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Effect of ablation ring and soil temperature on 3-yr spring CO₂ efflux along the trans-Alaska pipeline, Alaska

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Abstract

Winter and spring soil CO₂ efflux-measurements represent a significant component in the assessment of annual carbon budgets of tundra and boreal forest ecosystems, as a response to climate change in the Arctic. This study was conducted to quantify CO₂ efflux using a portable chamber system at representative sites along the trans-Alaska pipeline. The sites here are characterized as three tundra, two white spruce, and three black spruce forest sites during winter and spring seasons of 2010 to 2012; study of these sites will offer a better understanding of winter and spring carbon contributions to the annual carbon budget, as well as their affecting parameters by the effect of ablation ring in spring. 3 yr spring CO₂ efflux depends on soil temperature at 5 cm depth on a regional scale. At their highest, Q_{10} values were 4.2×10^6 , within the exposed tussock tundra of the upland tundra site, as tundra soils warmed from -0.9 to 0.5 °C, involving the soil microbial activity. With the forest census (400 m^2) of the two white spruce forest sites, CO₂ emissions were estimated to be 35 to 145 gC day⁻¹ in winter and 56 to 1980 gC day⁻¹ in spring, corresponding to 1–3 and 1–27 % of annual carbon, respectively. The contributions from spring CO₂ emissions are likely to increase as exposed soils widen in average length (major axis) from east, west, and south, as well as north-side length (minor axis). Considering the periods of winter and spring seasons across tundra and boreal forests, average winter- and spring-seasonal CO₂ contributions to annual carbon budgets correspond roughly to 14–22 % in tundra and 9–24 % in boreal forest sites during 2011–2012. Contributions from spring carbon comparable to growing season CO₂ emissions are sensitive to subtle changes at the onset of spring and during the snow-covered period in northern high latitudes, in response to recent Arctic climate change.

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1 Introduction

Northern high latitudes exhibit Arctic climate change very prominently, with increasing air temperature, deepening active layers, thawing permafrost, changing snow cover, increasing shrub abundance, greening in tundra and browning in boreal forest ecosystems, and prolonged vegetation growing season within terrestrial ecosystems (Sturm et al., 2001; ACIA, 2004; Verbyla, 2008; AMAP, 2011; de Jong et al., 2011; Bhatt et al., 2013). Terrestrial ecosystem carbon (e.g., CO₂ and CH₄) is obviously susceptible to these climate change responses (Chapin et al., 2000). Of them, it is no exaggeration to say that temperature is a significant driver in positive feedbacks on regional and pan-Arctic scales (Chapin et al., 2000; ACIA, 2004). Carbon dynamics in tundra and boreal forest ecosystems represent the dependence of temperature – the so-called Q_{10} value – based on many field-based and modeling observations (Xu and Qi, 2001; Davidson and Jassens, 2006; Bond-Lamberty and Thomson, 2010; Mahecha et al., 2010). Bond-Lamberty and Thomson (2010) estimated global soil respiration at 98 ± 12 GtC (1 GtC = 10^{15} gC), which shows an increase of 0.1 GtC yr^{-1} over two decades. This suggests a CO₂ emission response factor of 1.5 relative to air temperature (Q_{10}), consistent with an enhanced response from the terrestrial carbon cycle to global climate change (Bond-Lamberty and Thomson, 2010).

Soil CO₂ efflux, produced by 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). Recent studies suggest that the magnitude of soil CO₂ efflux is related to tundra greening and boreal forest browning (Verbyla, 2008; Bhatt et al., 2010; Parent and Verbyla, 2010), as well as the timing of snow disappearance and the snow-covered period (Stone et al., 2002; McDonald et al., 2004; Sturm et al., 2005). During the seasonally snow-covered period, winter CO₂ efflux measurements have been gathered in tundra (Oechel et al., 1997; Fahnstock et al., 1998, 1998; Björkman et al., 2010; Kim et al., 2013), alpine and subalpine forests (Brooks et al., 1996; Mast et al., 1998; Monson et al., 2006a,

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b), and boreal forests (Hardy et al., 1995; Winston et al., 1995, 1997; Kim et al., 2007, 2013), accounting for 10–30% of the variability in annual carbon emissions. On the other hand, it is difficult to determine the timing of snow disappearance in the early spring season, due to shorter snow disappearance time spans, including changes of -0.13 d yr^{-1} over 60 yr in Barrow, Alaska according to NOAA/CMDL historical data (Stone et al., 2000), and -0.94 d yr^{-1} over 14 yr using microwave remote sensing (McDonald et al., 2004). This shift may cause decreased Arctic winter CO₂ efflux, as well as increased efflux during the vegetation growth period (Sturm et al., 2005), resulting from changes in solar radiation (e.g., energy exchange) (Eugster et al., 2000). It is significant, therefore, to understand and qualify soil carbon balance – whether it is the acceleration of photosynthesis and respiration or their decline – which controls the terrestrial carbon budget in response to a changing climate in northern high latitudes.

Soil temperature and moisture are important parameters in regulating soil CO₂ efflux across tundra and boreal forest ecosystems (Lloyd and Taylor, 1994; Davidson et al., 1998; Xu and Qi, 2001; Davidson and Janssens, 2006; Rayment and Jarvis, 2000; Kim et al., 2007, 2013); further, these parameters will be efficiently validated for terrestrial ecosystem process-based models, for the assessment of carbon budgets on region and globe scales. Also noted are snow depth and snow crust, which slightly affect winter/spring CO₂ efflux in vegetation types across the North Slope of Alaska ($R^2 = 0.19$; Fahnestock et al., 1998), and in subalpine soils in Rocky Mountain National Park, Colorado (Mast et al., 1998), respectively. Exertions are needed to evaluate these environmental parameters influencing soil CO₂ efflux during seasonally snow-covered and snow-disappeared periods, across tundra and boreal forest ecosystems.

The aims of this study are to (1) determine the environmental parameters resolving CO₂ efflux in exposed and snow-covered soils along the trans-Alaska pipeline; (2) understand the characteristics of CO₂ efflux in exposed and snow-covered soils, considering the effect of ablation rings in the spring season; and (3) assess the contributions of winter and spring carbon toward annual carbon balance during the winter and spring

seasons of 2010–2012, based on a constant area (400 m²) in white spruce sites and during the winter and spring periods.

2 Materials and methods

2.1 Sampling descriptions and methods

5 Using the dynamic chamber system method, soil CO₂ efflux was measured at three tundra sites and five boreal forest sites along the trans-Alaska pipeline, over a distance of 660 km, during winter and spring seasons of 2010–2012, as shown in Fig. 1. Site information is shown in Table 1; sites were located within coastal tundra (CT, northernmost), upland tundra (UT, between CT and SaT), subalpine tundra (SaT, north slope of Brooks Ranges), ecotone (TZ, a transition zone between the tundra and boreal forest and white spruce forest), a white spruce forest in Gold Creek (GC), a younger black spruce forest near Coldfoot (BC), and two black spruce forest sites along the upper and lower Yukon River (YU and YL, southernmost). The flux-measuring periods were 12–25 January 2010, 26 February–12 March 2011, and 5–22 March 2012 during the winter season; and 7–23 April 2010, 23 April–4 May 2011, and 21 April–3 May 2012 during the spring season.

Sites were classified as three ecotypes: tundra (CT, UT, and SaT), white spruce forest (TZ and gC), and black spruce forest (BC, YU, and YL), depending on dominant vegetation and permafrost. Dominant species are listed in Table 1. The general distribution of Alaska tundra vegetation is covered with moss, sedge, and dwarf shrubs (Bliss and Matveyeva, 1992). Patterns in the northern foothills of the North Slope include cotton-grass tussock tundra, bryophyte, lichen, and graminoid communities (Raynolds et al., 2006). Meanwhile, the boreal forest extends to the lowlands and uplands of the Tanana-Yukon flats, comprising white and black spruce and deciduous forests (Raynolds et al., 2006; Kim et al., 2013). Continuous and discontinuous permafrost underlies the tundra and boreal forest ecosystems, respectively, while no

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was measured in the exposed and snow-covered soil of boreal forest (Fig. 2a–c) and tussock tundra (Fig. 2d) during the spring. In boreal forest sites, efflux measurements were conducted in exposed and snow-covered soils in four directions from the stems of the white spruce forest, at intervals of 50–60 cm from the stem, due to differences in snowmelt rate from four directions of solar radiation. Generally, the expansion of exposed soil on the south side is much faster and wider than on other sides, as shown in Fig. 2b.

Taking into account the contribution of spring CO₂ efflux by the effect of ablation ring in white spruce forest, the forest census was investigated in TZ and GC sites. Tree density and height within a 20 × 20 m plot were 32 trees/400 m² and 5.1 m for TZ, and 30 trees/400 m² and 8.8 m for GC (Suzuki et al., 2013). I have assumed here that the extent of the lowest branch in the targeted white spruce is as same as in the exposed area, due to relatively lower snowpack under branches of white spruce compared to openings, and have calculated the area of exposed soil with measured four-directional lengths. The oval shape (using averaged length from the east, west, and south sides as the length of the semi-major axis and the north side as the length of the semi-minor axis) shows that the 2010 extents of exposed and snow-covered areas were 135 and 265 m² for TZ, and 102 and 298 m² for GC, respectively.

2.2 Estimation of soil CO₂ flux

Using a portable chamber CO₂ efflux system, soil CO₂ efflux measurement was conducted during snow-covered and snow-melting periods to minimize artificial effects. As described in Kim et al. (2013), the measurement system consisted of a transparent-material chamber (24 cm in diameter and 8 cm high); a stainless steel base (24 cm in diameter and 10 cm high); input and output polyurethane-material tubing (6 mm outside diameter, 4 mm inside diameter; LI-COR. Inc., USA) and pressure vent; a micro pump (CM-15-12, Enomoto Inc., Japan) equipped with a mass flow meter (1 L min⁻¹); a Licor-820 NDIR CO₂ analyzer (LI-COR. Inc., USA); a 12 V battery for power; and a laptop computer running software for calculations from following Eq. (1). Nine chamber

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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 2 to 3 times occurs for every 10 °C rise in temperature (Lloyd and Taylor, 1994).

Soil temperature at 5 cm below the surface, in conjunction with soil CO₂ efflux measurement, was measured at each site with a portable thermometer (Model 8402-20, Cole-Palmer, USA). For additional measurements of soil temperature and moisture, hourly temperatures at depths of 5, 10, and 20 cm and at 1.3 m above ground (HOBO data logger U-12 and sensor TMC6-HD, Onsetcomp, USA) were monitored at each site. Monitoring of soil moisture at depths of 5 and 20 cm (THLog data logger and sensor HH2, Delta-T Devices, UK) was conducted at intervals of 1 h.

A one-way or two-way ANOVA (95% confidence level) and regression analysis of data using Microsoft Excel Data Analysis software were performed.

3 Results and discussion

3.1 Estimation of winter and spring soil CO₂ efflux

During winter, average and standard deviation for winter CO₂ efflux in boreal forest and tundra were 0.18 ± 0.07 and 0.11 ± 0.10 gC m⁻² day⁻¹ during 2011, and 0.22 ± 0.11 and 0.05 ± 0.11 gC m⁻² day⁻¹ during 2012, respectively. Average soil temperature at 5 cm in boreal forest and tundra were -8.3 ± 1.8 and -12.7 ± 2.9 °C during 2011, and -3.8 ± 1.4 and -14.4 ± 12.8 °C during 2012, respectively. Because of extremely colder ambient temperature in January of 2010 (e.g., < 30 °C below zero), the Non-Dispersive Infrared (NDIR) CO₂ analyzer shut down and winter CO₂ efflux and soil temperature were not measured. In the Canadian boreal forest, Winston et al. (1995, 1997) explained that an important mechanism of CO₂ transport through the forest snowpack was by macro-channels along trunks and stems, as previously described regarding snow-melting mechanisms near the tree stem. Furthermore, winter CO₂ concentration gradients in bare soils and near tree wells were 2.52 to 4.78 ppm cm⁻¹ and 0.93

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to 1.20 ppm cm^{-1} with the CO_2 profile measurement, respectively, suggesting that a lower winter CO_2 gradient near the tree results in faster CO_2 transport from the soil through snowpack to the atmosphere than in bare soils. This demonstrates that the air-snow-soil interface surrounding the tree trunk is much thinner than in forest opening areas.

During the end of the winter season, three-year average snow depth in boreal forest and tundra were 51.2 ± 15.3 (CV: 30 %) cm, and 36.0 ± 8.6 (CV: 24 %) cm respectively, as shown in Table 2. Winter CO_2 efflux depends on soil temperature at 5 cm below the surface, a depth at which the relationship equation amounts to winter CO_2 efflux = $0.42 \times e^{(0.126 \times \text{ST}5)}$ ($R^2 = 0.82$; $Q_{10} = 3.5$; $p < 0.001$; not shown).

During the spring season, average CO_2 efflux in exposed and snow-covered soils of the boreal forest and tundra, as shown in Fig. 2, were 1.31 ± 0.25 (CV: 20 %) and 0.17 ± 0.18 (108 %) $\text{gC m}^{-2} \text{ day}^{-1}$ in 2010, 5.38 ± 3.67 (69 %) and 0.30 ± 0.33 (110 %) $\text{gC m}^{-2} \text{ day}^{-1}$ in 2011, and 2.71 ± 1.77 (65 %) and 0.27 ± 0.20 (74 %) $\text{gC m}^{-2} \text{ day}^{-1}$ in 2012, respectively. Spring CO_2 efflux in exposed soil in 2011 indicated values at least ten times higher than in snow-covered soil, suggesting that the snow-disappearance date in 2011 was approximately 10 to 17 days earlier than in both 2010 and 2012 (as measured by 4 h interval camera), as shown in Fig. 2.

Three-year average spring CO_2 effluxes in four directions within the white spruce forest were 3.87 ± 4.45 (CV: 115 %) $\text{gC m}^{-2} \text{ day}^{-1}$ to the eastern side, 3.00 ± 3.60 (120 %) $\text{gC m}^{-2} \text{ day}^{-1}$ to the west, 4.64 ± 4.61 (91 %) $\text{gC m}^{-2} \text{ day}^{-1}$ south, and 1.25 ± 2.46 (197 %) $\text{gC m}^{-2} \text{ day}^{-1}$ north, at the GC site, respectively. At TZ, average effluxes were 2.40 ± 2.60 (108 %) $\text{gC m}^{-2} \text{ day}^{-1}$ east, 2.31 ± 2.53 (109 %) $\text{gC m}^{-2} \text{ day}^{-1}$ west, 3.00 ± 3.12 (104 %) $\text{gC m}^{-2} \text{ day}^{-1}$ south, and 1.50 ± 1.66 (110 %) $\text{gC m}^{-2} \text{ day}^{-1}$ north, respectively. The magnitude of snow disappearance depends on solar radiation and the strength of long wavelengths from the tree trunk during nighttime in the spring. The much wider exposed area showed south > east west \gg north, in turn, from trunks in the white spruce forest. Average diameter at breast height (DBH: 18 ± 4.5 cm) of white spruce is much thicker than black spruce (DBH: 5.8 ± 3.2 cm), suggesting that

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then, was higher than 2010 and 2012 in exposed and snow-covered soils of the boreal forest and tundra. Further, the response of soil CO₂ efflux to soil temperature at 5 cm showed an exponential curve in these boreal forest and tundra sites along the trans-Alaska pipeline, during winter and spring seasons of 2010–2012 (Fig. 3), indicating a surge in soil CO₂ efflux when soil temperature changes from below to above zero. This may be the result of enhanced soil microbial activity upon an increase in soil temperature just after the snowpack has disappeared. Hence, soil temperature is a significant factor in determining winter/spring soil CO₂ efflux, as reported by many researchers. As shown in Fig. 3, the range of soil temperature differs greatly, indicating seasonal snow-disappearance timing. This demonstrates that soil CO₂ efflux is constrained by seasonal snowpack below zero and is stimulated within exposed soil above zero. In particular, soil CO₂ efflux (> 10 gC m⁻² day⁻¹) within white spruce forest sites in 2011 corresponds to summer soil CO₂ efflux (Fig. 3b). As a result, spring soil CO₂ efflux needs to assess for its contribution to annual soil carbon efflux, in spite of change in snow-disappearance timing (Richter et al., 2000). When soil temperature is above zero at white spruce forest sites (Fig. 3b), spring soil CO₂ efflux greatly varied spatially; however, the variation is due to the fact that the data were obtained at four-directional sides from the trunk, as described in Sect. 3.1.2 (Fig. 2). Hence, the magnitude of spring CO₂ efflux is determined by soil temperature at 5 cm depth at below or above zero, indeed reflecting the stimulation of soil microbial activity with or without seasonally covered snowpack.

The response from spring soil CO₂ efflux at white spruce forest sites (e.g., gC and TZ) toward soil temperature at 5 cm is shown in Fig. 4. At the GC site (Fig. 4a), equations were CO₂ efflux = 0.59 × e^(0.69×ST5) (R² = 0.89) on the south side, CO₂ efflux = 0.64 × e^(0.68×ST5) (R² = 0.73) on the east, CO₂ efflux = 0.70 × e^(0.60×ST5) (R² = 0.81) west, and CO₂ efflux = 0.64 × e^(0.67×ST5) (R² = 0.67) north, respectively. At the TZ site (Fig. 4b), equations were CO₂ efflux = 0.52 × e^(0.40×ST5) (R² = 0.67) south, CO₂ efflux = 0.52 × e^(0.38×ST5) (R² = 0.74) east, CO₂ efflux = 0.26 × e^(0.59×ST5) (R² = 0.62) west, and CO₂ efflux = 0.44 × e^(0.65×ST5) (R² = 0.64) north, respectively. Q₁₀ values in

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GC and TZ sites ranged from 414 west to 1,003 south, and from 43 west to 658 north, respectively. Further, Q_{10} value was 2.6×10^5 at black spruce forest sites during the spring of 2011, as shown in Table 3.

Within the tundra ecosystem (Fig. 3c), although the soil temperature was below zero, soil CO_2 efflux was quite higher. This may be due to (1) shallower thawed soil surface (less than 5 cm) and (2) absorption of solar radiation by exposed plants (see Fig. 2d). It was difficult to measure soil temperature near the soil surface with the portable thermometer. The response from spring soil CO_2 efflux toward soil temperature at 5 cm depth in the upland tussock tundra was $\text{CO}_2 \text{ efflux} = 1.22 \times e^{(0.15 \times \text{ST}5)}$ ($R^2 = 0.43$; $Q_{10} = 4.4$; not shown). On the other hand, during the winter seasons of 2010-2012, the equations for winter soil CO_2 efflux and soil temperature at 5-cm depth over the entire tundra and tussock tundra were $\text{CO}_2 \text{ efflux} = 1.57 \times e^{(0.294 \times \text{ST}5)}$ ($R^2 = 0.62$; $Q_{10} = 19.0$; not shown) and $\text{CO}_2 \text{ efflux} = 75.4 \times e^{(0.64 \times \text{ST}5)}$ ($R^2 = 0.59$; $Q_{10} = 605$; not shown), respectively. Q_{10} values from Eq (3) were calculated at boreal forest and tundra sites, as shown in Table 3.

Higher Q_{10} values in winter and spring seasons were found within boreal white and black spruce forests, and tundra sites across the trans-Alaska pipeline, compared to Q_{10} values of 2.1 to 18 during the growing season (Kim et al., 2013). The possibility that Q_{10} values during winter and spring seasons were much higher than growing season would suggest the exponential growth of microbes (e.g., snow molds and fungi), considering that beneath-snowpack soils warming from -3 to 0°C have also been shown to produce higher CO_2 production in a high-elevation, subalpine forest within the Colorado Front Range (Rocky Mountains) (Monson et al., 2006a, b; Schmidt et al., 2009). There, Monson et al. (2006a, b) demonstrated that soil microbes' beneath-snow CO_2 efflux response (e.g., Q_{10} value: $105-1.25 \times 10^6$) corresponded with a narrower range of soil temperature (-1.0 to 0.0°C). Also, the drastic increase in CO_2 efflux was induced by a strong response from beneath-snow microbes with a much higher dependence from microbial biomass upon increase in soil temperature in the late winter and early spring seasons (Schmidt et al., 2009). In this study, two colonies of unidentified fungi on cry-

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oturbed soils within the chamber base were found at the upland tundra (UT) site on 18 April 2010, as shown in Fig. 5, and where soil CO₂ efflux was not much higher than expected, due to dehydrated fungi. Nevertheless, the Q_{10} value of 4.2×10^6 was the highest in the exposed tussock tundra and cryoturbed soils of the UT site, reflecting the sharp rise in soil CO₂ efflux (0.5 to $2.2 \text{ gC m}^{-2} \text{ day}^{-1}$) as the tundra soils warmed from -0.9 to 0.5°C . While acknowledging the important role of saprotrophic snow molds forming a dense hyphal mat and showing high levels of subnivean respiration in alpine forests (Monson et al., 2006a, b), the snow fungi found in this study disappeared within days of the soils becoming snow-free (Schmidt et al., 2007) as shown in Fig. 5 and did not produce the high CO₂ efflux due to the dehydration in spring.

Fungi are omnipresent in Arctic and sub-Arctic soils, where they function as plant symbionts, parasites, pathogens, and decomposers and may affect the carbon balance of terrestrial ecosystems subjected to climate change in the Arctic (Timling and Taylor, 2012). For example, Panikov et al. (2006) demonstrated evidence that soil CO₂ was produced by microbial activity even at the extremely low temperature of -39°C in Arctic soils from Barrow, West Siberia, and Sweden. Further, it's been widely shown that microbial metabolism occurs in Arctic, sub-Arctic, and subalpine soils under seasonally covered snowpack, even at soil temperatures below 0°C (Sommerfeld et al., 1993; Brooks et al., 1996; Oechel et al., 1997; Winston et al., 1997; Fahnestock et al., 1998; Monson et al., 2006a, b; Schmidt et al., 2006; Kim et al., 2007, 2013; Björkman et al., 2010). Fungal activity in the cold soils of the Arctic and sub-Arctic is a significant key in determining the susceptibility of old-aged soil organic carbon from a deepening active layer and thawing permafrost in response to Arctic warming (Marchenko et al., 2008; Ping et al., 2008; Tarnocai et al., 2009; Grosse et al., 2011).

3.3 Effect of snow depth and snow crust

Contrary to soil temperature, snow depth is not significantly related to determination of spring CO₂ efflux, as in Figure 6a, showing that exponential and linear equations in

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tundra sites during the spring season are CO_2 efflux = $0.43 \times e^{(-0.054 \times \text{ST5})}$ ($R^2 = 0.22$) and CO_2 efflux = $-0.02 \times \text{ST5} + 0.83$ ($R^2 = 0.27$), respectively. This suggests that microbial activity did not occur at these sites, due to the elapsed spring season, as shown in Figure 5. During winter and early spring seasons, Fahnestock et al. (1998) reported that the response from CO_2 efflux to snow depth was quite weak in vegetation community types of Alaska tundra. Although snow depth is not necessarily an important key in influencing winter and spring CO_2 efflux in tundra ecosystem, it has a significant effect on the tall shrub community because deep snowpack provides a better insulation stimulating CO_2 efflux from the soil (Sturm et al., 2005). Hence, additional research needs not only to observe soil temperature in deep and shallow snow accumulation areas, but also to monitor soil CO_2 efflux using a simple Forced Diffusion (FD) chamber method (Risk et al., 2011).

Snow crust is formed by strong winds, and is found across snowpack pit-wall observations in the Arctic. The characteristics of this crust correspond to the horizontal ice layer in temperate regions. Several researchers have suggested that ice layers within the snowpack may have a significant effect on CO_2 transport from seasonally snow-covered soils (Hardy et al., 1995; Winston et al., 1997). Mast et al. (1998) suggested that horizontal ice layers had a considerably lower CO_2 diffusivity than the surrounding snow, but did not block CO_2 efflux from the snowpack surface in subalpine soils of Colorado. They described no effect from ice layers in estimating winter CO_2 efflux, as the concentration gradients above and below these layers were almost linearly the same. CO_2 efflux after the removal of snow crust is much higher – by 2.8 to 28 times – than before the removal, suggesting that snow crust likely plays a role in blocking CO_2 transport through the snowpack to the atmosphere over the North Slope of Alaska. As shown in Figure 6b, the relationship between CO_2 efflux and soil temperature at 5 cm with and without snow crust were CO_2 efflux = $0.10 \times e^{(0.18 \times \text{ST5})}$ ($R^2 = 0.27$; $Q_{10} = 6.0$) and CO_2 efflux = $0.98 \times e^{(0.31 \times \text{ST5})}$ ($R^2 = 0.29$; $Q_{10} = 23$), respectively. Although continuous CO_2 efflux measurement was not conducted in spring, once the seasonally cov-

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at the top of the tussock and in the inter-tussock were monitored at the UT site from 28 August 2010 to 11 July 2012, as shown in Fig. 9. Interestingly, the temperature difference between the two steadily increases with time. Most temperature features at the top are likely to be affected by changes in ambient temperature due to geographical relief, and showed much greater differences during spring of 2011 and 2012, and during early winter of 2012. This suggests that spring-season CO₂ efflux from tussock tundra depended upon the temperature of tussock tundra during 2011 and 2012. Hence, tussock tundra represented a significant carbon source in the tundra ecosystem during winter and spring for the estimation of the seasonal and annual carbon budget in the Arctic (Oechel et al., 1997; Fahnestock et al., 1998, 1999; Kim et al., 2007, 2013). Further, the contribution of average three-year winter and spring CO₂ emissions to the atmosphere corresponds roughly to 14–22 % in tundra, and to 9–24 % in boreal forest sites, of the total annual carbon respired using data from both the 2010 growing season and Kim et al. (2013), as shown in Table 4. Winter CO₂ contributions to annual carbon emissions within tundra, alpine, and boreal forest ecosystems represent 17 % in Alaskan tundra (Fahnestock et al., 1998) to > 25 % in alpine and subalpine regions (Sommerfeld et al., 1993), as reported by many researchers, suggesting that the results of this study are comparable with others. However, spring CO₂ contributions in the boreal forest reached to almost 50 % of total annual carbon emissions, demonstrating the strong tree-well effect (Hardy et al., 1995; Winston et al., 1995, 1997) of the boreal forest, as well as the significance of tussock tundra (Oechel et al., 1997; Fahnestock et al., 1998, 1999; Kim et al., 2007) in tundra and boreal forest ecosystems.

Considering the effect of ablation ring in white spruce forest sites, CO₂ effluxes in the spring, winter, and summer seasons of 2010 were 1.8, 0.6, and 13.2 gC m⁻² day⁻¹ for TZ; and 2.4, 0.4, and 10.4 gC m⁻² day⁻¹ for GC, respectively. Summer season CO₂ emission can be estimated based on an area of 400 m², due to the much smaller tree area at each site. As a result, the contributions of spring, winter, and summer CO₂ emissions, based on this 400 m² area are shown in Table 5, corresponding to 4, 3, and 93 % of the annual carbon budget for TZ; and 5, 3, and 92 % for GC. Using 2010

summer soil CO₂ data, the contributions to the annual carbon budget of spring, winter, and summer CO₂ emissions in the two white spruce forest sites during 2011 and 2012 are shown in Table 5. This feature suggests that the wider the extent of exposed soil, the greater the contribution to the annual carbon budget, based on a constant area.

5 Although up to 5 % sounds small, the estimation might change the estimation of NEE (net ecosystem exchange) from a sink to a source (Ueyama et al., 2013).

4 Conclusions

Here, soil CO₂ efflux measurements were conducted three tundra sites and five boreal forest sites along the trans-Alaska pipeline, during the winter and spring seasons of 10 2010–2012, for the estimation of spring CO₂ efflux and the corroboration of environmental factors determining efflux.

At boreal forest sites, tree trunks and tussock tundra played significant roles in the disappearance of seasonally covered snowpack. Just after snow melt, three-year spring CO₂ efflux in exposed soils is tenfold higher than in snow-covered soil, corresponding to growing-season CO₂ efflux. Spring CO₂ efflux represents dependence on soil temperature at 5 cm below the surface, which accounts for 67 and 72 % of the variability of spring CO₂ efflux in white and black spruce forest soils, respectively. Efflux indicates south > east west >> north side, in turn, in four directions from tree trunks in the white spruce forest, attributing the magnitude of spring CO₂ efflux to the expansion of exposed soil by the difference in solar radiation.

At tundra sites, spring CO₂ efflux in exposed tussock tundra soils is much higher than in seasonally snow-covered soils, as reported by many scientists studying the North Slope of Alaska, which suggests that tussock tundra plays an important conduit in transporting soil CO₂ through the snowpack, and is a significant carbon source during winter and spring. Also, the temperature at the top of tussock tundra is relatively higher than in inter-tussock, indicating a clear difference in temperature during the snow-covered and snow-melting seasons of 2011–2012. Three-year average spring

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CO₂ efflux depends on soil temperature at 5 cm below the surface, explaining 45 % of the variability of spring CO₂ efflux in tundra soils.

Further, the contribution of subnivean respiration from snow molds and fungi should be as critical an issue to understanding carbon dynamics as recent research results in sub-alpine, alpine, boreal forest, and tundra regions suggesting that microbial activity depends explicitly on soil temperature in the early spring season. Fungal activity in the cold soils of the Arctic and sub-Arctic is a significant decomposer when assessing the vulnerability of old-soil organic carbon from a deepening active layer, as well as the degradation of permafrost in response to recent Arctic warming. Considering the distribution areas of tussock/moss in the Northern high-Hemisphere (6.5×10^{12} m²; Whalen and Reeburgh, 1998) and the acclimation of snow molds and fungi in polar environments (Tojo and Newshan, 2012), the contributions from tussock tundra and beneath-snowpack microbes in winter and spring seasons toward the soil CO₂ efflux outburst within a narrower range of soil temperatures should not be overlooked when estimating regional and pan-Arctic scale carbon budgets.

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Table 1. Site information in black spruce, white spruce, and tundra sites across the haul road of Alaska during winter and spring seasons of 2010–2012.

Ecosystem	Site	Latitude (N)	Longitude (W)	Elevation (m a.s.l.)	Aspect	Slope °	Dominant species
Black spruce	YL	65°50′30.5″	149°38′44.2″	360	N65E	6	<i>Picea mariana</i> , <i>Ledum palustre</i> , <i>Vaccinium vitis-idaea</i> , <i>Vaccinium uliginosum</i>
	YU	66°04′48.2″	150°09′56.3″	220	N50W	5	<i>Picea mariana</i> , <i>Vaccinium vitis-idaea</i> , <i>Vaccinium uliginosum</i> , <i>Betula glandulosa</i>
	BC	67°10′47.6″	150°18′24.9″	349	N60W	5	<i>Picea mariana</i> , <i>Vaccinium vitis-idaea</i> , <i>Ledum palustre</i> , <i>Betula glandulosa</i>
White spruce	GC	67°44′09.5″	149°45′23.1″	478	N55W	2	<i>Picea glauca</i> , <i>Betula glandulosa</i> , <i>Vaccinium uliginosum</i> , <i>Vaccinium vitis-idaea</i>
	TZ	67°59′27.5″	149°45′37.5″	690	N80W	10	<i>Picea glauca</i> , <i>Vaccinium uliginosum</i> , <i>Vaccinium vitis-idaea</i> , <i>Empetrum nigrum</i>
Tundra	SaT	68°10′32.4″	149°26′26.3″	1064	N60E	5	<i>Vaccinium uliginosum</i> , <i>Dryas integrifolia</i> , <i>Carex bigelowii</i> , <i>Salix reticulata</i>
	UT	68°53′57.7″	148°52′02.5″	425	S60E	3	<i>Eriophorum vaginatum</i> , <i>Ledum palustre</i> , <i>Betula glandulosa</i> , <i>Vaccinium vitis-idaea</i>
	CT	69°50′26.8″	148°42′31.6″	35	S40W	2	<i>Eriophorum vaginatum</i> , <i>Betula glandulosa</i> , <i>Salix pulchra</i> , <i>Carex lugens</i>

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Table 2. Snow depth in spring season, and air temperatures in winter season of November to March, and in spring season of April 15 to June 15 during 2011–2012.

Year	Site	Snow depth (cm)	Air temperature in winter (°C)				Air temperature in spring (°C)				
			Average	Stdev	Min	Max	Average	Stdev	Min	Max	
2010	CT	25	-22.0	9.0	-41.3	-2.0	-3.4	6.4	-14.2	12.5	
	UT	50	-21.3	11.1	-43.6	0.8	-1.8	4.0	-11.8	14.4	
	SaT	27	-17.1	8.5	-35.2	-0.4	-0.3	4.2	-9.0	6.0	
	TZ	19	-17.7	7.6	-36.3	-2.5	6.7	6.1	-8.6	15.4	
	GC	29	-23.0	10.0	-46.4	-1.3	8.1	6.3	-7.6	17.0	
	BC	30	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	
	YU	48	-22.1	8.8	-48.5	-2.2	10.1	5.9	-4.8	17.8	
	YL	66	-20.8	7.2	-42.6	-4.5	9.2	5.6	-3.9	17.7	
	2011	CT	32	-22.1	9.6	-47.9	-0.7	-5.5	8.5	-20.3	13.6
		UT	30	-19.8	9.6	-42.5	1.7	-2.2	9.9	-22.4	12.4
SaT		47	-16.6	7.6	-37.2	-2.7	0.6	7.8	-16.4	13.1	
TZ		34	-17.5	7.2	-35.3	-3.4	4.3	7.3	-10.5	16.4	
GC		44	-24.2	10.2	-45.1	-4.0	5.6	7.6	-11.5	17.5	
BC		46	-19.3	9.7	-29.6	-1.7	6.9	7.7	-8.6	21.3	
YU		55	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	
YL		69	-19.2	10.8	-41.6	0.1	6.6	7.4	-7.9	19.6	
2012		CT	37	-24.3	7.3	-41.9	-6.1	-4.0	6.6	-15.9	10.3
		UT	36	-17.6	7.5	-45.3	2.0	2.1	7.9	-10.6	16.4
	SaT	40	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	n.m.*	
	TZ	39	-20.9	7.6	-43.1	-6.3	3.9	6.6	-10.7	16.1	
	GC	58	-25.9	9.7	-50.0	-8.3	5.8	6.5	-8.2	19.1	
	BC	63	-13.7	6.5	-37.3	-5.7	6.5	7.3	-5.9	20.4	
	YU	33	-21.1	11.2	-49.7	3.4	11.7	6.7	-6.9	23.8	
	YL	73	-13.7	7.0	-38.2	7.2	7.9	6.6	-5.3	19.5	

* n.m. denotes not measured.

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Table 3. Constants and correlation coefficients in exponential equation of soil CO₂ efflux on soil temperature at 5 cm below the surface in white spruce, black spruce and tundra sites across haul road of Alaska during spring seasons of 2010–2012, which the equation is as CO₂ efflux = $\beta_0 \exp(\beta_1 ST_5)$, based on a one-way ANOVA at the 95 % confidence level.

Year	number	Whole					White spruce					Black spruce					Tundra				
		β_0	β_1	R^2	Q_{10}^*	p	β_0	β_1	R^2	Q_{10}^*	p	β_0	β_1	R^2	Q_{10}^*	p	β_0	β_1	R^2	Q_{10}^*	p
2010	49	1.064	0.373	0.90	41.7	< 0.001	0.766	0.343	0.53	31	0.075	1.414	0.588	0.77	358	0.0125	0.588	0.310	0.59	22.2	0.0030
2011	100	0.890	0.337	0.61	29.1	< 0.001	0.530	0.506	0.73	158	0.002	0.664	0.841	0.90	4492	0.0083	0.379	0.290	0.40	18.2	< 0.001
2012	67	0.889	0.282	0.72	16.8	0.0015	0.448	0.851	0.66	4964	0.007	0.143	1.248	0.77	263 024	< 0.001	0.793	0.254	0.62	12.7	< 0.001
Total	216	0.937	0.328	0.72	26.6	< 0.001	0.525	0.531	0.67	202	< 0.001	0.522	0.512	0.72	167	< 0.001	0.515	0.256	0.45	12.9	< 0.001

* Q_{10} is calculated from the Eq. (3).

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Table 4. Contribution (%) of seasonal CO₂ emissions to the annual carbon budget in tundra and boreal forest ecosystems under the averaged seasonal period during 2010 to 2011*.

Ecosystem	Season	2010		2011*		2012*		Period days
		CO ₂ emission	Contribution	CO ₂ emission	Contribution	CO ₂ emission	Contribution	
		gC m ⁻²	%	gC m ⁻²	%	gC m ⁻²	%	
Tundra	Winter	33	14	45	17	28	12	250
	Spring	46	20	72	27	47	21	60
Boreal Forest	Winter	61	9	95	11	63	8	180
	Spring	108	16	264	31	176	24	80

* Summer CO₂ emission of 2011 and 2012 was used by the average of 2010 data and Kim et al. (2013).

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Table 5. Contribution of seasonal CO₂ emissions to the annual carbon budget on the basis of a constant area (400 m²) in white spruce forest TZ and GC sites during 2010 to 2011*.

Site	Season	2010		2011**				2012**		Remarks
		May		April		May		May		
		CO ₂ emission	Contribution	CO ₂ emission	Contribution	CO ₂ emission	Contribution	CO ₂ emission	Contribution	
cline3-10		gC d ⁻¹	%	gC d ⁻¹	%	gC d ⁻¹	%	gC d ⁻¹	%	
TZ	Winter	145	3	46	1	18	1	32	1	Snow-covered exposed
	Spring	241	4	301	5	1978	27	56	1	
GC	Winter	121	3	90	2	81	1	35	1	Snow-covered exposed
	Spring	246	5	316	7	1241	23	815	16	

* After the forest census in TZ and GC sites by Suzuki et al. (2013), the calculation was used the tree density within a 20 × 20 m².

** Summer 2010 CO₂ efflux was used in 2011 and 2012 due to late fall observation as described in the text.

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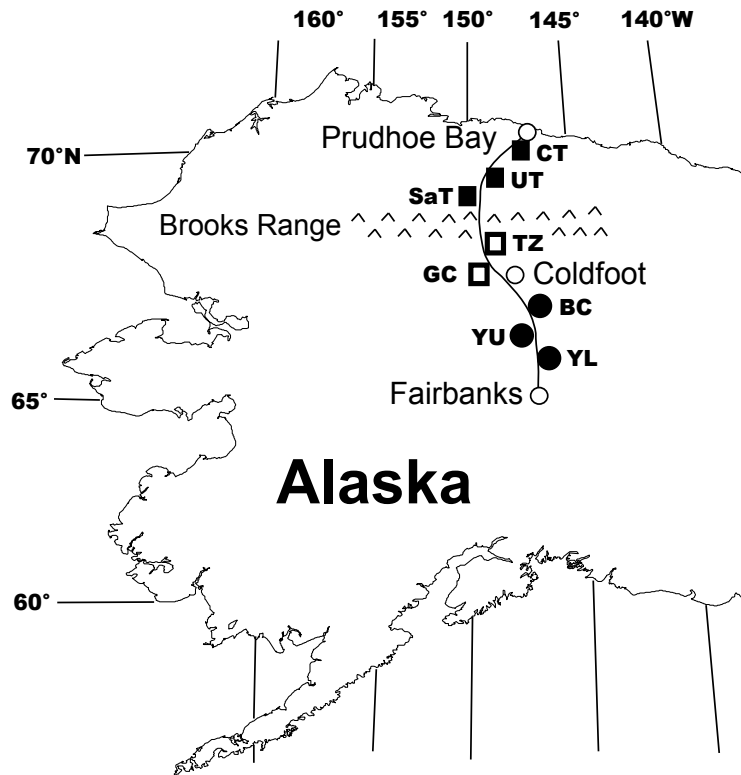



Fig. 1. Site locations along the trans-Alaska pipeline of Alaska, during the winter and spring seasons of 2010–2012. Solid circles are black spruce forest sites, open squares are white spruce forest sites, and solid squares denote tundra sites.

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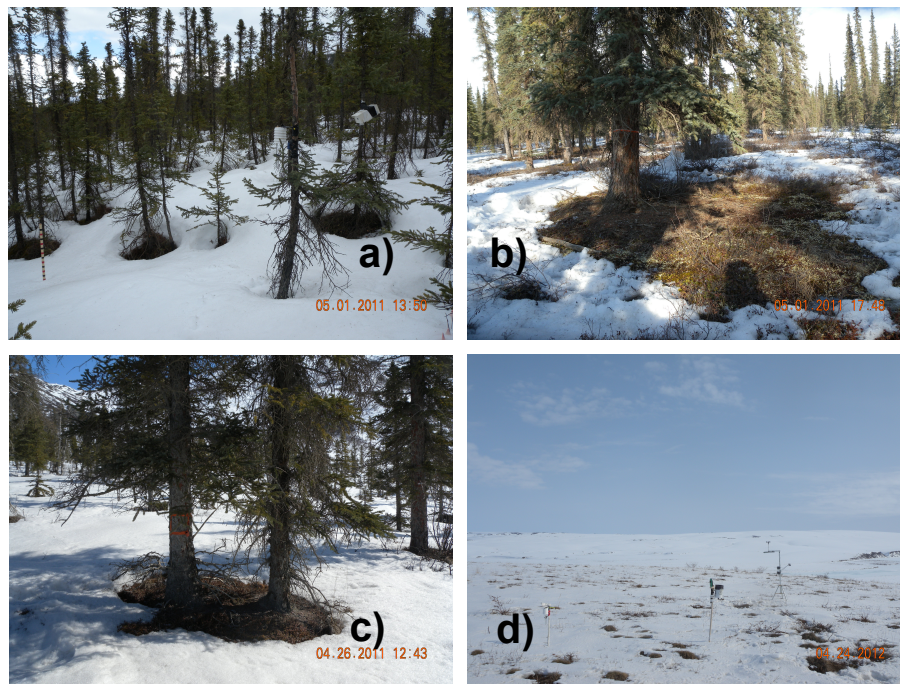


Fig. 2. Site views at **(a)** black spruce forest site (BC); **(b)** and **(c)** white spruce sites (GC and TZ); and **(d)** tundra site (UT) during spring of 2011. Exposed soils were found in surrounding trunk wells **(a–c)** and in tussock **(d)** due to fast snow-melting from nighttime long wave radiation.

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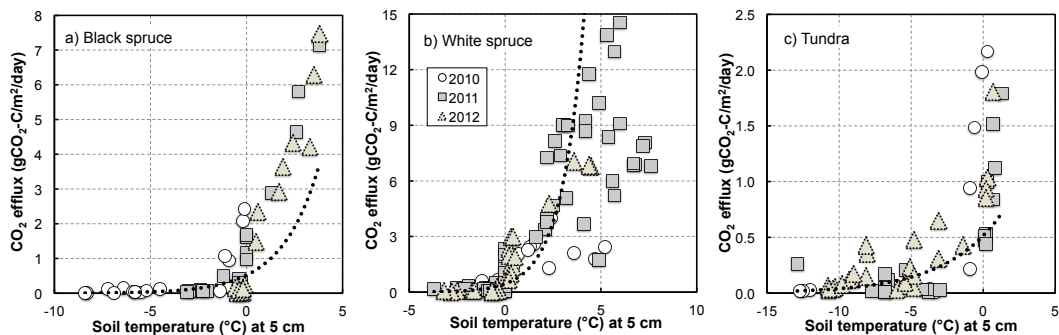


Fig. 3. Spring CO₂ efflux responses to soil temperature at 5 cm below the surface at **(a)** black spruce forest sites; **(b)** white spruce forest site; and **(c)** tundra sites during the spring of 2010–2012. Dotted curves denote the 3 yr exponential relationship between spring CO₂ efflux and soil temperature.

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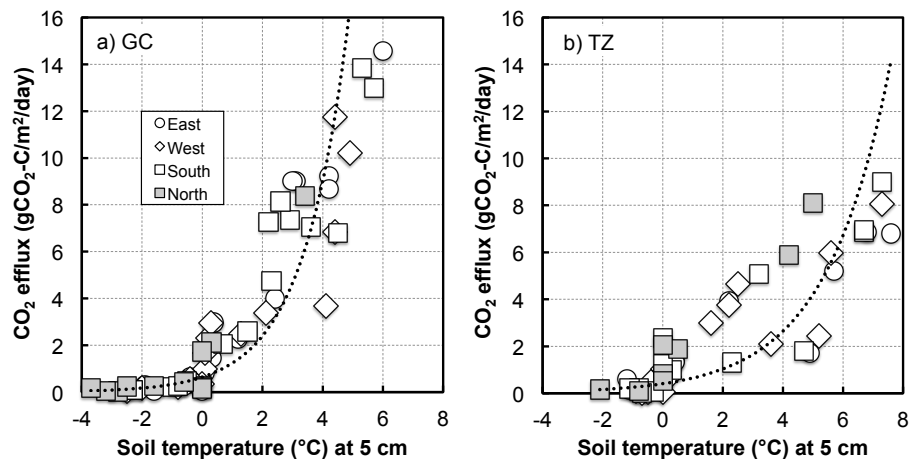


Fig. 4. Spring CO₂ efflux responses to soil temperature at 5 cm below the surface measured in four directions from the stem of white spruce at (a) GC and (b) TZ sites during the spring. Dotted curves denote the 3 yr exponential relationship between spring CO₂ efflux and soil temperature.

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Fig. 5. Two colonies of unidentified fungi within the chamber base were found in the cryoturbed soils of UT site on 18 April 2010. Soil CO₂ efflux of 0.5 gC m⁻² day⁻¹ was not significantly higher due to the desiccated condition.

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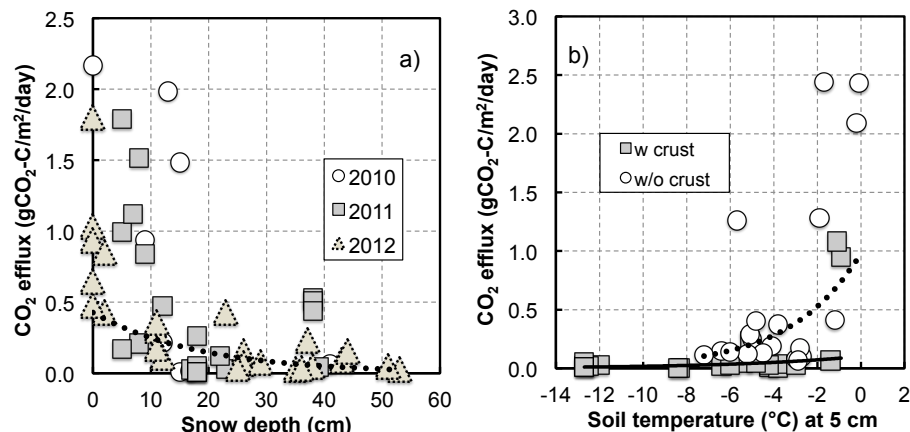


Fig. 6. Spring CO₂ efflux responses to **(a)** snow depth and **(b)** soil temperature at 5 cm below the surface with and without snow crust at tundra sites during the spring. Dotted and solid curves denote the 3 yr exponential relationship between spring CO₂ efflux and **(a)** snow depth and **(b)** soil temperature before and after cluster removal.

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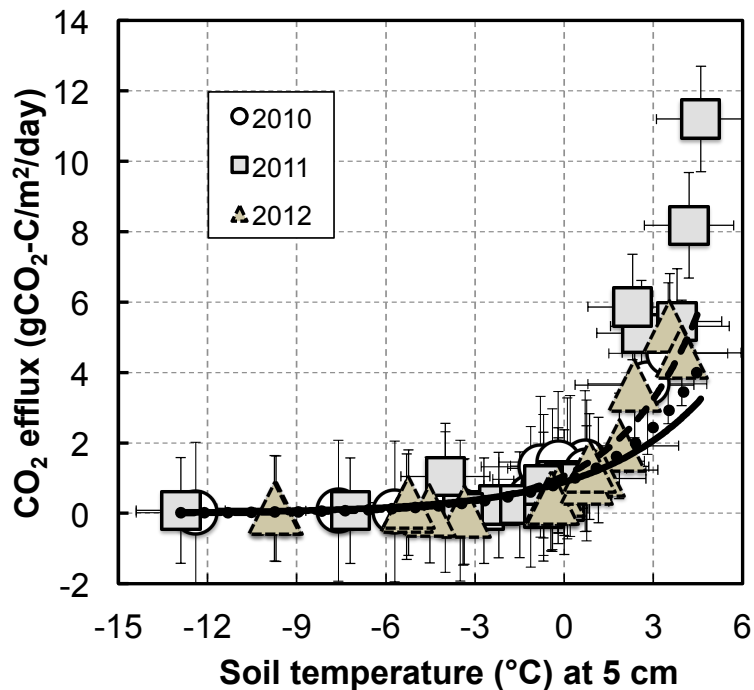


Fig. 7. Spring CO₂ efflux responses to soil temperature at 5 cm below the surface across entire sites during the spring seasons of 2010 and 2012. Dashed, dotted, and solid curves shows 2010, 2011, and 2012, respectively.

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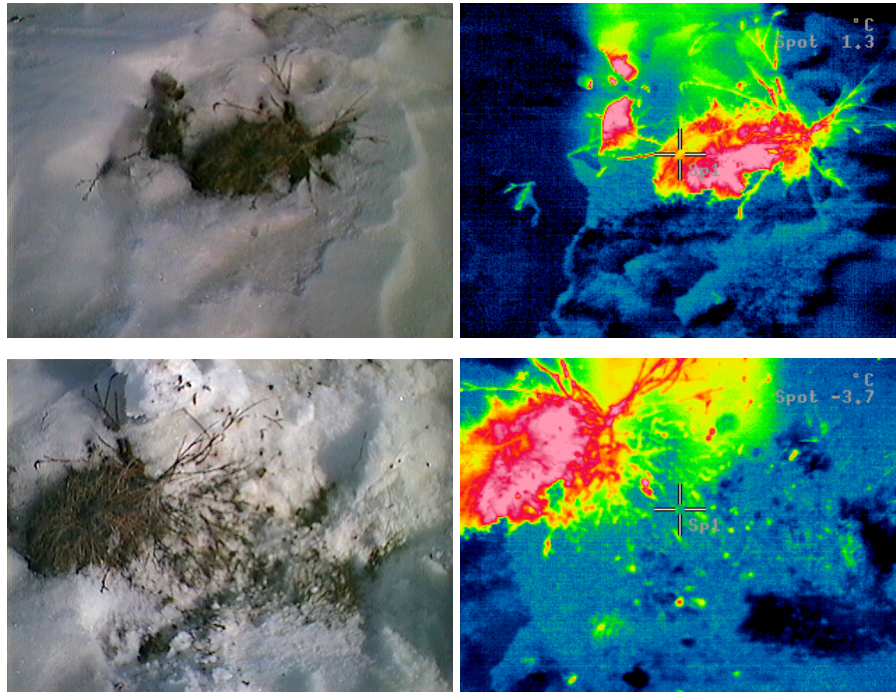


Fig. 8. Temperatures from IR camera denote 1.3°C at the top of tussock and -3.7°C at the snow surface at the TZ site on 19 April 2010, suggesting that the sharp difference between the tussock top and the snow surface (Image courtesy of H. Enomoto).

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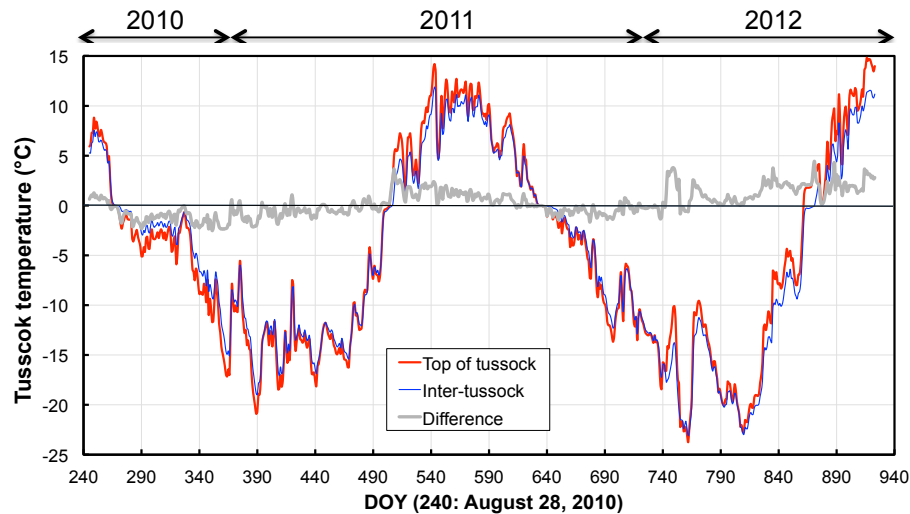


Fig. 9. Temporal temperature variations for the top of tussock (red), inter-tussock (blue), and the temperature difference (gray) between the two at the upland tundra (UT) site from 28 August 2010 (DOY 240) to 11 July 2012 (DOY 923).

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