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Methane fluxes from three peatlands in the La Grande Rivière watershed, James Bay lowland, Canada

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[1] Methane fluxes were measured on vegetated surfaces (2003) and pools (2004) of three peatlands (LG1-LG2-LG3) located 30, 100, and 200 km along a transect from the James Bay coast, in the La Grande Rivière watershed, James Bay lowland, Quebec, Canada. Fluxes were measured with static chambers at sites chosen to represent the biotypes characteristic of each peatland, from hummocks with a water table 35 cm below the surface to pools 100 cm deep. Average CH_4 fluxes for the biotypes on vegetated surfaces sampled during summer 2003 ranged from 3.5 to 197 mg m^{-2} d^{-1}, while summer 2004 average floating chamber pool fluxes ranged between 6.2 and 3165 mg CH_4 m^{-2} d^{-1}. Seasonal average daily CH_4 fluxes on vegetated surface were strongly correlated with average water table depth, greater fluxes occurring where the water table was close to the surface, and with vegetation cover, particularly the aboveground biomass of sedges. Within the summer, increasing CH_4 fluxes from vegetated surfaces were correlated with rising peat temperature. Pool fluxes from the LG1 and LG2 peatlands decreased with increasing pool depth, but not at LG3. Estimated growing season CH_4 emissions for the three peatlands were of 44 ± 21 (standard error), 21 ± 9.4 and 52 ± 17 mg CH_4 m^{-2} d^{-1} for the LG1, LG2, and LG3 peatlands, respectively. Estimated annual release of CH_4 is 3.8 g m^{-2} with the winter contributing to 13% of the overall emission, based on winter-time measurements at LG2.

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1. Introduction

[2] Northern peatlands are an important source of methane (CH_4) to the atmosphere, estimated to be between 20 and 50 Tg yr^{-1} [*Mikaloff Fletcher et al.*, 2004a, 2004b]. Fluxes of CH_4 from peatlands during snow-free periods show large spatial and temporal variability, ranging from a slight uptake of 3.5 mg CH_4 m^{-2} d^{-1} to emissions of more than 1000 mg CH_4 m^{-2} d^{-1} [*Blodau*, 2002]. During winter, CH_4 is released from the peatland through the frozen peat surface and snowpack but the fluxes are smaller, ranging between 5 and 23 mg CH_4 m^{-2} d^{-1} [e.g., *Panikov and Dedysh*, 2000]. Peatland pool diffusive and bubble CH_4 fluxes are variable and generally greater than for vegetated surfaces [e.g., *Hamilton et al.*, 1994; *Dove et al.*, 1999; *Waddington and Roulet*, 1996].

[3] These large variations in fluxes from northern peatlands are linked to environmental controls that affect CH_4 production, oxidation and transport. Methanogenic bacteria produce CH_4 under anoxic conditions, primarily beneath and just above the water table in wetter parts of the peat layer. On vegetated surfaces, water table position controls CH_4 production by changing the thickness of the anoxic zone and the thickness of the overlying unsaturated zone, which may consume CH_4. Many studies have found strong relationships between mean summer water table depth and summer mean daily CH_4 fluxes, which are partially explained by the thickness of the oxic and anoxic zones [e.g., *Moore and Roulet*, 1993; *Huttunen et al.*, 2003]. Peat temperature also controls CH_4 production and oxidation [e.g., *Moore and Dalva*, 1993; *Updegraff et al.*, 1995; *Thérien and Morrison*, 2005]. CH_4 consumption is less responsive to temperature than CH_4 production with average Q_{10} values of 1.9 for consumption compared to 4.1 for production [*Segers*, 1998]. The surface vegetation plays a role in methane production by providing labile C through root decay and exudation, which can act as substrates for CH_4 production [*Whiting and Chanton*, 1992, 1993; *Waddington et al.*, 1996; *Bellisario et al.*, 1999]. Vascular plants such as sedges can act as conduit for oxygen from the atmosphere to the rhizosphere, and for CH_4 from the anoxic layer to the atmosphere, the former increasing CH_4 oxidation and decreasing potential emissions and the latter having the opposite effect, CH_4 bypassing the oxic layer [*Whiting and Chanton*, 1992; *Bellisario et al.*, 1999]. In a similar

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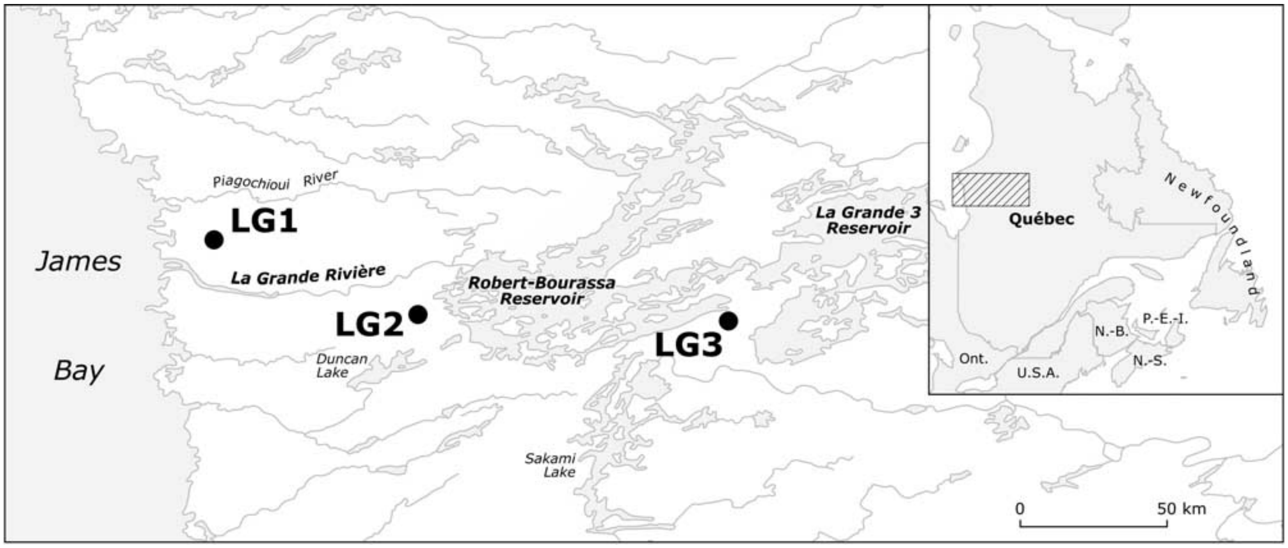

Figure 1. Study area and location of the three peatlands.

way, ebullition fluxes in the pools allow CH_4 to go directly from the sediments to the atmosphere.

[4] In this paper, we examine CH_4 fluxes from three peatlands in the La Grande Rivière region of Quebec on the eastern side of James Bay as part of a broader project on past and present carbon dynamics in boreal peatlands. Despite extensive peatlands and hydro-electric development in this region, measurements of peatland CH_4 exchange have been restricted to the Schefferville region to the east in subarctic Quebec [*Moore et al.*, 1990] and the Hudson Bay Lowlands to the west [e.g., *Roulet et al.*, 1994]. The research is driven by the need to estimate emission rates of CH_4 before and after flooding of low-lying areas. We chose these three sites, adjacent to the main reservoirs, to represent a chronosequence of peatland development from young at the coast to older inland. Our aim was to determine the exchange of CH_4 from the vegetated parts of the peatland to pools of varying depth in each peatland and to identify the primary controls on these fluxes, testing relationships derived elsewhere. We used aerial photography to estimate the coverage of each unit in the peatlands to produce an overall spatial estimate for each of the three peatlands. For one peatland, we also measured winter fluxes and estimated an annual CH_4 flux. These results can be used to estimate landscape fluxes of CH_4 as the peatlands evolve and prior to flooding, to assess the impact of hydro-electric reservoir construction on trace gas exchanges.

2. Study Area and Climate

[5] The three peatlands are located in the La Grande Rivière area, part of the humid high boreal wetland region (Figure 1). Peatland coverage is approximately 29% [*Collins*, 2005], is larger close to the coast and decreases inland. During the last glaciation, the Laurentian ice sheet covered the region, with ice retreating between 8100 and 7000 years BP [*Dyke and Prest*, 1989], leaving important Quaternary deposits such as the Sakami moraine. At La Grande Rivière airport (YGL), located 5 km south of the LG2 peatland, the 1971–2000 mean annual temperature and precipitation was $-3.1°C$ and 684 mm, respectively. The 2003 summer was drier and warmer than normal, especially for the months of May and August, while summer 2004 was generally cooler and wetter (Figure 2).

3. Peatland Description

[6] The LG1 peatland is located 30 km east of the James Bay coast (53°54′N, 78°46′W; altitude: 38 m) in a bedrock depression next to a very shallow lake. The peatland is a patterned rich fen with treed islands [*Collins*, 2005], covers approximately 22 ha and drains into the lake. Basal dates indicate that peat started accumulating 2460 ± 40 yr BP [*Beaulieu-Audy et al.*, 2004], with an average peat thickness of 122 cm. The LG2 peatland (53°38′N, 77°43′W; altitude 195 m) is located near the city of Radisson, 100 km east of James Bay. The peatland covers approximately 165 ha, but its limits are difficult to establish since it is part of a large peatland complex, which has the Sakami moraine for a border on the east side. Basal dates indicate that peat started accumulating 6100 ± 40 yr BP [*Beaulieu-Audy et al.*, 2004], with an average peat thickness of 264 cm. The peatland is a raised bog with a poor fen margin on its eastern side [*National Wetlands Working Group*, 1988]. The LG3 peatland (53°34′N, 76°08′W; altitude 244 m) is located a further 100 km inland from the LG2 site, covers an area of approximately 59 ha and basal dates indicate that peat started accumulating 6000 ± 60 yr BP [*Beaulieu-Audy et al.*, 2004]. The average peat thickness is 273 cm. Long parallel pools and ridges cover the pools sector surface pattern. On the basis of aerial photography and field checking, we identified several surface patterns, mapped and delineated the coverage of each in the three peatlands and identified biotypes, dominant plant species and relative coverage within each of the surface patterns (Tables 1 and 2).

4. Methods

4.1. Vegetated Surface Measurements

[7] At the end of May 2003, 20 collars (diameter 25 cm) were installed in the LG1 and LG2 peatlands and 19 collars

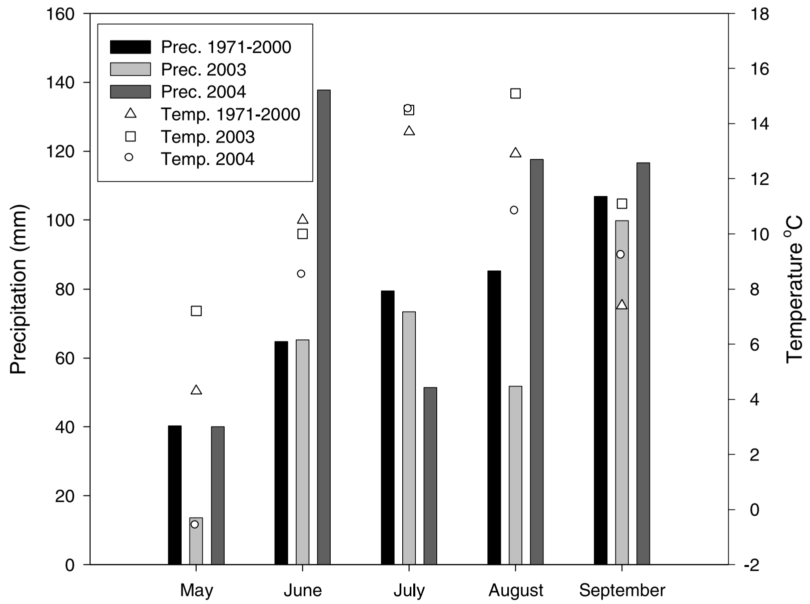

Figure 2. Monthly average precipitation (mm) and temperature (°C) for 1971–2000, 2003, and 2004.

in the LG3 peatland, with 2 to 4 collars covering each biotype (Table 1). Planks were installed on the peat surface next to each group of collars to minimize disturbance during flux measurements. PVC tubes were inserted in the peat to measure WTD next to each biotype where gas flux measurements were made. A meteorological tower was installed in each of the three peatlands in order to continuously measure water table depth (WTD), air temperature, peat temperature at 5, 10, 20 and 40 cm depth and photosynthetic photon flux density (PPFD). The tower in LG1 was located on biotype SeV while the towers in LG2 and LG3 were located on biotype LHuS (Table 1). Daily precipitation at La Grande Rivière airport and daily water table depth measured at the meteorological tower in the three peatlands are presented in Figure 3.

[8] Methane flux measurements on vegetated surfaces were made between June and August 2003 by sampling the headspace in an 18-L chamber placed on the collar. Chambers were covered with tinfoil to prevent heating inside and there was a water seal between chamber and collar. Air in the chamber was mixed prior to sampling, using a 60-mL syringe, and 10-mL samples were collected in syringes every 5 min for a 20-min period.

[9] Methane fluxes were measured at the LG2 site during one week in November 2003 and one week in March 2004. Samples were taken using the same collars as during the 2003 growing season, after removing the snow pack covering them. The snow was removed to allow access to the collar rim. There was inevitable disturbance to the snow within the collar. However, no measurements were made on the *WS* and *WD* biotypes during November 2003 and March 2004, and on the *SHo* and the *SeV* biotypes during March 2004. These collars were covered by a thick layer of ice, making it impossible to reach the sampling collar. Gas samples were collected using the same equipment used for CH_4 sampling during the 2003 growing season. However,

Table 1. Biotypes Characteristic of the Three Peatlands, and Associated Vegetation

Biotype	Abbreviation	Vegetation	Peatland
Treed island: *Sphagnum* spp. hummock with shrubs	*TiSpHuS*	*Sphagnum fuscum*, *Pleurozium schreberi*, *Chamaedaphne calyculata*, *Ledum groenlandicum*	LG1
Sphagnum spp. hummock	*SpHu*	*S. fuscum*, *C. calyculata*, *Rubus chamaemorus*	LG1-LG2-LG3
Sphagnum spp. hummock with shrubs	*SpHuS*	*S. fuscum*, *L. groenlandicum*, *C. calyculata*	LG1-LG2-LG3
Sphagnum spp. hummock with *Picea mariana*	*SpHuPim*	*S. fuscum*, *P. mariana*	LG3
Sphagnum spp. hollow	*SpHo*	*Sphagnum balticum*, *Sphagnum pulchrum*, *Carex* spp.,	LG1-LG2-LG3
Sedges and vascular	*SeV*	*Carex* spp., *Kalmia polifolia*, *Myrica gale* (LG1 only), *Equisitum palustris* (LG1 only)	LG1-LG3
Lichen hummock	*LHu*	*Cladonia stellaris*	LG2-LG3
Lichen hummock with shrubs	*LHuS*	*C. stellaris*, *L. groenlandicum*, *C. calyculata*	LG2-LG3
Pools	*P*	*Carex* spp., *Menyanthes trifoliate* (LG1 only), *E. palustris* (LG1 only)	LG1-LG3
Wet depression: *Sphagnum* spp. covered bottom	*WS*	*Sphagnum lindbergii*, *S. majus*	LG2
Wet depression: decomposing sediment	*WD*	-	LG2

Table 2. Surface Patterns, Their Coverage in Each of the Three Peatlands, and the Coverage of Biotypes Within the Surface Patterns

Peatland	Surface Pattern	Area, ha	Percentage of Total Peatland Area, %	Biotype	Coverage of Surface Pattern, %
LG1	raised bog island	0.9	4	SpHuS	100
	treed island	10	45	TiSpHuS	40
				SpHuS	60
	herbaceous	5.3	24	SeV	100
	open – uniform	0.3	1	SpHuS	100
	spotted	1.1	5	SpHuS	30
				SpHo	70
	ribbed	2.9	13	SeV	60
				P (2003)	40
	structured fen	1.4	6	SeV	30
				P (2004)	70
	large pools	0.2	1	P (2004)	100
LG2	structured fen	2.3	1	SeV	60
				P	40
	open-uniform	53	32	SpHu	40
				SpHuS	40
				LHu	10
				LHuS	10
	spotted	22	13	SpHu	15
				SpHuS	15
				SeV	70
	ribbed	46	28	SeV	25
				SpHo	25
				SpHu	20
				SpHuS	20
				LHu	5
				LHuS	5
	structured pools	42	25	WS + WD	10
				P (2004)	30
				SpHu	20
				SpHuS	20
				LHu	10
				LHuS	10
LG3	pools sector	22	37	SpHu	15
				SpHuS	15
				SpHuPi	15
				LHu	5
				LHuS	5
				SpHo	25
				P (2003)	15
				P (2004)	5
	ribbed	37	63	SpHu	10
				SpHuS	17.5
				SpHuPi	17.5
				LHu	2.5
				LHuS	2.5
				SpHo	50

10-mL glass vials with a rubber stopper and a metal crimp were used instead of 10-mL syringes. Air contained in the sealed glass vial was removed prior to sampling, using a 60-mL syringe with a 25-gauge needle. Samples were taken every 15 min for a 60-min period. Air in the chamber was mixed prior to sampling, using a 60-mL syringe. The longer sampling period is justified by the fact that the flux rates are smaller during winter than summer [*Dise*, 1992; *Alm et al.*, 1999; *Panikov and Dedysh*, 2000].

[10] Methane concentrations were determined within 48 hours of collection on a Shimadzu Mini-2 gas chromatograph using a 5-mL hand-injected sample, a 1-mL injection loop and a 6′ Poropak-Q column (50/80 mesh) at 45°C. Detector temperature was 100°C. N_2 was used as the carrier gas at a flow rate of 30 mL min^{-1}. CH_4 standards of 2.73 and 200 parts per million by volume (ppmv) were used before each analysis run. CH_4 fluxes were calculated by linear regression using the concentration change with time in the five samples, rejecting fluxes with coefficients of determination (r^2) of <0.85.

4.2. Pool Measurements

[11] During the 2004 growing season, chamber and ebullition CH_4 flux measurements were made at 15 sites within 5 to 8 pools, representing the different types of pools in each of the three peatlands. Five sites in each peatland were chosen for ebullition flux measurements, where the water column was >30 cm deep. Wood stakes, inserted in the vegetated surface peat at both ends of each transect, were used to attach the inverted funnels and/or the floating chambers to prevent them from moving during the sampling period. Chamber CH_4 flux measurements were made approximately every 10 days from the last week of June to the end of August 2004 while ebullition CO_2 and CH_4 flux measurements were made from the last week of July to the end of August. The late start was caused by frozen sediment impeding equipment insertion and leakage from the inverted funnels.

[12] Chamber CH_4 fluxes from pools were measured with floating collars, 2.5 cm above the base of the chamber, using the same sampling method and analysis used during growing season. Methane ebullition emissions in 2004 were measured with 30-cm-diameter floating inverted funnels fitted with a 100-mL graduated cylinder and rubber septum. The gas bubbles released by the sediments enter the water-filled inverted funnel and are trapped in the graduated cylinder and withdrawn with a 10-mL syringe. Ebullition fluxes were calculated by measuring the volume of gas/bubbles accumulated in the cylinder and the CH_4 mixing ratio of gas accumulated over time between the samplings. Gas samples were analyzed as described above.

5. Results

5.1. Vegetated Surface Fluxes

[13] A total of 470 flux measurements were made during summer 2003, of which 44 were rejected (see section 4). The remaining 426 measurements ranged from −2.9 to 1844 mg CH_4 m^{-2} d^{-1}, with a mean and median of 53 and 25 mg CH_4 m^{-2} d^{-1}, respectively. LG1 peatland individual CH_4 fluxes had a mean and a median of 72 and 34 mg CH_4 m^{-2} d^{-1}, respectively. Average CH_4 fluxes for each of the LG1 biotypes ranged from 5.7 mg CH_4 m^{-2} d^{-1} on the *TiSpHuS* biotype to 197 mg CH_4 m^{-2} d^{-1} in the *SpHo* biotype (Table 3). The highest biotype values of 165 and 197 mg CH_4 m^{-2} d^{-1} from the *P* and *SpHo* biotypes at LG1 are probably the result of ebullition in collars 10 and 15 during the last day of sampling (Figure 4). If these extreme fluxes are removed, the summer averages were 125 and 71 mg CH_4 m^{-2} d^{-1} for the *P* and *SpHo*, respectively. Therefore the maximum average biotype value at LG1 would be 125 mg CH_4 m^{-2} d^{-1}. At the LG2 peatland, the individual fluxes had a mean of 39 and a median of 25 mg CH_4 m^{-2} d^{-1}. Biotype summer average fluxes ranged from 3.5 mg CH_4 m^{-2} d^{-1} on the *LHu* to

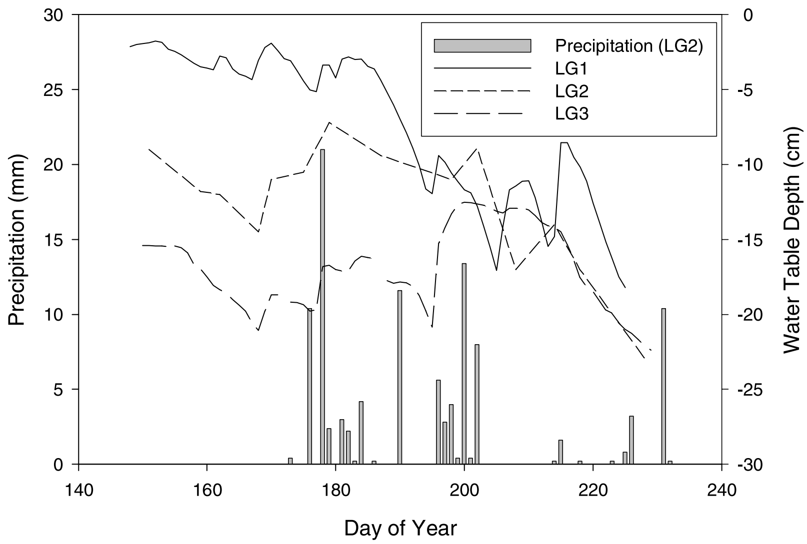

Figure 3. Daily precipitation at La Grande Rivière airport and daily water table depth measured at the meteorological tower in the three peatlands.

70 mg CH_4 m^{-2} d^{-1} in the W*S* biotype (Table 3). The LG3 peatland fluxes had a mean and median of 60 and 26 mg CH_4 m^{-2} d^{-1}, respectively. Biotype averages ranged from 6.4 mg CH_4 m^{-2} d^{-1} on the *SpHu* biotype to 124 mg CH_4 m^{-2} d^{-1} in a *SpHo* biotype (Table 3).

[14] CH_4 fluxes varied during the summer among the different peatlands. In all three sites, lowest emission rates were observed early in the season with averages showing similar patterns during the first half of the growing season, with emission rates starting between 10 and 19 mg CH_4 m^{-2} d^{-1} early in the growing season and increasing from day of year (DoY) 160 to 200. At the LG2 site, average emission peaked at 68 mg CH_4 m^{-2} d^{-1} around DoY 200 and emission patterns in all three peatlands differed after this date. Average emission from the LG2 site decreased until the end of the summer, following the peak around DoY 200. At the LG3 peatland, CH_4 flux peaked around DoY 220 at approximately 100 mg CH_4 m^{-2} d^{-1} and reached a maximum in LG1 of 217 mg CH_4 m^{-2} d^{-1} around DoY 230. Peak values are respectively 15, 5, and 8 times greater than the early season emissions measured respectively in the LG1, LG2 and LG3 peatlands. Individual flux ranges, within single days, increased through the summer at the LG1 and LG3 peatlands as shown by the increasing range of percentiles. At the LG2 peatland, the largest difference between fluxes was observed around DoY 200. In general,

Table 3. Mean Summer CH_4, Mean Water Table Depth and Q_{10} Values for Each Biotype in the Three Peatlands During Summer 2003[a]

Site	Biotype	CH_4 mg m^{-2} d^{-1} Mean	SE	n	Mean Water Table Depth, cm	Q_{10}
LG1	Treed island: *Sphagnum* spp. with shrubs (TiSpHuS)	5.7	3.2	24	−29	1.5
	Sphagnum spp. hummock (SpHu)	18	6.3	14	−24	1.5
	Sphagnum spp. hummock with shrubs (SpHuS)	21	11	17	−30	2.8
	Sphagnum spp. hollow (SpHo)	197	244	14	−8.0	1.9
	Sedges and vascular (SeV)	53	12	48	−11	2.6
	Pools (P)	165	90	24	5.5	4.1
LG2	Lichen hummock (LHu)	3.5	4.5	14	−29	2.3
	Lichen hummock with shrubs (LHuS)	5.4	4.0	12	−29	1.0
	Sphagnum spp. hummock (SpHu)	12	11	10	−16	4.1
	Sphagnum spp. hummock with shrubs (SpHuS)	3.4	3.4	7	−26	2.5
	Sphagnum spp. hollow (SpHo)	48	20	28	−7.1	1.7
	Sedges and vascular (SeV)	54	15	32	−6.7	1.9
	Sphagnum spp. bottom pool (SpP)	65	56	13	0.4	5.1
	Decomposition pool (DP)	46	35	14	0.4	1.1
LG3	*Sphagnum* spp. hummock (SpHu)	6.2	3.5	11	−28	1.9
	Sphagnum spp. hummock with shrubs (SpHuS)	9.1	5.5	12	−21	4.7
	Sphagnum hummock with *Picea mariana* (SpHuPi)	10	5.4	13	−27	2.6
	Lichen hummock (Lhu)	12	8	10	−20	1.8
	Lichen hummock with shrubs (LHuS)	8.8	10	13	−21	0.8
	Sphagnum spp. hollow (SpHo)	96	28	44	−5.2	3.8
	Pool (P)	109	34	24	2.8	2.5

[a]SE is the standard error of the mean. Q_{10} values are derived from peat temperature 20 cm below surface at the meteorological tower site.

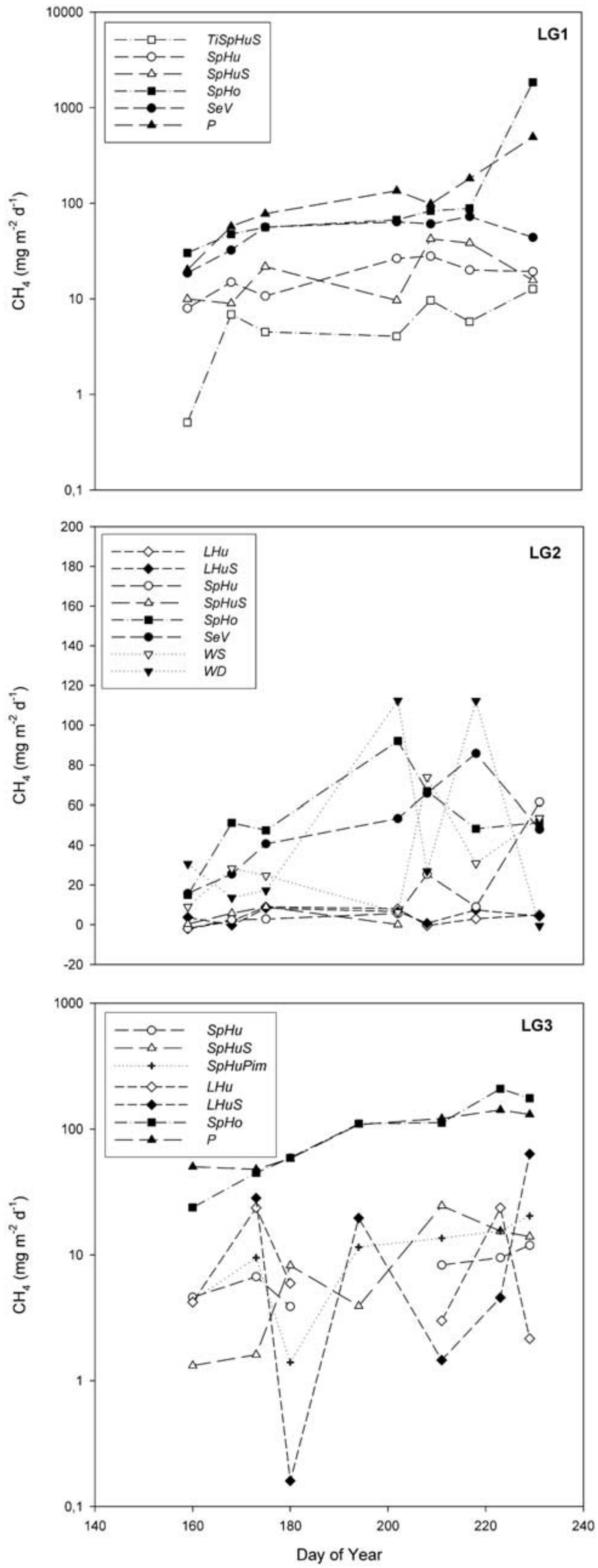

Figure 4. Seasonal variation in CH_4 flux within major biotypes in (top) LG1, (middle) LG2, and (bottom) LG3. Note the logarithmic scale for LG1 and LG3.

ranges between the 25th and 75th quartiles are greater in LG1 and LG3 than LG2 throughout the summer.

[15] Methane flux variations during the summer for each biotype show that, in general, average flux and average flux variation of the hollows were greater than for the hummocks biotype in all three peatlands. LG1 and LG3 hollows showed increasing average fluxes as the summer advanced. All three peatlands hummocks average fluxes ranged between 0 and 45 mg m^{-2} d^{-1} except for the *SpHu* biotype at LG2 and the *LHuS* biotype at LG3, which had greater fluxes for the last sampling of the growing season.

5.2. LG2 Peatland Winter Fluxes

[16] CH_4 fluxes in November 2003 ranged from −2.9 to 32.8 mg CH_4 m^{-2} d^{-1} with a mean and median of 2.0 and 0.7 mg CH_4 m^{-2} d^{-1}, respectively (Table 4). Biotypes mean CH_4 fluxes ranged from −0.4 mg CH_4 m^{-2} d^{-1} on the *LH* biotype to 4.7 mg CH_4 m^{-2} d^{-1} on both *SpHo* and *SeV* biotypes. *SeV* biotype mean CH_4 flux is statistically greater than all other biotype, except the *SpHo* ($p < 0.05$). Only the collars located on hummocks were sampled in March 2004, with fluxes ranging from 0.3 to 6.4 mg CH_4 m^{-2} d^{-1}, with a mean and median of 2.1 and 2.1 mg CH_4 m^{-2} d^{-1}, respectively. *LH* biotype mean flux was 0.6 mg CH_4 m^{-2} d^{-1}, while the *LHuS* biotype mean flux was 1.1 mg CH_4 m^{-2} d^{-1}. *SpHu* and *SpHuS* mean CH_4 fluxes were 3.8 and 3.3 mg CH_4 m^{-2} d^{-1} (Table 3). Overall, the March 2004 mean values from the hummock biotypes are statistically greater than the November 2003 values ($p <$ 0.001, Kruskal-Wallis).

5.3. Pool CH_4 Fluxes

[17] A total of 270 individual chamber fluxes were made, of which 17 were rejected. Flux value of the remaining 253 measurements ranged from −32 to 8192 mg CH_4 m^{-2} d^{-1} with a mean and median of 136 mg and 25 mg CH_4 m^{-2} d^{-1} (Figure 5 and Table 5). The largest fluxes were measured on the LG3 peatland pools with an individual summer mean flux of 329 mg CH_4 m^{-2} d^{-1}, compared to 54 and 34 mg CH_4 m^{-2} d^{-1} in the LG1 and LG2 pools, respectively. Summer average pool fluxes from LG3 are statistically greater than LG2 ($p < 0.05$) but not greater than LG1 ($p = 0.09$, Kruskal-Wallis).

Table 4. LG2 Cold Season Biotype Mean Daily CH_4 Fluxes, With Standard Error in Parentheses, in November 2003 and March 2004[a]

	November 2003		March 2004	
Biotype	Flux	n	Flux	n
Lichen hummock (LHu)	−0.36 (0.35)	8	0.56 (0.10)	12
Lichen hummock and shrubs (LHuS)	0.51 (0.05)	8	1.13 (0.04)	11
Sphagnum spp. hummock (SpHu)	1.22 (0.69)	8	3.76 (0.11)	10
Sphagnum spp. hummock with shrubs (SpHuS)	0.55 (0.71)	8	3.32 (0.67)	11
Sphagnum spp. hollow (SpHo)	4.65 (5.58)	16	-	-
Sedges and vascular (SeV)	4.62 (1.62)	16	-	-

[a]Fluxes are given in mg m^{-2} d^{-1}.

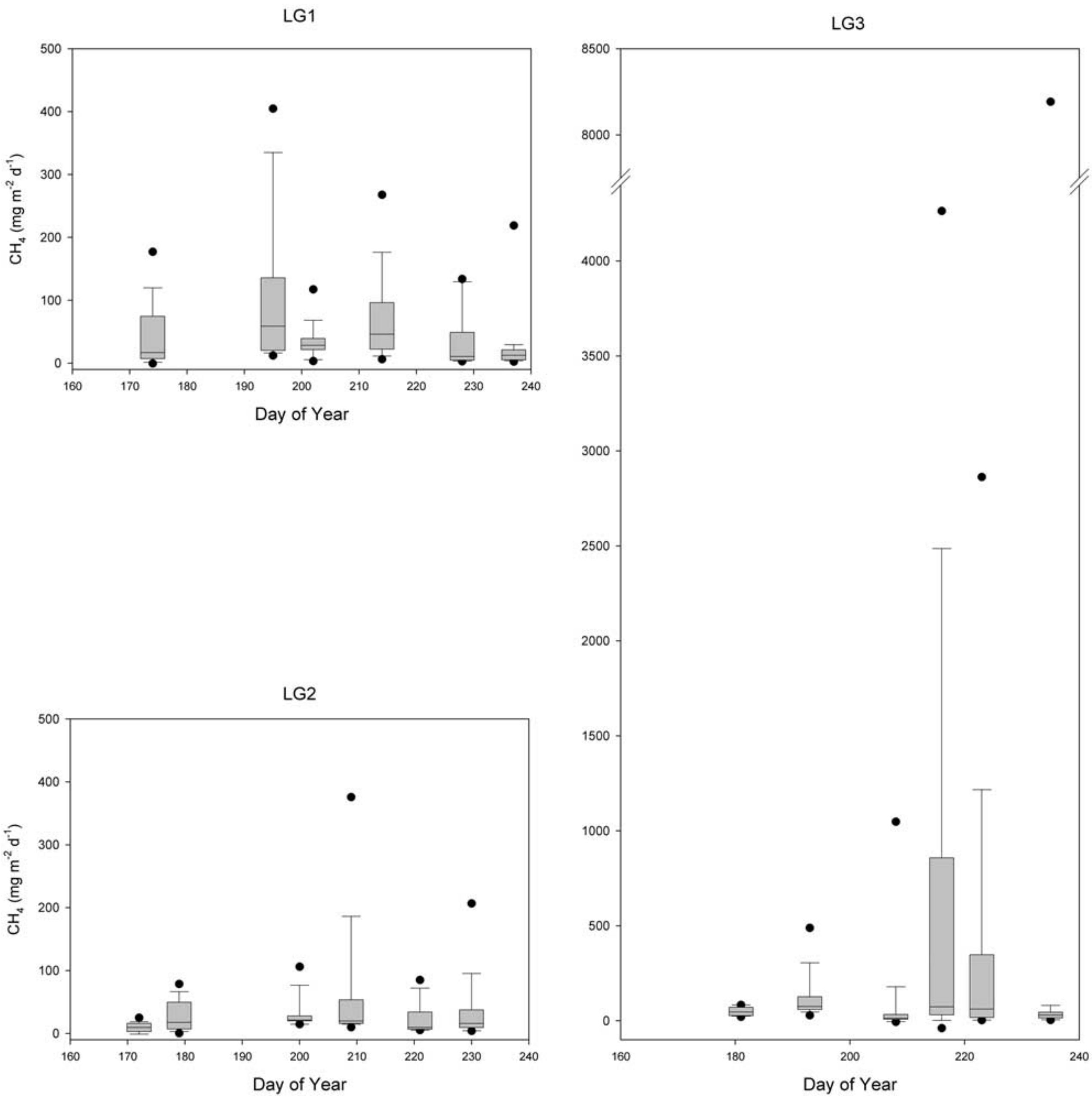

Figure 5. CH_4 flux from pools, summer 2004. The boxes represent the 25th and 75th percentile; the lower and upper bars represent the 10th and 90th percentiles; the black line in the box represents the average; and the dots represent the outliers.

Table 5. Summer Mean and Standard Error (SE) of CH_4 Fluxes for Individual Collars in the LG1, LG2, and LG3 Peatland Pools

		CH_4 Flux, mg m^{-2} d^{-1}		
Peatland	Pool	Mean	SE	*n*
LG1	1[a]	108	138	28
	2[a]	114	159	17
	3[a]	37	33	12
	4[b]	91	56	6
	5[b]	41	28	6
	6[b]	79	57	6
	7[b]	13	8,4	6
	8[b]	65	107	6
LG2	1	145	190	15
	2	16	13	12
	3	11	20	29
	4	13	7,5	11
	5	41	21	17
LG3	1	915	1906	23
	2	190	506	23
	3	62	56	12
	4	45	28	15
	5	38	29	12

[a]Upper pools.
[b]Structured fen pools.

[18] Within the LG1 peatland, the summer average fluxes from the structured fen section pools were not statistically different ($p > 0.05$) from the average flux from the larger pools in the higher portion of the LG1 peatland. In the LG2 peatland, average CH_4 fluxes from the sites 13 to 15 at LG2 were statistically greater than average fluxes measured from the larger and deeper pools (site 1–12) in the same peatland ($p < 0.05$, Kruskal-Wallis).

[19] Individual ebullition CH_4 fluxes from the last week of July to the end of August 2004 range from 0.002 to 117 mg CH_4 m^{-2} d^{-1} for the three peatlands. As for chamber fluxes, the largest emissions were from the LG3 peatland, with a single measurements average of 21 mg CH_4 m^{-2} d^{-1}, statistically greater than the 1.61 and 0.81 mg CH_4 m^{-2} d^{-1} mean fluxes from the LG1 and LG2 peatlands, respectively ($p < 0.05$). Mean ebullition fluxes from the 5 sites within the LG3 peatland ranged from 2.9 to 67 mg CH_4 m^{-2} d^{-1} and the largest fluxes were measured at site 1.

5.4. Controls on CH_4 Fluxes

[20] As expected, average seasonal flux of CH_4 from the vegetated surface increased with a rise in the average water table: There was a correlation between $\log_{10}CH_4$ flux and water table in each peatland (r^2 = 0.78 to 0.93, $p < 0.02$, Figure 6a). There were no significant differences in regression slopes and intercepts for the three peatlands and combination of all data resulted in an r^2 of 0.78 (p = 0.001). Seasonal average CH_4 fluxes from the pool sites in 2004 were not as strongly related (p = 0.012 to 0.079) to average pool depth with negative slopes in LG1 and LG2 and a positive slope for LG3 (Figure 6). In LG1 and LG2, there was an increase CH_4 flux as the average water table rose from 35 cm below to 5 cm above the peat surface, followed by a decrease in fluxes with increasing pool depth. In LG3, however, there was an increase in flux from sites with a water table 35 cm below peat surface to pool depth of 80 cm. When data are combined for vegetated surface and pools at each site, and overall, there is a significant convex-up relationship (Figure 6b).

[21] Within the season, CH_4 fluxes, expressed as the average of the 20 collars in each peatland on each sampling day, increased with increasing peat temperature measured at the meteorological towers (Table 6). Relationship between the CH_4 fluxes and peat temperature at 20 cm was significant ($p < 0.06$) in each peatland and explained between 63 and 83% of the seasonal variation in CH_4 flux within each peatland. The relationship was also significant for peat temperature at 40 cm at LG1 and LG3 where it explained 94% and 85% of the seasonal variation in CH_4 flux, respectively.

[22] Vegetation also played a role in controlling CH_4 emissions. Above-ground biomass of individual species within each collar were combined into groups (e.g., trees, shrubs, sedges, herbs, lichens and mosses) and entered into a step-wise regression against $\log_{10}CH_4$ flux. The relationship between the four major plant groups (sedge, hummock, Cuspidata *Sphagnum* and shrub) and CH_4 flux represent the "best" relationship between CH_4 flux and the biomass of plant groups with an r^2 of 0.59, with sedge and cuspidata *Sphagnum* (those species in biotypes *SpHo* and *WS* in Table 1) showing a strong positive influence on CH_4 flux (Table 7). Although the sedge biomass was correlated with CH_4 flux when all collars are included (r^2 = 0.30, p < 0.001), restriction to the 10 *SeV* collars in LG1 and LG2 improved the relationship (r^2 = 0.55, p = 0.014, Figure 7). Combination of water table position and above-ground, green sedge biomass explained 70% of the variance in CH_4 fluxes (Table 7).

5.5. Seasonal and Annual Peatland CH_4 Flux Estimate

[23] To spatially weight CH_4 fluxes for the three peatlands, coverage of each biotype was estimated using a multiscale approach. Biotypes present in the peatlands were identified from vegetation relevés made on the three peatlands. Surface patterns were identified and delimited and their surface area was numerized using georeferenced aerial photographs of the three peatlands in ARCMAP. For each surface pattern, biotype and pool coverage were estimated (Table 2).

[24] The growing season for the CH_4 budget in the three peatlands was arbitrarily defined as 15 May to 31 August (109 days). For the LG2 annual budget, growing season period was extended to 20 October, for a total of 159 days. Cold season corresponds to the period between 21 October and 14 May (206 days). The 15 May date is based on field observation, as no snow was left on the ground and the air temperature was warm enough to allow photosynthesis. The 15 May date is also consistent with peat temperature >0°C, 5 cm below the surface measured in 2004. The 20 October end of growing season date corresponds to peat temperature <0°C, 5 cm below the surface.

[25] The average daily CH_4 fluxes (Table 3) for each biotype were used to estimate the growing season CH_4 budget. Contributions to the CH_4 budget from the shallow pools at LG2 (2003) and the larger pools in the three peatlands (2004) were estimated using summer average daily CH_4. In order to get a more representative estimation of gas release from the pools, average values are used for the different pool types within peatlands. For example, LG1

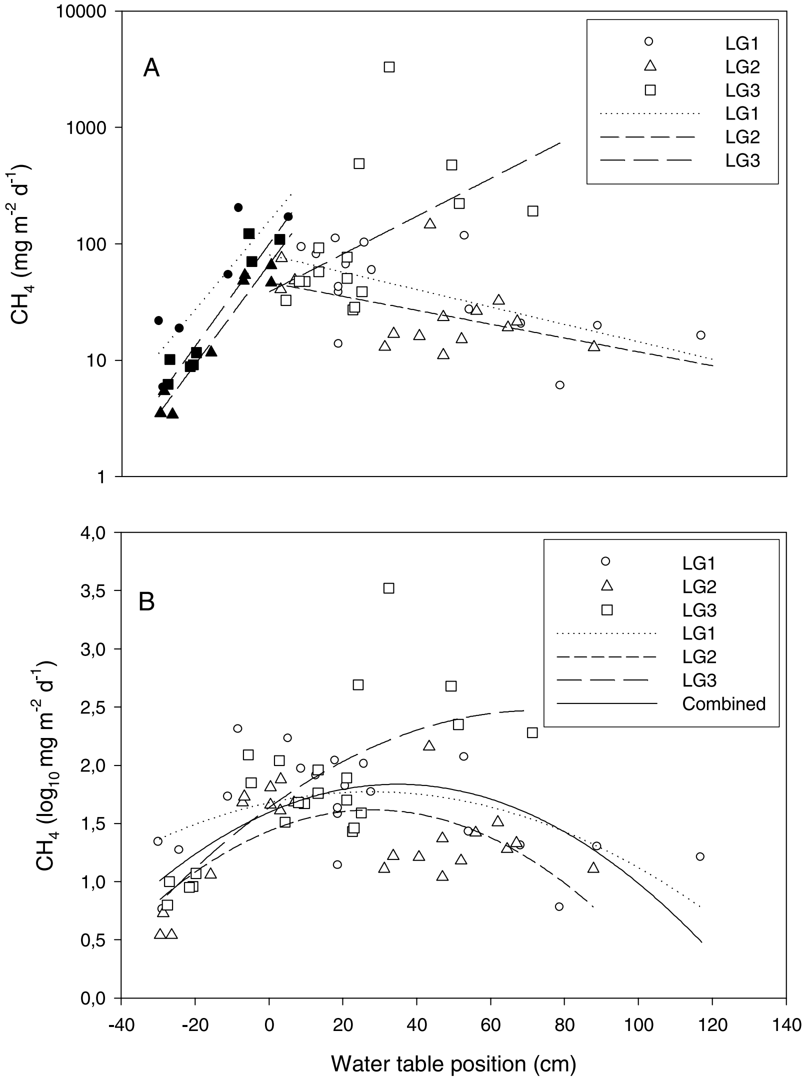

Figure 6. Relationship between summer mean daily CH_4 fluxes and mean water table depth at the LG1, LG2 and LG3 peatlands. Negative water table values represent depth below peat surface. (a) Linear regression, each data point represents a biotype or pool: solid symbols, vegetated surface; open symbols, pools. (b) Polynomial regression for combined data at each peatland, and overall. Vegetated surface: LG1, $\mathrm{Log_{10}}\ CH_4 = 0.038\ (\pm0.010)\ \mathrm{WTD} + 2.20\ (\pm0.21)$, $r^2 = 0.78$, $p = 0.020$; LG2, $\mathrm{Log_{10}}\ CH_4 = 0.043\ (\pm0.005)\ \mathrm{WTD} + 1.83\ (\pm0.09)$, $r^2 = 0.93$, $p < 0.001$; LG3, $\mathrm{Log_{10}}\ CH_4 = 0.044\ (\pm0.006)\ \mathrm{WTD} + 2.00\ (\pm0.11)$, $r^2 = 0.92$, $p = 0.001$; combined, $\mathrm{Log_{10}}\ CH_4 = 0.041\ (\pm0.005)\ \mathrm{WTD} + 1.99\ (\pm0.09)$, $r^2 = 0.78$, $p = 0.001$. Pools: LG1, $\mathrm{Log_{10}}\ CH_4 = -0.008\ (\pm0.003)\ \mathrm{D} + 1.90\ (\pm0.14)$, $r^2 = 0.40$, $p = 0.012$; LG2, $\mathrm{Log_{10}}\ CH_4 = -0.006\ (\pm0.003)\ \mathrm{D} + 1.67\ (\pm0.15)$, $r^2 = 0.22$, $p = 0.079$; LG3, $\mathrm{Log_{10}}\ CH_4 = 0.016\ (\pm0.008)\ \mathrm{D} + 1.59\ (\pm0.24)$, $r^2 = 0.26$, $p = 0.053$. Vegetated surface and pools: LG1, $\mathrm{Log_{10}}CH_4 = -0.0001x^2 + 0.0068x + 1.68$, $r^2 = 0.30$, $p = 0.040$; LG2, $\mathrm{Log_{10}}CH_4 = -0.0002x^2 + 0.0130x + 1.68$, $r^2 = 0.38$, $p = 0.009$; LG3, $\mathrm{Log_{10}}CH_4 = -0.0002x^2 + 0.0229x + 1.64$, $r^2 = 0.55$, $p < 0.001$; combined, $\mathrm{Log_{10}}CH_4 = -0.0002x^2 + 0.0139x + 1.59$, $r^2 = 0.29$, $p < 0.001$.

Table 6. Coefficient of Determination (r^2) and Probability (p) Values for Relationships Between CH_4 Fluxes, Expressed As the Average of the 20 Collars in Each Peatland on Each Sampling day, and Peat Temperature at 5, 10, 20, and 40 cm Measured At the Meteorological Tower

		Depth, cm			
Peatland	Property	5	10	20	40
LG1	r^2	0.40	0.44	0.72	0.94
	p	0.180	0.148	0.033	0.001
LG2	r^2	0.36	0.74	0.63	0.54
	p	0.212	0.061	0.060	0.095
LG3	r^2	0.32	0.63	0.83	0.85
	p	0.244	0.059	0.011	0.010

pool daily average CH_4 values are separated into "upper pools" and "structured fen pools" (Table 4). LG3 CH_4 pool fluxes from site 1 were not included in the average daily CH_4 flux from LG3 peatlands, because of evidence of ebullition through disturbance, so that value was reduced from a high value of 345 mg CH_4 m^{-2} d^{-1} (± 215) to a more rational 134 mg CH_4 m^{-2} d^{-1} (± 43). LG3 site 1 fluxes are high and probably result from ebullition induced by accidental sediment disturbance during sampling. In the LG2 annual budget, average values calculated for each biotype from the November 2003 and March 2004 CH_4 measurements are used in the CH_4 winter budget calculation.

[26] Spatially weighted growing season CH_4 flux was significantly larger in the LG1 and LG3 peatlands (44 ± 21 and 52 ± 17 mg CH_4 m^{-2} d^{-1}) than in the LG2 peatland (21 ± 9.4 mg CH_4 m^{-2} d^{-1}) (Table 8). The standard error was derived from individual biotype standard error extrapolated spatially on the basis of coverage of each biotype (Table 1) and does not include errors linked to biotype coverage extrapolation. Growing season emission of CH_4 was 4.8 ± 2.3, 2.3 ± 1.0 and 5.7 ± 1.9 g CH_4 m^{-2} at LG1, LG2 and LG3, respectively. In the LG2 peatland, the extended season to 20 October resulted in a flux of 3.3 ± 1.5 g CH_4 m^{-2} and combination with the estimate of cold season flux resulted in an estimated annual flux of 3.8 g m^{-2}, with the winter contributing to 13% of the overall emission. The estimate does not include possible episodic emissions of CH_4 during spring thaw.

6. Discussion

6.1. Methane Fluxes

[27] The CH_4 fluxes measured in the La Grande peatlands are similar to those reported in other northern peatlands. The hummock average fluxes ranged between 3.4 and 21 mg CH_4 m^{-2} d^{-1}, similar to those measured on hummocks in other Canadian peatlands of −1.3 to 23 mg CH_4 m^{-2} d^{-1} [*Bubier*, 1995; *Bubier et al.*, 1995; *Liblik et al.*, 1997]. From biotypes with the water table closer to the surface, not including the shallow pools (2003), fluxes ranged from 48 to 197 mg CH_4 m^{-2} d^{-1}, which is similar to values of 47 to 221 mg CH_4 m^{-2} d^{-1} presented by *Liblik et al.* [1997], for two peatlands in Fort Simpson, Mackenzie Valley, Canada. Although daily winter fluxes from the LG2 peatland are approximately 20 times smaller than those in the summer, the winter contribution to the annual CH_4 release is significant. The LG2 winter CH_4 fluxes averaged 2.0 and 2.1 mg m^{-2} d^{-1}, smaller than the range of 5 to 23 mg m^{-2} d^{-1} presented in the literature [*Dise*, 1992; *Alm et al.*, 1999; *Panikov and Dedysh*, 2000].

[28] The summer average fluxes of 54 and 34 mg CH_4 m^{-2} d^{-1} from the LG1 and LG2 pools are similar to 17 mg CH_4 m^{-2} d^{-1} measured by *Kelly et al.* [1997] while the LG3 mean flux of 329 mg CH_4 m^{-2} d^{-1} is in the same order of magnitude as fluxes measured by *Hamilton et al.* [1994] with 110 to 180 mg CH_4 m^{-2} d^{-1}. The large variation in fluxes from the pools at LG3 may be a function of ebullition because of the floating peat debris and collapsing ridges that were observed in pools 1 and 2. The ebullition flux measurements showed only small releases of CH_4 through bubbling at LG1 and LG2 peatlands. *Hamilton et al.* [1994] reported no ebullition from their ponds on the Hudson's Bay lowlands. On the other hand, the LG3 peatland CH_4 ebullition fluxes are smaller than those reported by *Dove et al.* [1999] of 31 and 160 mg CH_4 m^{-2} d^{-1} for a beaver pond.

6.2. Controls on CH_4 Flux

[29] The strong relationships between average summer CH_4 flux and average water table depth (Figure 6) are in accord with other studies [*Roulet et al.*, 1992; *Moore and Roulet*, 1993; *Moore et al.*, 1994; *Bubier*, 1995; *Bubier et al.*, 1995; *Liblik et al.*, 1997; *Nykänen et al.*, 1998; *Huttunen et al.*, 2003]. The slopes and intercepts of the regressions of $\log_{10}$ CH_4 flux against water table (0.038 to 0.044, and 1.83 to 2.20, respectively) are within the range reported by these other studies. In 2004, increasing pool depth resulted in decreased CH_4 flux in the LG1 and LG2 pools, with slopes significantly different from zero. This pattern may be explained by slower CH_4 production in the sediment of the deeper pools, which may contain well-decomposed organic matter. In a Wisconsin lake, *Barber and Ensign* [1979] found that methanogenesis was more rapid in shallow than deep-water sediments (1 and 3 m). Colder sediment tem-

Table 7. Step-Wise Regression Between Seasonal Average CH_4 Flux and Water Table Depth and Aboveground Biomass of Major Plant Groups[a]

Regression Equations	r^2	p	SE
$\log_{10}CH_4 = 1.80 + 0.041WT$	0.67	<0.001	0.345
$\log_{10}CH_4 = 1.12 + 0.025sedge$	0.30	<0.001	0.502
$\log_{10}CH_4 = 1.80 + 0.036WTD + 0.009sedge$	0.70	<0.001	0.334
$\log_{10}CH_4 = 1.80 + 0.015sedge - 0.001hummock + 0.005cusp. - 0.001shrub$	0.59	<0.001	0.397

[a]Flux is given in mg m^{-2} d^{-1}. Water table depth, WT, is given in centimeters. Biomass is given in g m^{-2}. SE denotes standard error.

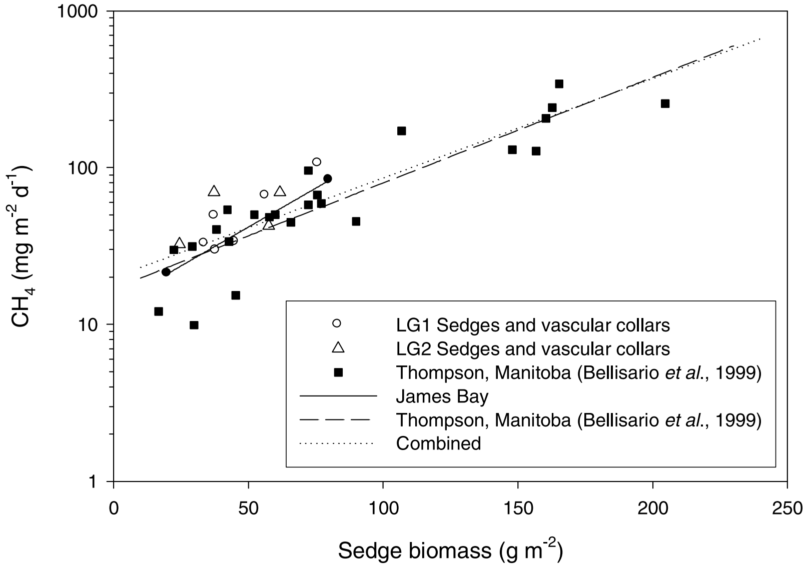

Figure 7. Relationship between summer mean daily CH_4 fluxes and end-of-season above-ground sedge biomass in James Bay (this study) and Thompson, Manitoba [*Bellisario et al.*, 1999]. James Bay: Log_{10} CH_4 = 0.009 (±0.003) S.B. + 1.27 (±0.14), $r^2 = 0.55$, $p = 0.014$; Thompson, Manitoba: Log_{10} CH_4 = 0.007 (±0.001) S.B. + 1.22 (±0.07), $r^2 = 0.80$, $p < 0.001$; combined: Log_{10} CH_4 = 0.006 (±0.001) S.B. + 1.30 (±0.06), $r^2 = 0.75$, $p < 0.001$.

perature in deep portions of the pools could also reduce CH_4 production. In the LG3 peatland, CH_4 fluxes increased with pool depth, possibly caused by greater ebullition than in the other pools.

[30] Variations of CH_4 flux within the season were correlated with peat temperature and other studies have found that peat temperature at the water table position was the best predictor of CH_4 fluxes [*Bubier et al.*, 1995; *Nykänen et al.*, 1998; *Bellisario et al.*, 1999]. In this study, the CH_4–peat temperature relationships only show the general summer trend effect of peat temperature on fluxes because peat temperature was not measured at each individual collars at time of sampling. The range of Q_{10} values (0.8–5.1) is in the lower range of values reported by *Segers* [1998] of 1.5 to 28.

[31] The positive relationship between summer average CH_4 flux and sedge biomass for the collars within the *SeV* biotypes in the LG1 and LG2 peatlands suggests that the sedges act as a conduit to the atmosphere for CH_4, bypassing the oxidation layer and may stimulate methanogenesis [*Whiting and Chanton*, 1992; *Waddington et al.*, 1996; *Bellisario et al.*, 1999]. The CH_4 flux: sedge biomass relationship found in the La Grande Rivière peatlands is not significantly different from found in northern Manitoba by *Bellisario et al.* [1999] and suggests that end-of-season biomass may be a useful predictor, more so than for other vegetation characteristics.

[32] Peatland-average, summer estimated CH_4 fluxes of 2.3 to 5.7 g CH_4 m^{-2} are similar to the estimates of *Bubier et al.* [1993] of 3.4 g CH_4 m^{-2} for Clay Belt wetlands located in northeastern Ontario, Canada and of 2.5 to 8.2 g CH_4 m^{-2} reported for hummock, transitional fens and low sedge fens by *Nilsson et al.* [2001] in boreal Sweden. *Alm et al.* [1999] found the winter contribution to represent 8 to 17% of the annual CH_4 flux and the winter contribution to CH_4 flux annual budget in LG2 represents 13%.

[33] CH_4 fluxes from these northern boreal peatlands can be significant, from the perspective of both the carbon budget of the peatland and the emission of greenhouse gas. While there are orders of magnitude variations in CH_4 flux across the peatland surface, variations on the terrestrial portions of the peatland can be related to water table position, peat temperature and vegetation cover, particularly sedges. The quantitative similarity of flux:environment relationships that we found to those from other northern peatlands suggests that overall relationships can be applied and scaled up in these landscapes, using simple remote sensing tools. CH_4 emissions from pools are not as strongly related to simple environmental properties, such as pool depth or size and differences in the evolution of the pools through degradation may lead to substantial differences in CH_4 emission. Episodic CH_4 ebullition is difficult to measure and may play a dominant role in flooded sections of the peatland. Combination of spatial estimates of CH_4 emission from peatlands such as these can then be compared with emissions from the water surface after flooding.

Table 8. Estimated Spatially Averaged Daily CH_4 Flux During 2003 Growing Season in the LG1, LG2, and LG3 Peatlands, and the 2003/2004 Cold Season and Annual CH_4 Flux at LG2 Only[a]

Peatland	Growing Season	Cold Season	Annual
LG1	44 (21)		
LG2	21 (9)	2.3 (1.1)	10 (11)
LG3	52 (17)		

[a]Flux is given in mg m^{-2} d^{-1}. Standard error is given in parentheses.

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