Dear Dr. Obrist,

Thank you for these suggestions. We have addressed them as follows:

(1) In the author's response to reviewer 2 criticism about the heating issues of the open-path IRGA, the authors present detailed evidence that this is not likely a concern. These points of the author response, however, should be published with the manuscript to distribute this information to the readership, e.g., submitting this information in a supplemental information section. In the methods section and/or discussion, the authors should then refer to this supplemental information.

Response: We have incorporated the response to reviewer 2 as supplementary information. In the methods section, we refer to the supplementary material (lines 167-168) for more information regarding the heating issues of the IRGA.

(2) The measurement period are extremely limited, ranging from June 23 to July 3 (early), then to July 20 (middle), then to July 28 (late). These periods really don't correspond to early/middle/end of growing season, and don't cover the full growing season (which to my knowledge range from May to September in the High Alaskan arctic (e.g., at Toolik). It needs to be clarified that these measurements don't represent early, middle, end of growing season, but rather a month with some phenological and physiological differences).

Response: We acknowledge that we did not measure the full growing season, but we did conduct measurements through the majority of the season and have updated text to reflect the sampling period (lines 46, 429, 464). At our High Arctic study site, located at a latitude of 80°N, the growing season is very short. The growing season lasts from mid June until early August (8-10 weeks) and most plants complete their seasonal cycle in as few as 50 days (Bliss, 1977), thus our choice of dates accurately represent each of these phenological periods. We have mentioned the limitations associated with the sampling period and identify the important contribution of shoulder season fluxes (that were not measured in this study) on lines 510-518.

(3) Chamber measurements and partitioning of NEE: It should be emphasized and clarified that chamber measurements were performed only during daytime periods. When comparing EC with chamber-based fluxes, daytime measurements only should be compared for a meaningful comparison. Similarly, flux partitioning is based only on daytime measurements, and of course during daytime a significant respiration term is from plant autotrophic respiration (and respiration at nights can be quite different). Therefore, it needs to be clarified that respiration does not only refer to heterotrophic respiration from soil carbon losses, this is quite important.

Response: We have updated the text to reflect chamber measurements represent daytime fluxes (line 40, also 452-454, 955). We have clarified that respiration includes both heterotrophic respiration and autotrophic respiration. We have added the following statement to the methods section, (lines 308 –311): "Chamber measurements were only made during daytime periods, thus respiration includes heterotrophic respiration from soil

carbon losses and residual photosynthetic respiration. The site has 24 h of light and photosynthesis (and associated respiration) can occur over the entire 24 h period."

Minor comments in regards to these points:
Table 1: add dates to day of the year
Response: We have added in a date row in Table 1, which provides date ranges in conjunction with the DOY values.

Line 36: "Before full leaf out in early July, the undisturbed tundra was a small source of CO2, but shifted to a sink for the remainder of the sampling season (July), whereas the disturbed tundra remained a source of CO2 throughout the season." Clarify that late July does not necessarily correspond to late growing season, in the high Alaska arctic the growing season generally lasts until September.
Response: At our study site (80º N), late July corresponds with the late growing season and senescence has begun as the growing season ends in early August.

Line 39: A static chamber system was also used… - clarify that these are daytime measurements/partitioning, therefore ecosystem respiration is unlikely dominated only by heterotrophic soil C loss (but includes plant respiration).
Response: We have clarified that the static chamber system was used to measure daytime fluxes (line 40), because there was 24 hours of daylight during the entire study period.

Line 46: during one month in the growing season.
Response: We have corrected this statement to reflect sampling over the majority of the growing season (late June and July) (line 46).

Line 427: change "during the 2014 growing season" to In June and July of the 2014 growing season….
Response: We have adjusted the text as follows, "Over the majority of the 2014 growing season (late June and July) …" (line 429).

Line 439: "Based on chamber measurements, we found permafrost disturbance alters carbon dynamics by decreasing GPP and Re". A problem here is that lower plant respiration also contributes to lower ecosystem respiration, so reductions in respiration can not only be attributed to heterotrophic respiration processes. This needs to be clarified here, and the limitations of measuring respiration during daytime with a dark chamber needs to be clarified.
Response: We have added a statement clarifying chamber measurements. Lines 452 -454 read "… Our chamber study only measured daytime fluxes, thus reduced respiration may be due to decreases in plant respiration in addition to heterotrophic respiration processes."

Line 457: here, it needs to be clarified that the measurement period only covered end of June to end of July, i.e., a small component of the full growing season. This needs to be clarified. This does not allow to fully characterize early, peak, and end of growing season processes.

Response: We have tried to make it clear throughout the manuscript that the measurement period (late June and July) was the majority of the growing season at our site, which begins in mid June and ends in early August. We have added in a clarification re: the limited sampling season. On lines 462-464, we clarify, "… By separating the growing season into three periods related to plant phenology, we were better able to identify differences in NEE between undisturbed and disturbed tundra throughout the sampling period in June and July 2014."

Line 523: "nearly continuously over a majority of the 2014 growing season" – this statement is misleading, the one month period is unlikely covering a "majority" of the 2014 growing season.
Response: At our study site, this is the majority of the growing season, as our sampling period accounts for ~70% of the growing season, which begins in mid June and ends in early August.

Line 525: "The disturbance reduced the magnitude of both Re and GPP, although reductions to GPP were greater." – clarify based on daytime flux partitioning.
Response: We have corrected the sentence as follows (lines 530-531), "Based on daytime flux partitioning, the disturbance reduced the magnitude of both R_e and GPP, although reductions to GPP were greater."

References:
Bliss, L. C. (1977). *Truelove Lowland, Devon Island, Canada: A High Arctic Ecosystem*. University of Alberta.

Title: The effect of a permafrost disturbance on growing-season carbon-dioxide fluxes in

a high Arctic tundra ecosystem

Running Head: Permafrost disturbance and CO_2 fluxes

Authors: Cassidy, AE, Christen, A, Henry, GHR

Institute: Department of Geography, The University of British Columbia,

1984 West Mall, Vancouver, British Columbia, Canada, V6T1Z2

Corresponding Author: AE Cassidy

                          Telephone: +001 778 840 3018

                          Email: alison.cassidy@geog.ubc.ca

Keywords: eddy covariance, permafrost disturbance, thermokarst, net ecosystem

exchange, retrogressive thaw slump, tundra ecosystem

Manuscript Type: Research Article

Abstract

Soil carbon stored in high-latitude permafrost landscapes is threatened by warming, and could contribute significant amounts of carbon to the atmosphere and hydrosphere as permafrost thaws. Thermokarst and permafrost disturbances, especially active layer detachments and retrogressive thaw slumps, are present across the Fosheim Peninsula, Ellesmere Island, Canada. To determine the effects of retrogressive thaw slumps on net ecosystem exchange (NEE) of CO_2 in high Arctic tundra, we used two eddy covariance (EC) tower systems to simultaneously and continuously measure CO_2 fluxes from a disturbed site and the surrounding undisturbed tundra. During the 32 day measurement period in the 2014 growing season the undisturbed tundra was a small net sink (NEE = -0.1 g C m^{-2} d^{-1}); however, the disturbed terrain of the retrogressive thaw slump was a net source (NEE = +0.4 g C m^{-2} d^{-1}). Over the measurement period, the undisturbed tundra sequestered 3.8 g C m^{-2}, while the disturbed tundra released 12.5 g C m^{-2}. Before full leaf out in early July, the undisturbed tundra was a small source of CO_2, but shifted to a sink for the remainder of the sampling season (July), whereas the disturbed tundra remained a source of CO_2 throughout the season. A static chamber system was also used to measure daytime fluxes in the footprints of the two towers, in both disturbed and undisturbed tundra, and fluxes were partitioned into ecosystem respiration (R_e) and gross primary production (GPP). Average GPP and R_e found in disturbed tundra were smaller (+0.40 μmol m^{-2} s^{-1} and +0.55 μmol m^{-2} s^{-1}, respectively) than those found in undisturbed tundra (+1.19 μmol m^{-2} s^{-1} and +1.04 μmol m^{-2} s^{-1}, respectively). Our measurements indicated clearly that the permafrost disturbance changed the high Arctic tundra system from a sink to a source for CO_2 during the majority of the growing season (late June and July).

1 Introduction

Permafrost soils in the Arctic store vast amounts of carbon. The northern permafrost zone carbon inventory estimates the quantity of soil organic carbon stored in the top 3 m of frozen and unfrozen soils in northern circumpolar permafrost regions to be 1035 ±150 Pg, or approximately 50% of worldwide soil organic carbon (Tarnocai et al., 2009, Grosse et al., 2011, Hugelius et al., 2013, Schuur et al., 2015). Measurement difficulties and uncertainty regarding carbon storage in cryoturbated soils may result in an underestimation of current estimates, by as much as a factor of two (Hugelius et al., 2013). As ground temperatures increase due to global climate change and permafrost thaws, this organic carbon becomes available for microbial decomposition (Schuur et al., 2008). McGuire et al. (2006) noted the implications for feedbacks to Arctic climate resulting from disturbance and enhanced decomposition including positive feedbacks as more CO_2 released leads to warmer temperatures, thus exacerbating thaw and leading to further release of CO_2. Conversely, a negative feedback may result if soil carbon inputs offset decomposition, as the balance between litter accumulation and decomposition determines the net effect on climate (Davidson et al., 2006, Cornelissen et al., 2007).

Predicted climate change is expected to increase the frequency and extent of land surface disturbances in the Arctic (ACIA, 2005, Vincent et al., 2011). These disturbances are usually linked to thermokarst and affect soil temperature, water quality and soil nutrients (Mackay, 1970, Lamoureux and Lafrenière, 2009, Lantz et al., 2009, Kokelj and Lewkowicz, 1998, Kokelj and Lewkowicz, 1999). In the High Arctic, these disturbances commonly take the form of retrogressive thaw slumps (RTS). RTS are initiated by the exposure of ground ice (sometimes linked to coastal erosion) and result in the removal of

71   soil and vegetation as the slump retreats further upslope (Lantuit and Pollard, 2008). As

72   ground ice thaws, the headwall regresses and will remain active until falling blocks of

73   soil and vegetation insulate exposed ice and prevent further thaw (Burn and Friele, 1989).

74   Within the overall landscape, these distinct landforms often create unique microclimates

75   resulting in increased landscape heterogeneity (Ukraintseva, 2008, Lantz et al., 2009,

76   Bosquet, 2011). Climate warming may cause differential responses in disturbed and

77   undisturbed tundra. For example, the response of plants to increases in temperature may

78   be intensified when disturbance occurs (Lantz et al., 2009). Lantz et al. (2009) suggested

79   disturbances play a more significant role in vegetation modification than temperature

80   changes, particularly at the fine scale. We hypothesize that those changes in the landscape

81   (slumping and vegetation loss) will have a significant effect on the carbon balance of

82   tundra systems. However, no direct measurements of net ecosystem exchange (NEE) and

83   its component fluxes, ecosystem respiration (R_e) and gross primary productivity (GPP),

84   have been completed to determine the effect of these permafrost disturbances.

85   Eddy covariance (EC) has been used to quantify NEE in the Arctic and

86   measurements vary greatly, depending on location and ecosystem type. The magnitude

87   of CO_2 fluxes are generally greater at low latitudes than in the high Arctic (Lafleur et al.,

88   2012) and in wet sedge areas than dry heath tundra (Kwon et al., 2006; Groendahl et al.,

89   2007). Variability may be explained by plant composition and abundance, nutrient

90   availability, substrate quantity and soil organic matter (Mbufong et al., 2014). Typical

91   mean daily values measured during the growing season ranged between 0.2 and 2.2 g C

92   m^{-2} d^{-1} at a wide range of Arctic sites (Lafleur et al., 2012). Previous studies have found

93   large inter-annual variability within and among sites, which can shift the site from a

94   carbon sink to carbon source (Griffis and Rouse, 2001; Kwon et al., 2006; Merbold et al.,

95   2009). Large variability in tundra vegetation communities over short distances increases

96   difficulty in assessing NEE fluxes across the Arctic, and determining their responses to

97   disturbance and environmental change (Lafleur et al., 2012).

98   Static chamber systems, which partition NEE into component fluxes GPP and R_e,

99   are an alternative method of measuring ecosystem fluxes. Chamber studies in the Arctic

100 have found a loss of carbon during the winter, and increasing sink potential with a longer

101 growing season (Welker et al., 2000; Welker et al., 2004). At Alexandra Fiord, Ellesmere

102 Island, experimental warming impacted NEE differently based on soil moisture, with a

103 greater increase in respiration in dry than wet sites (Welker et al., 2004). Across a

104 latitudinal gradient, warming tended to increase respiration, with the greatest increases

105 found in dry ecosystems (Oberbauer et al., 2007).

106   While NEE values are generally similar between chamber and EC methods,

107 differences are attributed to the scale of the measurements (Stoy et al., 2013). Fox et al.

108 (2008) showed there was large bias in upscaling chamber measurements, relative to EC

109 values in a tundra ecosystem, due to microscale surface heterogeneity of the landscape.

110 Further, in the high Arctic with 24 hours of daylight during which the sun remains

111 relatively high above the horizon, the usual partitioning methods for EC measurements

112 into component fluxes (Reichstein et al., 2012) are not applicable, as they rely on

113 nighttime measurements, or measurement during low light conditions. Consequently, to

114 measure the impact of the RTS on the CO_2 exchange of high Arctic tundra we used both

115 EC and chamber measurements.

116   In this study, we analyze the impacts of RTS on CO_2 exchange in a high Arctic

117   tundra ecosystem. Our main research objective was to examine how growing season NEE

118   and its component fluxes vary between an active RTS and undisturbed tundra.

119

120   **1.1   Study Area**

121

122   Our research was conducted on the Fosheim Peninsula, located on western Ellesmere

123   Island, Canada (79° 58' 56" N 84° 23' 55" W (WGS-84), elevation 100 m asl). The field

124   site had an active, isolated retrogressive thaw slump (RTS) (6300 m^2) within a relatively

125   flat area and wind patterns were constrained (NNE-SSW) by its location near a shallow

126   valley bottom (Fig. A1). Ice-rich permafrost is found throughout the study region and

127   increased summer temperatures and precipitation over the past 20 years have resulted in

128   greater occurrence of active layer detachment slides and RTS (Lewkowicz and Harris,

129   2005a). The geological substrate is mainly sandstones of the Eureka Sound group (Bell,

130   1996) with marine deposits of silts and fluvial sandy soils varying in thickness above

131   bedrock (Robinson and Pollard, 1998). The limit of ocean inundation at the end of the last

132   glaciation in the area lies at approximately 140 m above sea level (Bell, 1996), with

133   limited vegetation above this level; our study location was located below the marine

134   limit. Vegetation at the site was a relatively uniform dwarf-shrub-graminoid community

135   on moderately drained, slightly alkaline soils. Vegetation located in the undisturbed

136   tundra was dominated by the dwarf shrubs *Salix arctica, Dryas integrifolia*, the sedge

137   *Carex nardina,* and mosses and lichens. Within the disturbance, the dominant plant

138   species was the grass *Puccinellia angustata*, which is able to colonize the disturbed area

139   and proliferate. Vegetation cover within the RTS varied based on moisture and proximity

140   to undisturbed vegetation, and was much lower than the surrounding undisturbed areas

141   (with estimates of cover averaging (±SE) 3(±0.5)% and 27(±1.5)% total cover,

142   respectively). The nearest weather station, Eureka, is located 40 km to the west and has a

143   mean temperature of 6.1°C and mean precipitation of 14.5 mm in July over the 1981-

144   2010 period (Environment Canada, 2015).

2   Materials and Methods

2.1   Eddy covariance measurements of carbon-dioxide fluxes

An appropriate sampling design was necessary to quantify the CO_2 fluxes between land surface and atmosphere simultaneously from disturbed and undisturbed sites in close proximity (Hollinger and Richardson, 2005). We used a dual eddy covariance approach, which was advantageous over a single eddy covariance tower as we were able to measure fluxes simultaneously from disturbed tundra and the surrounding undisturbed tundra (Fig. 1; Fig. 2). However, direct placement of an EC system within the disturbance was not possible due to the active mass movements in the RTS creating risk for researchers and equipment. Two towers were established on opposite sides of the RTS, at the boundary between disturbed and undisturbed terrain (Fig. 1). Tower 1 was established on the southern boundary of the RTS and Tower 2 was established on the northern boundary at a distance of 90 m from Tower 1. Disturbed tundra were areas impacted by RTS, while undisturbed tundra were areas located outside the boundary of the RTS. This set-up allowed the measurement of fluxes containing signals from both areas simultaneously. By using turbulent source area modeling (see below) we then estimated the contribution of disturbed and undisturbed tundra to each of the signals.

Both EC systems were established on tripods located on the periphery of the active RTS on 26 June 2014 and operated continuously until 28 July 2014. On each system the instrumentation included: an ultrasonic anemometer (CSAT-3, Campbell Scientific Inc., Logan, UT, USA) and a co-located infrared gas analyzer (IRGA) (LI-7500, LI-COR Inc., Lincoln, NE, USA). The IRGA was tilted 30° from the vertical to minimize issues associated with sensor heating and reduce pooling of moisture on the windows (see supplementary information). The IRGA and ultrasonic anemometer were established at a

169 height of 1.3 m on both towers; a temperature and humidity sensor (HMP, Campbell

170 Scientific Inc.) at 1 m; a quantum sensor (SQ-110, Apogee Instruments Inc., Logan, UT,

171 USA; height: 1 m); a net radiometer (NR Lite, Kipp & Zonen B.V., Delft, The

172 Netherlands; height: 1 m); and all sensors were attached to a data logger (CR1000,

173 Campbell Scientific Inc.). This double EC sampling technique allowed for simultaneous

174 sampling of fluxes from the disturbed tundra and the surrounding undisturbed (control)

175 terrain for most time steps. Previous knowledge of wind direction ϑ based on the location

176 of the disturbance within a valley constrained winds along the valley axis into up-valley

177 wind ($0° < \vartheta < 40°$) and down-valley wind ($160° < \vartheta < 200°$) directions, which resulted in

178 aligning the sector facing towards 290°, having a sector free of flow distortion from 140º

179 to 80º (distorted sector was 80º to 140º). The towers were established at a distance of 3 m

180 from the slump edge to ensure stability, and were moved periodically throughout the

181 season due to recession of the slump edge. Additionally, the potential impacts of step

182 changes due to the placement of the flux tower at the boundary of disturbed and

183 undisturbed tundra was minimized through the use of friction velocity thresholds and

184 removing data with wind along the discontinuity with obvious flow distortion. Both

185 IRGAs were calibrated prior to the field season using a two-point calibration in the lab

186 against standards from the Greenhouse Gas Measurement Laboratory (GGML),

187 Meteorological Service of Canada using a zero gas and span gas of known mixing ratio.

188   Fluxes of CO_2 (F_C) were computed in EddyPro® (V5.1.1, LI-COR Inc.) with a

189 missing sample allowance of 30%. F_C was calculated over a 30 minute averaging interval

190 using double rotation for tilt correction, block average detrending, contact time lag

191 detection, and density corrections using mixing ratios (Burba et al., 2012). Data were

192 quality checked using the flagging system proposed by Mauder and Foken (2004).

193 **2.2 Turbulent source area model**

194

195 To estimate the instantaneous turbulent source area that influences sampled NEE, a 2-

196 dimensional gradient diffusion and crosswind dispersion model (Kormann & Meixner,

197 2001) was run for all 30 min periods between 26 June 2014 and 28 July 2014 at a 1 m

198 grid resolution over a domain of 300 x 300 m with the tower situated in the centre (see

199 Fig. 2). Model inputs included wind direction ϑ (º), standard deviation of the lateral wind

200 component σ_v (m), roughness length z_0 (m) and Obukhov length L (m) separately for

201 each tower and for each time step. ϑ, σ_v and L were calculated directly by EddyPro®

202 based on measurements by the two ultrasonic anemometers. Roughness length varied

203 depending on whether the upwind surface in a particular time period was in the RTS or

204 representing undisturbed tundra. z_0 was determined separately for 10º wind direction bins

205 based on the ensemble of measurements from the entire dataset following Paul-Limoges

206 *et al.* (2013). For each wind sector ϑ, z_0 was calculated for cases with near-neutral

207 stability (-0.05 < z/L < +0.05) using Eq. 1:

$$z_0(\vartheta) = z \, \exp\left(-\frac{k\bar{u}}{u_*}\right) \tag{1}$$

208

209 where z is the measurement height (1.3 m), k is the von Kármán constant (0.4), $\bar{u}$ is

210 the measured mean horizontal wind (m s^{-1}) from this wind direction, and u_* is the

211 simultaneously measured friction velocity (m s^{-1}) calculated as $u_* = (\overline{u'w'}^2 + \overline{v'w'}^2)^{0.25}$

212 where $\overline{u'w'}$ and $\overline{v'w'}$ are covariances of longitudinal (u), lateral (v) and vertical (w) wind

213   components. Mean wind $\bar{u}$ and covariances were calculated by EddyPro[®] based on

214   measurements from the ultrasonic anemometer. The disturbed sectors of both towers had

215   an average $z_0 = 0.032$ m whereas the undisturbed sectors had an average $z_0 = 0.017$ m.

216   Gridded flux footprints (or vertical per unit point source) ϕ *(x,y)* were calculated in with 1

217   m resolution for each 30 min step following Christen et al. (2011). A fraction of the flux

218   footprint was predicted to be outside the 300 m study area, which was assumed to

219   represent an undisturbed (control) surface (as no additional permafrost disturbances were

220   located within proximity of the towers).

221   The 300 m x 300 m model domain included the entire disturbance and a spatial mask

222   I (x,y) of the domain was created with a value of 1 inside the disturbance boundary and 0

223   for undisturbed tundra. For each grid-cell, I (x,y) was multiplied by ϕ (x,y), and then

224   summed to determine the fraction of the footprint that originates from inside the RTS

225   (Eq. 2):

$$\Phi_d = \sum_{x=1}^{300} \sum_{y=1}^{300} I(x,y)\phi(x,y) \tag{2}$$

226

227   Φ_d is the fraction of the tower signal (from 0 to 1) influenced by the disturbed surface

228   of the RTS. The fraction of the signal influenced by the undisturbed tundra Φ_c is then

229   calculated as $\Phi_c = 1 - \Phi_d$. By solving a set of linear equations (Eq. 3 and Eq. 4), we

230   are able to partition the component fluxes of CO_2 (Fig. 2) from the disturbed tundra

231   (NEE_d) and from the undisturbed tundra (NEE_c) from both towers (T1 and T2):

$$NEE(T1) = \Phi_d(T1)NEE_d + \Phi_c(T1)NEE_c \tag{3}$$

232

$$\text{NEE(T2)} = \Phi_d(\text{T2})\text{NEE}_d + \Phi_c(\text{T2})\text{NEE}_c \tag{4}$$

233   Turbulent source areas calculated for each time step over the sampling period are

234   shown in Fig. 2. These two example time steps from Fig. 2 can be solved as follows. In

235   the first time-step (09:00), Φ_c for T1 is 1, therefore the NEE(T1) $= NEE_c = $ -0.17 µmol

236   m^{-2} s^{-1}. For T2, 88% (Φ_d) was disturbed while the remaining 12% was allocated as

237   undisturbed (Φ_c), so NEE$_c$ and NEE$_d$ were solved with NEE(T2) = 1.20 µmol m^{-2}s^{-1} and

238   resulted in NEE$_d$ = 1.39 µmol m^{-2} s^{-1}. Corresponding to the second time step from Fig.

239   A1 (18:00), T1 is influenced by both undisturbed and disturbed NEE as Φ_d $(T1) = 0.73$

240   and Φ_c $(T1) = 0.27$ and NEE(T1) is 0.38 µmol m^{-2} s^{-1}. At T2, Φ_d is 0, while Φ_c is 1, so

241   NEE(T2) $=$ NEE$_c$ = -0.03 µmol m^{-2} s^{-1}. Consequently, NEE$_c$ $= -0.03$ µmol m^{-2}s^{-1} and

242   NEE$_d$ $= 0.54$ µmol m^{-2}s^{-1}.

243   Calculations of NEE$_d$ and NEE$_c$ were numerically unstable under multiple

244   combinations of surface fractions, including when winds were parallel to the edge of the

245   disturbance and when Φ_d and Φ_c were roughly equal to one another. As a result, values

246   where the absolute difference between Φ_d and Φ_c was less than 0.05 were removed and

247   fluxes were gap-filled as detailed below during these periods.

248   The resulting NEE$_c$ and NEE$_d$ were compared and fluxes that had a difference from

249   the daily average that was greater than 5 standard deviations of the 30 min values of the

250   same day (applied iteratively) were removed. For further analysis, half hour fluxes were

251   averaged to calculate hourly fluxes. If one of the two 30 min values was invalidated, then

252   the hourly value was calculated based on the remaining other 30 min period. Hourly gaps

253   that still existed were then filled using the following methods: a) gaps in NEE$_c$ and NEE$_d$

254   of less than 2 hours were filled using a linear interpolation; and b) gaps greater than 2

255 hours were filled using aggregate averaging over a rolling three-day window selecting the

256 same time of the day. The cleaned and filled dataset is composed of 86% original data

257 and 14% gap filled (of a total of 750 data points, 106 of these were modeled). Data were

258 also removed during times of maintenance, when the towers were moved and when

259 manual chamber or vegetation measurements were made within the tower footprint.

260 **2.3   Portable chamber system**

261
262 On 27 June 2014, 63 opaque PVC collars (10 cm diameter, $A = 78.5$ cm^2, 6 cm depth)

263 were installed across the source areas of T1 and T2, in both the disturbed and undisturbed

264 zones (disturbed tundra N=21, undisturbed tundra N=42). They were inserted 4 cm into

265 the ground so as to minimally disturb soil and vegetation and left to protrude 2 cm above

266 the soil surface. As moss cover was minimal and discontinuous, the location of the

267 ground surface could be easily identified as the upper surface of the soil. Collar locations

268 were randomly determined based on the generation of random distances and angles from

269 the flux tower within disturbed and undisturbed flux source areas, with a minimum

270 distance of 2 m and a maximum distance of 30 m from the towers. The disturbed areas of

271 the RTS were not entirely devoid of vegetation, as clumps of soil and plants existed

272 sporadically throughout the disturbance; 9 of 21 collars contained at least one individual

273 plant. Measurements of CO_2 fluxes began on 29 June, to allow the immediate disturbance

274 effects of installation to dissipate.

275   A non-steady state vented portable chamber system similar to Jassal *et al.*(2005)

276 was used to measure fluxes from each collar using transparent and opaque chambers. The

277 measurement head was a PVC chamber with a volume of 1.4 x 10^{-3} m^3 (height: 15.6 cm,

278 diameter: 10.7 cm). Fluxes from all collars were measured six times throughout the study

279   period, at 5-day intervals. The chamber head was placed on each collar and a foam

280   gasket sealed the connection between the collar and the chamber head. Measurements

281   were made for two minutes. A pump (flow rate 600 cm^3 min^{-1}) circulated air from the

282   chamber head into a portable, battery operated infrared gas analyzer (IRGA) (LI-840, LI-

283   COR Inc., Lincoln, USA) and back into the chamber head through a closed circuit. The

284   IRGA determined CO_2 mixing ratios ([CO_2] in ppm) and water vapour concentrations at a

285   temporal resolution of 1 Hz during the run. The IRGA was calibrated in the laboratory

286   prior to sampling using a two-point calibration, against standards from the Greenhouse

287   Gas Measurement Laboratory (GGML), Meteorological Service of Canada, using a zero

288   gas and span gas of known mixing ratio. The IRGA has been calibrated in the laboratory

289   for effective volume, which exceeds geometric volume by 10% due to absorption of CO2

290   on the walls of the chamber and contribution of near-surface soil porosity (Jassal et al.,

291   2012). This calibration was carried out in the laboratory by determining the difference

292   between two flux measurements, one immediately following the other, where the second

293   measurement included a known rate of injection of CO_2 into the chamber.

294   Fluxes were calculated from Δ[CO_2]/Δt (linear regression over 2 min, discarding

295   the first 10 seconds), using Eq. 5:

$$Fc = \frac{\rho \, \overline{D} V}{A} \frac{\Delta[CO_2]}{\Delta t} \tag{5}$$

296

297   where ρ is molar air density (mol m^{-3}) calculated from measured air temperature, D is

298   dilution considering [H_2O], Δ[CO_2]/Δt is the rate of change in CO_2 mixing ratio over

299   time (μmol mol^{-1} s^{-1}), and V and A are chamber volume and area, respectively. To obtain

300   measurements of NEE, the transparent chamber head was used on each collar. For

301   ecosystem respiration (R_e) measurements, the chamber was removed and allowed to

302   equilibrate to ambient [CO_2] before being replaced on the collar, and a dark shroud was

303   placed over the transparent chamber head to block out all PAR. GPP was calculated

304   based on GPP = R_e – NEE, where NEE is negative if GPP > R_e and both R_e and GPP are

305   positive values. NEE and R_e measurements were taken within minutes at each collar

306   allowing for comparison. Measurements were conducted over a 7-hour sampling period

307   and were always completed between 10:00 and 18:00 CDT to reduce diurnal changes in

308   light and temperature. Chamber measurements were only made during daytime periods,

309   thus respiration includes heterotrophic respiration from soil carbon losses and residual

310   photosynthetic respiration. The site has 24 h of light and photosynthesis (and associated

311   respiration) can occur over the entire 24 h period.

312   **2.4   Environmental Variable Sampling**

313

314   Soil temperature loggers (HOBO Pendant Temperature/Light Data Loggers, Onset

315   Computer Corporation, Bourne, MA, USA) were installed at randomly selected collars

316   throughout the study area within 0.5 m of the collar. A total of 21 HOBO sensors (14

317   sensors located in undisturbed tundra and 7 sensors in disturbed tundra) measured soil

318   temperatures at 5 cm every minute throughout the sampling season. The soil temperatures

319   were aggregated into hourly averages to allow for comparison with hourly EC data. Soil

320   moisture was measured adjacent to collars every five days as volumetric water content

321   (%) using a Time Domain Reflectometry (TDR) sensor (HydroSenseII Soil Water TDR,

322   Campbell Scientific Inc., Logan, UT, USA) with 12 cm rods. After rain events,

323   measurements were delayed for 24 hours.

324

3 Results

3.1 Environmental conditions during the study period

The measured variations over the study period in air temperature (T_a), net radiation (Q^*,

over undisturbed tundra), incoming photosynthetically active radiation (PAR), and

vapour pressure deficit (VPD) measured at Tower 2, and soil temperature from the

disturbance and undisturbed tundra area near Tower 2 are shown in Fig. 3. The early

season was characterized by clear skies, however the middle of July was dominated by a

period of cloudy, cooler conditions (exemplified by decreased Q^*, Fig. 3). Air and soil

temperatures showed distinct diurnal and seasonal patterns (Fig. 3; Fig. 4), characterized

by an increase in both temperatures early in the season, which were sustained through the

peak season, followed by decreases in both during the end of the season. Three distinct

periods (early, peak and late season) were identified throughout the study period based on

plant phenological development and environmental conditions (Fig. 3; Fig. 4). These

periods varied in their duration (see Table 1). During the measurement period, T_a

increased from 10.5ºC in the early season (DOY=175-185) to 12.2°C during the peak of

the growing season (DOY=186-202) and then decreased to 7.2°C by the end of July. On a

diurnal basis, disturbed soils reached greater temperatures than undisturbed soils earlier

in the season (12.6°C and 11.6°C, respectively), but cooled off more quickly later in the

season (7.8°C and 8.1°C, respectively), due to the lack of insulating vegetation (Mann

Whitney U-Test ($V = 181992$, p < 0.01)). In undisturbed terrain, soil moisture decreased

during peak season, while soil moisture increased steadily in disturbed tundra (Table 1).

Overall, soil moisture values were significantly greater (Mann Whitney U-Test ($V =$

7023, p < 0.01)) in disturbed soils (24.1% ± 0.9) than in undisturbed soils (13.9% ± 0.4).

3.2 NEE of disturbed and undisturbed tundra

The early season was characterized by leaf emergence, cool temperatures, and elevated soil moisture (Table 1) due to recent snowmelt. The peak season was characterized by maximum leaf area and flowering of vegetation and a decrease in surface soil moisture as warm air temperatures and large VPD persisted. The late season was characterized by the beginning of leaf senescence, dry soils, and the greatest active layer depth. Precipitation was minimal throughout the season (1.2 mm at Eureka), with isolated rain events occurring on July 17, 21, and 26. There was a significant windstorm beginning on 22 July and that lasted 24 hours, with wind speeds (as determined from the raw 20 Hz spikes) of up to 21 m s^{-1}.

NEE$_c$ and NEE$_d$ were analyzed separately for three periods (early, peak and late season). In the undisturbed tundra, NEE$_c$ was initially a small CO_2 source in the early period and transitioned to a small sink as photosynthesis increased during the peak season. In the late season, NEE$_c$ became a small source consistent with decreased air and soil temperatures and the beginning of leaf senescence. This was in contrast with fluxes measured in the disturbed area (NEE$_d$), which remained a CO_2 source throughout the sampling period and displayed only slightly dampened values during peak season. Overall, NEE$_c$ and NEE$_d$ were significantly different throughout the sampling period (Mann-Whitney U-Test ($V = 45839$, $p < 0.01$)).

Aggregate fluxes calculated over the study period showed an overall loss of CO_2 from disturbed tundra, and a modest CO_2 sink in the undisturbed tundra (Fig. 6). Daily averages of NEE$_c$ ranged from -0.89 to +0.54 g C m^{-2} day^{-1}. NEE$_d$ ranged from -0.29 to +1.63 g C m^{-2} day^{-1}. During the early season, the average daily NEE$_c$ was a small source

17

373   of CO_2 to the atmosphere (+0.07 g C m^{-2} day^{-1}) while disturbed tundra was a greater

374   source of CO_2 (NEE$_d$ = +0.55 g C m^{-2} day^{-1}). During peak growth, this shifted as the

375   undisturbed tundra sequestered -0.29 g C m^{-2} day^{-1} and disturbed tundra continued to emit

376   CO_2 at an average of +0.26 g C m^{-2} day^{-1}. During the end of the sampling season, the

377   undisturbed was a very small sink of CO_2 with mean NEE of -0.02 g C m^{-2} day^{-1} and the

378   NEE of the disturbed tundra was +0.47 g C m^{-2} day^{-1}. Over the duration of the entire

379   sampling period, the disturbed tundra was a source of CO_2 with an average of +0.39 g C

380   m^{-2} day^{-1} while the undisturbed tundra was a sink for CO_2 with an average uptake of -0.12

381   g C m^{-2} day^{-1} (Fig. 5). In total, the undisturbed tundra sequestered 3.8 g C m^{-2}, while the

382   disturbed tundra released 12.5 g C m^{-2} over the 32-day measurement period.

383   Diurnal NEE from the tower systems correspond with soil temperatures. In

384   disturbed areas, as soil temperatures warmed, CO_2 emissions increased, consistent with

385   increased respiration. However, fluxes in undisturbed areas showed increased

386   sequestration during midday, due to greater photosynthetic activity dominating over

387   respiration increases.

388   Temporal patterns of fluxes and climatic and environmental variables were

389   analyzed for disturbed and undisturbed areas. In the disturbed area, regression analysis

390   revealed strong relationships between NEE and soil temperature, PAR, T_a and VPD for

391   the early and peak season periods (p<0.001), while PAR was the most important control

392   during the late season (r^2=0.50, p < 0.001). Over the undisturbed tundra, correlations

393   between NEE and environmental variables varied throughout the sampling period. During

394   the early season, PAR was most strongly correlated (r^2=0.16, p<0.001) with NEE,

395   however, during the peak season temperature (r^2=0.08, p<0.001) and vapour pressure

396   deficit (VPD) (r^2=0.08, p<0.001) became important controls on NEE. At the end of the

397   sampling season once again PAR was most strongly correlated with NEE (r^2=0.25,

398   p<0.001) in the undisturbed tundra.

3.3   Partitioning of NEE

401   Measurements from the static chamber system were allocated to one of the three

402   seasonal periods, allowing comparison with EC data (Fig. 7). The NEE values measured

403   using the chamber technique supported the EC measurements, but allowed fluxes to be

404   partitioned into their component parts. The chamber measurements showed that the

405   magnitude of GPP and R_e were roughly similar, resulting in minimal NEE in both

406   disturbed and undisturbed areas (Table 2; Fig. 8). Variability in GPP was greater in the

407   undisturbed tundra with values up to 8.03 µmol m^{-2} s^{-1} while the maximum GPP in the

408   disturbed tundra reached 2.47 µmol m^{-2} s^{-1}. R_e ranged up to +5.92 µmol m^{-2} s^{-1} in the

409   undisturbed tundra and to +2.23 µmol m^{-2} s^{-1} in the disturbed tundra. Over the sampling

410   season in the disturbed areas, chamber-measured GPP averaged 0.40 µmol m^{-2} s^{-1}

411   increasing during peak season to 0.45 µmol m^{-2} s^{-1}, before falling to 0.24 µmol m^{-2} s^{-1} in

412   the late season. Respiration was greatest during the early season with +0.70 µmol m^{-2} s^{-1},

413   decreasing to +0.53 µmol m^{-2} s^{-1} during peak season, and finally to +0.35 µmol m^{-2} s^{-1}

414   during the late season. These opposing fluxes resulted in the disturbed tundra being a

415   small source for CO_2 throughout the entire sampling season. NEE measured by the

416   chamber system varied between +0.05 and +0.41 µmol m^{-2} s^{-1} in the disturbance with the

417   largest NEE occurring early in the season due to high respiration. R_e was always greater

418   in magnitude than GPP over disturbed tundra resulting in positive NEE values.

419   The undisturbed areas were small sources of CO_2 early in the season as R_e

420   outpaced productivity. During the early season GPP averaged 0.85 μmol m^{-2} s^{-1}, nearly

421   doubling during peak season to 1.47 μmol m^{-2} s^{-1}, before falling to 1.00 μmol m^{-2} s^{-1} late

422   in the season. R_e in the undisturbed tundra ranged from +0.62 μmol m^{-2} s^{-1} to +1.14 μmol

423   m^{-2} s^{-1}, with the greatest respiration occurring during peak growth. Both GPP and R_e

424   peaked during the middle of the sampling period (mid July), before decreasing at the end

425   of the season, but GPP was always greater in magnitude than R_e.

426

4   Discussion

Over the majority of the 2014 growing season (late June and July), the RTS at our high

Arctic site was a CO_2 source while undisturbed tundra was a small sink. All fluxes were

quite low, but similar to those measured in other high Arctic sites (Lafleur et al. 2012).

Multi-year measurements of NEE in high Arctic tundra indicate that initial uptake of

carbon coincides with snowmelt and increases in CO_2 emission rates correspond with

deep and long-lasting snowpack (Lund et al., 2012). Arctic sites show significant inter-

annual variability, which is controlled by temperature; increased temperatures may result

in enhanced emissions (Griffis and Rouse, 2001; Kwon et al., 2006; Merbold et al., 2009;

Lund et al., 2012). In the High Arctic, soil moisture differences result in variations in

ecosystem respiration (measured using chamber systems) and may enhance the impacts

of warming (Welker et al., 2004). Warming has been found to increase respiration along a

latitudinal gradient with the greatest increases found in dry ecosystems (Oberbauer et al.,

2007).

Based on chamber measurements, we found permafrost disturbance alters carbon

dynamics by decreasing GPP and R_e (Fig. 7). However, reductions to GPP are greater

than reductions to R_e, resulting in the disturbance becoming a net carbon source.

Decreases in GPP are due to lower vegetation cover within disturbed terrain. Decreases in

respiration have been found within slumps and slides and are linked with carbon export

from the disturbed area (Abbott and Jones, 2015; Beamish et al., 2014). Respiration

measured in other high Arctic polar desert sites was positively correlated with soil

moisture (Emmerton et al., 2015). This balance between reduced R_e as a result of

disturbance and potential increases as a result of increased soil moisture may result in the

451 greater magnitude of R_e relative to GPP and thus the overall shift to carbon source within

452 the disturbance. Our chamber study only measured daytime fluxes, thus reduced

453 respiration may be due to decreases in plant respiration in addition to heterotrophic

454 respiration processes.

455   Despite the small magnitude of these high Arctic fluxes, there was a considerable

456 effect of the permafrost disturbance as the net CO_2 emissions from the disturbance was

457 approximately three times larger than the net sequestration in the undisturbed tundra.

458 Overall, the double EC system approach coupled with a source area model proved to be

459 an effective method of accurately partitioning measured fluxes into undisturbed and

460 disturbed contributions, and values were consistent with the static chamber

461 measurements.

462   By separating the growing season into three periods related to plant phenology,

463 we were better able to identify differences in NEE between undisturbed and disturbed

464 tundra throughout the sampling period in June and July 2014. Initial sampling

465 corresponded with leaf emergence, and as the season progressed, plant growth and leaf

466 area increased, resulting in increased photosynthetic activity. The changes in NEE also

467 corresponded to differences in PAR during the three periods of the growing season.

468 These phenological changes, especially in leaf emergence, growth and senescence, can be

469 compared to the shift in CO_2 fluxes as initially the undisturbed tundra was a source of

470 CO_2, but during peak growth there was a distinct shift to CO_2 sink. By the end of the

471 sampling season, vegetation has begun to senescence, and this was reflected in reduced

472 sink strength of NEE_c in the undisturbed tundra. The disturbed areas contained low

473 vegetation cover, resulting in a very low magnitude of GPP. Throughout the season, the

474 environmental controls on CO_2 fluxes in the disturbed tundra were PAR, T_a and VPD

475 during the early and peak season, while PAR was a control in the late season.

476   Estimates of landscape level impacts of permafrost disturbances in an 81 km^2 ice-

477 free land area on the Fosheim Peninsula, which included the area used for our study, were

478 determined from satellite imagery and ground truthing in 2013. The analyses revealed

479 that permafrost disturbances currently accounted for 0.34 km^2 or only 0.4% of the

480 landscape (A.C.A. Rudy, personal communication, 2015). Although the landscape area

481 directly impacted by disturbance at this time is minimal, indirect impacts such as the

482 lateral export of dissolved and particulate organic matter (hence, carbon) through streams

483 and the hydrologic network are also important (Lamoureux and Lafrenière, 2009, Kokelj

484 and Lewkowicz, 1998, Kokelj and Lewkowicz, 1999). The frequency and magnitude of

485 these land surface disturbances appear to be increasing across the Fosheim Peninsula (and

486 elsewhere in the Arctic) as a result of the warming climate, thus exacerbating these

487 impacts (Lewkowicz, 1990; Lewkowicz and Harris, 2005b; Lantz and Kokelj, 2008). The

488 increasing frequency and magnitude of these disturbances will affect the carbon balance

489 at the landscape scale and could result in increased net CO_2 emissions from these areas in

490 the future. Organic carbon stored within permafrost has the potential to be released to the

491 atmosphere as permafrost thaws (Schuur et al., 2008; Hicks Pries et al., 2011; Hicks Pries

492 et al., 2013). We quantified this release to the atmosphere and demonstrated that these

493 permafrost disturbances are sources of CO_2 over the measurement period during the

494 growing season, and are likely sources throughout the year.

495   Potentially, some of the carbon in the soils could also be released in form of

496 methane (Anisimov, 2007; IPCC, 2007; Walter Anthony et al., 2012). Soil oxygen

497 availability has been found to influence permafrost carbon that is released as both carbon-

498 dioxide and methane, and under aerobic conditions significantly more carbon is released

499 as CO_2 than CH_4 (Lee et al., 2012). We expect that methane release was relatively

500 minimal from both the undisturbed and disturbed sites because of the aerobic conditions

501 present in the moderately drained soils found in our study location. However, we also

502 expect increased release of carbon with the deepening of the active layer and the increase

503 in frequency and magnitude of permafrost disturbances. In addition, inorganic carbon

504 released with the dissolution of carbonates and weathering may result in ventilation of

505 CO_2 and thus increased emissions (Lovett et al., 2006; Perez-Priego et al., 2013; Serrano-

506 Ortiz et al., 2010). With increasing soil moisture, soil ventilation associated with

507 carbonates may increase overall R_e (Emmerton et al., 2015). However, slow carbon

508 evolution in tundra soils (as a result of the release of inorganic carbon from carbonates)

509 would limit this influence (Billings et al., 1977).

510   Due to logistical constraints, our sampling period was limited to approximately 30

511 days after snowmelt had occurred. As these disturbances were dynamic in nature, the site

512 could not be left alone as personnel were needed to monitor the slide edge location and

513 adjust the equipment as needed. Leaving the site unmanned would have put the

514 equipment at risk. Shoulder season and winter respiration have been shown to be

515 significant in various studies for year-round estimates of the effects on the carbon cycle

516 (Nordstroem et al., 2001; Welker et al., 2004; Johansson et al., 2006; Humphreys and

517 Lafleur, 2011; Wang et al., 2011; Lund et al., 2012), however only growing season fluxes

518 were considered in our study. Starr and Oberbauer (2003) found photosynthetic activity

519 in vascular plants under snow further indicating the importance of fluxes outside the

520 snow free period. These fluxes were not considered in our study and could alter the

521 annual carbon balance. However, year round measurements of carbon exchange in areas

522 impacted by permafrost thaw in Alaska indicate these areas act as sources of carbon over

523 multiple years (Vogel et al., 2009).

524 **5   Conclusion**
525
526   Using a dual EC sampling approach, in combination with the turbulent source

527 area model and complemented by static chamber measurements, we were able to

528 determine fluxes from one representative retrogressive thaw slump nearly continuously

529 over a majority of the 2014 growing season. We found that these disturbances modify the

530 NEE of the tundra, changing it from a net sink to a source of CO_2. Based on daytime flux

531 partitioning, the disturbance reduced the magnitude of both R_e and GPP, although

532 reductions to GPP were greater. The dual EC approach in combination with the source

533 area model allowed accurate assessments of the contributions of disturbed and

534 undisturbed areas to CO_2 fluxes so we could quantify the effect of permafrost disturbance

535 on NEE. This approach may be preferable to measurements taken using manual portable

536 chamber systems due to the continuous sampling frequency and spatial integration of the

537 signal.

538

539

540

541

542

543

Acknowledgements

References

Abbott, B. W. and Jones, J. B.: Permafrost collapse alters soil carbon stocks, respiration, CH_4, and N_2O in upland tundra. Glob Chang. Biol, 21: 4570–4587. doi:10.1111/gcb.13069, 2015.

ACIA: Arctic Climate Impact Assessment and Arctic Monitoring and Assessment Programme and Program for the Conservation of Arctic Flora and Fauna and International Arctic Science Committee, Cambridge University Press, New York, USA, 2005.

Anisimov, O. A.: Potential feedback of thawing permafrost to the global climate system through methane emission, Environ. Res. Lett., 2, 045016, doi:10.1088/1748-9326/2/4/045016, 2007.

Beamish, A., Neil, A., Wagner, I., Scott, N.A.: Short-term impacts of active layer detachments on carbon exchange in a High Arctic ecosystem, Cape Bounty, Nunavut, Canada, Pol. Biol., 37, 1459–1468, 2014.

Bell, T.: The last glaciation and sea level history of Fosheim Peninsula, Ellesmere Island, Canadian High Arctic, Can. J. Earth Sci., 33, 1075-1086, 1996.

Billings, W. D. and Mooney, H. A.: The ecology of arctic and alpine plants, Biol. Rev., 43, 481–529, doi:10.1111/j.1469-185X.1968.tb00968.x, 1968.

Billings, W.D., Peterson, K.M., Shaver, G.R. and Trent, A.W.: Root growth, respiration, and carbon dioxide evolution in an arctic tundra soil, Arctic & Alp. Res., 9:129-137, 1977.

Bosquet, L.: The effects of observed and experimental climate change and permafrost disturbance on tundra vegetation in the western Canadian High Arctic, Canadian theses, Kingston, Ontario., 2011.

Burba, G., Schmidt, A., Scott, R. L., Nakai, T., Kathilankal, J., Fratini, G., Hanson, C., Law, B., McDermitt, D. K., Eckles, R., Furtaw, M. and Velgersdyk, M.: Calculating CO2 and H2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio, Glob. Chang. Biol., 18, 385–399, doi:10.1111/j.1365-2486.2011.02536.x, 2012.

Burn, C. and Friele, P.: Geomorphology, Vegetation Succession, Soil Characteristics and Permafrost in Retrogressive Thaw Slumps near Mayo, Yukon Territory, Arctic, 42(1), 31–40, 1989.

Christen, A., Coops, N. C., Crawford, B. R., Kellett, R., Liss, K. N., Olchovski, I., Tooke, T. R., Van Der Laan, M. and Voogt, J. A.: Validation of modeled carbon-dioxide

emissions from an urban neighborhood with direct eddy-covariance measurements, Atmos. Environ., 45, 6057–6069, doi:10.1016/j.atmosenv.2011.07.040, 2011.

Cornelissen, J. H. C., Van Bodegom, P. M., Aerts, R., Callaghan, T. V., Van Logtestijn, R. S. P., Alatalo, J., Stuart Chapin, F., Gerdol, R., Gudmundsson, J., Gwynn-Jones, D., Hartley, A. E., Hik, D. S., Hofgaard, A., Jónsdóttir, I. S., Karlsson, S., Klein, J. A., Laundre, J., Magnusson, B., Michelsen, A., Molau, U., Onipchenko, V. G., Quested, H. M., Sandvik, S. M., Schmidt, I. K., Shaver, G. R., Solheim, B., Soudzilovskaia, N. A., Stenström, A., Tolvanen, A., Totland, Ø., Wada, N., Welker, J. M., Zhao, X., Brancaleoni, L., Brancaleoni, L., De Beus, M. A. H., Cooper, E. J., Dalen, L., Harte, J., Hobbie, S. E., Hoefsloot, G., Jägerbrand, A., Jonasson, S., Lee, J. A., Lindblad, K., Melillo, J. M., Neill, C., Press, M. C., Rozema, J. and Zielke, M.: Global negative vegetation feedback to climate warming responses of leaf litter decomposition rates in cold biomes, Ecol. Lett., 10, 619–627, doi:10.1111/j.1461-0248.2007.01051.x, 2007.

Davidson, E. A. and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change., Nature, 440, 165–173, doi:10.1038/nature04514, 2006.

Edlund, S., Alt, B. and Young, K.: Interaction of climate, vegetation, and soil hydrology at Hot Weather Creek, Fosheim Peninsula, Ellesmere Island, Northwest Territories, Geol. Surv. Canada Curr. Res. 1989-D, 125-133, 1989.

Emmerton, C. A., St. Louis, V. L., Humphreys, E. R., Gamon, J. A., Barker, J. D. and Pastorello, G. Z.: Net ecosystem exchange of CO_2 with rapidly changing high Arctic landscapes. Glob Chang. Biol. Accepted Author Manuscript. doi:10.1111/gcb.13064, 2015.

Environment Canada, Canadian Climate Normals 1981-2010 Station Data, Environment Canada, available at: http://www.climate.weather.gc.ca (last access: 15 April 2015), 2015.

Fox, A. M., Huntley, B., Lloyd, C. R., Williams, M. and Baxter, R.: Net ecosystem exchange over heterogeneous Arctic tundra: Scaling between chamber and eddy covariance measurements, Global Biogeochem. Cy., 22, GB2027, doi:10.1029/2007GB003027, 2008.

Griffis, T. J. and Rouse, W. R.: Modelling the interannual variability of net ecosystem CO2 exchange at a subarctic sedge fen, Glob. Chang. Biol., 7(5), 511–530, 2001.

Groendahl, L., Friborg, T. and Soegaard, H.: Temperature and snow-melt controls on interannual variability in carbon exchange in the high Arctic, Theor. Appl. Climatol., 88, 111–125, doi:10.1007/s00704-005-0228-y, 2007.

Grosse, G., Harden, J., Turetsky, M., McGuire, A. D., Camill, P., Tarnocai, C., Frolking, S., Schuur, E. A. G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K., French, N., Waldrop, M., Bourgeau-Chavez, L., and Striegl, R.G.: Vulnerability of high-

latitude soil organic carbon in North America to disturbance, J. Geophys. Res., 116, G00K06, 2011.

Hicks Pries, C. E., Schuur, E. A. G. and Crummer, K. G.: Holocene Carbon Stocks and Carbon Accumulation Rates Altered in Soils Undergoing Permafrost Thaw, Ecosystems, 15(1), 162–173, doi:10.1007/s10021-011-9500-4, 2011.

Hicks Pries, C. E., Schuur, E. a G. and Crummer, K. G.: Thawing permafrost increases old soil and autotrophic respiration in tundra: partitioning ecosystem respiration using δ(13) C and Δ(14) C., Glob. Chang. Biol., 19(2), 649–61, doi:10.1111/gcb.12058, 2013.

Hollinger, D. Y. and Richardson, A. D.: Uncertainty in eddy covariance measurements and its application to physiological models., Tree Physiol., 25, 873–885, doi:10.1093/treephys/25.7.873, 2005.

Hugelius, G., Tarnocai, C., Broll, G., Canadell, J. G., Kuhry, P. and Swanson, D. K.: The northern circumpolar soil carbon database: Spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions, Earth Syst. Sci. Data, 5, 3–13, doi:10.5194/essd-5-3-2013, 2013.

Humphreys, E. and Lafleur, P.: Does earlier snowmelt lead to greater CO_2 sequestration in two low Arctic tundra ecosystems?, Geophys. Res. Lett., 38, L09703, doi:10.1029/2011GL047339, 2011.

Jassal, R., Black, A., Novak, M., Morgenstern, K., Nesic, Z. and Gaumont-Guay, D.: Relationship between soil CO_2 concentrations and forest-floor CO_2 effluxes, Agric. For. Meteorol., 130, 176–192, doi:10.1016/j.agrformet.2005.03.005, 2005.

Jassal, R. S., Black, T. A., Nesic, Z., & Gaumont-Guay, D.: Using automated non-steady-state chamber systems for making continuous long-term measurements of soil CO_2 efflux in forest ecosystems. Agric. For. Meteorol., 161, 57-65, doi:10.1016/j.agrformet.2012.03.009, 2012.

Johansson, T., Malmer, N., Crill, P. M., Friborg, T., Åkerman, J. H., Mastepanov, M. and Christensen, T. R.: Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing, Glob. Chang. Biol., 12, 2352–2369, doi:10.1111/j.1365-2486.2006.01267.x, 2006.

Kokelj, S. and Lewkowicz, A.: Long-term influence of active-layer detachment sliding on permafrost slope hydrology, Hot Weather Creek, Ellesmere Island, Canada, … Int. Conf. Permafrost, …, (55), 583–589, 1998.

Kokelj, S. and Lewkowicz, A.: Salinization of permafrost terrain due to natural geomorphic disturbance, Fosheim Peninsula, Ellesmere Island, Arctic, 52(4), 372 – 385, 1999.

Kormann, R. and Meixner, F. X.: An analytical footprint model for non-neutral stratification, Boundary-Layer Meteorol., 99, 207–224, doi:10.1023/A:1018991015119, 2001.

Kwon, H.-J., Oechel, W. C., Zulueta, R. C. and Hastings, S. J.: Effects of climate variability on carbon sequestration among adjacent wet sedge tundra and moist tussock tundra ecosystems, J. Geophys. Res.- Biogeosciences, 111, G03014, doi: 10.1029/2005JG000036, 2006.

Lafleur, P., Humphreys, E., St Louis, V., Myklebust, M., Papakyriakou, T., Poissant, L., Barker, J., Pilote, M. and Swystun, K.: Variation in peak growing season net ecosystem production across the Canadian Arctic, Enviro Sci Tech, 46, 7971–7977, 2012.

Lamoureux, S. and Lafrenière, M.: Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada, Arctic, Antarct. Alp. Res., 41(1), 59–68, doi:10.1657/1523-0430-41.1.59, 2009.

Lantuit, H. and Pollard, W. H.: Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada, Geomorphology, 95(1), 84–102, 2008.

Lantz, T. C. and S. V. Kokelj, S.V.: Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada, Geophys. Res. Lett., 35, L06502, doi:10.1029/2007GL032433, 2008.

Lantz, T.C., Kokelj, S. V., Gergel, S.E. and G.H.R. Henry: Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps, Glob. Chang. Biol., 15(7), 1664–1675, doi:10.1111/j.1365-2486.2009.01917.x, 2009.

Lee, H., Schuur, E. A. G., Inglett, K. S., Lavoie, M. and Chanton, J. P.: The rate of permafrost carbon release under aerobic and anaerobic conditions and its potential effects on climate, Glob. Chang. Biol., 18, 515–527, doi:10.1111/j.1365-2486.2011.02519.x, 2012.

Lewkowicz, A. and Harris, C.: Morphology and geotechnique of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada, Geomorphology, 69(1-4), 275–297, doi:10.1002/ppp.522, 2005.

Lewkowicz, A. G.: Morphology, frequency and magnitude of active-layer detachment slides, Fosheim Peninsula, Ellesmere Island, N.W.T., Nordicana, 54, 111–118, 1990.

Lewkowicz, A. G. and Harris, C.: Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada, Permafr. Periglac. Process., 16(1), 115–130, 2005.

Lovett, G.M., Cole, J.J., Pace, M.L.: Is net ecosystem production equal to ecosystem carbon accumulation? Ecosystems, 9, 152–155, 2006.

Lund, M., Falk, J. M., Friborg, T., Mbufong, H. N., Sigsgaard, C., Soegaard, H. and Tamstorf, M. P.: Trends in CO2 exchange in a high Arctic tundra heath, 2000-2010, J. Geophys. Res. Biogeosciences, 117, G02001, doi:10.1029/2011JG001901, 2012.

Mackay, J.: Disturbances to the tundra and forest tundra environment of the western Arctic, Can. Geotech. J.,7, 420-432, 1970.

Mauder, M. and Foken, T.: Documentation and Instruction Manual of the Eddy Covariance Software Package TK2, Arbeitsergebn., Univ. Bayreuth, Abt. Mikrometeorol, Bayreuth, Germany, 2004.

Mbufong, H. N., M. Lund, M. Aurela, T. R. Christensen, W. Eugster, T. Friborg, B. U. Hansen, E. R. Humphreys, M. Jackowicz-Korczynski, L. Kutzbach, P. M. Lafleur, W. C. Oechel, F. J. W. Parmentier, D. P. Rasse, A. V. Rocha, T. Sachs, M. M. van der Molen, and M. P. Tamstorf (2014) Assessing the spatial variability in peak season CO2 exchange characteristics across the Arctic tundra using a light response curve parameterization. Biogeosciences 11, 4897–4912.

McGuire, A. D., Chapin, F. S., Walsh, J. E. and Wirth, C.: Integrated Regional Changes in Arctic Climate Feedbacks: Implications for the Global Climate System *, Annu. Rev. Environ. Resour., 31(1), 61–91, doi:10.1146/annurev.energy.31.020105.100253, 2006.

Merbold, L., Kutsch, W. L., Corradi, C., Kolle, O., Rebmann, C., Stoy, P. C., Zimov, S. A. and Schulze, E. D.: Artificial drainage and associated carbon fluxes (CO2/CH4) in a tundra ecosystem, Glob. Chang. Biol., 15(11), 2599–2614, 2009.

Nordstroem, C., Soegaard, H., Christensen, T. R., Friborg, T. and Hansen, B. U.: Seasonal carbon dioxide balance and respiration of a high-arctic fen ecosystem in NE-Greenland, Theor. Appl. Climatol., 70, 149–166, doi:10.1007/s007040170012, 2001.

Oberbauer, S. F., Tweedie, C. E., Welker, J. M., Fahnestock, J. T., Henry, G. H. R., Webber, P. J., Hollister, R. D., Walker, M. D., Kuchy, A., Elmore, E. and Starr, G.: Tundra CO2 fluxes in response to experimental warming across latitudinal and moisture gradients, Ecol. Monogr., 77(2), 221–238, 2007.

Paul-Limoges, E., Christen, A., Coops, N. C., Black, T. A. and Trofymow, J. A.: Estimation of aerodynamic roughness of a harvested Douglas-fir forest using airborne LiDAR, Remote Sens. Environ., 136, 225–233, doi:10.1016/j.rse.2013.05.007, 2013.

Pérez-Priego O, Serrano-Ortiz P, Sánchez-Cañete EP, Domingo F, Kowalski AS (2013) Isolating the effect of subterranean ventilation on CO_2 emissions from drylands to the atmosphere. Agric. For. Meteorol., 180, 194–202, 2013.

795   Rennermalm, A. K., Soegaard, H. and Nordstroem, C.: Interannual Variability in Carbon
796   Dioxide Exchange from a High Arctic Fen Estimated by Measurements and Modeling,
797   Arctic, Antarct. Alp. Res., 37, 545–556, doi:10.1657/1523-
798   0430(2005)037[0545:IVICDE]2.0.CO;2, 2005.
799
800   Robinson, S.: Thaw-slump-derived thermokarst near Hot Weather Creek, Ellesmere
801   Island, Nunavut, Geol. Surv. Canada Bull., 529, 335–345, 2000.
802
803   Robinson, S. D. and Pollard, W. H.: Massive ground ice within Eureka Sound bedrock, in
804   Permafrost, Proc. 7th International Conf. on Permafrost, Yellowknife, Canada, Collection
805   Nordicana, 23-27 June, 1998, 949–954, 1998.
806
807   Schuur, E. A. G., McGuire, A. D., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G.,
808   Koven, C. D. and Kuhry, P.: Climate change and the permafrost carbon feedback, Nature,
809   520, 171–179, doi:10.1038/nature14338, 2015.
810
811   Schuur, E. A. G., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin,
812   S. V, Hagemann, S., Kuhry, P., Lafleur, P. M., Lee, H., Mazhitova, G., Nelson, F.E.,
813   Rinke, A., Romanovsky, V.E., Shiklomanov, N., Tarnocai, C., Venetsky, S., Vogel, J.G.,
814   and Zimov, S.A.: Vulnerability of permafrost carbon to climate change: Implications for
815   the global carbon cycle, Bioscience, 58(8), 701–714, 2008.
816
817   Starr, G. and Oberbauer, S. F.: Photosynthesis of arctic evergreens under snow:
818   Implications for tundra ecosystem carbon balance, Ecology, 84, 1415–1420,
819   doi:10.1890/02-3154, 2003.
820
821   Stoy, P., Williams, M., Evans, J., Prieto-Blanco, A., Disney, M., Hill, T., Ward, H.,
822   Wade, T. and Street, L.: Upscaling tundra CO_2 exchange from chamber to eddy
823   covariance tower, Arctic, Antarct. Alp. Res., 45, 275–284, doi:10.1657/1938-4246-
824   45.2.275, 2013.
825
826   Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G. and Zimov, S.:
827   Soil organic carbon pools in the northern circumpolar permafrost region, Global
828   Biogeochem. Cycles, 23, GB2023, doi:10.1029/2008GB003327, 2009.
829
830   Ukraintseva, N.: Vegetation response to landslide spreading and climate change in the
831   west Siberian tundra, in Proc. 9th International Conf. on Permafrost, Fairbanks, Alaska,
832   28 June – 3 July 2008, 2, 1793–1798., 2008.
833
834   Vincent, W., Callaghan, T., Dahl-Jensen, D., Johansson, M., Kovacs, K., Michel, C.,
835   Prowse, T., Reist, J. and Sharp, M.: Ecological implications of changes in the Arctic
836   cryosphere, Ambio, 40, 87-99, doi:10.1007/s13280-011-0218-5, 2011.
837
838   Vogel, J., Schuur, E. A. G., Trucco, C. and Lee, H.: Response of CO_2 exchange in a
839   tussock tundra ecosystem to permafrost thaw and thermokarst development, J. Geophys.
840   Res. Biogeosciences, 114, G04018, doi:10.1029/2008JG000901, 2009.

Walter Anthony, K. M., Anthony, P., Grosse, G. and Chanton, J.: Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers, Nat. Geosci., 5, 419–426, doi:10.1038/ngeo1480, 2012.

Wang, T., Ciais, P., Piao, S. L., Ottlé, C., Brender, P., Maignan, F., Arain, A., Cescatti, A., Gianelle, D., Gough, C., Gu, L., Lafleur, P., Laurila, T., Marcolla, B., Margolis, H., Montagnani, L., Moors, E., Saigusa, N., Vesala, T., Wohlfahrt, G., Koven, C., Black, A., Dellwik, E., Don, A., Hollinger, D., Knohl, A., Monson, R., Munger, J., Suyker, A., Varlagin, A. and Verma, S.: Controls on winter ecosystem respiration in temperate and boreal ecosystems, Biogeosciences, 8, 2009–2025, doi:10.5194/bg-8-2009-2011, 2011.

Welker, J. M., Fahnestock, J. T. and Jones, M. H.: Annual CO2 flux in dry and moist arctic tundra: Field responses to increases in summer temperatures and winter snow depth, Clim. Change, 44, 139–150, doi:10.1023/a:1005555012742, 2000.

Welker, J. M., Fahnestock, J. T., Henry, G. H. R., O'Dea, K. W. and Chimner, R. A.: CO2 exchange in three Canadian High Arctic ecosystems: Response to long-term experimental warming, Glob. Chang. Biol., 10(12), 1981–1995, 2004.

Tables

Table 1: Summary of net ecosystem exchange (*NEE*), soil temperatures (Soil T) and soil moisture (Soil M) from disturbed (d) and undisturbed (c) tundra, and air temperature (measured at T2) throughout the growing season.

Variable	Early Season	Peak Season	End Season
DOY	175-185	186-202	203-210
Date	24 June – 4 July	5 – 21 July	22 – 29 July
NEE_c (µmol m^{-2} s^{-1})[*]	0.080 ± 0.03	-0.28 ± 0.03	-0.015 ± 0.05
NEE_d (µmol m^{-2} s^{-1})[*]	0.55 ± 0.03	0.25 ± 0.03	0.58 ± 0.13
Air Temperature (°C)			
mean (±SE)	10.5 ± 0.17	12.2 ± 0.10	7.2 ± 0.22
min/max	5.3 / 15.0	6.9 /16.1	2.0 / 12.0
Soil T$_c$ (°C)[*] at 5 cm			
mean (±SE)	11.6 ± 0.05	11.9 ± 0.29	8.1 ± 0.05
min/max	5.4/ 19.8	6.9/19.8	2.6 / 16.2
Soil T$_d$ (°C)[*] at 5 cm			
mean (±SE)	12.6 ± 0.07	11.9 ± 0.04	7.8 ± 0.07
min/max	6.6 / 19.1	6.8 / 19.5	2.1/ 15.2
Soil M$_c$ (%)[*]			
mean (±SE)	14.4 ± 0.5	12.9 ± 0.4	16.9 ± 1.0
min/max	3.4 / 28.4	1.1 / 31.6	0.6 / 34.2
Soil M$_d$ (%)[*]			
mean (±SE)	20.5 ± 0.8	24.8 ± 1.0	30.5 ± 1.6
min/max	9.7 / 41.2	4.1 / 45.4	6.9 / 44.8

[*] NEE_c = average net CO_2 flux from undisturbed (control) tundra.
[*] NEE_d = average net CO_2 flux from disturbed tundra.
[*] Soil T$_c$ = average soil temperature from undisturbed tundra
[*] Soil T$_d$ = average soil temperature from disturbed tundra
[*] Soil M$_c$ = average soil temperature from undisturbed tundra
[*] Soil M$_d$ = average soil temperature from disturbed tundra

Table 2: Summary of measurements (mean ± SE) from the portable chamber system (in

μmol m^{-2} s^{-1})

Variable	Location	Early	Peak	End	Total
DOY		175-185	186-202	203-210	
NEE	undisturbed	0.25 ± 0.10	-0.33 ± 0.15	-0.37 ± 0.15	-0.14 ± 0.13
	disturbed	0.31 ± 0.12	0.07 ± 0.13	0.11 ± 0.07	0.15 ± 0.06
GPP	undisturbed	0.85 ± 0.16	1.47 ± 0.26	1.00 ± 0.19	1.19 ± 0.19
	disturbed	0.39 ± 0.14	0.45 ± 0.16	0.24 ± 0.08	0.40 ± 0.03
R_e	undisturbed	1.10 ± 0.13	1.14 ± 0.15	0.62 ± 0.06	1.04 ± 0.12
	disturbed	0.70 ± 0.08	0.53 ± 0.10	0.35 ± 0.05	0.55 ± 0.06

Figures

Figure 1. Aerial image of the dual eddy covariance system setup with the location of both flux towers indicated. The valley trends NNE-SSW. View is to the south.

Figure 2. Turbulent source areas for two time-steps on DOY 186: a) 09:00 and b) 18:00, with ellipses displaying areas contributing to the given percentage of the signal from each instrument tower (T1 and T2). Three ellipses from each tower represent the 50%, 80%, and 90% cumulative source area. The shaded area represents a signal from the disturbed part of the surface. The white polygon represents the furthest extent of headwall retreat, as the initial image was taken in July 2013 (Worldview-2) and significant retreat occurred between image acquisition and the summer 2014 sampling period.

Figure 3. Meteorological conditions during the 2014 growing season at T2. Height of all instrumentation on the tower was 1 m above the canopy. Soil temperatures were measured at a depth of -5 cm, and mean temperature is shown for the disturbance (dashed line; n=7) and undisturbed tundra (solid line; n=14). DOY = day of the year.

Figure 4. Ensemble average diurnal course of soil temperatures in the disturbed and undisturbed sites throughout the season: Early season = 24 June – 4 July; Peak season = 5 July – 21 July; End of season = 22 July – 29 July. Boxes show the 25th and 75th percentiles, dots are the outliers, horizontal lines are medians.

Figure 5. Ensemble diurnal course of CO_2 fluxes from the retrogressive thaw slump (disturbed) and undisturbed tundra separated into the three sampling periods: top (early season), middle (peak season) and bottom (end season). Boxes show the 25th and 75th percentiles, black circles are outliers, horizontal lines are medians.

Figure 6. Average daily net CO_2 flux for the three sampling periods as measured by the two EC systems and the net effect for the entire season.

Figure 7. Comparison of NEE measurements from static chamber (square) and calculated from the two EC systems (circle). Open symbols represent measurements from undisturbed tundra while closed symbols are measurements in the disturbed areas. Measurements were made in 21 collars in each of the disturbed and both undisturbed footprint areas of the EC towers.

Figure 8. Partitioning of NEE data from static chamber measurements into component fluxes, GPP and R_e for the undisturbed and disturbed sites. Measurements were made in 21 collars during daytime hours in each of the disturbed and both undisturbed footprint areas of the EC towers.