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Title: Latitudinal distributions of soil CO_2 efflux and temperature along the Dalton Highway, Alaska

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Executive summary: The Arctic is vulnerable to a changing climate in abrupt ways, offering a significant warning to human beings. Based on snow-pit wall observation and microwave satellite (AMSR-E) analysis along 147.5°W longitude, the start and end of snow-melting days trend earlier with increasing latitude. Considering these circumstances for the terrestrial ecosystem response to Arctic climate change, we must assess changes to the snow-covered period and snow depth along a particular latitude—significant keys in the timing of spring, soil temperature/moisture, active layer, soil microbial activity, phenology of on-ground plants, and subsequently, soil CO_2 efflux. The goal, therefore, is to assess and interpret the latitudinal distribution of soil CO_2 efflux along the Dalton Highway (660 km) of Alaska, in response to changes in the snow-covered period and snow depth, for better understanding of carbon dynamics and budget on a regional scale in the Arctic. Monitoring of soil CO_2 efflux and environmental factors since 2005 at four tundra sites, one ecotone site between tundra and boreal forest, and five boreal forest sites underlain by permafrost regime along the haul road of the trans-Alaska pipeline is required for a proper response to changing climate in the Arctic. The contribution of winter and growing season CO_2 efflux to annual carbon emission at each site will be assessed in response to the recently abrupt climate change in the Arctic. Here, we investigated spatial variations in soil CO_2 efflux and carbon dynamics across five sites located between 65.5°N and 69.0°N in tundra and boreal forest biomes of Alaska. Growing and winter mean CO_2 effluxes for the period of 2006–2010 were 261 ± 124 (Coefficients of Variation: 48%) and 71 ± 42 (CV: 59%) gCO_2/m^2, respectively. This indicates that winter CO_2 efflux contributed 24 % of the annual CO_2 efflux over the period of measurement. In tundra and boreal biomes, tussock is an important source of carbon efflux to the atmosphere, contributing 3.4 times more than other vegetation types. To ensure the representativeness of soil CO_2 efflux was determined, 36 sample points were used at each site during the growing season, so that the experimental mean fell within ±20 % of the full sample mean at 90 % confidence levels. We found, then, that soil CO_2 efflux was directly proportional to the seasonal mean soil temperature, but inversely proportional to the seasonal mean soil moisture level—rather than to the elevation-corrected July air temperature. This suggests that the seasonal mean soil temperature is the dominant control on the latitudinal distribution of soil CO_2 efflux in the high-latitude ecosystems of Alaska.

Background and Goals

The carbon cycle in tundra and boreal forest ecosystems is vulnerable to Arctic climate change, as biological processes (e.g., decomposition and growth) are strongly affected by the degradation of permafrost and the duration of the snow-free season. These phenomena have contributed to tundra greening and boreal forest browning in Alaska (Alcaraz-Segura et al., 2010; Bhatt et al., 2010; Hudson and Henry, 2009; Parent and Verbyla, 2010; Verbyla, 2008). Further, a shorter snow-covered period may contribute to a decrease in winter CO_2 efflux and an increase in CO_2 efflux during the growing period in the Arctic (Sturm et al., 2005). Therefore, in a high-latitude terrestrial ecosystem, it is important to understand whether it is CO_2 uptake by vegetation or CO_2 release from the soil that controls carbon balance and its response to a changing climate.

Soil temperature and moisture are important parameters in regulating soil CO_2 efflux in terrestrial ecosystems (Bond-Lamberty and Thomson, 2010; Bronson et al., 2008; Davidson and Jassens, 2006; Davidson et al., 1998; Gaumont-Guay et al., 2006a, b, 2008; Lavigne et al., 1997; Lloyd and Taylor, 1994; Rayment and Jarvis, 2000; Xu and Qi, 2001). Also, these parameters have been efficiently validated for ecosystem process-based models, for the estimation of a regional carbon budget.

We selected five monitoring sites in the area between 65.5°N and 69.0°N in the Arctic tundra and Subarctic boreal biomes, accessed via the Dalton Highway–Trans-Alaska Pipeline corridor in north–central Alaska. Estimated levels of soil CO_2 efflux may be affected by the measurement method used, due to factors such as chamber size, measurement frequency (e.g., hourly, weekly, seasonal, or annual), and the type of flux measurement system (i.e., automated chamber system or manual system). The variability of soil CO_2 efflux within a constant area can be described by the coefficient of variation (CV), and the number of sampling points required for estimating a statistically significant mean soil CO_2 efflux can be obtained from this CV value. Manual chamber systems can more easily capture the spatial heterogeneity of a site throughout a year; on the other hand, the automated chamber system offers greater measurement frequency during snow-free periods. As this study intended to focus on the spatial heterogeneity of CO_2 efflux at each site, we used a manual chamber system.

The goals of this 2006-2011 research were to: 1) determine the environmental factors regulating the latitudinal distribution of soil CO_2 efflux; 2) evaluate the contribution of winter-season CO_2 efflux through the snowpack to annual carbon emission; and 3) assess the spatial representativeness of soil CO_2 efflux within a plot at each site along the Dalton Highway during the growing season.

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Methodology

We measured soil CO_2 efflux (using a manual chamber system) inside 25 × 25 m plots at five sites along the Dalton Highway–Trans-Alaska Pipeline corridor, which spans a distance of 650 km. Approximately 36 measurements (samples) per site were made during the growing season, and 6 to 15 measurements per site during winter. Specifically, we performed measurements in July 2006, August/September 2007, June and August/September 2008, September 2009, and August/September 2010 to represent the growing (snow-free) season; and in February/March 2007, March 2008, March 2009, and January/April 2010 to represent the winter season. The sites were located in biomes defined as upland tundra (UT, northernmost), subalpine tundra (SaT, north slope of Brooks Range), ecotone (TZ, a transition zone between the tundra and boreal forest), a younger black spruce forest

Figure 1. Representative study sites along the Dalton Highway. UT (upland tundra), SaT (Sub-alpine tundra), TZ (Ecotone), BS1 and BS2 (black spruce forest at Coldfoot and Fairbanks) with the latitude.

near Coldfoot (BS1), and an older black spruce forest near Fairbanks (BS2, southernmost); these sites are shown in Figure 1, and Table 1 includes site descriptions.

Regarding the general pattern of vegetation in northern Alaska, Bliss and Matveyeva (1992) reported low-shrub/dwarf-shrub tundra and sedge/dwarf-shrub tundra as most representative of the area. According to Raynolds et al. (2006), the northern foothills of the Brooks Ranges are covered by cotton-grass tussock tundra and dwarf-shrub moss communities. At higher elevations near Atigan Pass, the vegetation of the subalpine tundra comprises prostrate dwarf-shrub graminoid communities, while the lowlands and uplands of the Tanana-Yukon flats are covered extensively by boreal forest and, in the valley bottoms and lowlands, by wetlands. Soil CO_2 efflux was measured on tussock tundra and non-tussock tundra (such as sphagnum and feather moss and lichen) within the sample plot at each of the five sites.

The temperatures recorded across the sites in January were similar, while those in July differed. The mean annual air and soil (5-cm depth) temperatures for this period were –7.2 °C and –4.0 °C at UT, –4.9 °C and –4.2 °C at SaT, –6.2 °C and –3.8 °C at TZ, –4.8 °C and –2.3 °C at BS1, and –3.1 °C and –1.7 °C at BS2, respectively.

Soil CO_2 efflux-measurement was conducted during snow-free and snow-covered periods, noting local weather conditions and taking care to minimize artificial effects. We used a portable manual chamber CO_2 efflux system at each site. The system consisted of a semi-transparent chamber, 24 cm in diameter and 8 cm high, with a stainless steel base (10 cm high), input and output urethane tubing (6 mm outside diameter, 4 mm inside diameter) and pressure vent, a CM-15-12 Enomoto Micro Pump equipped with a mass flow meter (1 L/min), a Licor-820 NDIR CO_2 analyzer, a 12-V battery for power, and a laptop computer running software for the flux calculation shown in the following equation 1. This system is similar to the manual system of Savage and Davidson (2003; see Figure 1). The 36-chamber bases were inserted into the soil during the summer prior to CO_2 efflux measurement. To prevent disturbance, the bases were not used due to the soft snow surface at the boreal sites during the winter (Kim et al., 2007). The base was used to measure CO_2 efflux when the snow surface was hardened by sublimation and wind at the tundra sites.

The flux measurement time interval was 5-10 minutes, depending on the weather and soil surface conditions, and we calculated the flux from this equation:

$$F_{CO2} = \rho_a \times (\Delta C/\Delta t) \times (V/A), \qquad (1)$$

where ρ_a is the molar density of dry air (mol m^{-3}), ΔC (ppmv) is the change in CO_2 concentration during the measurement period (Δt, min), V is chamber volume, and A is surface area (cross section = 0.045 m^2). The pump was maintained at a flow rate of 0.5 L/min to avoid underestimation or overestimation of soil CO_2 efflux due to under- and over-pressurization, and restrictions in flow and air circulation in the chamber (Davidson et al., 2002). The height of each chamber was also measured alongside soil CO_2 efflux during the winter and growing seasons to allow calculation of the efflux.

Results and Discussion

Latitudinal variation in soil CO_2 efflux

The mean soil CO_2 efflux and standard deviation within the 25 × 25 m sample plots at each site were 4.8 ± 3.3 $mgCO_2/m^2$/min (CV 69%) at UT, 1.5 ± 0.9 $mgCO_2/m^2$/min (CV 60%) at SaT, 6.7 ± 2.5 $mgCO_2/m^2$/min (CV 37%) at TZ, 3.6 ± 2.0 $mgCO_2/m^2$/min (CV 55%) at BS1, and 6.6 ± 2.9 $mgCO_2/m^2$/min (CV 44%) at BS2 (Table 2). The average sampling frequency ranged from 31 samples per growing season at UT to 36 at TZ and BS2, and depended chiefly on weather conditions. The overall mean CV was 53%, indicating a greater spatial variation in the efflux of CO_2. This may result from a difference in accumulated soil organic carbon (SOC) within the sample plot at each site during the summer and winter months (Sommerfeld et al., 1996). Over a range of 10-100 m, Sommerfeld et al. (1996) describe spatial variations that were approximately double the mean winter efflux, suggesting that the mean CV obtained here is reasonable.

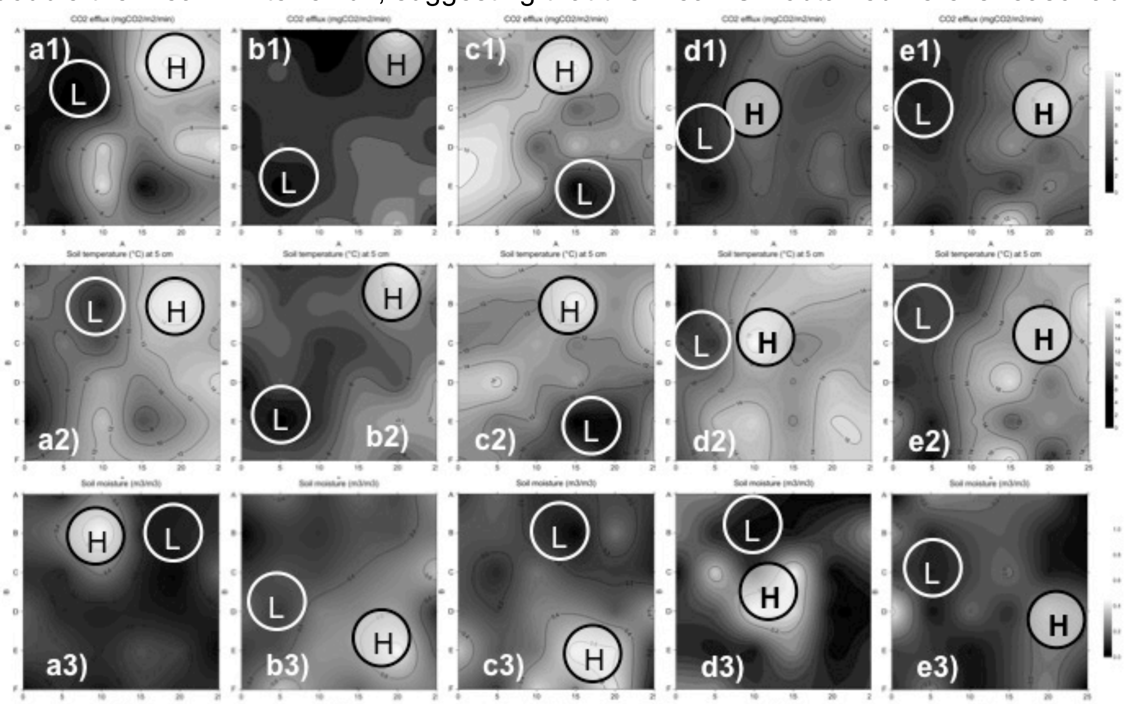

Figure 2. Spatial variations of sol CO_2 efflux (mgC/m²/min; upper: 1), soil temperature at 5 cm (°C; middle: 2) , and soil moisture (m³/m³; lower: 3) in a) UT, b) SsT, c) TZ, d) BS1 at Coldfoot, and e) BS2 at Fairbanks at an interval of 5-m within a 25 X 25m (36 points) during the growing season. H and L denote high and low soil CO_2 efflux, soil temperature, and soil moisture, respectively at each panel.

Figure 2 shows the spatial variation in soil CO_2 efflux within the sample plots at the five sites, with white and black areas denoting higher and lower soil CO_2 efflux, respectively, at each site. Soil CO_2 efflux at the boreal forest sites was higher than at tundra sites. The ecotone site showed the highest CO_2 efflux of the five sites, possibly due to the contribution of CO_2 efflux from well-developed tussock tundra, also indicated by higher CO_2 efflux at the UT and BS2 sites, in addition to differences in the topography and accumulated SOC (10.8, 11.2, and 19.0 kgC/m^2 at UT, TZ, and BS2, respectively; unpublished data). Soil CO_2 effluxes in July 2006 and June 2008 were much higher than effluxes measured during other months, when soil moisture was lower across all sites. This suggests stimulation of soil microbes by an increase in soil temperature.

Tussock tundra is well developed at the UT, TZ, and boreal forest sites, and is widely distributed and typical as vegetation in Arctic tundra and boreal forest ecosystems (Miller et al., 1983; Oechel et al., 1997; Walker et al., 2008; Whalen and Reeburgh, 1988). Mean soil CO_2 effluxes from tussock tundra and non-tussock (i.e., not inter-tussock) tundra sample locations within the plots were 8.1 ± 1.8 (CV 20 %) and 2.4 ± 1.8 (CV 74 %) mgCO_2/m^2/min, respectively. This shows that soil CO_2 efflux in tussock is much greater than in non-tussock. This is due to a difference in the surface area covered by the chamber in tussock (cross section 0.107 m^2), based on the height and diameter of tussock and non-tussock plant structures (cross section 0.045 m^2). The surface area for cone-type tussock was at least 2× greater than that for other on-ground vegetation. Oechel et al. (1997) noted that CO_2 efflux in tussock was a significant CO_2 source, and was 10× greater than in wet sedge. Moreover, tussock covers a pan-Arctic area equal to 9×10^{11} m^2 (Miller et al., 1983), or 6.5×10^{12} m^2 if moss is included (Whalen and Reeburgh, 1988), providing a quantitative understanding of the scale of the release of atmospheric CO_2 from Arctic tundra and boreal forest ecosystems. Considering the extensive distribution of tussock and moss across northern high-latitude ecosystems, the levels of soil CO_2 efflux measured here suggest that the contribution from on-ground vegetation should not be overlooked when estimating regional/global carbon budgets.

Winter CO_2 efflux through the snowpack in Arctic tundra and boreal forest ecosystems represents an important source of atmospheric carbon within the annual carbon budget (Fahnestock et al., 1998; 1999; Kim et al., 2007; Oechel et al., 1997; Zimov et al., 1993, 1996). Winter CO_2 emission corresponds to between 10 % and 30 % of the annual soil respiration rate in alpine, Subarctic, and Arctic regions during the long (> 200 days) yearly snow-covered period (Kim et al., 2007; Oechel et al., 1997; Mast et al., 1998; Wickland et al., 2001; Zimov et al., 1993, 1996). This suggests that the contribution of winter CO_2 efflux should not be overlooked when evaluating the annual carbon budget on regional and global scales.

Mean winter CO_2 efflux during the three winters of 2007–2010 ranged from 0.43 ± 0.25 mgCO_2/m^2/min (CV 57 %) at UT to 1.34 ± 1.05 mgCO_2/m^2/min (CV 78 %) at BS2 (Table 2). This indicates that winter efflux tends to increase moving southward, forming a latitudinal gradient. The average sampling frequency ranged from 7 samples per winter at the UT site to 13 at the BS2 site, depending on accessibility. Although winter CO_2 efflux is much (a tenth to a third) smaller than that in the growing season, the contribution of winter carbon to the total annual emission of soil carbon to the atmosphere is not negligible, due to the long winter period of over 200 days in the high latitudes of Alaska and elsewhere. The snow-covered period ranged from 208 days at BS2 to 270 days at UT (average 225 days), corresponding to 7.5 months per year. The mean winter (snow-covered period) CO_2 efflux was 71 ± 42 gCO_2/m^2 (CV 59 %), while the mean summer (snow-free period) CO_2 efflux was 261 ± 124 gCO_2/m^2 (CV 48 %). Winter CO_2 efflux contributed 24 % of the annual CO_2 efflux from our study sites in Alaska. This is comparable to values reported previously from alpine, subalpine, tundra, and boreal forest ecosystems (Kim et al., 2007; Oechel et al., 1997; Wickland et al., 2001).

Latitudinal variation in environmental factors

Soil microbes tend to be very active by the middle of the growing season. The distributions of soil CO_2 efflux at each site in June 2008 (Fig. 2a–e) show a pattern similar to soil temperature at a depth of 5 cm (Fig. 2f–j) (as well as at 10 cm; not shown). The distribution of soil CO_2 efflux shows a pattern that is reciprocal to soil moisture at the UT, TZ, and BS2 sites. Generally, the CV (41 % to 52 %) in soil temperature at a depth of 10 cm is much greater than the CV (21 % to 34 %.) at 5 cm depth. This variation reflects the differences in thaw depth, water saturation, and relief. Soil temperatures at greater depths are more sensitive to soil CO_2 efflux (Mikan et al., 2002; Pavelka et al., 2007), and also vary in response to site characteristics such as aspect, elevation, slope, and vegetation.

Spatial variation in soil moisture (Fig. 2k–o) shows an inverse pattern relative to soil CO_2 efflux and soil temperature at a depth of 5 cm. Lower CO_2 efflux and soil temperature at each site correspond to a relatively higher soil moisture content. The relationship between soil moisture and soil temperature at a depth of 5 cm shows a negative exponential curve at the five sites. Soil moisture explained 30 % of the variability in soil temperature at a depth of 5 cm, and ranged from 18 % at SaT to 47 % at TZ.

Mean soil moisture over the growing season correlates with soil temperature at depths of 5 and 10 cm, with R^2 values of 0.71 and 0.48, respectively. This indicates that soil moisture and soil temperature at both depths across all sites are inversely related. Soil moisture is significantly influenced by snowmelt in late April (boreal forest) and in mid-May (tundra) in Alaska (Sturm et el., 2005).

Environmental factors modulating soil CO_2 efflux

Figure 3 shows the response of soil CO_2 efflux to soil temperature and moisture at a depth of 5 cm at each site in June 2008. To develop a better understanding of temperature sensitivity of soil CO_2 efflux, we fitted an exponential curve to the relationship between soil CO_2 efflux and soil temperature at a depth of 5 cm (Fig. 3a) using the equation

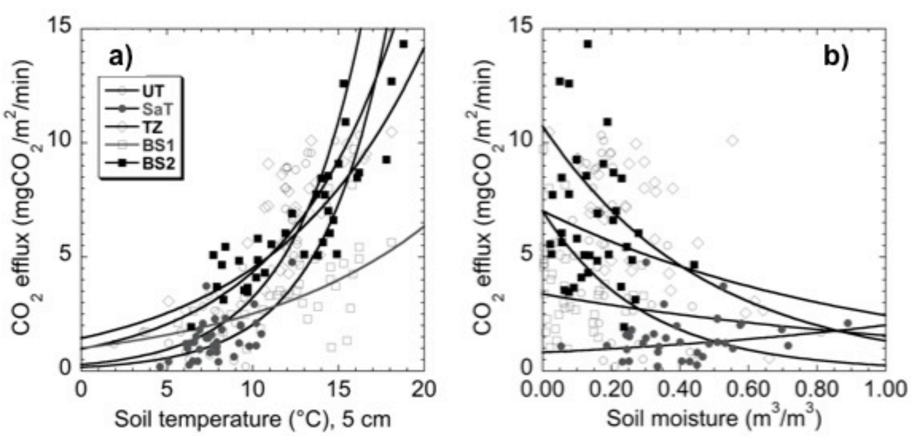

Figure 3. Exponential relationships between soil CO_2 efflux and a) soil temperature at 5 cm, and b) soil moisture at the representative sites, within a 25 × 25 m grid during the growing season.

$$SR = \beta_0 \cdot e^{\beta_1 \cdot T}, \quad (2)$$

where *SR* is the measured soil CO_2 efflux ($mgCO_2/m^2/min$), *T* is soil temperature (°C), and β_0 and β_1 are constants. This exponential relationship is commonly used to represent soil CO_2 efflux as a function of temperature (Davidson et al., 1998; Gaumont-Guay et al., 2006a, b, 2008; Lavigne et al., 1997; Rayment and Jarvis, 2000; Xu and Qi, 2001). The Q_{10} temperature coefficient values were calculated as in Davidson et al. (1998):

$$Q_{10} = e^{\beta 1 \cdot 10}. \qquad (3)$$

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 that a rate increase of the order of 2 to 3 times occurs for every 10 °C rise in temperature (Lloyd and Taylor, 1994). Table 3 shows the mean and range of Q_{10} values, as well as the correlation coefficients (R^2) of the relationship between soil CO_2 efflux and soil temperature at depths of 5 and 10 cm from each site during the summer monitoring periods, based on a one-way ANOVA at a 95 % confidence level. Contrary to the relationship between CO_2 efflux and soil temperature, soil CO_2 efflux at each site follows soil moisture with a decreasing logarithmic relationship, whereas soil moisture increases logarithmically (R^2 = 0.05 to 0.26), as shown in Fig. 3b.

Seasonal mean CO_2 efflux at each site followed soil temperature (ST) exponentially, such that at a depth of 5 cm, soil CO_2 efflux = 0.28·exp (0.24·ST_5) (R^2 = 0.66, Q_{10} = 11.0, p = 0.0015), while at 10 cm, soil CO_2 efflux = 0.88·exp (0.35·ST_{10}) (R^2 = 0.58, Q_{10} = 33.1, p = 0.0799; Fig. 4a) during the growing season. Mikan et al. (2002) reported that Q_{10} increased abruptly with freezing, varying from 4.6 to 9.4 in thawed soils (+0.5 °C to +14 °C), and from 63 to 237 in frozen soils (−10 °C to −0.5 °C) for tundra soils in Alaska based on their incubation experiment. For the narrower range of soil temperature shown at 10 cm below the surface, for example, soil CO_2 efflux is more sensitive than at 5 cm below the surface, suggesting that there may be an increased CO_2 time-delay with depth (Pavelka et al., 2007). Pavelka et al. (2007) calculated Q_{10} values based on the cross-correlation of each depth's temperature time series with efflux, and found an exponential increase in Q_{10} with depth, reaching an extremely high Q_{10} value of 799 at 30 cm. However, in this study, snow-free and snow-covered soil CO_2 effluxes increased exponentially with seasonal soil temperature at a depth of 5 cm: soil CO_2 efflux = 2.33·exp (0.044·ST_5) (R^2 = 0.77, Q_{10} = 1.55, p = 0.179), reflecting the temperature sensitivity of soil CO_2 efflux with latitude, in spite of the temperature dependence on soil depth at each site. Panikov et al. (2006) reported that the lowest temperature with detectable CO_2 production was –39 °C in tundra soil, while boreal forest soils showed no activity at –31 °C during their soil incubation experiment, reflecting seasonal changes in the abundance of cold-active microorganisms. This difference in CO_2 production may be due to the presence of different microbial communities during the growing and winter seasons.

The seasonal mean CO_2 efflux at each site also tracked soil moisture closely, decreasing exponentially as soil moisture (SM) increased: soil CO_2 efflux = 9.20·exp (–3.46·SM), (R^2 = 0.48, p = 0.0020) based on a one-way ANOVA at a 95% confidence level (Fig. 4b). This suggests seasonal CO_2 efflux depends on soil moisture in tundra and boreal forest ecosystems during the growing season.

The mean air temperature in July required an elevation correction. This was achieved by simply applying the lapse rate of 0.5 °C/100 m to the elevation for the latitudinal gradient of soil CO_2 efflux. For example, 13.1 ± 1.0 °C mean air temperature at 440 masl (meters above sea level) for the UT site (see Tables 1 and 2) was corrected to 15.3 ± 3.2 °C at 0 masl. Figure 5 shows the response of mean soil CO_2 efflux to elevation-corrected air temperature during the growing season in July. This indicates three site clusters: 1) the alpine tundra site; 2) the upland tundra/ecotone sites; and 3) the boreal black spruce forest site. The alpine tundra site shows lower CO_2 efflux and temperatures, the boreal black spruce forest sites show higher CO_2 efflux and temperatures, while the upland tundra and ecotone sites show higher CO_2 efflux and lower temperatures. These differences suggest that the latitudinal gradient of annual mean air temperature may affect the distribution of CO_2 efflux in a north–south direction across Alaska (see Table 2).

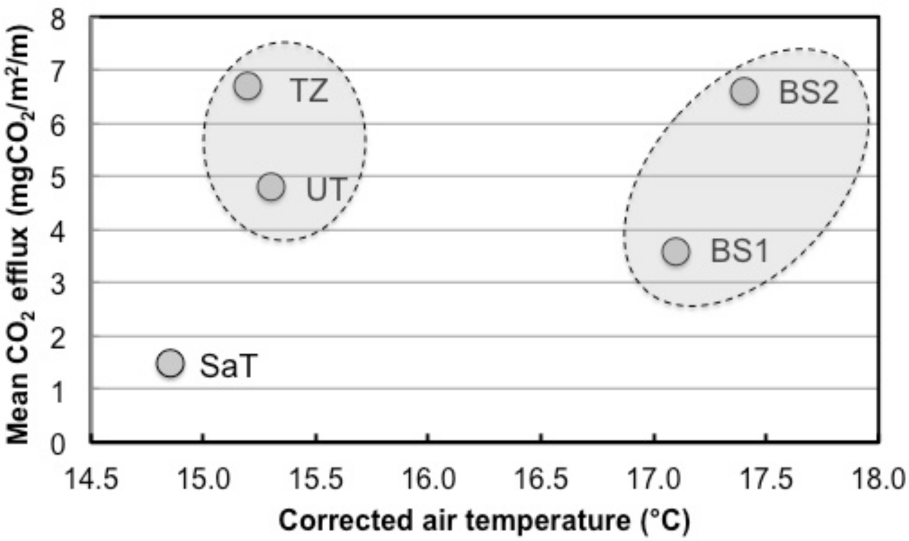

Figure 5. Response of mean soil CO_2 efflux to the elevation-corrected air temperature in July, indicating that three similar group sites: 1) the alpine tundra site, 2) the upland tundra/ecotone sites, and 3) the black spruce forest sites.

Figure 6 shows the latitudinal gradients of mean soil CO_2 effluxes during snow-free and snow-covered periods, elevation-corrected air temperature in July, soil temperature at 5 cm, and soil moisture. The latitudinal gradient of soil temperature, rather than elevation-corrected air temperature, is similar to that of soil CO_2 efflux. However, soil moisture is inversely related to soil temperature. Soil moisture tends to increase to the north (BS2 to SaT), and then to sharply decrease to the northernmost site, UT. This feature could be due to the effects of

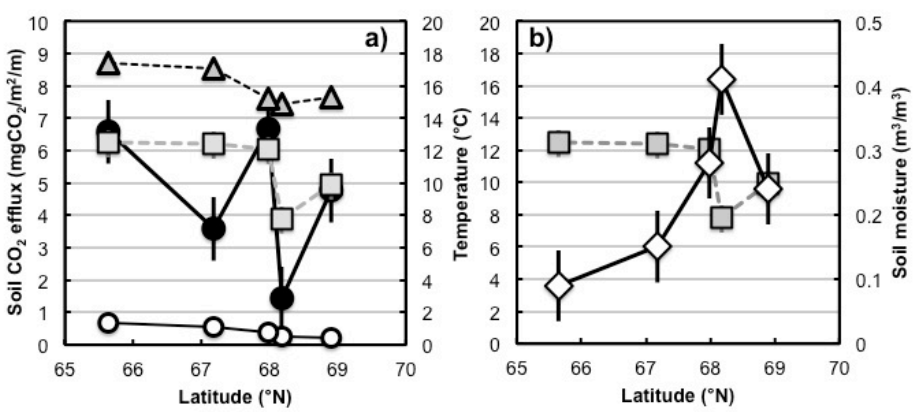

Figure 6. Latitudinal distributions of (a) mean soil CO_2 efflux for growing (solid circle) and winter (open circle) to the elevation-corrected air temperature in July (triangle) and mean soil temperature at 5 cm (square), and of (b) soil temperature and soil moisture (diamond) during the growing season along the Dalton Highway, Alaska, suggesting that soil temperature rather than the corrected air temperature leads to change in soil CO_2 efflux.

elevation and thaw depth at each site. The gradient of winter CO_2 efflux simply decreases with latitude and is possibly correlated with snow depth (Sturm et al., 2005). The effect of snow depth is not limited to individual shrubs or patches of shrubs in tundra, nor to crown snow on branches in the boreal forest. When snow depths from shrubland (containing shrubs up to 1.5 m high) covering 100 ha in Alaska were compared with depths from nearby shrub-free tundra, snow in the shrubland was consistently deeper by 17-28 % (Sturm et al., 2005). The researchers concluded that increasing shrub density leads to greater snow depths, which stimulate higher winter soil temperatures and greater microbial activity, and which subsequently enhances soil CO_2 efflux through the snowpack to the atmosphere, resulting in the warming of tundra during winter (Sturm et al., 2005).

Spatial representativeness of soil CO_2 efflux

Many different methods have been employed to measure soil CO_2 efflux, each with advantages and disadvantages (Davidson et al., 2002; Hutchinson and Livingston, 2002; Savage and Davidson, 2003; Yim et al., 2003). Manual chamber systems are easily constructed at sample sites, as we have described, but also have associated drawbacks with respect to measurement frequency and constraints on time, labor, and unexpected weather conditions. Nevertheless, this method offers simplicity and efficiency when covering a wide area, with the aim of estimating spatial representativeness of soil CO_2 efflux. On the other hand, automated chamber systems offer a much higher temporal frequency of measurement and can operate under any weather conditions. However, these systems require a much greater operating infrastructure, such as a constant power supply and storage, and are much more expensive than manual systems. As a result of these constraints, monitoring programs based on automated systems tend to cover a smaller area than those using manual systems.

Spatial variation in soil CO_2 efflux is related to the size of vegetation communities, pockets of fine root proliferation, and the remnants of decomposing organic matter (Davidson et al., 2002). In this study, CV ranged from 37 % to 69 % (according to manual chamber). The surface area covered by a chamber influences the number of chambers required to estimate representativeness of soil CO_2 efflux 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 this equation:

$$n = [ts/D]^2, \quad (4)$$

where n is the number of sample 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, and D is the desired interval about the full sample mean, within which a smaller experimental mean is expected to fall.

Table 4 demonstrates that each site requires 36 sampling points (within a 25 × 25 m plot) to generate an experimental mean falling within ±20 % of the overall mean at the 80 % and 90 % confidence levels, and at the 95 % level for all sites other than UT.

However, to achieve within ±10 % at all confidence levels, we must consider a larger chamber size than that used in this study, with increased sampling points for seasonal flux-measurements. This type of intensive study may help to guide future researchers as they attempt to establish how many flux measurements are routinely needed per site in each monitoring period, based on the spatial and/or temporal differences they aim to investigate at a particular level of statistical confidence (Davidson et al., 2002). Large numbers of flux measurements are ideal, but the logistical constraints of labor and time often limit the number of measurements that are feasible. Yim et al. (2003) showed that the CV of the spatial variation of soil CO_2 efflux across 50 sampling points within a 30 × 30 m plot was 28 %. The average number of sampling points required to estimate soil CO_2 efflux within 10 % and within 20 % of its actual mean, at the 95 % confidence level, were estimated to be 30 and 8, respectively. This required number of sampling points may depend on the area covered by a chamber; Yim et al.'s (2003) chamber had an area of 0.0125 m^2, which is much smaller than those used in this study. Hence, a larger chamber may require fewer sampling points, and a smaller chamber may require more.

Conclusions and future directions

As soil temperature changes in Alaska, representative sites' soil CO_2 efflux show patterns similar to the latitudinal gradient of the temperature. Simply taking the lapse rate of the elevation-corrected air temperature in July into account, the relationship between mean soil CO_2 efflux and the corrected mean air temperature revealed three similar clusters: 1) alpine tundra; 2) upland tundra/ecotone; and 3) boreal black spruce forest. These sites have distinct site characteristics that indicate that the latitudinal gradient of CO_2 efflux is dependent on soil temperature, rather than elevation-corrected air temperature. To provide further support for this conclusion, soil CO_2 efflux measurements and the monitoring of other environmental variables are required at additional sites (e.g., 3-5 tundra sites and 3-5 boreal forest sites) using the Forced Diffusion (FD) chamber method (Risk et al., 2011), in order to better understand latitudinal changes in soil CO_2 efflux and environmental variables in Alaska during the snow-free period.

Based on our study during the winter season (7.5 months duration), CO_2 efflux contributes 24 % of the annual CO_2 efflux from the tundra and boreal forest ecosystems of Alaska. As the response to Arctic climate change continues, the contribution of winter CO_2 efflux to annual emissions will be significant for carbon dynamics in tundra and boreal forest ecosystems. To understand the changes in soil CO_2 efflux in response to Arctic climate change, representative sites in coastal tundra and in burned ecosystems will be needed as well, and the number of sampling points at each site must be increased by using larger chambers and bi-monthly flux measurements.

Capabilities:

1) Understanding of the carbon dynamics and budget in tundra and boreal forest ecosystems in Alaska using a soil CO_2 efflux system for seasonal variability of soil CO_2 efflux during the growing season, and
2) Monitoring of environmental factors (e.g., soil temperatures and soil moisture at multi-depths, snow depth, snow density) along the Dalton highway during the snow-covered season.

Challenges: Vulnerability of soil CO_2 efflux, soil organic carbon, and *in-situ* albedo/NDVI in tundra and boreal forest regime response to changes in extent and duration of snow and thawing permafrost by climate change in the Arctic.

Sustainability: Long-term monitoring of soil CO_2 efflux along the latitudinal observation.

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