Response to Referee #1's comments

Effect of ablation ring and soil temperature on 3-yr spring CO_2 efflux along the trans-Alaska pipeline, Alaska

Y. Kim

Thank you for your invaluable comments on my manuscript.

First, the reason I have observed soil CO_2 efflux surrounding tree trunks in the spring season has been to better understand the effects of the ablation ring and subsequently-increased soil temperature in the snow-disappeared soils of coniferous forest and tussock tundra. The ablation ring was found in nearly all white and black spruce forests and across tussock tundra in the spring. I have many photos of this available upon request.

Considering the effect of this ablation ring and the subsequent increase in soil temperature, I measured efflux in the surrounding trunks of coniferous forest trees and tussock tundra—that is, in the snow-disappeared soil—for better understanding of the efflux between exposed and snow-covered soils. In particular, efflux measurement was also investigated for the difference in four-directional CO_2 emission from the white spruce stem. Further, despite the narrower range for soil temperature, soil CO_2 efflux increased greatly, with Q10 value highest, as I described in the manuscript.

For winter and spring, I also focus on the effect of snow depth and snow crust influencing soil CO_2 efflux, across boreal forest and tundra sites.

For these reasons, I focused on the effects of the ablation ring and subsequent soil temperature during this investigation of winter and spring CO_2 efflux along the unpaved 660-km haul road (total running distance: ca. 3800 km/year). Although the manual chamber system places some constraints on the temporal variability of soil CO_2 efflux at some points, I have observed efflux-measurements at the same points for each site during winter and spring, 2010-2012.

<u>Responses to comments</u>

1. The paper does not really focus on ablation rings as the title implies, nor are the other main objectives of the paper adequately addressed. One objective is to evaluate the environmental controls on spring respiration rates, but only soil temperature and snow depth are considered.

>>> As mentioned above, the paper focuses on the change in soil CO_2 efflux via the effect of the ablation ring and subsequently increasing soil temperature in exposed soil just after snow disappearance. As expected, it is not easy to match the timing of field observations, especially over a long-distance trip. In addition, I found higher emission of soil-originated CO_2 in surrounding tree trunks and

tussock tundra of exposed soil, resulting from the ablation ring, and subsequently increasing soil temperature in exposed soils rather than in snow-covered soils.

2. What is the temporal pattern of soil respiration and temperature and the timing of snowmelt and the formation of ablation rings. Do respiration rates at the different sites diverge after snowmelt or once the soils exceed 0C?

>>> As I mentioned above, I did not observe temporal variability of soil efflux, temperature, timing of snowmelt, and formation of ablation rings. Although the manual chamber system offered simplicity and efficiency for covering a wide range and easily estimating spatial CO_2 efflux, this system cannot conduct measurements at frequent periods due to disturbance of snow and soil surface after flux measurement. Further, it is difficult to observe with a manual chamber system for temporal variability of soil CO_2 efflux at the same point at each site. As a result, I must monitor additional year-round soil CO_2 efflux using the FD (forced diffusion chamber) system described by Risk et al. (2011), and in the text.

>>> I have monitored air and soil temperature and snowmelt timing/formation of ablation rings with a time-lapsed (4-hour interval) camera at each site from 2010 to now, as described in Lines 15-18 of page 3624.

>>> Despite different snowmelt timing at different sites, I was able to measure CO_2 effluxes in exposed soil of >0 °C just after snowmelt and in snow-covered soil of <0 °C at each site. The magnitude of soil CO_2 efflux depends on with/without snowpack, as shown in Figures 3-4 and 6-7, controlled by soil temperature.

3. What accounts for the inter-annual differences in respiration patterns and rates? Why is 2010 much lower than other years?

>>> This is due to the snowpack in 2010, which disappeared in areas surrounding tree trunks and tussock much later than in 2011 and 2012, suggesting a difference in soil temperature that also results in inter-annual differences in CO_2 efflux, as described in Lines 15-18 of page 3624.

>>> Spring soil CO_2 efflux in 2010 was much lower than other years, due to relatively early observation, as described in Line 15, page 3619. This suggests snowpack was still relatively deeper than in 2011 and 2012, and that soil temperature was much lower, as shown in Figures 3 and 7.

4. Spring soil respiration is highly heterogeneous, how does this compare to heterogeneity in the summer?

>>> I observed summer soil CO_2 effluxes during 2006-2010 within a 25 × 25 m plot (5-m interval: 36 points) at each site for spatial variability (Kim et al., 2013). During summer, boreal forest and tundra sites require 36 sampling points to

generate an experimental mean falling within ±20 % of the overall mean at the 95 % and 90 % confidence levels, respectively.

>>> During winter and spring seasons, it is difficult to observe spatial variability of soil CO_2 efflux due to the disturbance of snowpack and soft soil surface by CO_2 efflux-measurement. However, after minimal flux measurement, I was able to compare spring efflux for 2010-2012 with summer mean efflux at each site for spatiotemporal heterogeneity.

5. The methods need to be substantially improved in order to understand how data was collected.

>>> I organized '2.1 sampling description and methods' as suggested by R#1. For example, I deleted 'Line 3 to 6 of page 3620', moved 'Line 10 to 15 of page 3620' to 'Line 11 of page 3631', and added 'Line 29 of page 3620' to 'Line 22 to 25 of page 3623', all for better understanding of methodology.

o soil moisture measurements described in the methods are not reported.

>>> Although I had a probe for soil moisture, I could not measure soil moisture during winter and spring seasons. This is due to the longer probe (8 cm) necessary for soil moisture within frozen subsurface soil.

>>> I deleted the parts on soil moisture in 'Line 4 to 11 of page 3623' for the readers as follows.

< **Line 4 to 11 of page 3623**>
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 1.3m 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.~~

o replication of respiration measurements is unclear

>>> I did not observe replicated CO_2 efflux for the entire observation, as chamber bases were inserted into soil at least one day before prevention of disturbance. However, at white spruce sites in 2011, I measured replicated CO_2 efflux on April 25 and May 1 (GC), and in April 27 and May 2 at (TZ). Specifically, at site GC CO_2 efflux was 13.9 and 13.0 gCO_2-C/m^2/day south (60 cm) of the stem on April 27 and May 2, suggesting similar CO_2 effluxes.

o how many tree trunk or ablation ring areas were surveyed?

>>> I surveyed 1-3 trunks in the boreal forest for four-directional CO_2 efflux-measurements, and 8-15 points in tussock and inter-tussock over tundra, due to the limited number of chamber bases and deeper snowpack. Figure 7 shows mean CO_2 efflux at each site.

o P. 3622 line 2: this sentence is confusing, were bases only used in certain circumstances?

>>> The chamber base was used in exposed soil and on hardened snow surface. I corrected the sentence in Line 1-5 of page 3622, as pointed out by R#1, as follows.

<Line 1-5 of page 3622>
To prevent contamination and disturbance, bases were **not** used due to the soft snow surface at boreal sites during winter and spring seasons (Kim et al., 2007, 2013). Bases were **~~also~~** used to measure winter CO2 efflux when the snow surface was hardened by sublimation at the tundra sites.

o P. 3624 line 1: soil CO2 flux was estimated with profile measurements? I thought all the measurements were chamber based

>>> I corrected the sentences in 'Line 25 of page 3623' to 'Line 5 of page 3624' as follows. I did not measure soil CO_2 profile throughout the entire observation, though snowpack CO_2 profiles between trees and in surrounding white spruce stem during the winter season were performed for soil-originated CO_2 transport.

<Line 25 of page 3623 to Line 5 of page 3624>
Furthermore, during the winter season, snowpack CO2 concentration gradients in snowpack between trees and near tree wells were 2.52 to 4.78 ppm cm^{-1} and 0.93 to 1.20 ppm cm^{-1} using a stainless steel-made probe (0.4 cm OD; 0.2 cm ID; 80 cm long) with connecting tubing, tri-way stopcock, and syringe at sub-surface and bottom snowpack depths, respectively. This suggests that lower CO2 gradient near tree trunk results in faster CO2 transport from the soil through snowpack to the atmosphere than in snowpack between trees. This demonstrates that the air-snow-soil interface surrounding the tree trunk is much thinner than in forest opening areas.

o there is no description of how respiration measurements were scaled to calculate a spring contribution to annual CO2 loss

>>> I described spring contribution in white spruce forest sites loss in 'Line 8 to 18 of page 3621' and added to 'Line 10 to 15 of page 3620'.

o what does fig 7 show? Are these site averaged fluxes and soil temperatures?

>>> Yes. Figure 7 shows likely latitudinal distribution of CO_2 efflux for soil temperature at 5 cm depth for whole sites throughout the three-year flux measurements.

o what were the ANOVA comparisons used for?

>>> This indicates the significance between soil CO_2 efflux and soil temperature at the 95 % confidence level, as shown in Table 3.

o What is the value of reporting CV?

>>> Coefficient of variation (CV, %) is found by dividing average by standard deviation, and is meant to quantify the spatial variation of obtained data (Kim et al., 2013).

o It is difficult to keep track of the sites based on the acronyms

>>> I fully recognize the tracking of sites based on acronyms throughout the manuscript. However, I have also explained the sites in 'Sampling descriptions and methods (Line 7 to 13 of page 3619)' and in Figure 1.

â˘A ´c The purpose of the temperature response functions is unclear. What do the different temperature response functions represent?

>>> I have used the temperature function (Line 17 of page 3622 to Line 4 of page 3623) used by many scientists, as I cited in the manuscript. Basically, the effect of the ablation ring results in a subsequent change in soil temperature between snow-disappeared and snow-covered soils at each site. Thus, despite different characteristics of each site, I suggest soil CO_2 efflux is regulated by soil temperature through the manuscript.

o If the temperature responses are dramatically different between sites (as Fig 3 suggests), then is it really appropriate to apply the same temperature response to all sites (as per Fig 7)?

>>> As described, sites where distinct ablation rings were found were white spruce, tussock tundra, and black spruce forests. I have shown average soil efflux and temperature for each site during each year in Figure 7, with the error bar as standard deviation. Because of the constraints of observation frequency and accessibility along the trans-Alaska pipeline, I may be missing tundra spring season flux. It is difficult to observe tundra spring CO_2 flux due to saturated waterlogged soil bysnow-melting water in coastal tundra, in contrast to boreal forests, from observation of the time lapse camera photo that follows (**CT site; May 24, 2013**). Thus, Figure 7 displays latitudinal distributions of CO_2 efflux and soil temperature (Kim et al., 2013).

o Does Fig 3 really represent intrinsically different temperature sensitivity? Or merely a different range of sample temperatures? While boreal forest sites have soil temperatures at 5C and 10C, tundra sites doe not exceed 2C. Are the temperature responses substantially different between -5C and 2C?

>>> I think this is due to the effect of the ablation ring in spring, as mentioned in 'Sampling descriptions and methods (Line 19 of page 3620 to 7 of page 3621)'. The difference in soil temperature is proportional to the magnitude of snow disappearance at each site, resulting from the effect of the ablation ring. Namely, this indicates the heat capacity of white spruce, black spruce, and tussock tundra from short wavelength of the sun during daytime. Subsequent soil temperature measured at each site depends on the extent of exposed soil, while wet soil also shows high heat capacity in spring.

>>> Yes. Though the range of soil temperature was different for each site, the magnitude of soil CO_2 efflux is followed by the extent of exposed soil as shown in Figure 2. Also, I showed Figure 3 for characteristics of vegetation type. Even as shown in Figure 4, where the strength of CO_2 efflux was different in four directions from the tree stem despite the same white spruce sites, efflux displays differences in accumulated soil organic matter, soil exposed time, forest floor plants and so on.

>>> The differences in soil temperature from three ecotypes represent differences in temperature range and subsequent magnitude of CO_2 efflux at each site, as shown in Figures 3 and 4. Therefore, I think the response of CO_2 efflux to temperature in tundra is much more sensitive than in boreal forest.

o Fig 4: shows that the temperature-flux relationship is driven by location around the tree – this is important as it creates large spatial heterogeneity. What additional value is derived from showing these two sites separately?

>>> I monitored environmental factors such as temperature and soil moisture at each site, indicating seasonal differences in air temperature between both sites, as listed in Table 2. Further, temporal variation in soil moisture at both sites is also differently displayed. Soil organic carbon in GC and TZ sites was 1.69 ± 0.31 and 1.53 ± 0.22 gC/m^2, respectively, indicating there is no significant difference between the sites.

o What do the Q10 values mean? Mikan et al 2002, Soil Biology and Biochemistry 34, demonstrate that the transition from frozen to thawed soil produces very different Q10 values, but that these are not truly thermodynamic temperature responses. It is a valuable point of discussion that respiration rates change extremely rapidly during the transition from frozen to thawed, and that the temperature response does not follow predictions from the growing season.

>>> I completely agree with your suggestion on the different temperature responses between frozen and thawed tundra soils through the culture experiment (Mikan et al., 2002). As a result, I have cited this reference in my manuscript for better understanding of temperature dependency regarding below and above 0 °C, in Line 21 of page 12 as follows.

< Line 21 of page 3626>

Mikan et al. (2002) demonstrated the temperature response on frozen and thawed tundra soils was differently displayed through the culture experiment of above and below 0°C because the unfrozen water content in frozen soil, that is a significant controlling factor, principally affected to the physiological response of soil microbes such as extracellular and intercellular mechanisms. However, the unfrozen water was unrelated to the soil organic matter quality and nutrients contained in tundra organic soils (Mikan et al., 2002). These results are beneficial to better understand the temperature response of spring CO2 efflux on below and above freezing in tundra and boreal forest soils.

â˘A ´c The results contain too much discussion and unnecessary detail (see below for further details)

â˘A ´c The relevance of some data is unclear, eg:

o Fig 6: shows that snow depth is important for flux at tundra sites and even at similar temperatures the presence of a snow crust suppressed flux rates. Is a comparison with and without snow-crust an accurate representation of the thawing process? Presumably the dynamics in a naturally thawed patch are different than in a patch where the snow is removed between measurements. How does this data inform temperature and ablation ring dynamics?

>>> I measured CO_2 efflux with and without snow crust in snow-covered tundra soils, except for the snow-disappeared tussock tundra area. These data are not related to the effect of the ablation ring and temperature response in frozen soil, as shown in Figure 6. Actually, despite the spring season, tundra soils are mostly covered by seasonal snowpack, as shown in Figure 2. I focus the conduit of CO_2 emission to be tussock tundra in snow-disappeared tundra soils, which are affected by the ablation of tussock and subsequently increasing temperature, compared to snow-covered soils.

o the presence of unidentified fungal communities (fig 5)?

>>> After CO_2 efflux measurement in snow-disappeared, inter-tussock tundra soils, I found the presence of unidentified fugal colonies within the chamber base. I consulted Professor Lee Taylor (Institute of Arctic Biology, University of Alaska Fairbanks) for identification, though he could not identify the community because I was unable to collect samples due to the disturbance. However, he offered the following by e-mail. I will have a chance to collect these samples in next spring season.

Interesting! That does look like fungal growth. It could be any of thousands of species. Did you collect any of it? If so, we might be able to run a molecular analysis. A variety of snow molds are quite common in Interior Alaska; they are most noticeable right at spring breakup.

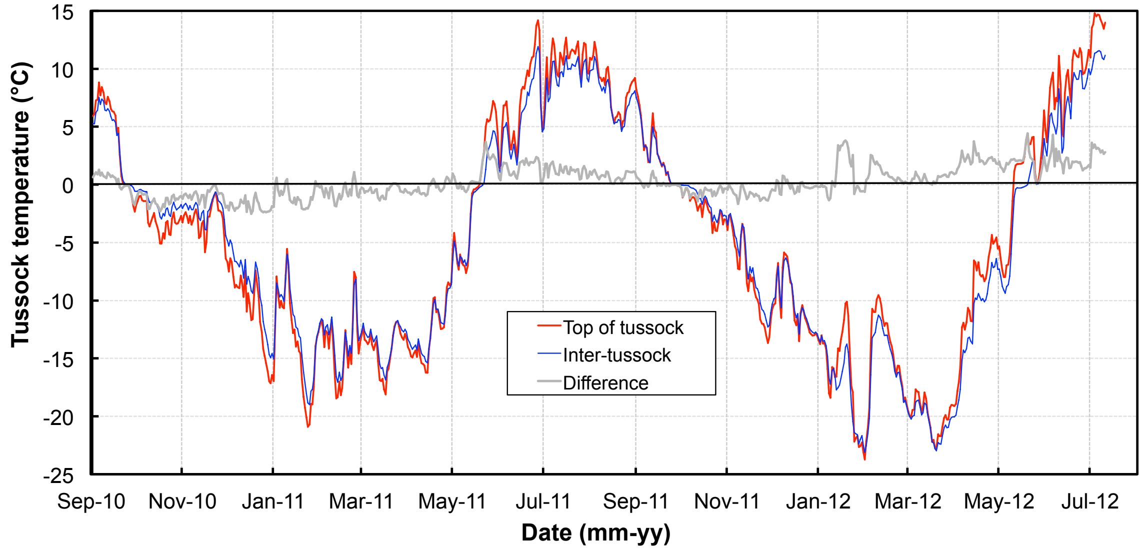
o the temperature differences between tussock tops and bottoms (fig 8&9). While very interesting, how does this relate to the rest of the data?

>>> My colleague and I measured IR temperature on April 19, 2010, before the installation of soil temperature sensors on August 28, as shown in the captions of Figures 8 and 9. After IR photos, I considered it an important conduit of soil CO_2 emission, and have observed spring CO_2 emission from ablation and subsequently stimulated soil temperature in exposed soils.

o In figure 9 it is confusing that doy counts incrementally from the beginning, rather than starting over at 1 in each year.

>>> I will make the change to an x-axis for ‘mm-yy’, as suggested by Reviewer

#1, as follows.



âˇA ´c The discussion needs to address the mechanisms which could be responsible for these differences.

>>> I will add the mechanism for the temperature difference between areas in 'Line 3 of page 3631' as suggested by Reviewer #1, as follows.

< Line 3 of page 3631>
The temperature difference between top of tussock and inter-tussock was distinctly displayed during the spring seasons of 2011 and 2012. The mechanism is identical to the ablation effect in boreal forests as shown in Figure 2. This results from the strong solar radiation in daytime in exposed top of tussock.

o Could the impact of snow depend on the time of year? In winter snow insulates, so respiration rates may depend on a combination of snow factors. On the one hand, greater snow cover in winter, which insulate from cold air temperatures. On the other, more rapid thaw, exposure to radiation and higher temperatures in spring, which enhance decomposition rates.

>>> Yes, the snowpack is a critical factor influencing CO_2 efflux during winter and spring. Of the snow factors, snow depth, which regulates soil temperature, is the primary key in determining soil CO_2 production from microbial activity. I think monitoring snow depth is also significant for determination of snow-depth threshold. For example, I have measured snow depth in temperate forest soils, with threshold depth of 40 cm. Soil surface temperature suddenly rose to above 0 °C when snow depth was greater than 40 cm. Unfortunately, I did not monitor snow depth during 2010 to 2012; however, I have observed snow depth at each site with time-lapse camera since 2013.

o How long before these high flux rates decline?

>>> As I did not monitor CO_2 efflux at each site, I am not sure. However, this may be extended to mid-spring. Thus, I require additional research such as monitoring of CO_2 efflux, as well as environmental parameters at each site, as mentioned in the manuscript (Line 9-12 of page 3629).

o What is the mechanism for such high fluxes? Microbial stress response? Turnover/community composition change of the microbial community? Depletion of labile C?

>>> Higher spring efflux was similar to summer efflux; however, I think the mechanisms for CO_2 production during spring and summer may be different, despite the temperature dependency. Mikan et al. (2002) suggested a temperature response to CO_2 efflux in thawed tundra soils. I cited this paper in Line 13, page 3626.

< Line 13 of page 3626>
Mikan et al. (2002) found the temperature response of CO2 efflux was related to soil organic matter (SOM) quality and soil microbial community in thawed tundra soils. Thus, the higher spring efflux in white spruce forest may be resulted from the accumulated SOM quality and the decomposition of preferentially labile carbon by soil microbes in exposed soils.

â˘A ´c Discuss limitations of the study:
o The latitudinal gradient confounds the temporal component since spring in the tundra sites will be delayed relative to the boreal forests.

>>> I thoroughly agree with your suggestion. Our spring CO_2 effluxobservation depends greatly on road conditions and transport distance along the pipeline. In spite of the lag from spring timing between tundra and boreal forest, I observed the exposed tussock tundra for every spring season, as shown in Figure 2. In fact, I even attempted to depict latitudinal gradients of CO_2 efflux and environmental parameters; it is extremely difficult, however, to understand the spatiotemporal variability of CO_2 efflux and environmental parameters along the pipeline without monitoring of CO_2 efflux at each site.

Specific points regarding the results section:

P. 3620: the site description here is very detailed and reads like results, either simplify and refer to tables, or include in results section

>>> I deleted ‘Line 3 to 6 of page 3620’, which is also listed in Table 2.

>>> I moved ‘Line 10 to 15 of page 3620’ to ‘Line 11 of page 3631’ for estimation

of winter/spring CO_2 contribution.

P. 3623 line 19 – paragraph end: discussion? Or reword to make a better connection to the results P. 3625 line 9 – section end: discussion

>>> I moved 'Line 19 to 22 of page 3623' to 'Line 5 of page 3622' for methodology.

>>> I also moved 'Line 22 to 25 of page 3623' to 'Line 29 of page 3620' for better understanding of the ablation ring.

P. 3624 line 12, line 18: neither of these points is illustrated in Fig. 2

>>> I deleted 'Line 12 of page 3624' and 'Line 18 of page 3624': '~~**as shown in Figure 2**~~'.

P. 3624 line 16: this statement is confusing, how does the flux data suggest a 10-17 day earlier melt? This conclusion must come from the photos and the flux data shows that timing of melt-out strongly impacts flux. Reword.

>>> I rewrote 'Line 15 to 18 of page 3624' as follows.

<Line 15 to 18 of page 3624>
Because the snow-disappearance date in 2011 was approximately 10 to 17 days earlier than in both 2010 and 2012, based on the measurement of 4-h time-lapse camera, spring CO2 efflux in exposed soils in 2011 was at least tenfold higher than in snow-covered soils.

P. 3624 line 20: I would find this easier to follow if the data was organized either by magnitude or going around the compass rose, N, E, S, W

>>> I agree the suggestion; however, the length from stem to point was quite different due to the extension of exposed soil. Further, the number of figures would be too many if the compass rose was plotted.

>>> Magnitude was described in 'Line 25 to 28 of page 3624', and Q10 values were described in 'Line 29 of page 3626 to Line 3 of page 3627', as calculated in Table 3.

>>> I deleted 'Line 23 to 29 of page 3626' for the response of temperature dependence to CO_2 efflux at the four directional sides of each white spruce site, at ***the suggestion of R#1***.

P. 3625 line 9 – these values are not a ten-fold increase?

>>> I corrected this range, as suggested by R#1:

>>> 1.05 ± 0.057 gC m^{-2} day^{-1} to **0.13 ± 0.09 gC m^{-2} day^{-1}**.