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Warmer spring conditions increase annual methane emissions from a boreal peat landscape with sporadic permafrost

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Abstract

About a fifth of the global wetland methane emissions originate from boreal peatlands, which represent an important land cover type in boreal landscapes in the sporadic permafrost zone. There, rising air temperatures could lead to warmer spring and longer growing seasons, changing landscape methane emissions. To quantify the effect of warmer spring conditions on methane emissions of a boreal peat landscape in the sporadic permafrost zone of northwestern Canada, we analyzed four years (2013 – 2016) of methane fluxes measured with the eddy covariance technique and long-term (1951-2016) meteorological observations from a nearby climate station. In May, after snowmelt was complete, mean air temperatures were more than 2 °C warmer in 2013, 2015, and 2016 than in 2014. Mean growing season (May-August) air temperatures, in contrast, differed by less than 1 °C over the four years. Warmer May air temperatures caused earlier wetland soil warming, with temperatures rising from ~0 °C to >12 °C 25 to 40 days earlier and leading to ~6 °C warmer mean soil temperatures between May and June. However, from July to August, soil temperatures were similar among years. Mean May to August and annual methane emissions (6.4 g CH_4 m^{-2} and 9.4 g CH_4 m^{-2}, respectively) of years with warmer spring (i.e., May) temperatures exceeded emissions during the cooler year by 20-30 % (4.5 g CH_4 m^{-2} and 7.2 g CH_4 m^{-2}, respectively). Among years with warmer springs, growing season methane emissions varied little (±0.5 g CH_4 m^{-2}). The observed interannual differences are most likely caused by a strong soil temperature control on methane fluxes and large soil temperature differences during the spring. Thus, in a warming climate, methane emissions from waterlogged boreal peat landscapes at the southern limit of permafrost are likely to increase in response to more frequent occurrences of warm springs.

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1. Introduction

Boreal peatlands contribute about 20 % of the global wetland methane emissions (Bridgham *et al* 2013; Saunois *et al* 2016), which mainly control interannual variability in global atmospheric methane concentrations (Bousquet *et al* 2006). At the same time, methane emissions from wetlands are the largest source of uncertainty in the global methane budget (Saunois *et al* 2016). In a warming climate, boreal landscape methane emissions are expected to increase with wetland extent (e.g., Helbig *et al* 2017a) and warming soil temperatures (e.g., Olefeldt *et al* 2013, Turetsky *et al* 2014), while varying in their response to changing hydrological conditions (e.g., Moore *et al* 2011). Peatlands in the sporadic permafrost zone of northwestern Canada store large amounts of organic carbon (C) (Tarnocai *et al* 2009), which could be partly released to the atmosphere as methane in a warming climate (e.g., Moore *et al* 1998). For example, thaw-induced wetland expansion in the sporadic permafrost zone has been shown to increase landscape methane emissions exerting a warming effect on climate (Helbig *et al* 2017a).

In boreal peat landscapes at the southern limit of permafrost, spatial variability in growing season methane emissions is strongly controlled by the heterogeneity in water table position across the landscape (Bubier *et al* 1995; Sabrekov *et al* 2014; Olefeldt *et al* 2017). In contrast, temporal variability in methane emissions is strongly controlled by wetland soil temperature seasonality, when the water table is close to the peat surface. With a shallow methane oxidation zone between water table and peat surface, methane emissions to the atmosphere are primarily driven by temperature-controlled methane production in the anaerobic zone (Shannon and White 1994; Waddington *et al* 1996; Christensen *et al* 2003; Treat *et al* 2007; Malhotra and Roulet 2015; Helbig *et al* 2017a). In a changing climate, wetland soil temperature regimes will likely be modified by warming air temperatures and altered snowpack dynamics (Maurer and Bowling 2014; Zhao *et al* 2016). Warmer wetland soils may also promote vascular plant productivity and consequently lead to higher root exudation and labile organic C supply for methanogens (Bergman *et al* 2000; Rustad *et al* 2001; Aerts *et al* 2006; Chanton *et al* 2008; Dorodnikov *et al* 2011). For example, Prater *et al* (2007) have shown that large methane emissions in recently thawed wetlands are partly driven by the high productivity of the colonizing herbaceous vascular plants. These herbaceous plants with aerenchymous tissue additionally facilitate gas exchange between roots, shoots, and leaves, and act as conduits between the rhizosphere and the atmosphere. And as methane is efficiently transported through air-filled aerenchyma, it can bypass oxidizing soil layers (Shannon *et al* 1996).

The first few weeks after the completion of snowmelt may be a particularly important period for soil temperature dynamics and thus for methane emissions: After the removal of the insulating snow layer (e.g., Zhang 2005), wetland soils often remain close to 0°C despite positive air temperatures as ground ice in the top soil layers delays soil warming by consuming melt energy (e.g., Hayashi *et al* 2007). Once ground ice melted in spring, high thermal heat conductivity of saturated peat soils allows rapid soil warming (O'Donnell *et al* 2009). Warmer spring air temperatures in North America (e.g., Wang *et al* 2011) may therefore lead to warmer soil temperatures and increased spring methane emissions, but their magnitude and the effect on growing season and annual methane emissions remains unknown. Supported by long-term meteorological observations, we analyzed four years of methane emissions from a boreal peat landscape in the sporadic permafrost zone of northwestern Canada to examine the effect of interannual variations in air and soil temperature seasonality on methane emissions.

2. Materials and methods

2.1. Study site

We examined methane fluxes from a boreal peat landscape located in the southern portion of the Scotty Creek watershed (61° 18' 29" N; 121° 17' 57" W) in the sporadic permafrost zone of the Canadian Taiga Plains (figure 1). The continental subarctic climate is characterized by a mean annual air temperature of -2.8 °C and an annual total precipitation of 388 mm [1981-2010] at Fort Simpson Airport, which is located ca. 60 km north of Scotty Creek (WMO ID: 71946; Environment Canada, 2016). The Scotty Creek landscape comprises approximately equal proportions of coniferous forest, which are found on forested permafrost peat plateaus with oxic soil conditions, and mostly saturated permafrost-free wetlands, mainly collapse-scar bogs (figure 1). The deep peat soils (>3 m) have mean organic C stocks of

167±11 kg C m^{-2} (n = 3; Pelletier *et al* 2017). Thawing permafrost at Scotty Creek is replacing forested permafrost peat plateaus with collapse-scar bogs and channel fens (e.g., Quinton *et al* 2011; Baltzer *et al* 2014; Helbig *et al* 2016a). Landscape methane emissions at Scotty Creek originate almost exclusively from permafrost-free wetlands, while the black spruce (*Picea mariana*)-dominated permafrost peat plateaus appear to be negligible sources or sinks of methane (Helbig *et al* 2017a). Collapse-scar bogs are characterized by a shallow water table that drops from the moss surface shortly after snowmelt to about 10 cm to 30 cm below the moss surface at the end of the growing season (Helbig *et al* 2017a). Collapse-scar bog vegetation mainly consists of *Sphagnum balticum* and *magellanicum* and ericaceous shrubs (*Chamaedaphne calyculata*, *Andromeda polifolia*, and *Vaccinium oxycoccos*). In the wettest bog sections, *Scheuchzeria palustris* is abundant and its well-developed aerenchyma and allocation of recent photosynthates to roots enhances methane emissions (Shannon *et al* 1996; Dorodnikov *et al* 2011).

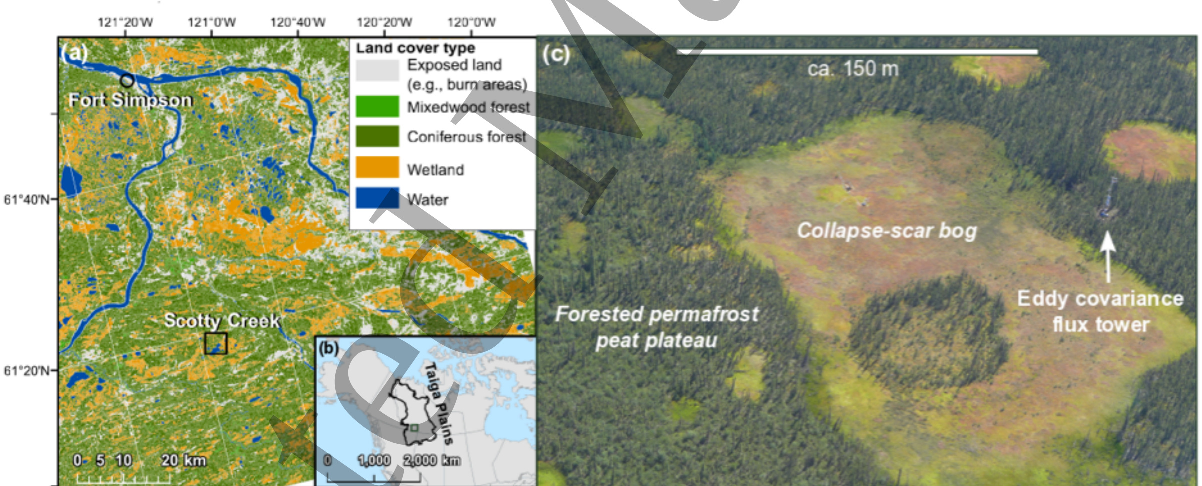

Figure 1. (a) Land cover types in the southern Taiga Plains (data from Land Cover, *ca*. 2000-Vector; Olthof *et al* 2009) and **(b)** location of the Scotty Creek watershed (black rectangle) in the Taiga Plains ecozone. **(c)** Aerial photograph of the boreal peat landscape surrounding the flux tower (taken on 20 July 2014).

2.2. Long-term meteorological observations

Long-term monthly air temperature and precipitation data was obtained from the nearest climate station at Fort Simpson Airport in order to compare 2013-2016 site measurements to long-term climate normals. From year 1951 through 2016, we derived growing season (average of monthly May to August air temperatures) and May air temperatures and total annual (October to September) and growing season precipitation. In the southern Taiga Plains, May is usually the month of snowmelt completion and the first month with positive monthly mean air temperatures (figure S1). For the Scotty Creek watershed, the month of May is thus defined as spring in this study.

2.3. Eddy covariance and supporting measurements

Half-hourly methane fluxes from the boreal peat landscape were measured using the eddy covariance technique. Between 15 May 2013 and 16 December 2016, an eddy covariance system was deployed on the top of a triangular 15-m tower structure. The system consisted of an open-path LI-7700 CH_4 analyzer (LI-COR Biosciences, Lincoln, NE, USA), a CSAT3A sonic anemometer (Campbell Scientific Inc., Logan, UT, USA), and an open-path EC150 CO_2/H_2O gas analyzer (Campbell Scientific Inc.). Between 2013 and 2015, the LI-7700 was removed from the flux tower due to electrical power limitations between September and October (at the end of each measurement period) and reinstalled before the beginning of snowmelt (between March and April). We checked the performance of the LI-7700 CH_4 analyzer using a zero- and a span-gas (Ultra Zero Ambient Air & 2.02±0.1 ppm; Praxair Canada Inc, Mississauga, ON, Canada) at the beginning and end of each measurement period, and once or twice during growing season. Methane fluxes were calculated using the EddyPro software (version 6.1.0, LI-COR Biosciences). A more detailed description of instrumental setup, post-processing, and quality control is given by Helbig *et al* (2017a). Overall, 42 % of half-hourly methane fluxes passed quality control (2013: 31 %; 2014: 46 %; 2015: 42 %; 2016: 44 %). Gaps in methane fluxes were filled using a marginal distribution sampling algorithm (Reichstein *et al* 2005). To estimate annual emissions, we assumed a constant daily winter methane flux between November and April. We derived the winter flux estimate (0.006±0.006 g CH_4 m^{-2} day^{-1} [±1 standard deviation]) as the average of non-gapfilled wintertime methane fluxes between 2013 and 2016 (i.e., soil temperature at 32-cm depth below the moss surface < 0.2 °C). We also assessed if flux footprint contributions from forested permafrost peat plateaus and collapse-scar bogs differed among study years using a 2-D footprint modelling approach (Kljun *et al* 2004; Kljun *et al* 2015). The mean collapse-scar bog contribution to flux footprints was 53 % with individual years ranging from 52 % to 54 %. Forested permafrost peat plateaus contributed on average 47 % with individual years ranging from 45 % to 48 %. Interannual variability in methane emission was therefore not affected by flux footprint composition. More details on the flux footprint modelling approach can be found in Helbig *et al* (2016b).

Wetland soil temperature and water table position ca. 100 m north of the flux tower in a collapse-scar bog within the eddy covariance flux footprint were examined as environmental controls on methane emissions. Air temperature (at 2 m; HC2-S3, Rotronic AG, Bassersdorf, Switzerland), rainfall (TE25WS, Texas Instruments, Dallas, TX, USA), and snow depth (using a sonic ranger; SR50A, Campbell Scientific, Logan, UT, USA) were analyzed to characterize the coupling between soil thermal and moisture dynamics and meteorological conditions. Between 2014 and 2016, soil temperature at 32 cm below the moss surface (just beneath the water table) was measured with a type T thermocouple (Omega Engineering, Stamford, CT, USA). Water table position in the centre of the bog was recorded with a vented pressure transducer (OTT PLS, Mellingen, Switzerland). In 2013, water table position relative to the moss surface was measured in the same collapse-scar bog using a HOBO U20 Water Level Logger (Onset Computer Corporation, Bourne, MA, USA). To approximate soil temperatures in 2013 for our analysis, we used soil temperatures measured at 30 cm depth (109 Temperature Probe, Campbell Scientific Inc.) from a collapse-scar bog located ~700 m from the flux tower. A linear regression between soil temperatures in both bogs in 2014 (r^2 = 0.98; RMSE = 0.9 °C; n = 7838) was used to create the soil temperature time series for 2013. We estimated the relative importance of monthly soil temperature and water table position in a linear model of monthly methane emissions using the *relaimpo* package

(Grömping 2015) in the R statistical computing environment (R Foundation for Statistical Computing, version 3.3.2, Vienna, Austria). All statistical tests used a significance level of 5 % ($\alpha = 0.05$).

2.4. Vegetation productivity and greenness index

To relate vegetation productivity to methane emissions, we derived daily gross primary productivity (g C m^{-2} day^{-1}) of the collapse-scar bog (wetland; 2014-2016) from net ecosystem CO_2 exchange measurements at a nearby (ca. 100 m) 2 m eddy covariance flux tower (see Helbig *et al* 2017b). Detailed information on net ecosystem CO_2 exchange measurements and instrumental setup can be found in Helbig *et al* (2016c). Between 2013 and 2015, daily vegetation greenness of the wetland was tracked with a greenness index (green chromatic coordinate; Sonnentag *et al* 2012). We obtained the greenness index from hourly photographs taken during day-time hours from the 15-m flux tower with a digital camera (PlantCam WSCA04, Wingscapes, Calera, AL, USA). The green chromatic coordinate was calculated from the red-green-blue color channel information from the digital photographs and processed (e.g., outlier filtering) using methods implemented in the *phenopix* R package (Filippa *et al* 2016).

3. Results

3.1. Climate and meteorological conditions

In the southern Taiga Plains, the median of May-August (i.e., growing season) air temperatures between the periods 1951-1981 and 1981-2010 significantly increased by 0.4°C (Wilcoxon rank sum test, $p = 0.01$, $n = 30$; table 1 & figure S2). The growing seasons during 2013-2016 were 1-2 °C warmer than mean growing season air temperature during the period 1981 to 2010.

During 2013 - 2016, snow disappeared from the ground each year in early May and the timing of snowmelt completion varied only by six days (figure 2). At the end of the growing season, the onset of a continuous snow-cover ranged from 9 October (2015) to 4 December (2016). In 2014, average May air temperature equalled the long-term (1951-2010) average May temperature. However, 2013, 2015, and 2016 were 2.4 °C to 4.1 °C warmer than the long-term average (table 1). Between 2011 and 2016, mean May air temperature was warmer than 10 °C in 83% of years, while it was warmer than 10 °C in 23% of years between 1981 and 2010 and only in 13% of years between 1951 and 1980. Accumulated air temperature from May through mid-August was lower in 2014 than in any of the other years of 2013-2016 driven by cooler air temperatures in May (figure 2).

Annual precipitation (October – September) increased significantly by 53 mm from 1951 – 1980 to 1981 – 2010 (Wilcoxon rank sum test, $p = 0.02$, $n = 30$) owing to an increase in May to August rainfall (table 1). Between 2013 and 2016, 2014 was the driest year and 2015 was the wettest year. May to June rainfall ranged from 24 mm (2015) to 100 mm (2016), whereas July to August rainfall ranged from 68 mm (2014 & 2016) to 179 mm (2015, figure 2). Mean March snow depth at Scotty Creek ranged from 47 cm to 67 cm (2013-2016).

Table 1. Growing season (May to August), May air temperatures (T_a), total annual (October to September) and growing season precipitation (P, May to August) at Fort Simpson Airport for the years 2013 to 2016 and for the climate normal periods 1951-1981 and 1981-2010. Medians of growing season and May T_a and of total annual and growing season P and their respective standard deviations are shown for the climate normal periods (data from Environment Canada, 2016).

	2013	*2014*	*2015*	*2016*	*1951-1981*	*1981-2010*
T_a *(May – Aug)*	15.7 °C	15.2 °C	15.1 °C	15.9 °C	13.5±0.8 °C	13.9±1.0 °C
T_a *(May)*	10.8 °C	8.4 °C	12.5 °C	10.8 °C	8.0±1.6 °C	8.8±2.2 °C
P (Oct – Sep)	327 mm	246 mm	432 mm	351 mm	350±58 mm	403±82 mm
P (May – Aug)	143 mm	121 mm	202 mm	169 mm	160±43 mm	218±65 mm

3.2. Water table dynamics

Interannual variability in water table position between May and June was small with mean positions ranging from -10 cm (2013) to -6 cm (2016), with -8 cm in 2014. Mean May to August deviations from the four-year average water table position ranged from -0.6 cm (2013) to +1.4 cm (2016). In July to August, mean water table deviations were slightly more pronounced ranging from -4.5 cm (2016) to +4.7 cm (2015). Despite considerable interannual variability in precipitation (see above), maximum interannual differences in water table position never exceeded 20 cm at any time of the year.

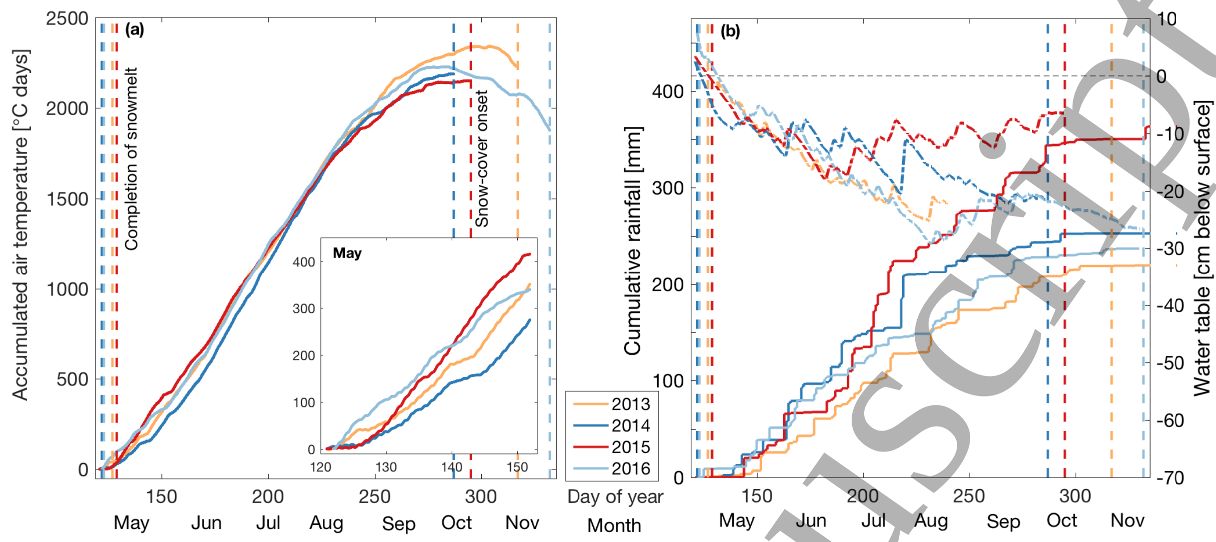

Figure 2. (a) Accumulated air temperature between May 1st and the onset of a continuous snow-cover for the years 2013 to 2016. The inset figure shows accumulated air temperature for May. **(b)** Cumulative rainfall at Scotty Creek (May – December, solid lines) and water table position in the interior of the wetland (dotted lines). Timing of snowmelt completion and snow-cover onset is indicated by vertical dashed lines.

3.3. Soil temperature dynamics

During the snow-cover period from December to April, wetland soil temperatures at 32 cm depth remained close to 0 °C despite large variations in air temperature from -40 °C to +10 °C (figure S3). In the three warmer years (i.e., 2013, 2015, and 2016), rapid soil warming from 0 °C to >12 °C occurred earlier than in 2014. Consequently, mean soil temperatures between May 15 and June 30 were about 6 °C warmer in 2013, 2015, 2016 (9.8±0.5 °C [±1 standard deviation]) than in 2014 (3.8 °C). The earliest soil warming occurred in 2016, but was followed by up to 2.5 °C cooler soil temperatures later in May compared to 2013 and 2015 (figure 3). The interannual soil temperature differences were less pronounced during the four study years in July (13.2 °C – 14.5 °C) and August (13.5 °C – 14.0 °C) and therefore May and June appear to have the largest interannual soil temperature variability.

3.4. Methane emissions from the boreal peat landscape

Summertime methane emissions characteristic for Scotty Creek (> 0.05 g CH_4 m^{-2} day^{-1}) were reached several weeks earlier (by the end of June) in years with warmer May air and soil temperatures than in 2014 (figure 3a). During the growing season, daily methane fluxes continued to increase before peaking in July and August at about 0.08 g CH_4 m^{-2} day^{-1} in the warmer years and at only 0.06 g CH_4 m^{-2} day^{-1} in 2014. At the start of the snow-cover period, methane fluxes dropped again close to pre-snowmelt methane emissions in each year. Total methane emissions between May 15 and August 31 were not significantly different among years with warm May temperatures (2013: 6.2 [6.0 – 6.6] g CH_4 m^{-2} with 95% confidence interval [CI]; 2015: 6.5 [6.4 – 6.9] g CH_4 m^{-2}; and 2016: 6.4 [6.3 – 6.8] g CH_4 m^{-2}). However, for the same period in 2014, total methane emissions were significantly smaller with 4.5 [4.3 – 4.7] g CH_4 m^{-2} (i.e., about 25 % smaller). The same pattern continued through to October 31, with total May to October methane emissions in the warm years exceeding the 2014 emissions by about 30 %. About half of the observed interannual differences in May to October methane emissions accumulated between May and June, while the remaining differences accumulated between July and October (total May to October differences: +2.4 g CH_4 m^{-2} in 2015 and +1.9 g CH_4 m^{-2} in 2016). Similarly, annual methane emissions in 2014 were about 20-25 % smaller than in 2015 and 2016 (2014: 7.2 g CH_4 m^{-2}, 2015: 9.6 g CH_4 m^{-2}, 2016: 9.1 g CH_4 m^{-2}).

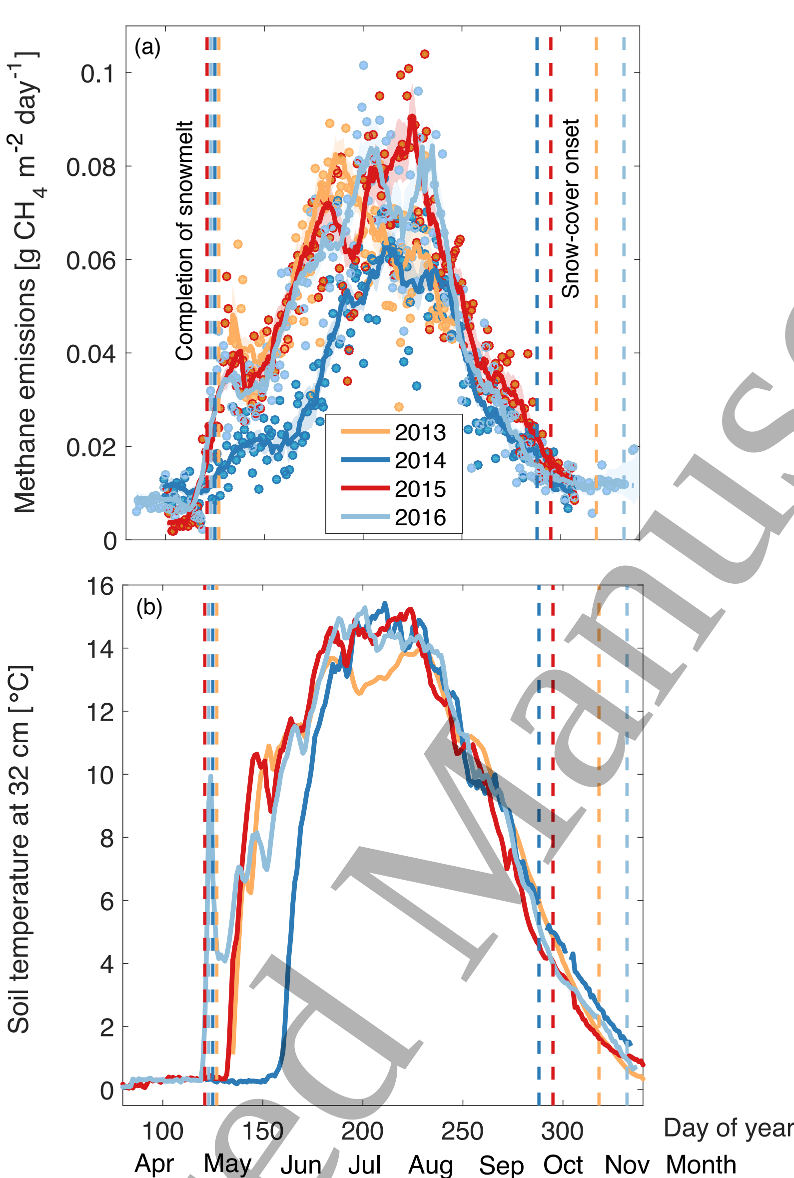

Figure 3. (a) Daily landscape methane emissions (circles) and their 7-day moving average (solid lines) between 2013 and 2016. Timing of snowmelt completion and snow-cover onset are indicated by dashed lines. **(b)** Seasonal dynamics of soil temperature at 32 cm in the wetland between 2013 and 2016.

3.5. Soil temperature controls on methane emissions

Monthly methane emissions were significantly correlated with monthly mean soil temperature at 32 cm and explained 90 % of the variance in monthly methane emissions (2013-2016; $r^2 = 0.90$; $p <$

0.001; $n = 28$, figure 4). In three out of four years (2014 - 2016), monthly methane emissions were correlated with soil temperature ($p \leq 0.01$; $n = 6$ [2014], 8 [2015], 10 [2016]) with linear regression slopes ranging from +0.09 g CH_4 m^{-2} per °C [2014] to +0.14 g CH_4 m^{-2} per °C [2016]. No significant correlation with soil temperature was observed in 2013 ($p = 0.21$; $n = 4$), most likely due to a smaller sample size and less variation in temperature than in the other three years. In contrast, monthly wetland water table position was not correlated with monthly methane emissions ($p = 0.14$; $n = 28$; figure S4). A multiple linear regression model with soil temperature ($p < 0.001$) and water table position ($p = 0.03$) explained only 1 % more of the variance in monthly methane emissions (adjusted R^2: 0.91) than soil temperature alone. The relative importance of water table position in the model was only 2.1 % (95 % CI: 0.5 % - 15.8 %) compared to 97.9 % (95 % CI: 84.1 % - 99.5 %) for soil temperature.

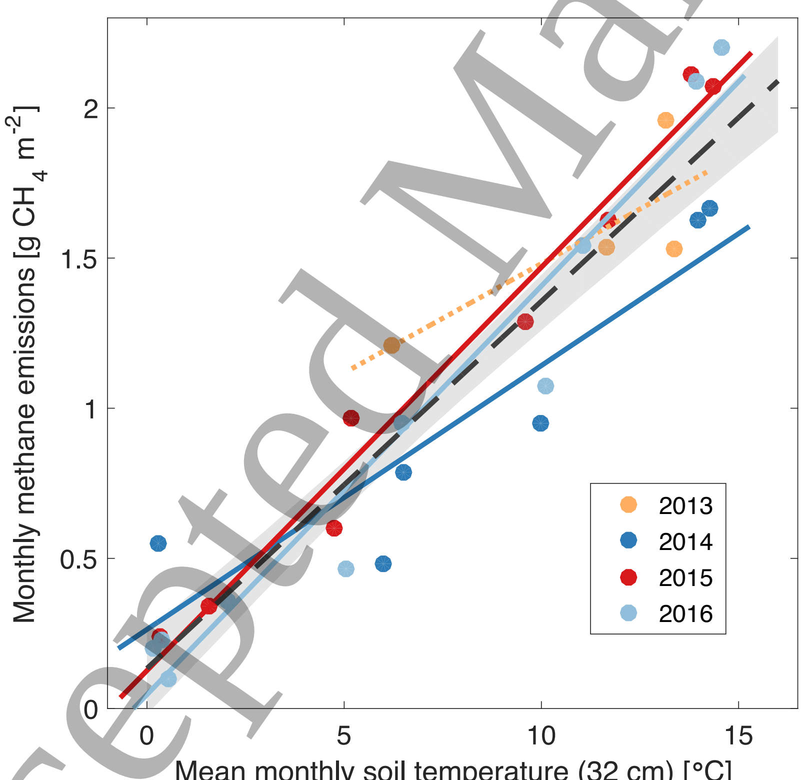

Figure 4. Relationship between mean monthly soil temperature and monthly methane emissions between 2013 and 2016. The dashed line shows best linear least-squares regression fit for all months with the grey shading showing the 95 % confidence interval as derived from bootstrapping the dataset 1000 times. Solid lines indicate significant linear regressions for

individual years, while the 2013 regression shown by the dotted line is not significant. Note that the number of months differs between years due to different lengths of measurement periods.

3.6. Vegetation productivity

Similar to the reduction in methane emissions in 2014, gross primary productivity of the wetland was smaller in 2014 than in the warmer years (figure 5). During the warmer years, a more rapid increase in gross primary productivity in the early growing season resulted in peak gross primary productivity rates exceeding those in 2014 by about 1 g C m^{-2} day^{-1}. Only in early September, did gross primary productivity rates become similar again. There were also interannual differences in green chromatic coordinate (GCC), with a consistently lower GCC between May and August 2014 compared to the warmer years 2013 and 2015.

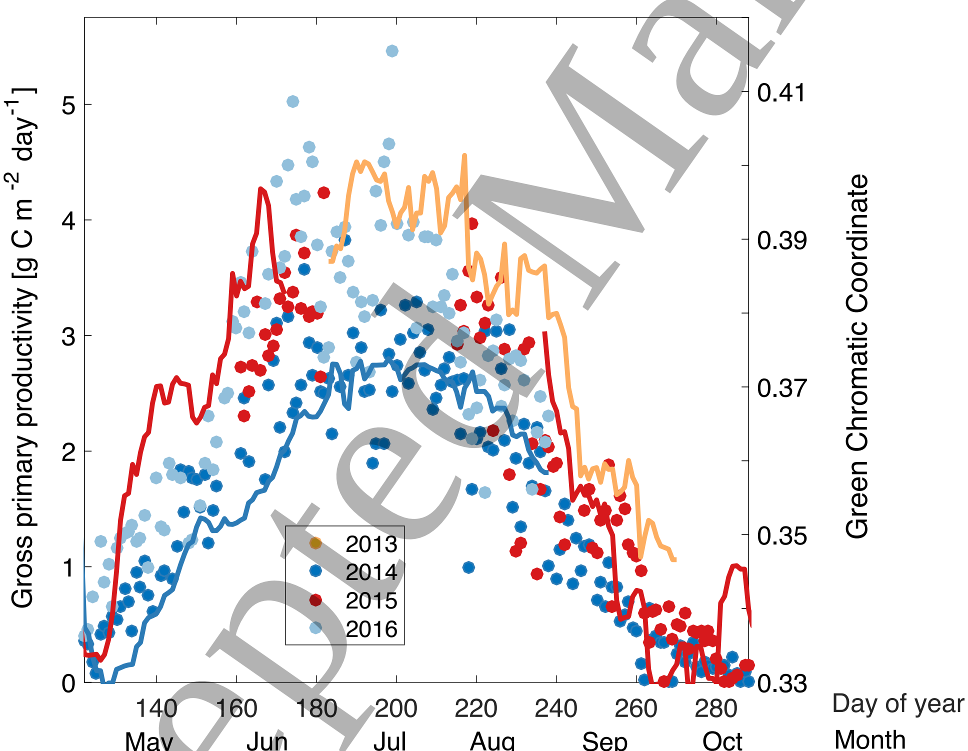

Figure 5. Daily gross primary productivity (2014-2016, circles) and camera-derived green chromatic coordinate (2013-2015, solid lines) of the wetland.

4. Discussion

4.1. Methane flux response to soil temperature and hydrology

We show that warmer May air and soil temperatures significantly increase annual landscape methane emissions by 20-25 % in a boreal peat landscape with sporadic permafrost. Increases in annual methane emissions are mainly caused by the large interannual variability in spring and early summer soil temperatures. Despite similar end-of-winter soil temperature profiles (figure S6 & S7), the interannual differences in wetland soil temperatures (at 32-cm below the moss surface) exceeded 10 °C in May, with cool May air temperatures in 2014 contributing to delayed soil thaw and warming. However, interannual differences in ground ice content in wetlands may have additionally modified soil warming rates in spring (e.g., Hayashi *et al* 2007). Soil temperature exerts a strong control on methane emissions in waterlogged boreal peat landscapes. For example, Helbig *et al* (2017a) showed that large differences in summertime methane emissions between forested permafrost peat plateaus and wetlands are reflected in up to 10 °C cooler soils (at 32-cm below the moss surface) on the plateaus compared to the wetland.

At Scotty Creek, the wetland water table position remained always within about 30 cm from the moss surface (figure 2) despite large variability in total annual precipitation (table 1). Thus, the water table likely did not drop below the rooting depth of herbaceous vascular plants, which usually extends to about 30 cm below the moss surface in peatlands (e.g., Pelletier *et al*. 2017; Strack *et al*. 2006) and can extend to more than 60 cm in collapse-scar bogs (Finger *et al* 2016). When water table positions are close to the moss surface early in the growing season, any delay in soil warming is likely to result in lower methane emissions. Thus, warmer May air temperatures and an earlier soil warming lead to increased annual methane emissions.

4.2. Methane flux response to vegetation productivity

Large July and August methane emissions were only observed in years with warmer May temperatures despite similar average soil temperatures in July and August in all years. The observed differences in late growing season methane emissions are reflected in interannual differences in wetland vegetation productivity and phenology (figure 5). Earlier onset of soil warming likely enables faster vegetation growth (Natali *et al* 2012; Peichl *et al* 2014; Zhao *et al* 2016) and leads to a "greener" (i.e., more abundant) vegetation, more plant biomass, and higher peak gross primary productivity rates (figures 5 & S5). Increased availability of labile organic C and a higher biomass of aerenchymous plants with larger wetland vegetation productivity likely explains larger late growing season methane emissions in the years with warmer spring seasons. Small mean growing season methane uptake rates on forested permafrost peat plateaus with lower soil moisture content typically range between -0.2 and -1 mg CH_4 m^{-2} day^{-1} (Bubier *et al* 2005; Savage *et al* 1997) and are therefore unlikely to explain interannual variability in methane emissions.

Plant productivity rapidly increased during warm springs (figure 5) and may have rapidly minimized substrate limitation of methane production and boosted methanogen activity. Metabolic activity of methanogens has been shown to increase exponentially with temperature (e.g., Yvon-Durocher *et al* 2014). In many wetlands, methane emissions show a similar exponential increase with soil temperature (e.g., Hartley *et al* 2015; Helbig *et al* 2017a). Here, we did not observe exponentially increasing, but linearly increasing methane emissions with soil temperatures on a monthly time-scale (figure 4). However, if summer soil temperatures become warmer in a changing climate, water table position remains close to the peat surface, and labile organic C supply is maintained, monthly methane emissions may deviate from the observed linear relationship. The methane emission response to warming spring air and soil temperatures may therefore change with continued warming.

4.3. Methane flux response to soil warming in warm spring seasons

Methane production rates at low soil temperatures (< 5°C) are strongly temperature-limited (Treat *et al* 2014). However, differences in annual and growing season methane emissions between years with warmer springs were small, despite differences in the timing of spring soil warming. The earliest soil warming among the four study years in 2016 was followed by soil cooling in late May (figure 3). A return to stronger temperature-limitation of methane production could explain the attenuated response of methane emissions to the early onset of soil warming. Also, vegetation productivity may not have immediately responded to the rapid and short-term warming (~four days) in May 2016 and the following return to lower soil temperatures may have further limited vegetation productivity. As a result, low production of root exudates may have limited the supply of labile organic C for methane production. In contrast, later onset of spring soil warming in 2015 was accompanied by increasing vegetation productivity (figure 5).

In peatlands, water table positions above the moss surface can reduce methane emissions (Pelletier *et al* 2007) and tend to limit plant productivity due to prevailing anoxic soil conditions (e.g., Sulman *et al* 2012). After snowmelt in 2016, water table position was above the moss surface and higher than in the other study years (figure 2). The high water table position may have contributed to the attenuated response of methane emissions to the early soil warming. Thus, our results suggest that warmer spring air temperatures and earlier soil thaw lead to larger growing season and annual methane emissions. However, spring methane emissions may be less sensitive to soil warming, if followed by intermittent cooler periods or if accompanied by flooding.

Here, we show that warmer spring temperatures can increase annual methane emissions by 20% to 25%. Thus, in a changing climate, an increase in long-term methane emissions from boreal peat landscapes in the sporadic permafrost zone can be expected with warmer spring conditions. Additionally, methane emissions in the southern Taiga Plains and similar regions in North America are projected to increase with thaw-induced wetland expansion (Lara *et al* 2016; Turetsky *et al* 2008; Helbig *et al* 2017a). In a warming climate with warmer spring temperatures (Wang *et al* 2011), thawing boreal peat landscapes along the southern limit of permafrost may therefore become increasingly important for the global methane budget.

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