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Boreal peatland C fluxes under varying permafrost regimes

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Abstract

Discontinuous permafrost in peatlands has recently been melting across western Canada, creating wet *Sphagnum-Carex* lawns (internal lawns) interspersed within drier ombrotrophic bog. Permafrost degradation alters peat hydrology, thermal regimes and plant species assemblages, all of which could affect gaseous C emissions in peatlands. We quantified CO_2 and CH_4 fluxes across the peat-atmosphere boundary using dark static chambers in adjacent internal lawns, continental bogs and frost mounds in an area of localized permafrost in north-central Saskatchewan. Carbon dioxide and CH_4 fluxes ranged from 0.2 to 14.6 mmol CO_2 m^{-2} d^{-1} and from -24 to 344 μmol CH_4, respectively, and differed significantly among peatland types and sampling dates. Our estimates of CH_4 flux are low compared to previous estimates from boreal wetlands, with net consumption of CH_4 typically in frost mounds. Permafrost melt in our study area is associated with 1.6- and 30-fold increases in CO_2 and CH_4 emissions, respectively. More widespread thaw across the discontinuous permafrost region will be an important consideration to boreal C budgets with future climatic changes. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Carbon dioxide; Methane; Peatlands; Permafrost; Permafrost melt

1. Introduction

Peatlands cover over 365 000 km^2 in Alberta, Saskatchewan, and Manitoba and store about 48 Pg of C as peat and living biomass (Vitt et al., 2000a). Within this region, about 28% of peatlands are underlain by permafrost that, in total, store 13 Pg of C (Vitt et al., 2000a). However, permafrost distribution ranges from continuous coverage in the northern continuous permafrost zone to discontinuous ice lenses in the localized permafrost zone (LPZ; Zoltai, 1995; Beilman et al., 2001). Near its southern limit in the LPZ, permafrost is restricted to ombrotrophic peatlands where black spruce (*Picea mariana*) stands and the underlying peat promote ice aggradation or persistence (Zoltai, 1995; Halsey et al., 1995; Vitt et al., 2000b).

The maximum extent of permafrost in western Canada occurred during the Little Ice Age (Halsey et al., 1995). Over the past 150–200 yr, temperatures across the boreal forest have increased by about 1 °C (Campbell and McAndrews, 1993), resulting in widespread permafrost degradation (Halsey et al., 1995; Vitt et al., 2000b). Peatland surface topography collapses with ice melt, increasing water availability, and increasing insolation by inundation of *P. mariana* roots resulting in tree death (Vitt et al., 1994, 2000b). Internal lawns are open, relatively wet *Sphagnum-Carex* lawns that represent localized permafrost degradation (Vitt et al., 1994).

Peatlands globally are believed to function as a net sink for atmospheric CO_2 and as a net source of CH_4 (Roulet et al., 1992; Bartlett and Harriss, 1993; Cao et al., 1998; Whalen and Reeburgh, 2000). Detailed C balance studies, however, often reveal that individual peatlands may switch from net C sinks to sources on an annual basis (Alm et al., 1997; Rivers et al., 1998; Waddington and Roulet, 2000). The presence or absence of permafrost may have important consequences for C cycling in peatlands, and for our understanding of the future responses of boreal systems to climatic change. However, there are few data comparing C emissions between peatlands with differing permafrost patterns (Bubier et al., 1995; Liblik et al., 1997).

Our research goal was to investigate differences in CO_2 and CH_4 fluxes across the peatland-atmosphere boundary between peatlands with differing permafrost regimes on a local spatial scale in the LPZ. Here, we quantify CO_2 and CH_4 fluxes in internal lawns, and compare these to C fluxes from surrounding peatlands, including frost mounds (with intact permafrost) and continental bogs (i.e. with no

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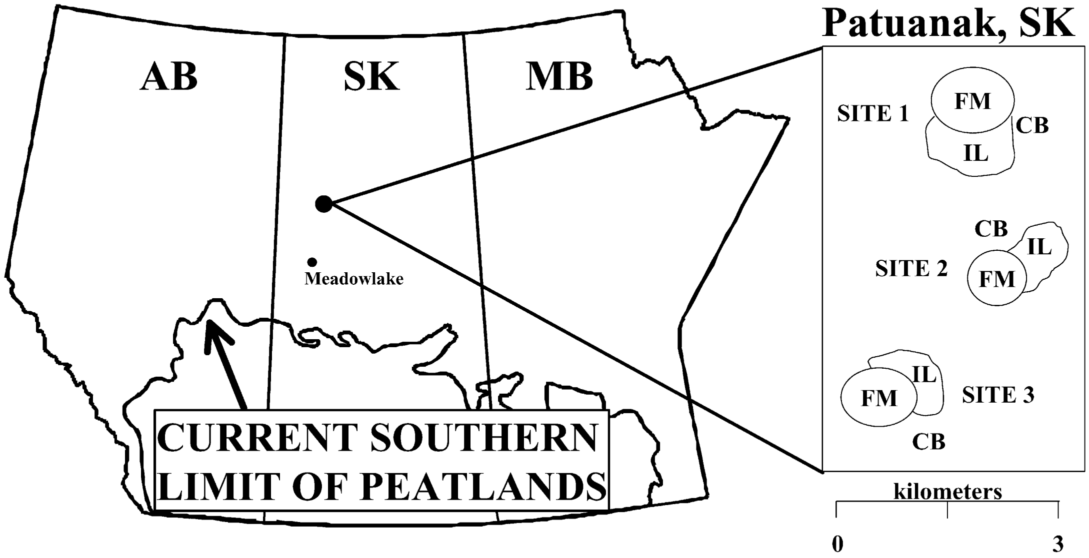

Fig. 1. Map of western, continental Canada [Alberta (AB), Saskatchewan (SK), Manitoba (MB)] showing the location of our study area in central Saskatchewan, and a schematic outlining our sampling design. We measured gaseous C emissions in three sites, each of which contained a bog underlain with intact permafrost (FM), an internal lawn (IL) and continental bog (CB).

evidence of permafrost; Vitt et al., 1994). We did not aim to capture the full extent of variability in emission rates over a growing season. Instead, we sampled in adjacent peatland features (internal lawn, frost mound, and bog) simultaneously to determine the influence of permafrost and permafrost melt on C emissions.

2. Materials and methods

2.1. Field sites

Our study area is a peatland complex near Patuanak, Saskatchewan (55°51′ N, 107°41′ W) situated in the LPZ (Fig. 1). Ombrotrophic bog, dominated by *P. mariana*, *Ledum groendlandicum*, and *Sphagnum fuscum*, is the most common wetland feature in the area. Isolated frost mounds are also present as well as internal lawns; the latter of which represent recent past or ongoing permafrost melt. Bogs underlain by permafrost have closed canopies of *P. mariana*; moss cover typically consists of *Pleurozium schreberi* and *Hylocomium splendens*. Internal lawns of western Canada are characterized by *S. riparium*, *S. angustifolium*, and *Carex* sp.

We established three study sites, each consisting of a frost mound, an adjacent internal lawn, and a nearby expanse of continental bog (Fig. 1). The internal lawns formed with the collapse of permafrost more than 100 yr ago (Turetsky, unpub data). Sites were sampled three times throughout the growing season of 1998 (referred to as 8/98, 9/98, 10/98). In the spring of 1999, a wildfire burned through Site 1, causing considerable melting of the local permafrost lens and extensive damage through the creation of a fire break (Turetsky and Wieder, 2001). We did not sample this site in 1999, but continued to quantify C emissions on four sampling dates (referred to as 7/99, 8/99, 9/99, 10/99) in the two unburned sites.

2.2. Sampling for CO_2 and CH_4 flux

Fluxes of CO_2 and CH_4 were quantified in each site using opaque closed chambers (2.5 l, 0.2 m^2 area) fitted with rubber septa for headspace sampling. On each sampling date, the three peatland features (frost mound, internal lawn, and continental bog) within a site were sampled simultaneously at midday. Five replicate chambers with sharp plastic edges were placed randomly on each peatland surface and inserted into the peat to a depth of about 5–8 cm. We attempted to minimise installation disturbance by cutting into the peat surface 15–30 min prior to final chamber placement and using temporary boardwalks during sampling in wet areas. Both vascular shrub and non-vascular communities were well represented within chambers, although our chamber volume necessitated the exclusion of larger shrubs and trees. We used syringes equipped with 3-way Luer-lock stopcocks to mix headspace gas within the chamber prior to collecting 15 ml of headspace gas at 0, 15, 30 and 45 min following the start of the measurement period. At each chamber during the measurement period, we recorded air temperatures near the peat surface and peat temperature at 5 cm depth. Afterwards, water table position relative to the peat surface was measured at several locations throughout the area of chamber placement.

Syringes were transported back to the University of Alberta and processed within 48 h. Gas samples were analyzed on a Hewlett Packard 5890 Series II chromatograph using a Chromosorb 102 column and purified He as

Table 1
Analysis of variance results conducted on ranks of the data, with site as a blocked effect, feature as a fixed effect and date as a random effect. The error mean square term is equivalent to variation among chambers for each site × feature × date combination. The feature × date mean square term is used to calculate the F statistic for the fixed feature effect; error mean square terms are used to calculate other F statistics (cf. Underwood, 1997)

	df	Type III sum of squares	F	P
CO_2 model effects				
Site	2	2188	0.71	0.4950
Feature	2	17437	3.84[a]	0.0513
Date	6	99961	10.76	< 0.0001
Feature × Date	12	27233	1.47	0.1475
Error	146	226081		
CH_4 model effects				
Site	2	10267	3.69	0.0271
Feature	2	93781	12.04[a]	0.0014
Date	6	47630	5.71	< 0.0001
Feature × Date	12	46721	2.80	0.0017
Error	155	215402		

[a] Feature × Date mean square used to calculate F statistic.

a carrier gas. Flame ionization and thermal conductivity detectors were used to quantify CH_4 and CO_2 concentrations, respectively. We used external standards of both CH_4 and CO_2 (Scott Gases, Plumsteadville, PA) for calibration, with standard error of multiple injections <5%. Flux rates were calculated from the slopes of headspace gas concentration regressed with time. Nonlinear regressions with R^2 values <0.95 (approximately 10% of chamber flux rates) due to disturbance or ebullion were rejected; data for these chambers are not included in our analysis.

2.3. Statistical design

Our design corresponds to a randomized complete block design with site (site 1,2,3) as the block effect, peatland feature (bog, frost mound, internal lawn) as a fixed effect, and date as a random effect (Fig. 1). Variation among individual chambers, placed randomly on each peatland feature within each site during each sampling date, represent the residual or error term in the ANOVA (cf. Underwood, 1997). The feature by × date mean square term was used to calculate the F statistic for the fixed feature effect; error mean square terms were used to calculate other F statistics (cf. Underwood, 1997). Residuals obtained subsequent to running the ANOVA were not normally distributed, for both CO_2 (Shapiro–Wilk, $W = 0.3373$; $P < 0.0001$) and CH_4 (Shapiro–Wilk, $W = 0.8076$; $P < 0.0001$). Therefore, we report results from an ANOVA run on rank-transformed data. Subsequent to obtaining a significant effect, a posteriori comparisons of rank means were accomplished using Tukey's Honestly Significant Difference tests (SAS, 1998).

Stepwise multiple regressions were used to determine the influence of peat temperature, air temperature, and water level height on both CO_2 and CH_4 respiration. We used a Spearman's correlation test to determine whether CO_2 and CH_4 fluxes were correlated, and Pearson's Correlation tests to investigate correlation between soil temperatures, air temperatures and water table height (SAS, 1998).

3. Results

3.1. CO_2 fluxes

CO_2 fluxes varied by feature and sampling date, with no significant interaction between these main effects (Table 1). Internal lawns had higher CO_2 fluxes (mean ± s.e.: 2.59 ± 0.34) than either frost mounds (1.62 ± 0.29) or bogs (1.94 ± 0.31 mmol CO_2 m^{-2} d^{-1}; Table 2). Across peatland types, C fluxes generally were higher during the 1998 sampling events compared to those in 1999 (Table 2; means ± s.e. for 1998 and 1999 of 2.44 ± 0.27 and 0.80 ± 0.14 mmol CO_2 m^{-2} d^{-1}, respectively).

3.2. CH_4 fluxes

CH_4 fluxes varied by a feature × sampling date interaction (Table 1). In 1998, fluxes were greater from internal lawns than from frost mounds; fluxes from bogs were intermediate and not different from fluxes from either internal lawns or frost mounds (Table 2). In contrast, in 1999 fluxes from internal lawns were lower than in 1998, such that there were no statistically significant differences between features.

Table 2
Mean (s.e.) CO_2 and CH_4 fluxes from adjacent bogs, internal lawns (melted permafrost), and frost mounds (intact permafrost) in north-eastern Saskatchewan on seven sampling dates. For CO_2, different superscript letters or numbers denote significant a posteriori differences between dates or features, respectively (Tukey's HSD). For CH_4, different letter superscripts denote significant a posteriori differences between feature × date means

	CO_2 flux (mmol m^{-2} d^{-1})			CH_4 flux (μmol CH_4 m^{-2} d^{-1})		
Date	Bogs^2	Internal lawns^1	Frost mounds^2	Bogs	Internal lawns	Frost mounds
8/98	3.40 (0.35)^a	4.44 (0.54)^a	2.25 (0.41)^a	6.26 (2.20)$^{a-c}$	26.18 (5.76)^a	0.26 (0.71)^{de}
9/98	2.89 (1.16)^b	1.38 (0.25)^b	1.66 (0.55)^b	3.64 (2.10)$^{b-e}$	9.18 (2.63)$^{a-c}$	0.28 (0.99)^{de}
10/98	2.01 (0.94)^b	3.39 (1.12)^b	2.49 (1.30)^b	2.64 (0.55)$^{a-e}$	38.27 (28.03)^{ab}	−1.20 (0.69)^e
7/99	0.78 (0.27)^{bc}	2.00 (0.43)^{bc}	0.29 (0.08)^{bc}	−0.11 (0.32)^{de}	0.56 (0.75)^{de}	0.04 (0.35)^{de}
8/99	0.82 (0.27)^{bc}	3.17 (2.19)^{bc}	0.72 (0.23)^{bc}	−0.40 (0.44)^{de}	1.50 (1.72)$^{b-e}$	−0.68 (0.83)^e
9/99	0.86 (0.18)^{bc}	1.55 (0.67)^{bc}	1.45 (0.52)^{bc}	3.76 (1.23)$^{a-d}$	3.94 (2.80)$^{b-e}$	0.71 (8.16)$^{c-e}$
10/99	0.38 (0.07)^c	0.42 (0.15)^c	0.59 (0.11)^c	0.69 (0.15)$^{c-e}$	3.48 (1.26)$^{a-e}$	0.002 (0.19)^{de}

Table 3
Mean surface peat temperatures, air temperatures, and water table position (± s.e.; $n = 15$ and 10 in 1998 and 1999, respectively) in continental bogs, internal lawns, and frost mounds during the 1998 and 1999 sampling events. In frost mounds, we measured depth to the permafrost table or active layer (i.e. seasonally melting ice lying above the permafrost table). Water tables at 0 cm would be flush with the moss surface

	Bogs	Internal lawns	Frost mounds
Air temperature (°C)			
8/98	40.0 ± 0.5	30.5 ± 0.3	28.7 ± 0.3
9/98	14.0 ± 0.7	14.0 ± 0.7	12.0 ± 0.5
10/98	12.0 ± 0.4	12.0 ± 0.4	9.7 ± 0.5
7/99	25.5 ± 0.5	23.5 ± 0.5	22.0 ± 0.01
8/99	18.5 ± 0.8	20.0 ± 1.3	19.0 ± 0.01
9/99	21.0 ± 0.3	17.0 ± 0.3	16.0 ± 1.3
10/99	9.5 ± 1.8	9.0 ± 1.7	8.5 ± 1.5
Peat temperature (°C)			
8/98	21.1 ± 0.8	15.6 ± 0.8	21.9 ± 0.5
9/98	11.9 ± 0.5	10.0 ± 0.4	13.6 ± 0.5
10/98	9.1 ± 0.4	7.6 ± 0.5	8.7 ± 0.2
7/99	19.1 ± 0.8	21.5 ± 0.2	21.1 ± 0.3
8/99	15.4 ± 1.2	16.1 ± 1.4	14.4 ± 0.8
9/99	13.6 ± 1.8	9.9 ± 0.5	9.4 ± 0.4
10/99	7.2 ± 1.07	5.2 ± 0.5	7.1 ± 1.0
Water table height (cm)			
8/98	36.6 ± 2.3	18.0 ± 1.4	65.0 ± 7.2
9/98	44.8 ± 2.9	19.8 ± 0.6	54.4 ± 1.1
10/98	70.7 ± 6.4	20.4 ± 1.9	57.8 ± 2.5
7/99	31.2 ± 0.6	18.8 ± 1.2	39.5 ± 1.8
8/99	36.5 ± 1.5	10.3 ± 0.5	30.4 ± 0.8
9/99	26.0 ± 0.5	14.8 ± 1.5	40.2 ± 3.7
10/99	30.7 ± 2.1	12.2 ± 3.1	40.0 ± 1.2

3.3. Interrelationships

Fluxes of CO_2 and CH_4 were significantly and positively correlated (Spearman's correlation coefficient $= 0.47$, $P = 0.0001$). Stepwise multiple regressions showed that both air and surface peat temperatures, but not water table position (Table 3), were significant predictors of CO_2 emission (model $R^2 = 0.27$; air temperature, $P < 0.0001$; peat temperature, $P = 0.0026$). Water table level and peat temperature, but not air temperature, were significant, but surprisingly weak predictors of CH_4 flux (model $R^2 = 0.18$; water level, $P < 0.0001$; peat temperature, $P = 0.0084$).

Peat temperature and air temperature were positively correlated throughout the two year sampling period (Pearson's correlation coefficient, $r = 0.81$, $P = 0.0001$). While water table levels and peat temperatures showed no correlation ($r = 0.09$, $P = 0.1381$), water table levels were negatively correlated with air temperatures ($r = -0.12$, $P = 0.0580$).

4. Discussion

CO_2 flux measurements using dark static chambers include respiration from living aboveground and belowground plant parts (mosses, sedges, short-statured shrubs) as well as aerobic and anaerobic microbial activity within the peat column. Generally, our values for CO_2 flux (mean ± s.e. $= 2.05 \pm 0.18$ mmol m^{-2} d^{-1} across 170 chambers) agree with other studies using static chambers to quantify CO_2 flux from peatlands. CO_2 emissions averaged 1.20 and 3.95 mmol m^{-2} d^{-1} for a bog and poor fen in Alberta, respectively (Vitt et al., 1990). Moore and Knowles (1987) reported rates of CO_2 evolution from subarctic fens in Quebec ranging from 2.00 to 29.00 mmol CO_2 m^{-2} d^{-1}, while fluxes measured in drained swamp peatlands in southern Quebec ranged from 0 to 0.36 mmol CO_2 m^{-2} d^{-1} (Shannon et al., 1993).

Both field and laboratory approaches have identified soil temperatures and water table position as important environmental controls on C mineralization to CO_2 in organic soils (cf. Scanlon and Moore, 2000; Chapman and Thurlow, 1998; Yavitt et al., 1987, 1997; Alm et al., 1997; Laine et al., 1996; Silvola et al., 1996). In this study, peat and air temperatures during chamber incubation (Table 3) together explained only about 25% of the variation in CO_2 flux, and showed significant collinearity. Additionally, height of water levels (bogs and internal lawns) or permafrost tables (frost mounds; Table 3) were not important controls on CO_2 flux in these boreal peatlands.

Methane fluxes from peatlands typically show large variation, both temporally and spatially (cf. Waddington and Roulet, 1996; Van den Pol-Van Dasselaar, 1999; Kettunen et al., 2000). Methane flux from our peatland sites ranged from -24.2 to 344.4 μmol CH_4 m^{-2} d^{-1}, and averaged 6.4 ± 2.1 μmol CH_4 m^{-2} d^{-1} (across 178 chamber measurements). These flux estimates are low compared to other published values. We note, however, that few studies have investigated CH_4 flux from western continental peatlands where conditions tend to be dry with low water tables (but see Suyker et al., 1996). Vitt et al. (1990) also used static chambers to quantify CH_4 emissions from peatlands in northern Alberta, and measured negligible CH_4 emissions from a bog, and mean rates of 56.3 μmol CH_4 m^{-2} d^{-1} from a poor fen. Episodic rain events may play important roles in controlling pulses of CH_4 emissions from these moisture deficient peatlands (cf. Kettunen et al., 2000). This process is difficult to characterize in a remote field setting, but points to the need for more temporally intensive measurements of CH_4 emissions in peatlands affected by permafrost melt.

Ombrotrophic peatlands in continental Canada typically have water tables lower than 40–50 cm below the moss surface. Low water tables probably contribute to minimal CH_4 flux to the atmosphere as CH_4 produced at depth is oxidized as it diffuses upward through the aerobic surface peat layers. Although water tables in our sites were slightly higher in 1999 than in 1988, particularly within frost mounds (Table 3), they were not high enough to significantly enhance CH_4 emission relative to 1998. Water level measurements in our sites were correlated with air temperatures, yet neither were important predictors of CH_4 flux.

Peat accumulation represents the balance between net primary production (NPP) and gaseous C losses from heterotrophic respiration plus dissolved C losses. Previous work has shown that internal lawns accumulate near-surface peat at rates faster than in bogs or frost mounds (Turetsky et al., 2000; Camill et al., 2001; Turetsky, unpub data). Here, we show that conversion of frost mounds to internal lawns is associated with 1.6- and 30-fold increases in CO_2 and CH_4 emissions, respectively. This suggests that internal lawn NPP also must be high compared to NPP in frost mounds, from which internal lawns are derived.

While frost mounds may act to remove CH_4 from the atmosphere through oxidation pathways, internal lawns showed elevated net CH_4 flux to the atmosphere in our sampling over two frost-free seasons. As CH_4 shows greater greenhouse warming potential relative to CO_2 (Schimel et al., 1996), continued permafrost melt on a regional scale in the LPZ of boreal western Canada may represent a positive feedback on climate change. Although internal lawns will undergo succession, eventually to continental bogs (Camill, 1999; Turetsky et al., 2000), the temporal trajectory of this development is poorly known. The internal lawns studied here formed from permafrost collapse more than a century ago (Turetsky, unpub data), suggesting that permafrost melt may yield elevated emissions of CH_4 over prolonged periods, particularly in the LPZ where temperatures may be too warm to support permafrost re-aggradation (Halsey et al., 1995). Different permafrost regimes appear to influence CH_4 and CO_2 fluxes across the peatland-atmosphere boundary, and therefore the patchy spatial distribution of peatland features (bogs without permafrost, frost mounds, and internal lawns representing recent thaw) should be considered when scaling-up from site-specific studies to estimate boreal peatland C budgets to regional scales.

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