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Methane Flux Influenced by Experimental Water Table Drawdown and Soil Warming in a Dry Boreal Continental Bog

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Abstract

To quantify the effects of water table drawdown and soil warming on CH_4 fluxes, we used a static chamber technique during the growing seasons (May–October) of 2011–2013 at hollow and hummock microforms at three sites of a continental bog near the town of Wandering River, Alberta, Canada: (1) Control, (2) Experimental drained, and (3) old Drained. To simulate climatic warming, we used open top chambers to passively warm half of the hollows and half of the hummocks at each of the water level treatment sites. Water table drawdown significantly reduced CH_4 flux by 50% in 3 years and 76% in 13 years of drainage. The hollows showed greater reduction of efflux as compared to hummocks. A persistent functional relationship of CH_4 flux with water level was found across all sites in all years. The relationship revealed that the contribution of change in vegetation type at hollows and hummocks to CH_4 production and emission was relatively less important than that of the water level. Hummocks and hollows responded to warming differently. At the control, experimental and drained sites, warming increased flux at hollows by 16, 21 and 26%, and reduced flux at hummocks by 4, 37, and 56%, respectively. The combined effect of lowered water table and warming on CH_4 emission was overall negative, although the interaction between the two contributing factors was not significant. Therefore, whereas climatic warming and subsequent lowering of water table are expected to reduce CH_4 efflux from dry ombrotrophic bogs of Alberta, different microforms at these bogs may respond differently with accelerated emissions at warmed, wetter (hollows) and reduced emissions at warmed, drier (hummocks) microforms. Overall, CH_4 efflux from Alberta's dry continental bogs that are not underlain by permafrost might be affected only slightly by the direct effect of predicted climate warming, although initial water table position will be an important control on the overall response.

Key words: carbon; methane flux; greenhouse gas; forested bog; open top chamber; wetland; climate change.

Introduction

Methane is a potent greenhouse gas (Howarth and others 2011) and may account for a significant portion of peatland carbon balance (Tarnocai and others 2009). The organic matter reserves of boreal peatlands (including Alberta and the boreal

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ecozone within Canada) are the world's densest carbon (C) stores, containing almost twice as much areal concentration of C per unit area (115 kg m^{-2}) as tropical forests (Vitt and others 2009; Carlson and others 2010), and equal approximately one-third (~500 Pg) of all terrestrial soil C stocks (Turunen and others 2002; Tarnocai and others 2009). The enormous organic matter stock under persistent saturated conditions enabled boreal peatlands to be the largest biological source of atmospheric methane (CH_4) with an annual contribution of about 46 Tg CH_4-C(Gorham 1991; IPCC 2007; Baird and others 2009). The biological and anthropogenic emissions of CH_4 combined are adding to the atmospheric concentration at the rate of approximately 7 ppb per year since 2007 (Sussmann and others 2012). Also, a linear increase in atmospheric carbon dioxide (CO_2) concentration has been observed for the last 80 years that may further warm the atmosphere (Gillett and others 2011). Warmer atmospheric temperature related to climate change may alter CH_4 fluxes from peatlands (Roulet and others 1992) resulting in either positive or negative feedback.

The net CH_4 produced is emitted into the atmosphere by diffusion through peat soil, transport through plant roots and stems, and ebullition events. Up to 100% of CH_4 being transported through diffusion from anoxic to oxic layers may be oxidized before it reaches the peat surface (Pearce and Clymo 2001). Plant-mediated transport dominates in the presence of vascular vegetation and it is primarily controlled by the dominant vegetation type present (Popp and others 1999; Keller and Bridgham 2007). Overall, the variation in production, oxidation, and transport of CH_4 is predominantly controlled by water level, air/peat temperature, easily decomposable substrate availability, and changing meteorological conditions (Vasander and Kettunen 2006), individually or interactively.

Air temperature is both a direct and indirect control over CH_4 fluxes from northern peatlands (Waddington and Day 2007; Lai 2009; Long and others 2010; Pypker and others 2013). Directly, increasing air temperature can increase the temperature of peat soil and can in turn enhance CH_4 production (Lovley and others 1996; Liblik and others 1997; Segers 1998; Turetsky and others 2008). In a northern poor fen, Pypker and others (2013) reported that CH_4 emissions increased from 70 to 220 mg m^{-2} day^{-1} with increased daily mean air temperature from mid-May to mid-July. They also found an indirect increase in CH_4 production due to a greater pore water C availability caused by an increase in gross ecosystem photosynthesis (GEP) resulting from increasing soil temperature at 20 cm depth.

Indirectly, higher air temperature may result in lower water table position due to increases in evapotranspiration (Roulet and others 1992). Water table position has often been reported to be a predominant and direct control over CH_4 flux in boreal peatlands (Roulet and others 1992; Moore and Dalva 1993; Updegraff and others 2001; White and others 2008; Pypker and others 2013) probably due to influencing the size of the zones of methanogenesis (CH_4 production) and methanotrophy (CH_4 oxidation; Turetsky and others 2008). Therefore, a positive correlation has often been found between water level and CH_4 fluxes (Moore and Dalva 1993; Couwenberg and Fritz 2012; Pypker and others 2013). For example, Strack and Waddington (2007) compared CH_4 emissions from drained and undrained peatlands in eastern Canada and found that the undrained peatland emitted generally more CH_4 than a site drained to simulate climate change impacts. The fluxes compared between microforms at their two sites revealed higher CH_4 emission at the undrained lawns and hummocks than that at the drained microforms. Lowered water table increases the thickness of the oxic zone and decreases the thickness of the anoxic zone which results in reduced CH_4 emissions to the atmosphere (Moore and Dalva 1993; Shurpali and others 1993; Alm and others 2007).

Open top chambers (OTCs) have been used for warming study plots to simulate climatic warming and to measure the response of greenhouse gas (GHG) fluxes in peatlands at northern latitudes. For example, Sullivan and others (2007) used OTCs in a high arctic fen for warming hummock and hollow plots to quantify response of CO_2 fluxes to warming. They found increased GEP at both hummock and hollow microforms with warming. Chivers and others (2009) and Turetsky and others (2008) used OTCs in a moderate rich fen for warming control, lowered and raised water table plots to quantify responses of CO_2 and CH_4 fluxes to warming, respectively. CH_4 efflux from OTC-warmed plots in the raised water table treatment increased by 80–300% (Turetsky and others 2008). CH_4 efflux substantially decreased from the lowered water table treatment with only small increases from OTC-warmed, lowered water table treatment plots. A slightly higher CH_4 efflux from OTC-warmed lawns and hummocks than that from the control microforms was observed by Johnson and others (2013) in a temperate poor fen.

Ongoing climate change is predicted to be most severe at mid-latitudes where dense peatlands are located (Tarnocai 2006; IPCC 2007). The increase in air temperature combined with altered precipitation patterns will lead to overall warming of the peat surface and subsequent lowering of the water table (Roulet 1991) across the mid-latitude region (IPCC 2007) leaving the fate of large C stocks uncertain (Frolking and others 2011). Moreover, some studies have demonstrated a positive feedback between climatic warming and C cycling at these peatland dense latitudes suggesting that these ecosystems will contribute to accelerated change in climate over the 21st century(Frey 2005; Davidson and Janssens 2006; Ise and others 2008; Sitch and others 2008; Meehl and others 2009).

Northern Alberta is situated at mid-latitude and falls within the southern boreal region having densest coverage (50%) of peatlands. The region is classified as severely sensitive to climate change (Kettles and Tarnocai 1999). Therefore, its massive pool of C is vulnerable to release to the atmosphere in response to the already detectable polar warming (Tarnocai 2006). The C balance of the boreal bogs in Alberta has been quantified by Wieder and others (2009), but the CH_4 flux was assumed to be a minor component of the overall C balance and thus it was excluded. We are unaware of any studies that have quantified the effect of warming using OTCs along a hollow and hummock microtopographic gradient on CH_4 fluxes within a subhumid climate, nor in a climate-sensitive treed bog. Therefore, how CH_4 flux from continental bogs in this region will feedback to oncoming climatic change remains unknown. Thus, the goal of our research was to quantify the response of CH_4 flux to predicted climatic warming and subsequent lowering of water level, using three sections of a continental boreal bog chosen at Wandering River, Alberta. We monitored CH_4 flux over a 3-year study period. Our specific objectives were (1) To quantify the effects of experimental changes in temperature and water table position on peatland-atmosphere CH_4 flux; (2) To assess whether the response varies between peatland microforms and over time; and (3) To investigate the controls on CH_4 fluxes across space (microforms) and time (3 and 13 years).

Materials and Methods

Study Sites

We chose two sections of a peatland complex, a dry continental bog. They are 8.9 km apart and are located in north central Alberta, 85 km northeast of Athabasca, Alberta, Canada. The sections are underlain by sandy clay substrate and have peat depth exceeding 4 m. Climate in this region is subhumid continental with 30-year (1971–2000) mean annual and growing season (May–October) temperatures of 2.1 and 11.7°C and precipitation of 504 and 382 mm, respectively, (Environment Canada 2013). In the study years of 2011–2013, the mean growing season air temperature and precipitation measured at our sites were 13.1, 13.2, 14.1°C and 403, 282, 267 mm, respectively.

The bog is classified as a treed low shrub bog with a typical mosaic of hollow and hummock microforms (Riley 2003). In 2011, the hollows and hummocks at the control and experimental sites were found similarly dominated by *Sphagnum* mosses with sparse shrubs whereas the drained site had higher coverage of shrubs in the hummocks and higher lichen coverage in the hollows. Common mosses included *Sphagnum fuscum*, *Sphagnum magellanicum*, S*phagnum angustifolium*, *Sphagnum capillifolium*, and *Pleurozium schreberi*. Common shrubs included Labrador Tea (*Rhododendron groenlandicum*), Lingonberry (*Vaccinum vitis-idaea*), small bog cranberry (*Oxycoccos microcarpus*), and the herbaceous cloudberry (*Rubus chamaemorus*). Black spruce (*Picea mariana*) was the most common tree in these bogs. Details of vegetation coverage and biomass at the control and drained sites were quantified and described by Munir and others (2014).

The two chosen sections of the dry continental ombrotrophic bog are located near the town of Wandering River, Alberta: an undisturbed or CONTROL (55°21′14.2″N, 112°31′3.7″W) section and a lowered water table section that was DRAINED (55°16′44.3″N, 112°28′8.2″W) in 2001. In the undisturbed section an EXPERIMENTAL (55°21′16.7″N, 112°31′5.9″W) site was created adjacent to the control site by digging a 100 cm × 100 cm (depth × width) ditch around an approximately 75 m × 75 m (length × width) quadrat, to lower the water table to simulate the water table drawdown predicted for mid-latitude peatlands under the 2 × CO_2 scenario (Roulet and others 1992). The ditch was dug at the start of growing season of 2011 to create a short-term (1–3 years) water table drawdown treatment for the study period of 2011–2013. The experimental site ditch drained into the existing drainage system of the managed peatland complex, and it lowered the water table by 36 cm compared to the control site during summer 2011. The drained site (drained 10 years prior to the study) allowed for the investigation of longer-term effects of persistent water table drawdown on CH_4 fluxes. Boardwalks were built at all sites in July 2010 followed by the preliminary measurements of CH_4 fluxes, water table position and chemistry of these sites at the end of the same field campaign. CH_4 fluxes at the control and experimental microforms were similar and generally higher than at the drained microforms (data not presented here). There was no significant difference found between mean (±SD) water table position at the control (−55.8 ± 21.6) and experimental (−56.7 ± 20.4) sites prior to the water table manipulation (ANOVA, $F_{1,5} = 0.55$, $P = 0.492$) in 2011. Mean (±SD) electrical conductivity (EC, μS cm^{-1}) and pH of pore water in the control (16.6 ± 0.7 and 4.1 ± 0.1, respectively) and experimental (15.2 ± 2.5 and 4.4 ± 0.3, respectively) sites were also found to be similar (ANOVA, EC: $F_{1,5} = 0.84$, $P = 0.401$; pH: $F_{1,5} = 2.63$, $P = 0.166$).

At each of the three sites (control, experimental, and drained), 12 plots (60 cm × 60 cm) were installed and divided equally between available hummocks and hollows. Before the growing season of 2011, permanent steel collars having grooves at the top were inserted about 6 cm into the peat surface at all study plots. A 150 cm long, PVC water well (diameter = 3.5 cm) perforated and covered with nylon cloth at the bottom 100 cm was inserted into the peat adjacent to each plot. Half of the hummocks and half of the hollows at each site were randomly selected and equipped in May 2011 with 60°, 50 cm tall open top hexagonal chambers of top and basal, side to side dimensions of 104 and 162 cm, respectively.

The OTCs (Molau and Mølgaard 1996) were constructed using 3.5-mm thick, translucent plexiglas (SUN-LITE HP, Solar Components Corporation, Manchester, New Hampshire, USA) with a goal of passively increasing internal air and surface soil temperature by about 1°C (Hollister and Webber 2000). Inside each OTC, two automatic data loggers (HOBO Pro V2, Onset computer corporation, Bourne, MA, USA) were installed facing north to avoid direct solar radiation loading and to continuously log temperatures. One of the HOBOs was programmed to logOTC air temperature only, and the other to logOTC air and OTC soil (5 cm) temperatures. The data loggers measured and recorded OTC temperature (warming) every 20 min during the growing season. Snowpack disturbance was minimized by removing the OTCs each October and reinstalling back on plots in early May during each of the study years of 2011–2013. Similar OTCs have been used by Sullivan and others (2007), Turetsky and others (2008), Chivers and others (2009), and Johnson and others (2013) to induce passive warming.

CH_4 Flux

CH_4 fluxes were measured every 1–2 weeks during May to October from 2011 to 2013, using a static flux chamber technique (Crill and others 1998). The CH_4 sampling chamber was constructed of 0.5 cm thick opaque plastic, of volume and area 0.108 m^3 and 0.36 m^2, respectively. The chamber volume was also corrected to account for moss surface height relative to the collar. The chamber was equipped with a small fan for gently mixing the air during flux measurements. However, the chamber had no pressure equilibrium port installed. At 7, 15, 25, and 35 min after chamber closure, 20 ml gas samples were extracted using a polypropylene syringe fitted with a 3-way stopcock connected to tubing running through a stopper into the chamber headspace. The samples were injected into labeled evacuated Exetainers (Labco Ltd., UK). Two ambient air samples were also taken daily during sampling days to use as initial concentration for the sequence of CH_4 samples. The sample Exetainers were taken to the Wetland Soil and Ecohydrology Laboratory at University of Calgary and analyzed with a Varian 3800 gas chromatograph equipped with a flame ionization detector (FID). The instrument performance was monitored by feeding a standard and a control (both having the same CH_4 concentration of 50 ppmv), after every eight samples in the sequence table and was recalibrated when the control read beyond ±5% of the standard value. The flux rates were calculated as the slope of the linear regression of CH_4 concentration in the chamber headspace over time. Flux measurements with sample concentrations that suggested possible ebullition events (Strack and others 2005) were discarded from our subsequent analysis results (8% of data) as it was unclear whether sampling had induced the event. Thus, values presented here represent diffusive fluxes.

Micrometeorology and Soil Hydroclimate

To relate the trace gas flux rates to prevailing environmental conditions of the study sites, each of the control, experimental, and drained sites was instrumented with the HOBO temperature sensors. The control/experimental sites were instrumented with: one additional soil temperature sensor (T109, Campbell Scientific Inc., Utah, USA; depth = 5 cm) and one tipping bucket rain gage (TE 525, Campbell Scientific Inc.; height = 150 cm),both wired to a data logger (CR 1000, Campbell Scientific Inc.) programmed to measure every minute and average at 20 min intervals. The soil temperatures at the depths of 2, 5, 10, 15, 20, 25, and 30 cm below the moss surface were also measured using a thermocouple thermometer during each flux measurement.

Water level in the PVC wells installed adjacent to the collars was measured manually every time CH_4 flux was sampled. Two automatic water level loggers (Levelogger Junior 3001, Solinst, Georgetown, Ontario, Canada) were installed at each of the three sites in two randomly selected wells: one at a hollow and another at a hummock plot. These leveloggers recorded temperature compensated water levels continuously at 20 min intervals throughout the three growing seasons (except at the drained hollow between May and early July 2011, due to malfunction of the levelogger), to relate with CH_4 fluxes. A Barologger (Barologger Gold, Solinst; height = 100 cm) was also installed to compensate water levels for barometric pressure changes. These records captured short-term water level fluctuations caused by precipitation events that were not captured by weekly manual measurements.

Data Analysis

To evaluate treatment effects on CH_4 flux we used a linear mixed-effects model (SPSS 20.1) with CH_4 flux as the response variable, water table treatment, warming (OTC) and microtopography as fixed effects and years as repeated measures (Table 3). We used the same fixed effects and repeated measures in all mixed-effects ANOVA models (described below). All two-way interactions between fixed effects were also included in the models. We used compound symmetry covariance structure for repeated measures analysis (Jennrich and Schluchter 1986). A mean value of flux determined at each plot in each growing season was used for all analyses. The CH_4 flux data were normally distributed in all years (Kolmogorov-Smirnov Z: 2011, $P = 0.967$; 2012, $P = 0.673$; 2013, $P = 0.571$).

The treatment effects on warming and net warming (warmed – un-warmed) were also evaluated by using the mixed-effects models (Table 2). A mean value of temperature at each plot in each growing season was used for analysis except in 2011 for: unwarmed air where temperature was logged only at two mid-points of the hollow-hummock microtopography for each water table treatment; unwarmed 5 cm deep soil where temperature was logged only at one mid-point of the microtopography for each water table treatment. The data were normally distributed in all years for air warming (Kolmogorov-Smirnov Z: 2011, $P = 0.676$; 2012, $P = 0.555$; 2013, $P = 0.881$), 5 cm deep soil warming (Kolmogorov-Smirnov Z: 2011, $P = 1.122$; 2012, $P = 0.941$; 2013, $P = 1.082$) and 30 cm deep soil warming (Kolmogorov-Smirnov Z: 2011, $P = 0.899$; 2012, $P = 0.732$; 2013, $P = 0.902$).

We also used the linear mixed-effects model to evaluate the treatment effects and the repeated measures on differential (warmed − un-warmed) CH_4 flux. Likewise, the differential CH_4 flux response to differential warming of soil was also evaluated.

We used linear regression models (SPSS 20.1) to predict the relationship of water table with CH_4 fluxes, at unwarmed and warmed microforms (Figure 3A, B), and Kendall's τb tests to determine relationships between mean seasonal differential (warmed − un-warmed) soil temperature and mean seasonal differential CH_4 flux, at hollows and hummocks (Figure 4A, B). We also used linear regressions to test whether the slopes of the lines between the water level and the differential CH_4 flux, and the differential warming and the differential CH_4 flux, at the microforms were different significantly.

Results

Environmental Conditions

Daily mean air temperature and seasonal precipitation were logged at the study sites in Wandering River bog. The growing seasons (May–October) of 2011, 2012, and 2013 were warmer by 1.36, 1.38, and 2.44°C, respectively, and wetter by 42 mm in 2011 and drier by 79 mm and 94 mm in 2012 and 2013, respectively, than 30 year means at Athabasca, Alberta (meteorological data have been described under "study sites").

The consecutive decline in rainfall and increase in temperature in the last 2 years of the study led to an average fall of water table in 2013 compared to 2011 at control, experimental, and drained hollows by 6, 6, and 4 cm, respectively, and at hummocks by 9, 8, and 8 cm, respectively. 3 and 13 years after initial drainage, the water table at the experimental and drained sites was as much as 36 and 82 cm lower than that at the control site (Figure 1).

The three water table treatment sites had clearly different average water table positions at the start of the study period in 2011 at 38, 73, and 111.6 cm below moss surface at control, experimental, and

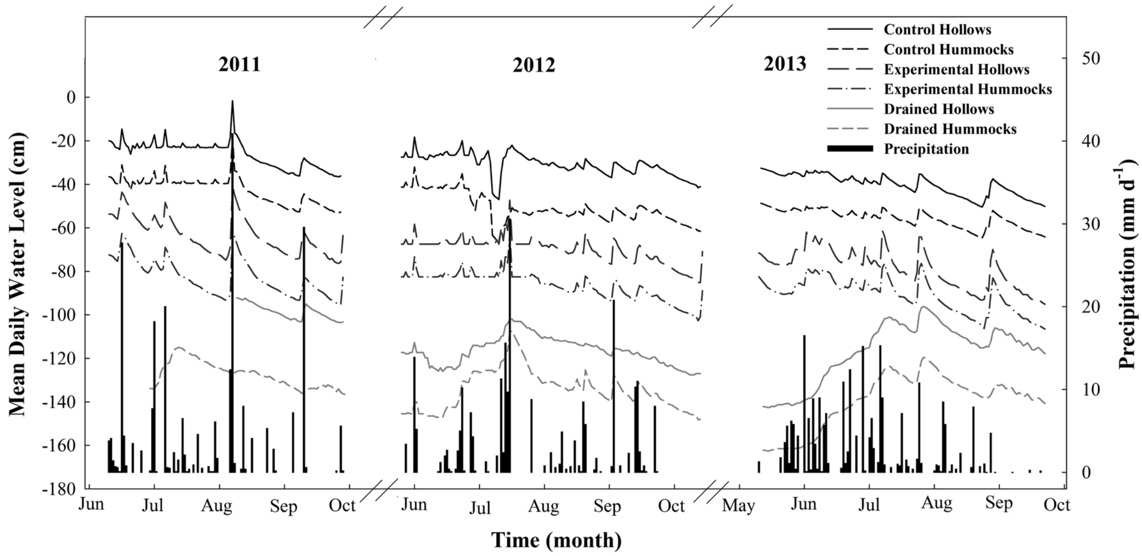

Figure 1. Water levels (*lines*) at hollow and hummock microforms and daily precipitation (*bars*) during growing seasons of 2011, 2012, and 2013. The cumulative seasonal precipitation during 2012 and 2013 was 30.0 and 35.3% lesser respectively than that in 2011.

drained site, respectively. However, the consecutive warmer and drier growing seasons lowered the water table positions in 2013 to an average of 47 cm at control, 81 cm at experimental, and 126 cm at the drained sites (Figure 1).

Average air temperature (T_{air}) inside the OTCs was significantly greater than that of the outside ambient air (ANOVA, $F_{2,24} = 215.87$, $P < 0.001$). This pattern was overall consistent at all water level treatments and microform types in all years (Table 1). Averaged across 2011–2013, the OTCs warmed the air inside on average (±SD), 1.0 ± 0.0°C at the control site, 0.9 ± 0.0°C at the experimental site and 0.8 ± 0.5°C at the drained site (Table 1). The warming at hollows was also significantly greater than at hummocks (ANOVA, $F_{1,24} = 4.85$, $P = 0.037$).

Average soil temperature at 5 cm depth ($T_{soil\ 5cm}$) inside the OTCs was also significantly greater than that of the outside soil temperature at the same depth, at all sites (ANOVA, $F_{1,24} = 37.59$, $P < 0.001$). Averaged across 2011–2013, the OTCs warmed the soil at 5 cm depth most at the control site (1.0 ± 0.3°C) followed by a warming of 0.7 ± 0.1°C at experimental and 0.7 ± 0.3°C at the drained site (Table 1). When comparing averaged $T_{soil\ 5cm}$ between microform types at the study sites across all study years, we found the least warming of 0.4 ± 0.3°C at drained hummocks and greatest warming of 1.3 ± 0.2°C at control hummocks.

Average soil temperature at 30 cm depth ($T_{soil\ 30cm}$) below the OTC-equipped plots was generally higher but not significantly different than that at the same depth at non-OTC plots across all sites (ANOVA, $F_{2,24} = 0.71$, $P = 0.053$) and microforms (ANOVA, $F_{1,24} = 0.95$, $P = 0.339$).

Very importantly, net warming (warmed − unwarmed) of T_{air} and $T_{soil\ 5cm}$ was significantly greater at the control water level treatment than those at the lowered water table treatments (ANOVA: T_{air}, $F_{2,24} = 4.12$, $P = 0.028$; $T_{soil\ 5cm}$, $F_{2,24} = 4.13$, $P = 0.029$). The warming, likely driven by the water level, was not statistically significant at 30 cm soil depth ($T_{soil\ 30cm}$) across sites (ANOVA, $F_{2,24} = 2.85$, $P = 0.077$), although hollows had generally warmer soil temperature at this depth than that of hummocks, at all sites (Table 1).

CH_4 Fluxes

A mixed-effects model analysis showed that the CH_4 fluxes were significantly affected by the water table treatment (Table 3). Greatest CH_4 efflux was observed at the shallowest water table site (control) followed by a smaller flux at the experimentally lowered water table site, and smallest at the deepest water level treatment at the drained site in all 3 years (Figures 2, 3). CH_4 fluxes consistently decreased from 2011 to 2013 across the water table treatments, but the total amount of reduction varied between sites as CH_4 flux changed from 4.0 to 3.3 mg m^{-2} day^{-1} at control, from 2.2 to 0.7 mg m^{-2} day^{-1} at experimental, and from 1.1 to 0.5 mg m^{-2} day^{-1} at drained site (Figure 2) likely

Table 1. Mean Seasonal Air Temperatures (T_{air}), 5 cm Deep Soil Temperatures ($T_{soil\ 5cm}$), and 30 cm Deep Soil Temperatures ($T_{soil\ 30cm}$) at all the Sites Measured During Growing Seasons (May–October) of 2011–2013

	Year	Control		Experimental		Drained	
		Hollows	Hummocks	Hollows	Hummocks	Hollows	Hummocks
T_{air} (°C)	2011						
	Un-warmed	13.1 ± 0.1[1]		13.4 ± 0.1[1]		13.9 ± 0.0[1]	
	Warmed	14.0 ± 0.4	13.7 ± 0.0	14.0 ± 0.2	14.2 ± 1.0	14.3 ± 0.1	14.9 ± 0.4
	2012						
	Un-warmed	13.1 ± 0.4	13.1 ± 0.3	13.6 ± 0.2	13.6 ± 0.1	14.3 ± 0.3	14.3 ± 0.2
	Warmed	14.1 ± 0.3	14.4 ± 0.7	14.8 ± 0.4	14.3 ± 0.3	14.5 ± 0.3	15.4 ± 1.4
	2013						
	Un-warmed	14.2 ± 0.2	14.0 ± 0.0	14.2 ± 0.1	14.3 ± 0.0	14.3 ± 0.4	14.5 ± 0.3
	Warmed	15.2 ± 0.9	15.1 ± 0.6	15.3 ± 0.4	15.5 ± 0.4	15.0 ± 0.3	15.2 ± 0.7
$T_{soil\ 5cm}$ (°C)	2011						
	Un-warmed	12.3[1,2]		12.6[1,2]		13.6[1,2]	
	Warmed	12.9 ± 0.0	13.5 ± 0.1	13.0 ± 0.6	13.7 ± 1.0	14.1 ± 0.5	14.5 ± 0.1
	2012						
	Un-warmed	12.0[2]	11.9[2]	13.6[2]	13.6[2]	13.9[2]	13.8[2]
	Warmed	12.7 ± 0.0	13.0 ± 1.0	14.5 ± 1.5	13.6 ± 0.0	13.9 ± 0.6	14.9 ± 0.7
	2013						
	Un-warmed	12.7[2]	12.6[2]	13.1[2]	13.0[2]	13.6[2]	13.6[2]
	Warmed	13.1 ± 0.7	14.2 ± 0.6	13.8 ± 0.5	13.9 ± 0.8	14.2 ± 0.8	14.5 ± 0.5
$T_{soil\ 30cm}$ (°C)	2011						
	Un-warmed	10.1 ± 2.3	10.7 ± 2.7	7.7 ± 2.7	10.1 ± 2.9	10.5 ± 3.8	12.5 ± 3.8
	Warmed	10.6 ± 2.1	12.0 ± 2.2	9.4 ± 2.0	10.9 ± 3.8	12.2 ± 3.9	12.7 ± 3.7
	2012						
	Un-warmed	10.6 ± 3.0	11.8 ± 3.0	11.6 ± 3.5	12.8 ± 3.3	13.0 ± 4.6	13.6 ± 4.3
	Warmed	11.4 ± 2.8	13.1 ± 3.6	12.5 ± 3.4	13.9 ± 4.4	12.7 ± 4.2	13.3 ± 4.3
	2013						
	Un-warmed	11.7 ± 2.3	10.6 ± 2.7	10.4 ± 2.0	10.7 ± 3.3	12.4 ± 2.6	13.5 ± 3.3
	Warmed	13.1 ± 2.0	12.0 ± 1.7	11.7 ± 2.8	11.5 ± 3.3	11.9 ± 3.2	12.1 ± 3.3

All temperatures are mean (±SD). All the OTC-equipped hollows (n = 3) and hummocks (n = 3) at each site were instrumented with HOBOs to log OTC warming of air (T_{air}) and 5 cm deep soil ($T_{soil\ 5cm}$). The 30-cm deep soil temperatures ($T_{soil\ 30cm}$) were measured using thermocouples, during collection of CH_4 samples in growing seasons of the study years.
[1]The non-OTC hollows (n = 3) and hummocks (n = 3) were not equipped separately, with HOBO data loggers during 2011.
[2]No replications.

due to drier and warmer growing seasons and subsequently lower water levels (Figure 1).

CH_4 fluxes also varied between microforms (Figures 2, 3). However, hollow and hummock microforms responded to warming treatment opposite to each other (Figure 4B). The differential response of hollows to warming from that of hummocks resulted in a statistically significant interaction between warming and microform type, but a non-significant effect involving the warming treatment alone (Table 3). The greatest CH_4 efflux was from warmed control hollows having the highest water level, whereas the smallest CH_4 flux, or consumption (negative value), was from warmed experimental and drained hummocks with the lowest water table in all years. Therefore, although the effect of warming on CH_4 fluxes was not significant, the effect of warming on flux appears to be dependent upon water table position. This potential relationship between warming effect and water table position is further illustrated by changes in mean site level CH_4 fluxes (Table 3) whereby warming tended to increase CH_4 flux at the control site, had little effect at the experimental, and reduced flux at the drained site, although the water table treatment × warming interaction was not significant (Tables 2, 3).

A significant positive relationship between CH_4 flux and water level was observed: shallower water table (control) resulted in greater emission whereas deeper water level (experimental and drained) led to flux reduction and even net consumption (Figure 3A). As stated above, warming across the three water table treatments tended to increase CH_4 emissions at the hollows and reduce CH_4 fluxes at the hummocks (Figure 4B). The warming

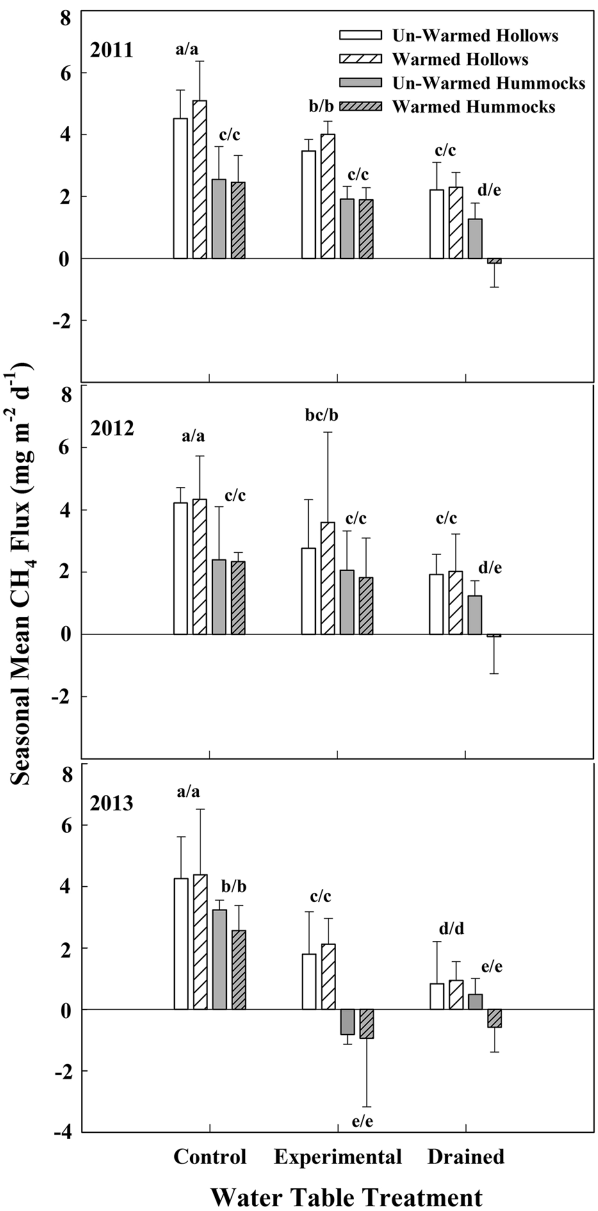

Figure 2. Mean seasonal CH_4 flux at hollow and hummock plots (n = 36) split between control, experimental, and drained sites in 2011, 2012, and 2013. CH_4 fluxes were measured during May to October in the first 2 years while May to September in the last year of the study. Negative values represent consumption of CH_4. *Error bars* indicate ±standard deviation. Results are from a linear mixed-effects model ANOVA and differences are evaluated between study plots grouped according to drainage, microform and warming and are indicated by *letter/s* at *each bar*. The *bars* are significantly different at $P < 0.05$ if they have *no letters* in common (*letters* should be compared only within 1 year).

increased the difference in CH_4 fluxes between hollows and hummocks at all sites and in all years, although the slope of the CH_4 flux–water table relationship was not significantly different between warmed and un-warmed plots (ANOVA, $F_{1,18} = 0.109$, $P = 0.742$). Therefore across all treatments, a 1 cm decline in water table position resulted in a reduction of flux by 0.03 mg m^{-2} day^{-1} (Figure 3).

The enhancement of CH_4 flux by warming at hollows was significantly related to their water table position (Figure 4A) with very little effect of warming at drained hollows. On the other hand, warming tended to increase consumption of CH_4 at hummocks, with greatest effect at drained hummocks, although the relationship with water table position was not statistically significant (Figure 4A). Because warming by OTCs was not consistent across all sites, we investigated the correlation between total induced warming and change in CH_4 flux. The exactly opposite responses of hollows and hummocks for net CH_4 flux to net warming caused by OTCs, supported the contrasting responses of hollows and hummocks at all sites (Figure 4B).

Discussion

We evaluated the response of CH_4 flux in a continental boreal bog to warming and water table drawdown expected to occur under climate change. The drainage treatment effectively lowered the water table from on average 38 cm below the surface at the control site to 73 and 112 cm below the surface at the experimental drained (1–3 years) and old drained (11–13 years) sites, respectively. Our OTC set up in the continental treed bog significantly warmed T_{air} by 1.0, 0.9, 0.7 and $T_{soil\ 5cm}$ by 1.0, 0.7, 0.7°C at control, experimental, and drained water table treatments, respectively. The significant OTC warming likely arose due to favorable average seasonal air temperature (Carlyle and others 2011), long day length (Elmendorf and others 2012), low precipitation and sub-humid environment (Johnson and others 2013). A similar level of in situ warming of about 1°C with the use of OTCs in a rich fen peatland has been reported by Sullivan and others (2007), Turetsky and others (2008), and Chivers and others (2009) whereas extreme OTC warming of up to 20°C in an Antarctic study has also been observed (Bokhorst and others 2011).We found diurnal T_{air} and $T_{soil\ 5cm}$ patterns in the OTCs to be significantly correlated with photosynthetically active radiation (t test, $P < 0.001$, $R^2 = 0.81$; t test, $P < 0.001$, $R^2 = 0.87$; respectively) at our dry continental bog sites. The mid-day full sun conditions resulted in OTCs air warming greater than outside by 4, 5, and 9°C at

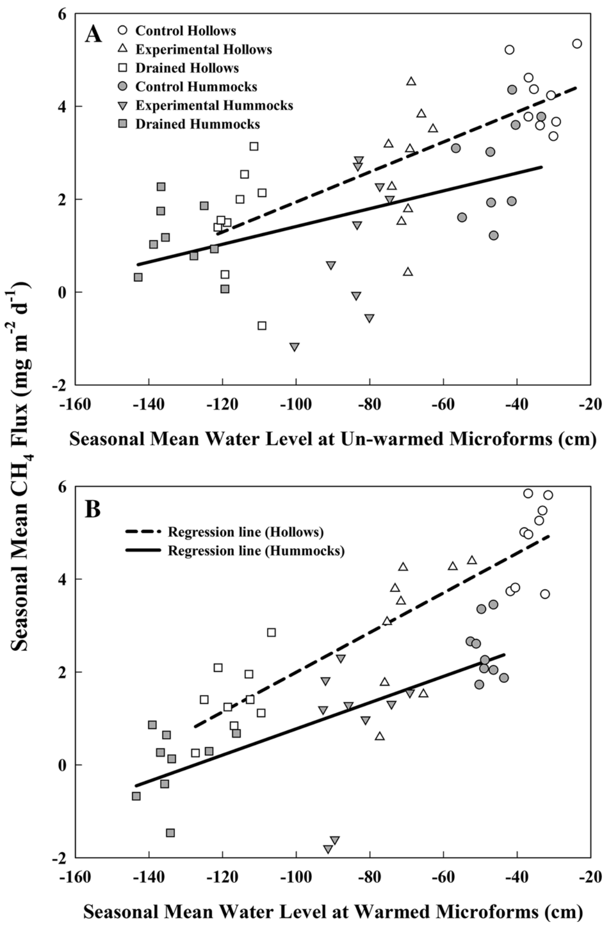

Figure 3. Seasonal mean CH_4 flux response to seasonal mean water level at the (**A**) un-warmed (n = 54) and (**B**) warmed (n = 54) hollow and hummock microforms at the three water level treatment sites (un-warmed: slope = 0.03, intercept = 4.75, $F_{2,12}$ = 23.53, $P < 0.001$, R^2 = 0.72; warmed: slope = 0.04, intercept = 5.63, $F_{2,12}$ = 18.92, $P < 0.001$, R^2 = 0.73). *Each point* is the mean CH_4 flux and water table position at one plot for one growing season in 1 year.

hummocks, and by 5, 7, and 6°C at hollows in the control, experimental, and drained sites, respectively. Similarly, the direct solar loading during sunny days increased the OTCs $T_{soil\ 5cm}$ greater than outside by 5, 3, and 8°C at hummocks, and by 2, 4, and 8°C at hollows in the control, experimental, and drained sites, respectively. We did not measure wind speeds at our study sites. Our observed diurnal patterns of warming driven by midday sunny conditions support the majority of earlier findings using OTCs (Hollister and others 2006; Bokhorst and others 2011; Carlyle and others 2011) but contradict those of Johnson and others (2013).

CH_4 flux varied between sites and microforms. The flux decreased at sites from control to experimental and drained, and at microforms from hollows to hummocks, with warming alone having no direct or significant effect on CH_4 flux (Tables 2, 3). This revealed that, as previously reported, the flux was largely related to water table position. On the other hand, the magnitude and effect of warming varied between sites and microforms depending on their water table position and the relative importance of CH_4 oxidation.

Effect of Water Table on CH_4 Flux

Warming and drying weather (increasing temperature and decreasing precipitation) from 2011 to 2013 lowered water level (Figure 1) and decreased CH_4 fluxes at all sites and microforms over the study period (Figures 2, 3). Our water table drawdown treatments greatly reduced flux and this reduction varied with time: 50% following 3 years (short-term) and 76% following 13 years (longer-term) of drainage; however, the greater effect at the old drained site is likely simply explained by its deeper water table position (Figure 3A). Therefore, water level was the dominant control on CH_4 dynamics across all sites and during all the years. Significantly greater fluxes at the shallowest water level treatment than at the deeper water level treatments might be due to one or more of favorable conditions of thicker anoxic layer, greater methanogenesis than methanotrophy, more availability of fresh sloughed off roots and root exudates and low EC. Our study provides additional support to all of the previously published studies that reported diminishing CH_4 emission or consumption with declining water level in peatlands (for example, Turetsky and others 2008). Noticeably, across all water table treatments at our sites, CH_4 fluxes fell along the same functional relationship with water level. Therefore the successional vegetation changes quantified by Munir and others (2014) and expected changes in peat properties (not studied) in response to longer-term drainage appear to have little influence on CH_4 flux at this site. Therefore, this new understanding on the little influence of the drainage-driven successional vegetation on the balance of CH_4 production and degradation does not support the conclusion of previously published studies that reported either enhanced emissions (for example, Strack and Waddington 2007) or declined fluxes (for example, Popp and others 2000).

The quantified reduction in CH_4 fluxes (Table 3) in response to lowering of water table is consistent with earlier water table-manipulation experiments in which water table was found to be the dominant

Table 2. Mixed-Effects ANOVA p values for the Fixed Effects of Water Table, Microform and OTC with Repeated Measures of Year, on Warming and Net Warming (warmed − un-warmed) of T_{air} (n = 36), $T_{soil\ 5cm}$ (n = 33), and $T_{soil\ 30cm}$ (n = 36)

	Average soil temperature (°C) P values			Net warming (warmed − unwarmed) (°C) P values		
	T_{air}	$T_{soil\ 5cm}$	$T_{soil\ 30cm}$	T_{air}	$T_{soil\ 5cm}$	$T_{soil\ 30cm}$
Water table	<0.001	<0.001	0.500	0.028	0.029	0.077
Microform	0.127	0.631	0.339	0.123	0.920	0.210
OTC	<0.001	<0.001	0.053	<0.001	<0.001	0.078
Water table × Microform	0.082	0.634	0.001	0.010	0.585	0.946
Water table × OTC	0.042	0.762	0.663	0.029	0.029	0.077
Microform × OTC	0.130	0.462	0.901	0.123	0.920	0.210
Water table × Microform × OTC	0.085	0.824	0.649	0.010	0.585	0.946

T_{air}, air temperature; $T_{soil\ 5cm}$, soil temperature at 5 cm depth; $T_{soil\ 30cm}$, soil temperature at 30 cm depth.

Table 3. Mixed-Effects ANOVA p values for the Fixed Effects of Water Table Treatments (Control, Experimental, Drained), Warming Treatments (non-OTC, OTC), and Microform Types (Hollow, Hummock) with Repeated Measures of Year, on CH_4 Flux at the Peatland Surface

	Numerator df	Denominator df	F	P
Water table	2	24	40.93	<0.001
Microform	1	24	57.14	<0.001
OTC	1	24	0.00	0.979
Water table × Microform	2	24	1.86	0.177
Water table × OTC	2	24	0.47	0.629
Microform × OTC	1	24	4.49	0.045
Water table × Microform × OTC	2	24	0.27	0.768

control on CH_4 fluxes. For example, Strack and Waddington (2007) lowered the water table of a poor fen by 20 cm and observed an approximately 80% reduction in CH_4 flux following 3 years of drainage. At the same study site, Strack and others (2004) lowered the water table of a poor fen by 20 cm and observed up to a 55% reduction in CH_4 flux following a longer-term (8 years) drainage. Similarly, Roulet and others (1993) lowered the water table of both a fen and a bog by between 10 and 60 cm and observed 98–105 and 100–200% reductions in flux, respectively, following 7 years of drainage. A flux reduction of greater than 100% represented a negative flux or consumption. Turetsky and others (2008) in a rich fen raised the water table by 11 cm and also lowered the water table by 8 cm and observed an increase of 75% and decrease of 53% in emission, respectively, following 2 years of manipulation. However, the CH_4 emissions we quantified at our dry continental bog were much lower (Table 3) than measured at fens (Roulet and others 1993; Strack and others 2004; Bridgham and others 2006), but fell well within the ranges previously reported from ombrotrophic bogs: 0–5 mg m^{-2} day^{-1} at a water level about 80 cm below the moss surface (Moore and Knowles 1990) and 0.38–5.50 mg m^{-2} day^{-1} under varying permafrost regimes (Turetsky and others 2002). Although previously reported flux reductions were observed in different sets of experimental conditions (depth of lowering of water table, initial water level, peatland type, vegetation, latitude, and climate) than the present study, the water table was the common strongest driver of CH_4 fluxes in all ecosystem manipulations.

The water table was also found to be the strongest driver of CH_4 fluxes in short-term peat core water table manipulation in laboratory experiments (Funk and others 1994; Aerts and Ludwig 1998; Blodau and Moore 2003; White and others 2008; Dinsmore and others 2009). Levy and others (2012) measured fluxes from 11 mineral soils with an assumed water level of 0 cm and 10 peat soils with a mean water table of 11 cm below the soil surface and obtained a CH_4 emission factor of 1.09 mg m^{-2} day^{-1} increase per cm increase in water table. By comparison, this emission factor is two orders of magnitude greater than our value of

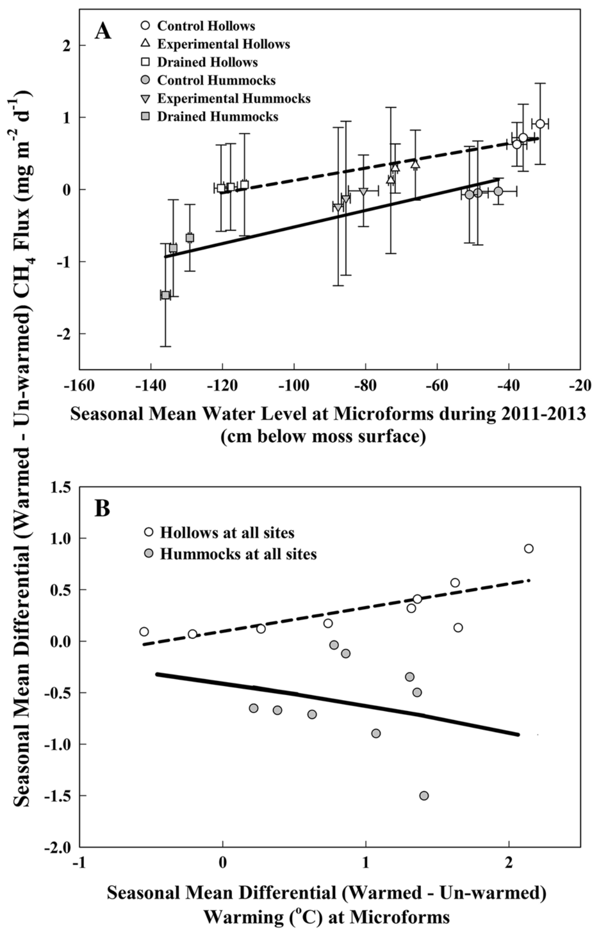

Figure 4. **A** Seasonal mean effect of warming on CH_4 flux versus water level (n = 18) at hollow and hummock microforms at the three water table treatment sites (hollows: slope = 0.011, intercept = 0.98, $F_{1,9}$ = 54.90, $P < 0.001$, R^2 = 0.86; hummocks: slope = 0.012, intercept = 0.63, $F_{1,9}$ = 24.51, $P < 0.001$, R^2 = 0.73). Warming effect was determined as the difference in mean flux between warmed and unwarmed plots for each microform-water level combination. The responses of hollows and hummocks are statistically different (ANOVA; $F_{1,18}$ = 41.56, $P < 0.001$). The *horizontal error bars* represent ±standard deviation of mean of the seasonal change in water level due to warming treatment (warmed − un-warmed water level) at the three replicate microforms. The *vertical error bars* represent ±standard deviation of mean of the seasonal change in CH_4 flux due to warming treatment (warmed − un-warmed CH_4 flux) at the three replicate microforms. **B** Seasonal mean effect of warming on CH_4 flux response versus total OTC warming (warmed − un-warmed) at the warmed (n = 18) hollow and hummock microforms at the three water table treatment sites (hollows: slope = 0.23, intercept = 0.01, $F_{1,9}$ = 12.68, P = 0.006, R^2 = 0.57; hummocks: slope = −0.23, intercept = −0.39, $F_{1,9}$ = 0.498, P = 0.498, R^2 = 0.23).

0.03 mg m^{-2} day^{-1} per cm change in water table. We derived the emission factor from mean CH_4 flux response to a combined mean water level of 81 cm below the surface considering all sites, microforms and years. Thus, the difference is not surprising given that an exponential relationship between CH_4 flux and water table has been reported (for example, Moore and Roulet 1993) and thus shifts in water table near the peat surface would be expected to have a substantially greater effect on CH_4 flux than those occurring much deeper in the peat profile. This does indicate that although water table drawdown in already dry continental bogs will likely have little effect on CH_4 emissions, water table shifts in wetter peatlands, such as rich fens, are expected to have much greater impact on CH_4 flux.

Effect of Microform Type on CH_4 Flux

Microform type influenced CH_4 fluxes significantly (Table 3) with consistently higher fluxes at hollows than that at hummocks at all sites and in all years (Table 3; Figure 3A) similar to the findings of Bubier and others (1993). This again illustrates the strong water table control on CH_4 flux. When comparing the response of microform types to water table drawdown, hollows showed greater reduction in fluxes than hummocks at all sites, although the microform–water table treatment interaction was not significant (Table 3). Greater flux reduction at hollows than at hummocks could be due to already higher fluxes and an initially shallower water table. In contrast, Strack and others (2004) observed a smaller reduction in efflux at hollows than that at hummocks due to difference in substrate availability, temperature regime, and potential for oxidation between microforms. Similarly, at the same study site, Strack and Waddington (2007) observed an overall reduced flux in response to short-term lowering of water table, although hollows, in contrast to our finding, responded little to the water table manipulation.

Warming Effect on CH_4 Flux

Warming alone reduced fluxes by 9 and 17% across the short-term and longer-term water table treatments, respectively, whereas at the control site warming increased CH_4 flux by 5%. However, this effect was not statistically significant. This supports the fact that, given saturated soil conditions, CH_4 flux is also dependent upon soil temperature (Kettunen and others 2000; Laine and others 2007) to initiate or enhance methanogenesis and/or methanotrophy and thus alter CH_4 flux (Macdonald and others 1998; Segers 1998; Updegraff and others 2001; Turetsky and others 2008; White and others 2008; Olefeldt and others 2013). These results are consistent with those of Turetsky and others (2008) who found that warming increased fluxes by 75% in a rich fen with water table elevated by 11 cm and decreased fluxes by 17% in the same rich fen with water table lowered by 8 cm. We found water table at sites to be related significantly to net warming at $T_{soil\ 5cm}$. Turetsky and others (2008) explained this relationship in that the position of the water table controls the exchange of heat between different peat layers through thermal conductivity. Therefore, water level in our water table and warming manipulation experiment had a two-prong effect on CH_4 flux, directly controlling depth of the anoxic zone, and indirectly controlling heat transfer to the anoxic layer. Our drained site hummocks had the deepest water table but still either emitted or consumed a small amount of CH_4, with flux ranging from 0.6 mg m^{-2} day^{-1} in 2011 to −0.5 mg m^{-2} day^{-1} in 2013. This smaller response to warming was due to low sensitivity of considerably deep water table to temperature changes (Olefeldt and others 2013). The small fluxes quantified at our dry sites fall well within the flux ranges found by Turetsky and others (2002). Overall, the deeper water table in the Wandering River continental bog compared to other peatland warming manipulation experiments, likely limited the effect of warming on CH_4 flux.

Microform type had a significant interaction with warming to influence CH_4 flux. Therefore, the warming increased fluxes at hollows and reduced fluxes at hummocks. This is likely due to the differential (warmed − un-warmed) warming and relative water table position (Figure 4). Higher warming sensitivity and shallower water table at hollows led to greater heat transfer to the anoxic zone that may have induced greater CH_4 production, transfer, and emission to the atmosphere. In contrast, at hummocks warming either reduced CH_4 emission or even resulted in CH_4 consumption. The inverse response of hummocks to warming treatment (Figure 4B) was likely due to their already deeper water table, higher availability of oxygen in the soil, and might also have been supported by greater coverage of woody shrubs resistant to decay and not involved in transport and emission of CH_4 in to the atmosphere. This result supports the work of Macdonald and others (1998) who found significantly higher fluxes at pools (wetter) than that at lawns (drier in this case) in response to OTC warming in blanket bog monoliths, and Johnson and others (2013) who also reported enhanced fluxes at wetter sites compared to those at hummocks that had oxic conditions and were composed of decay-resistant vegetation. However, the exactly opposite responses of hollows and hummocks to OTC warming observed are unique to the present study. To sum up, warming likely increased both production and consumption of CH_4, but the effect on production dominated at hollows and consumption at hummocks where increased rates of oxidation led to greater negative flux.

Conclusions

(1) Water table was the dominant control on CH_4 flux at the three dry ombrotrophic bog sites located at mid-latitude (55°N), during the growing seasons (May–October) of 2011–2013. Water table drawdown greatly reduced flux and the reduction varied with time: 50% in 3 years and 76% in 13 years of drainage, likely by thickening the oxic zone and reducing potential heat flow to the zone of methanogenesis. Therefore, CH_4 fluxes will likely be reduced by lowering of water table induced by climatic warming at the non-permafrost ombrotrophic bogs of Alberta. The initial water table position will also be an important control on the overall response.

(2) The CH_4 fluxes across all sites fell along the same functional relationship with water level. Therefore, the successional changes in vegetation and peat properties expected to occur in response to longer-term drainage appear to play a minor role in the balance of CH_4 production and degradation in continental bogs.

(3) Microforms at the studied Alberta bog sites responded to warming differently. After 3 and 13 years of water table drawdown, warming increased flux at hollows by 21 and 26%, and reduced flux at hummocks by 37 and 56%, respectively. Similarly, at the control site, warming increased hollow CH_4 flux by 16% while reduced flux at hummocks by 4%. Because hollows had net efflux of CH_4, warming likely increased CH_4 production and thus flux. In contrast, hummocks often had net CH_4 consumption suggesting that warming increased rates of microbial CH_4 oxidation leading to reduced flux. Therefore, although climatic warming is expected to reduce CH_4 efflux from dry ombrotrophic bogs of Alberta, different microforms at these bogs may respond differ-

ently with accelerated emissions at warmed, wetter (hollows) and reduced emissions at warmed, drier (hummocks) microforms. However, given the much lower emissions from these dry bogs in comparison with wetter fens in western Canada, emissions will likely be effected very little by the climatic warming. Hence we conclude that predicted soil warming will have a limited direct impact on overall CH_4 emissions from the non-permafrost dry continental bogs of Alberta.

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