as tundra soils warmed from −0.9 to 0.5 °C (Kim, 2014). Monson et al. (2006) and Schmidt et al. (2009) demonstrated the exponential growth of microbes (e.g., snow molds and fungi), including beneath-snow CO_2 production as subnivean soils warmed from −3 to 0 °C. Fungi are omnipresent in Subarctic and Arctic soils, where they function as plant symbionts, parasites, pathogens, and decomposers, and may influence the carbon dynamics of terrestrial ecosystems subjected to a changing climate and environment in the warming Arctic (Timling and Taylor, 2012; Tojo and Newsham, 2012). Considering the long duration of the snow-covered period at our high latitude monitoring location, as well as associated CO_2 contributions from fungi-infected

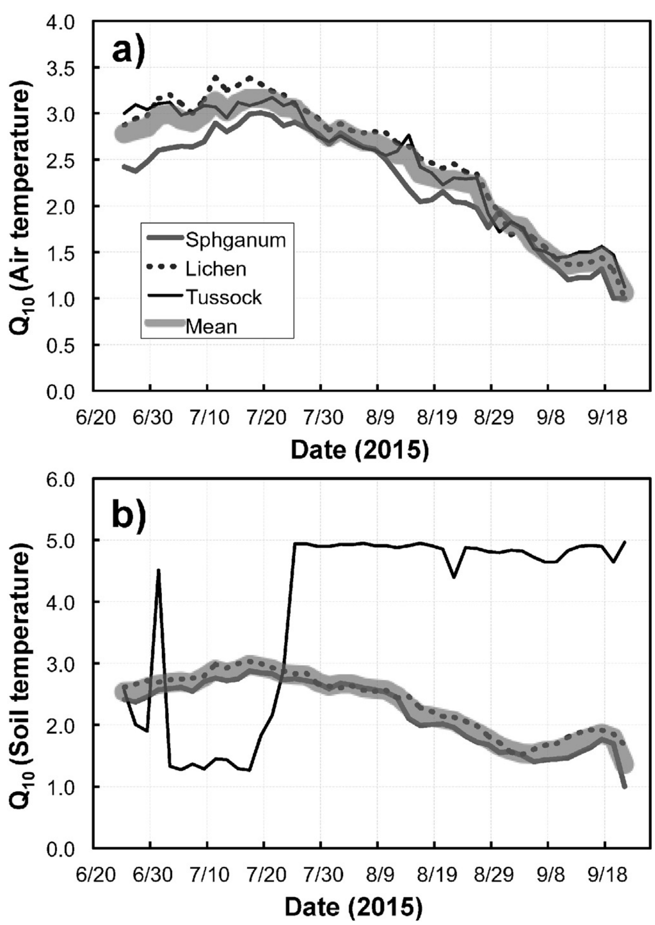

Fig. 6. Temporal variations in Q_{10} values using Eq. (6) for (a) air temperature and (b) soil temperature at 5-cm depth. Thick grey lines denote average and its 95% confidence level. Q_{10} values for soil temperature in tussock show a different pattern than the other two communities, due to a much slower response to air temperature.

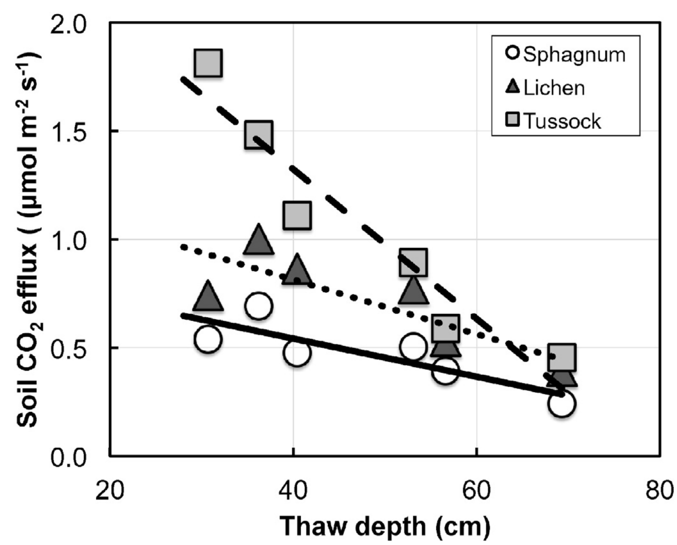

Fig. 7. Response from soil CO_2 efflux to thaw depth during the growing season (June–September) of 2015, reflecting that soil CO_2 efflux tends to decrease with thaw depth at three understory plants.

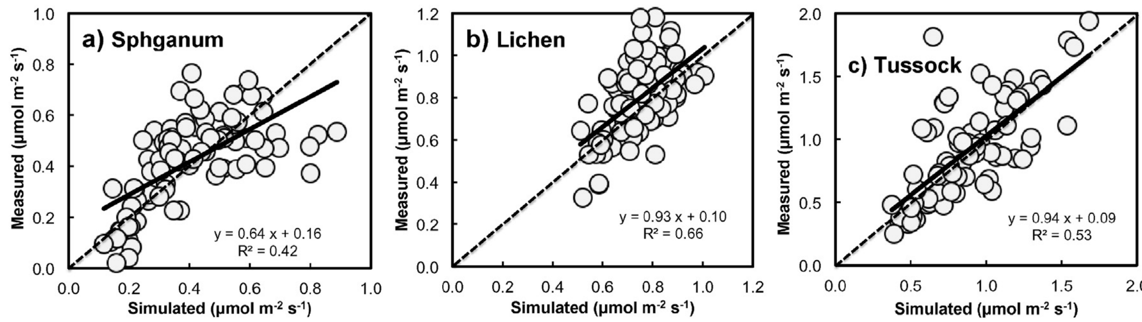

Fig. 8. Relationships between mean daily measured and simulated soil CO_2 efflux at (a) sphagnum, (b) lichen, and (c) tussock tundra. Dashed lines indicate a 1:1 line. This suggests a 36% higher deviation for measured and simulated daily soil CO_2 efflux at sphagnum moss regime than at lichen and tussock.

sphagnum (Monson et al., 2006; Schmidt et al., 2009; Kim, 2014), the annual carbon emissions at our plots may be substantially larger than expected, despite the fact we observed growing season fluxes that were lower than synoptic manual chamber CO_2 efflux sampling.

Fig. 6 shows fifteen-day moving Q_{10} values, determined for each of our study plots using Eq. (6). The thicker grey lines represent the average and its 95% confidence level at Fig. 6a and b. For Q_{10}'s determined using air temperature records (Fig. 6a), values generally fall from near 3.0 early in the monitoring period to roughly 1.0, and show a similar trend for all three plots. Fig. 6b shows fifteen-day moving Q_{10} values determined using soil temperature records and are somewhat higher, though there is a distinct difference in behavior at the tussock site. As mentioned previously, soil temperatures at this tussock site were not as well coupled to those for air. Since tussock tundra is such a prolific CO_2 source to the atmosphere (Oechel et al., 1997; Kim et al., 2007, 2014a; Kim, 2014) in the Subarctic and Arctic of Alaska, more study is required to evaluate heat transfer in *Eriophorum* community and others. Temperature in tussock tundra is higher than for the inter-tussock regime (e.g., sphagnum and lichen) (see Fig. 9; Kim, 2014). The temperature difference between the top of the tussock and the inter-tussock was shown distinctly during the spring season. This mechanism is thought to be similar to the ablation effect in boreal forests during the early spring (Winston et al., 1997; Kim, 2014).

Thaw depth in the active layer can vary substantially over short distances and time periods, as heat transfer in soils that are subject to freezing and thawing reflects the interaction of a large number of highly localized factors, including vegetation type, organic layer thickness, soil thermal properties, soil moisture, microtopography, and the operation of nonconductive heat-transfer processes (Outcalt et al., 1990; Hinzman et al., 1998). Thaw depth was measured eighty-one times during the growing seasons of 2011–2015. Mean thawing rate was 0.428 cm day^{-1} during the growing seasons of 2011–2014. But in 2015, the rate was quite a bit higher, at 0.495 cm day^{-1}. This suggests that thawing in 2015 was 15% faster than over the last four years. This may be due to much warmer mean monthly air temperatures in April (−3.9 °C) and May (7.3 °C) of 2015 than those of the last 64 years. The response from mean daily soil CO_2 efflux (Flux) to thaw depth (TD) from June to September 2015 is shown in Fig. 7. The correlation equations are $\text{Flux} = -0.0088 \times \text{TD} + 0.89$ ($R^2 = 0.72$) in sphagnum, $\text{Flux} = -0.0125 \times \text{TD} + 1.32$ ($R^2 = 0.67$) in lichen, and $\text{Flux} = -0.0345 \times \text{TD} + 2.70$ ($R^2 = 0.91$) for the tussock tundra community. This implies lower soil CO_2 production by soil microbes via decreasing soil temperature and increasing soil moisture over time, as shown in Fig. 3. Hence, temporal variation in thaw depth may act as a parameter for the estimation of soil carbon emission in the tundra understory plant community during the growing season. Because other studies show that soil CO_2 emissions have been enhanced by the degradation of permafrost in the Arctic (Lawrence et al., 2015; Natali et al., 2015), additional work is needed to help quantify the relationship with thaw under each of the communities measured. Thawing permafrost clearly alters hydrology, biology, and biogeochemistry in the Subarctic and Arctic (Hinzman et al., 2005; Schuur et al., 2009; Tarnocai et al., 2009; Grosse et al., 2011; Lawrence et al., 2015; Natali et al., 2015), and the resulting changes for soil communities can be complex.

3.4. Evaluation of simulated soil CO_2 efflux

Based on Q_{10} relationships, simulated daily soil CO_2 effluxes within sphagnum, lichen, and tussock communities were calculated using Eq. (4) and in-situ air temperature from October 1, 2014 to September 30, 2015. Of course, our monitoring period began in June 2015, but retrospective application of observed Q_{10} relations allows us to extrapolate for an annual CO_2 emission estimate. This approach also allowed us to compare our 2015 monitoring data against previously collected measurements at the site using manual chambers. According to measurements by time-lapse camera (Fig. A.1), snow first fell on October 23, 2014, and disappeared on May 5, 2015, so the extrapolation period includes these snow-covered intervals.

Fig. 8 shows the relationship between measured and simulated daily soil CO_2 efflux, suggesting that there is 36% greater deviation between measured and simulated daily soil CO_2 efflux under sphagnum moss cover than at the lichen or tussock plots. This pattern may be due to

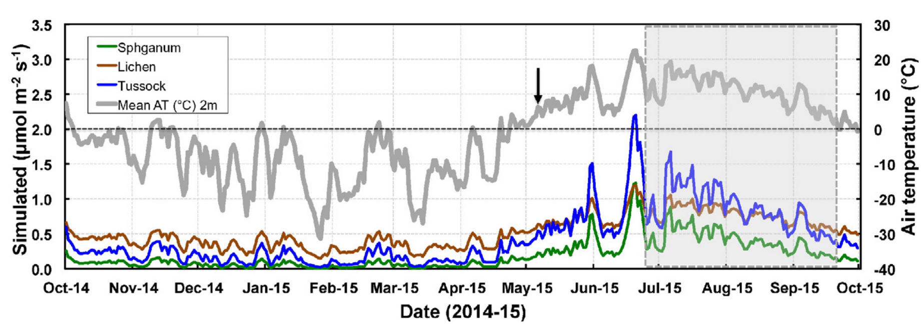

Fig. 9. Temporal variations in CO_2 efflux simulated by Eq. (4) and air temperature from October 1, 2014 to September 30, 2015. The arrow and shaded column represent onset of the snow melting and observed periods, respectively.

the slower response from sphagnum moss, which has higher water retention capacity relative to other understory plants, as shown in Fig. 5. Temporal variation in simulated daily soil CO_2 efflux at each community is shown in Fig. 9. Simulated daily soil CO_2 efflux in tussock tundra appears much more sensitive than for sphagnum and lichen species. Simulated mean monthly soil CO_2 efflux was also computed and is listed in Table 3, showing the seasonal pattern and including the low rate of CO_2 emission that can be expected overwinter during periods of snow cover.

Taking the annual carbon budget along with measurements from our time-lapse camera, we can establish budgets during snow-covered and snow-free periods. Mean simulated soil CO_2 efflux was 11.9, 72.0, and 34.2 gC m^{-2} $period^{-1}$ during the snow-covered period in the sphagnum moss, lichen, and tussock regimes, respectively, corresponding to 16.2, 36.3, and 20.4% of annual carbon emission. On the other hand, during the snow-free period, mean simulated soil CO_2 efflux was 62.0, 126.3, and 133.5 gC m^{-2} $period^{-1}$ in sphagnum moss, lichen and tussock, respectively, corresponding to 83.8, 63.7, and 79.6% of annual carbon emission. Overall, 24.3% of soil CO_2 efflux was likely emitted during the snow-covered period, with the rest during the snow-free season. Other studies have shown similar patterns, and that for seasonally snow-covered periods, winter contributions to CO_2 emission has accounted for 10–30% of the variability in annual CO_2 budget in tundra (Oechel et al., 1997; Fahnestock et al., 1999; Björkman et al., 2010; Kim et al., 2013), alpine and subalpine forests (Brooks et al., 1996; Mast et al., 1998; Monson et al., 2006), and boreal forests (Winston et al., 1997; Kim et al., 2007, 2013; Kim, 2014).

Kim et al. (2014a) demonstrated that obvious changes in soil moisture during the growing seasons of 2011 and 2012 resulted in an explicit difference between soil CO_2 effluxes, from both observed data by manual chamber and the posterior medians of a hierarchical Bayesian (HB) model, of 0.32 and 0.23 MgC $period^{-1}$ within a 40 × 40 m plot for the growing seasons of 2011 and 2012, respectively. The growing season soil CO_2 emission simulated in this study was 0.17 ± 0.06 MgC $period^{-1}$, suggesting the deviation between the manual chamber and continuous measurement by FD chamber methods was as high as 47%. This may be due to the difference in measuring method and frequency under sunny sky (manual) rather than continuous (FD). The added measurement frequency possible with FD could cause some re-evaluation of interpreted annual carbon budgets, and would aid in applying terrestrial ecosystem models to high time-resolution data, such as land surface models. Therefore, continuous monitoring of soil CO_2 efflux with FD chambers opens up new areas of opportunity and understanding. As warming stimulates the degradation of Subarctic and Arctic permafrost, we expect large amounts of ancient soil carbon to become available for microbial decay (Tarnocai et al., 2009; Grosse et al., 2011), as well as new ecological and biogeochemical regimes (Walter et al., 2008; Schuur et al., 2009; Zona et al., 2009; Sachs et al., 2010; Lawrence et al., 2015; Natali et al., 2015) across the landscape. Year-round soil CO_2 efflux-measurements will be required to track concomitant changes in carbon storage during this important time of transition.

Table 3
Mean (standard deviation) monthly CO_2 efflux simulated by Eq. (4) in representative understory sphagnum moss, lichen, and tussock tundra in Council, Seward Peninsula, Alaska from October 2014 to September 2015.

Month year	Simulated CO_2 efflux (μmol m^{-2} s^{-1})			Air temperature (°C)
	Sphagnum	Lichen	Tussock	
Oct-14	0.10 (0.04)	0.46 (0.06)	0.27 (0.08)	−2.4 (3.3)
Nov-14	0.08 (0.04)	0.41 (0.09)	0.22 (0.10)	−5.6 (6.2)
Dec-14	0.05 (0.03)	0.33 (0.09)	0.14 (0.08)	−11.2 (7.0)
Jan-15	0.04 (0.03)	0.31 (0.11)	0.13 (0.09)	−13.8 (9.4)
Feb-15	0.05 (0.04)	0.35 (0.10)	0.16 (0.10)	−10.3 (7.6)
Mar-15	0.03 (0.02)	0.29 (0.06)	0.10 (0.05)	−14.5 (6.2)
Apr-15	0.08 (0.05)	0.42 (0.11)	0.23 (0.12)	−5.4 (6.9)
May-15	0.29 (0.15)	0.68 (0.11)	0.65 (0.27)	7.6 (4.0)
Jun-15	0.48 (0.31)	0.80 (0.19)	0.98 (0.53)	11.7 (5.7)
Jul-15	0.56 (0.15)	0.88 (0.10)	1.13 (0.26)	14.5 (3.0)
Aug-15	0.36 (0.09)	0.75 (0.07)	0.79 (0.16)	10.3 (2.5)
Sep-15	0.21 (0.09)	0.60 (0.09)	0.50 (0.18)	4.7 (3.8)
Annual	0.20 (0.21)	0.52 (0.23)	0.44 (0.40)	−1.2 (11.6)

4. Conclusions

Soil CO_2 efflux measurement is an important component for estimating annual carbon budgets in response to changes in increasing air temperature, thawing permafrost, northward extending shrub community, and snow covered extent in the changing environment and climate of the Subarctic and Arctic. Here, continuous monitoring of soil CO_2 efflux using a Forced Diffusion (FD) chamber system was deployed at representative sphagnum moss, lichen, and tussock communities in western Alaska during the growing season of 2015.

Temperature was a significant driver in determining soil CO_2 efflux at three communities; however, the response from soil CO_2 efflux to soil temperature at tussock tundra was weak, due to much slower heat transfer by the higher density and rougher shape of the cotton grass community compared to other species. Nevertheless, tussock tundra is a significant source in contributing to atmospheric carbon in the Subarctic and Arctic terrestrial ecosystems (Oechel et al., 1997; Kim et al., 2007, 2013, 2014a; Kim, 2014) due to the wide-range distribution of tussock tundra in Northern High Latitudes (6.5×10^{12} m^2; Whalen and Reeburgh, 1998). Thaw depth was also a significant parameter in influencing soil CO_2 efflux, suggesting that increasing thaw depth with time is constrained to stimulating emissions due to increasing soil water content and decreasing soil temperature during the growing season.

Based on a model of soil CO_2 emission over the year, we estimated that snow-covered and snow-free environments contribute 24.3% and 75.7% of annual carbon emissions at our study sites, respectively. These values are similar to estimates from other studies (Oechel et al., 1997; Fahnestock et al., 1999; Kim et al., 2013). We did note that annual emissions estimates were sensitive to the measurement methodology used, and that continuous data at sub-diel frequency were superior to manual synoptic measurements, as they captured total variance during diel cycles. There are few Arctic and Subarctic studies of soil CO_2 efflux, and even fewer that extend into the non-growing season when production of CO_2 may still be significant. Yearly monitoring of soil CO_2 efflux using instruments like FD is needed at more locations in the Arctic and Subarctic, to quantify the soil carbon budget in response to locally and regionally changing climates, and to integrate/synthesize with simulations from land surface models.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.05.052.

Acknowledgements

This study was supported by a National Research Foundation of Korea Grant from the Korean Government (MSIP) (NRF-2016M1A5A1901769) (KOPRI-PN16081) (Title: Circum-Arctic Permafrost Environment Change Monitoring, Future Prediction and development Techniques of useful biomaterials (CAPEC Project)). Our research was also conducted under the JAMSTEC-IARC Collaboration Study (JICS), with funding provided by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) under a grant to the International Arctic Research Center (IARC). The authors appreciate Mr. N. Bauer of the International Arctic Research Center (IARC) of the University of Alaska Fairbanks (UAF) for professional English-language review and editing of the text. Finally, I would like to acknowledge the handing editor (Pavlos Kassomenos) and two anonymous reviewers who significantly improved the manuscript's quality and readability.

References

ACIA, 2004. (Arctic Climate Impact Assessment): Impacts of a Warming Arctic. Cambridge Univ. Press, Cambridge, U.K., p. 146.

AMAP, 2011. Snow, Water, Ice And Permafrost in the Arctic (SWIPA): Climate Change and the Crtosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, p. 538.

Barr, A.G., Black, T.A., Hogg, E.H., Griffis, T.J., Morgenstern, K., Kljun, N., Theede, A., Nesic, Z., 2007. Climatic controls on the carbon and water balances of a boreal aspen forest, 1994–2003. Glob. Chang. Biol. 13, 561–576. http://dx.doi.org/10.1111/j.1365-2486.2006.01220.x.

Bhatt, U.S., Walker, D.A., Raynolds, M.K., Bieniek, P.A., Epstein, H.E., Comis, J.C., Pinzon, J.E., Tucker, C.J., Polyako, I.V., 2013. Recent declines in warming and vegetation greening trends over pan-Arctic tundra. Remote Sens. 5, 4229–4254. http://dx.doi.org/10.3390/rs5094229.

Björkman, M.P., Morgner, E., Cooper, E.J., Elberling, B., Klemedtsson, L., Björ, R., 2010. Winter carbon dioxide effluxes from Arctic ecosystems: an overview and comparison of methodologies. Glob. Biogeochem. Cycles 24, GB0310. http://dx.doi.org/10.1029/2009 GB003667.

Bond-Lamberty, B., Thomson, A., 2010. Temperature-associated increases in the global soil respiration record. Nature 464, 579–582. http://dx.doi.org/10.1038/nature08930.

Brooks, P.D., Williams, M.W., Schmid, S.K., 1996. Microbial activity under alpine snowpacks, Niwot ridge, Colorado. Biogeochemistry 32, 93–113.

Chapin, F.S., McGuire, A.D., Randerson, J., Pielke, R., Baldocchi, D., Hobbie, S.E., Roulet, N., Eugster, W., Kashschke, E., Rastetter, E.B., Zimov, S.A., Running, S.W., 2000. Arctic and boreal ecosystems of western North America as components of the climate system. Glob. Chang. Biol. 6, 211–223.

Chapin, F.S., Sturm, M., Serreze, M.C., McFadden, J.P., Key, J.R., Lloyd, A.H., McGuire, A.D., Rupp, T.S., Lynch, A.H., Schimel, J.P., Beringer, J., Chapmam, W.L., Epstein, H.E., Euskirchen, E.S., Hinzman, L.D., Jia, G., Ping, C.-L., Tape, K.D., Thompson, C.D.C., Walker, D.A., Welker, J.M., 2005. Role of land-surface changes in Arctic summer warming. Science 310, 657–660. http://dx.doi.org/10.1126/science.1117368.

Darenova, E., Pavelka, M., Acosta, M., 2014. Diurnal deviations in the relationship between CO_2 efflux and temperature: a case study. Catena 123, 263–269. http://dx.doi.org/10.1016/j/catena.201408.008.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedback to climate change. Nature 440, 165–173.

Davidson, E.A., Belk, E., Boone, B.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob. Chang. Biol. 4, 217–227.

Davidson, E.A., Savage, K., Verchot, L.V., Navarro, R., 2002. 2002. Minimizing artifacts and biases in chamber-based measurements of soil respiration. Agric. For. Meteorol. 113, 21–37.

Dunn, A., Barford, C.C., Wolfsy, S.C., Goulden, M.L., Daube, B.C., 2006. A long-term record of carbon exchange in a boreal black spruce forest: means, responses to interannual variability, and decadal trends. Glob. Chang. Biol. 12, 1–14.

Epron, D., Ngao, J., Granier, A., 2004. Interannual variation of soil respiration in a beech forest ecosystem over a six-year study. Ann. For. Sci. 61, 499–505. http://dx.doi.org/10.1051/forest:2004044.

Euskirchen, E.S., McGuire, A.D., Kicklighter, D.W., Zhuang, Q., Clein, J.S., Dargaville, R.J., Dye, D.G., Kimball, J.S., McDonald, K.C., Melillo, J.M., Romanovsky, C.E., Smith, N.V., 2006. Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems. Glob. Chang. Biol. 12, 731–750. http://dx.doi.org/10.1111/j.1365-2486.2006.01113.x.

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

Flanagan, L.B., Johnson, B.G., 2005. Interacting effect of temperature, soil moisture and plant biomass production on ecosystem respiration in a northern temperate grassland. Agric. For. Meteorol. 130, 237–253.

Gaumont-Guay, D., Black, T.A., Griffis, T.J., Barr, A.G., Morgenstern, K., Jassal, R.A., Nesic, Z., 2006. Influence of temperature and drought on seasonal and interannual variations of soil, bole and ecosystem respiration in a boreal aspen stand. Agric. For. Meteorol. 140, 203–219.

Grosse, G., Harden, J., Turetsky, M., McGuire, A.D., Camill, P., Tarnocai, C., Frolking, S., Schuur, E.A.G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K.P., French, N., Waldrop, M., Bourgeau-Chaves, L., Striegl, R.G., 2011. Vulnerability of high-latitude soil organic carbon in North America to disturbance. J. Geophys. Res. 116, G00K06. http://dx.doi.org/10.1029/2010JG001507.

Hinzman, L.D., Goering, D.J., Kane, D.L., 1998. A distributed thermal model for calculating temperature profiles and depth of thaw in permafrost regions. J. Geophys. Res. -Atmos. 103, 975–991.

Hinzman, L.D., Bettez, N.D., Bolton, W.R., Chapin, F.S., Dyurgerov, M.B., Fastie, C.L., Griffith, B., Hollister, R.D., Hope, A., Huntington, H.P., Jensen, A.M., Jia, G.J., Jorgenson, T., Kane, D.L., Klein, D.R., Kofinas, G., Lynch, A.H., Lloyd, A.H., McGuire, A.D., Nelson, F.E., Oechel, W.C., Osterkamp, T.E., Racine, C.H., Romanovsky, V.E., Stone, R.S., Stow, D.A., Sturm, M., Tweedie, C.E., Vourlitis, G.L., Walker, M.D., Walker, D.A., Webber, P.J., Welker, J.M., Winker, K.S., Yoshikawa, K., 2005. Evidence and implications of recent climate change in northern Alaska and other arctic regions. Clim. Chang. 72, 251–298.

Khomik, M., Arain, M.A., McCaughey, J.H., 2006. Temporal and spatial variability of soil respiration in a boreal mixedwood forest. Agric. For. Meteorol. 140, 244–256.

Kim, Y., 2014. Effect of ablation rings and soil temperature on 3-year spring CO_2 efflux along the Dalton highway, Alaska. Biogeosciences 11, 6539–6553. http://dx.doi.org/10.5194/bg-11-6539-2014.

Kim, Y., Ueyama, M., Nakagawa, F., Tsunogai, U., Tanaka, N., Harazono, Y., 2007. Assessment of winter fluxes of CO_2 and CH_4 in boreal forest soils of Central Alaska estimated by the profile method and the chamber method: a diagnosis of methane emission and implications for the regional carbon budget. Tellus B 59, 223–233.

Kim, Y., Kim, S.-D., Enomoto, H., Kushida, K., Kondoh, M., Uchida, M., 2013. Latitudinal distribution of soil CO_2 efflux and temperature along the Dalton highway, Alaska. Polar Sci. 7, 162–173.

Kim, Y., Nishina, K., Chae, N., Park, S.-J., Yoon, Y.-J., Lee, B.-Y., 2014a. Constraint of soil moisture on CO_2 efflux from tundra lichen, moss, and tussock in council, Alaska, using a hierarchical Bayesian model. Biogeosciences 11, 5567–5579. http://dx.doi.org/10.5194/bg-11- 5567-2014.

Kim, Y., Kodama, Y., Shim, C., Kushida, K., 2014b. Carbon exchange rate in *Polytrichum juniperinum* moss of burned black spruce forest in interior Alaska. Polar Sci. 8, 146–155.

Lavigne, M.B., Ryan, M.G., Anderson, D.E., Baldocchi, D.D., Crill, P.M., Fitzjarrald, D.R., Goulden, M.L., Gower, S.T., Massheder, J.M., McCaughey, J.H., Rayment, M., Striegl, R.G., 1997. Comparing nocturnal eddy covariance measurements to estimates of ecosystem respiration made by scaling chamber measurements at six coniferous boreal sites. J. Geophys. Res. 102, 28977–28985.

Lavoie, M., Owens, J., Risk, D., 2012. A new method for real-time monitoring of soil CO_2 efflux. Methods Ecol. Evol. 3, 889–897.

Lawrence, D.M., Koven, C.D., Swenson, S.C., Riley, W.J., Slater, A.G., 2015. Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO_2 and CH_4 emissions. Environ. Res. Lett. 10, 094011. http://dx.doi.org/10.1088/1748-9326/10/9/094011.

Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8, 315–323.

Mahecha, M.D., Reichstein, M., Carvalhais, N., Lasslop, G., Lange, H., Seneviratne, S.I., Vargas, R., Ammann, C., Arain, M.A., Cescatti, A., Janssens, I.A., Migliavacca, M., Montagnani, L., Richardson, A.D., 2010. Global convergence in the temperature sensitivity of respiration at ecosystem level. Science 329, 838–840. http://dx.doi.org/10.1126/science.1189587.

Mast, M.A., Wickland, K.P., Striegl, R.T., Clow, D.W., 1998. Winter fluxes of CO_2 and CH_4 from subalpine soils in Rocky Mountain National Park, Colorado. Glob. Biogeochem. Cycles 12, 607–620.

Mikan, C.J., Joshua, P.S., Doyle, A.P., 2002. Temperature controls of microbial respiration in arctic tundra soils above and below freezing. Soil Biol. Biochem. 34, 1785–1795.

Monson, R.K., Lipson, D.L., Burns, S.P., Turnipseed, A.A., Delany, A.C., Williams, M.W., Schmidt, S.K., 2006. Winter forest soil respiration controlled by climate and microbial community composition. Nature 439. http://dx.doi.org/10.1038/nature04555.

Natali, S.M., Schuur, E.A.G., Mauritz, M., Schade, J.D., Celis, G., Crummer, K.G., Johnston, C., Krapek, J., Pegoraro, E., Salmon, V.G., Webb, E.E., 2015. Permafrost thaw and soil moisture driving CO2 and CH4 release from upland tundra. J. Geophys. Res. Biogeosci. 120, 525–537. http://dx.doi.org/10.1002/2014JG002872.

National Weather Service of National Oceanic and Atmospheric Administration, i. NOAA online weather datahttp://w2.weather.gov/climate/xmacis.php?wfo=pafg.

Oechel, W.C., Vourlitis, G., Hastings, S.J., 1997. Cold season CO_2 emissions from arctic soils. Glob. Biogeochem. Cycles 11, 163–172.

Outcalt, S.I., Nelson, F.E., Hinkel, K.M., 1990. The zero-curtain effect: heat and mass transfer across an isothermal region in freezing soil. Water Resour. Res. 26, 1509–1516.

Parkin, T.B., Kaspar, T.C., 2004. Temporal variability of soil carbon dioxide flux: effect of sampling frequency on cumulative carbon loss estimation. Soil Sci. Soc. Am. J. 68, 1234–1241.

Pavelka, M., Acosta, M., Marek, M.V., Kutsch, W., Janous, D., 2007. Dependence of the Q10 values on the depth of the soil temperature measuring point. Plant Soil 292, 171–179.

Piao, S., Ciais, P., Friedlingstein, P., Peylin, P., Reichstein, M., Luyssaert, S., Margolis, H., Fang, J., Barr, A., Chen, A., Grelle, A., Hollinger, D.Y., Laurila, T., Lindroth, A., Richardson, A.D., Vesala, T., 2007. Net carbon dioxide losses of northern ecosystems in response to autumn warming. Nature 451, 49–52. http://dx.doi.org/10.1038/nature06444.

Raich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44B, 81–99.

Rayment, M.B., Jarvis, P.G., 2000. Temporal and spatial variation of soil CO_2 efflux in a Canadian boreal forest. Soil Biol. Biochem. 32, 35–45.

Risk, D., Nickerson, N., Creelman, C., McArthur, G., Owens, J., 2011. Forced diffusion soil flux: a new technique for continuous monitoring of soil gas efflux. Agric. For. Meteorol. 151, 1622–1631.

Risk, D., Lee, C.K., MacIntyre, C., Cary, S.C., 2013. First year-round record of Antarctic Dry Valley soil CO_2 flux. Soil Biol. Biochem. 66, 193–196.

Sachs, T., Giebels, M., Boike, J., Kutzbach, L., 2010. Environmental controls on CH_4 emission from polygonal tundra on the microsite scale in the Lena river delta, Siberia. Glob. Chang. Biol. 16, 3096–3110. http://dx.doi.org/10.111/j.1365-2486.2010.02232.x.

Savage, K.E., Davidson, E.A., 2003. A comparison of manual and automated system for soil CO_2 flux measurements: trade-offs between spatial and temporal resolution. J. Exp. Bot. 54, 891–899.

Savage, K.E., Davidson, E.A., Richardson, A.D., 2008. A conceptual and practical approach to data quality and analysis procedures for high-frequency soil respiration measurements. Funct. Ecol. 22, 1000–1007.

Schlesinger, W.H., Andrews, J.A., 2000. Soil respiration and the global carbon cycle. Biogeochemistry 48, 7–20.

Schmidt, S.K., Wilson, K.L., Monson, R.K., Lipson, D.A., 2009. Exponential growth of "snow molds" at sub-zero temperatures: an explanation fro high beneath-snow respiration rates and Q_{10} values. Biogeochemistry 95, 13–21.

Schuur, E.A.G., Vogel, J.G., Crummer, K.G., Lee, H., Sickman, J.O., Osterkamp, T.E., 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature 459, 556–559. http://dx.doi.org/10.1038/nature08031.

Sturm, M., Racine, C., Tape, K., 2001. Increasing shrub abundance in the Arctic. Nature 411, 546–547. http://dx.doi.org/10.1038/35079180.

Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., Zimov, S., 2009. Soil organic carbon pools in the northern circumpolar permafrost region. Glob. Biogeochem. Cycles 23, GB2023. http://dx.doi.org/10.1029/2008GB003327.

Timling, I., Taylor, D.L., 2012. Peeking through a frosty window: molecular insights into the ecology of Arctic soil fungi. Fungal Ecol. 5, 419–429.

Tojo, M., Newsham, K.K., 2012. Snow moulds in polar environments. Fungal Ecol. 5, 395–402.

Ueyama, M., Iwata, H., Harazono, Y., 2014. Autumn warming reduce the CO_2 sink of a black spruce forest in interior Alaska based on a nine-year eddy covariance measurement. Glob. Chang. Biol. 20, 1161–1173. http://dx.doi.org/10.1111/gcb.12434.

Walter, K.M., Chaton, J.P., Chapin III, F.S., Schuur, E.A.G., Zimov, S.A., 2008. Methane production and bubble emission from arctic lakes: isotopic implications for source pathways and ages. J. Geophys. Res. 113, G00A08. http://dx.doi.org/10.1029/2007JG000569.

Whalen, S.C., Reeburgh, W.S., 1998. A methane flux time series for tundra environments. Glob. Biogeochem. Cycles 5, 261–273.

Winston, G.C., Sundquist, E.T., Stephens, B.B., Trumbore, S.E., 1997. Winter CO_2 fluxes in a boreal forest. J. Geophys. Res. 102, 28795–28804.

Wu, C., Chen, J.M., Gonsamo, A., Price, D.T., Black, T.A., Kurz, W.A., 2012. Interannual variability of net carbon exchange is related to the lag between the end-dates of net carbon uptake and photosynthesis: evidence from long records at two contrasting forest stands. Agric. For. Meteorol. 164, 29–38.

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

Zhou, T., Shi, P., Hui, D., Luo, Y., 2009. Global pattern of temperature sensitivity of soil heterotrophic respiration (Q_{10}) and its implications for carbon-climate feedback. J. Geophys. Res. 114, G02016. http://dx.doi.org/10.1029/2008JG000850.

Zona, D., Oechel, W.C., Kochendorfer, J., Paw, K.T., Salyuk, A.N., Olivas, P.C., Oberbauer, S.F., Lipson, D.A., 2009. Methane fluxes during the initiation of a large-scale water table manipulation experiment in the Alaskan Arctic tundra. Glob. Biogeochem. Cycles 23, GB2013. http://dx.doi.org/10.1029/2009GB003487.