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The importance of floating peat to methane fluxes from flooded peatlands

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Abstract. The effect of flooding on methane (CH_4) fluxes was studied through the construction of an experimental reservoir in a boreal forest wetland at the Experimental Lakes Area in northwestern Ontario. Prior to flooding, the peatland surface was a small source of CH_4 to the atmosphere (1.0 ± SD of 2.3 mg CH_4 m^{-2} d^{-1}). After flooding, CH_4 fluxes from the submerged peat surface increased to 64±68 mg CH_4 m^{-2} d^{-1}. CH_4 bubbles within the submerged peat caused about 1/3 of the peat to float. Fluxes from these floating peat islands were much higher (440±350 mg CH_4 m^{-2} d^{-1}) than from both the pre-flood (undisturbed) and the post-flood (submerged) peat surfaces.

The high fluxes of CH_4 from the floating peat surfaces may be explained by a number of factors known to affect the production and consumption of CH_4 in peat. In floating peat, however, these factors are particularly enhanced and include decreased oxidation of CH_4 due to the loss of aerobic habitat normally found above the water table of undisturbed peat and to increased peat temperatures. The extremely high fluxes associated with newly lifted peat may decrease as the islands age. However, CH_4 flux rates from floating peat islands that were several years old still far exceeded those from undisturbed peat surfaces and from the water surface of a newly created reservoir.

Introduction

Until recently, the potential for man-made reservoirs to be an important source of the greenhouse gases, methane (CH_4) and carbon dioxide (CO_2), has been largely overlooked (Rudd et al. 1993; Kelly et al. 1994; Duchemin et al. 1995). Of particular concern is the flooding of peatland areas in boreal and subarctic regions because they contain an estimated 455 × 10^{15} g of carbon (Gorham 1991), the largest amount of organic carbon per unit area in the world (Post 1982). Disruption by flooding, as when reservoirs are created, affects the carbon balance of peatlands, changing these areas from carbon sinks to carbon sources with respect to the atmosphere (Kelly et al. 1997).

A common feature of artificially flooded peatlands in northern reservoirs is floating peat islands (Ronka & Uusinoka 1976). When peatlands are flooded, the amount of peat experiencing anoxic conditions increases, which leads to increased methanogenesis (Kelly et al. 1997). CH_4 accumulates as gas bubbles that eventually cause portions of the flooded peat to rise to the surface of the water body as peat islands (Koskenniemi 1987). Once risen, peat islands may become recolonized by vegetation. Floating peat is a unique type of peat habitat that has never been quantified as a potential source of CH_4 to the atmosphere.

In this study, we compared the fluxes of CH_4 from undisturbed peat, newly flooded peat which remained submerged, and floating peat. The measurements were carried out in an experimental reservoir that flooded a boreal forest wetland. We found that CH_4 emissions from floating peat were much higher than from both undisturbed and submerged peat. Considering the extent of peatlands in areas where future hydroelectric projects are planned (Rudd et al. 1993), floating peat might be an important but previously unidentified source of CH_4 to the atmosphere.

Materials and methods

Field site descriptions

Field sites were located at two boreal forest wetlands, numbered 979 and 632, at the Experimental Lakes Area in northwestern Ontario. 979 is a *Sphagnum*-dominated wetland comprised of a 2.3 ha central pond surrounded by 14.4 ha of peatland. It receives flow from Lake 240, a stratified, Precambrian shield lake. After two years of pre-flood study, wetland 979 was flooded in June of 1993, increasing the pond depth by 1.3 m and the water-covered surface area by a factor of three. In the fall, the water level was lowered to pre-flood levels. This pattern of spring flooding and fall drawdown continued each year during this study (1993–1995). 632 is a *Sphagnum* dominated headwater wetland comprised of a 0.5 ha pond surrounded by 4.0 ha of peatland. This wetland was not experimentally manipulated and was sampled over a four year period between 1991 and 1994 to measure the natural variability in CH_4 fluxes from undisturbed peat surfaces.

Boardwalks were constructed to allow sampling of the peat surfaces with minimal disturbance to the sites. The main boardwalks at both wetlands ran from the pond edge to the wetland edge (Figures 1 and 2).

At wetland 979, pre- and post-flood CH_4 fluxes were measured at three sites: A, B, and C (Figure 1). Prior to flooding, the depth from the peat surface to the water table differed at each of these sites due to their location within

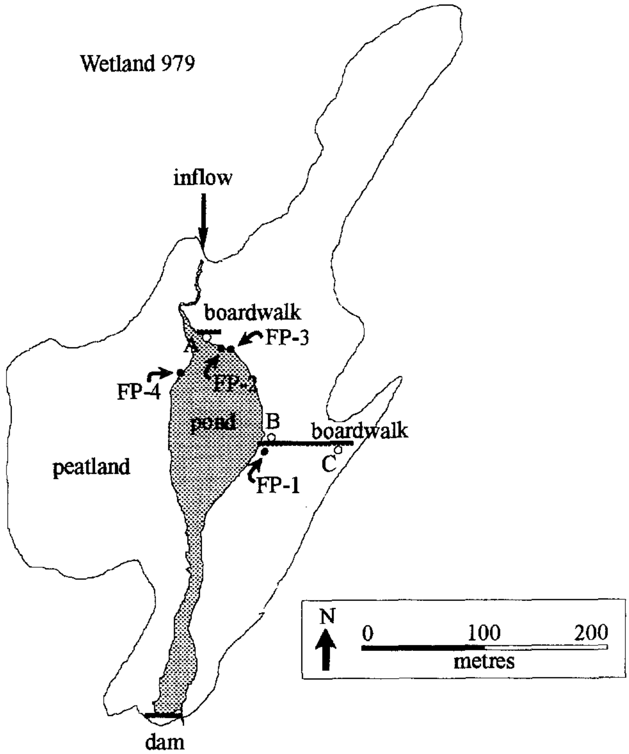


Figure 1. Map of wetland 979. Static/submerged chamber sites A, B, and C, and floating peat island sites FP-1, FP-2, FP-3, FP-4.

the wetland (Table 1). Site A was situated near a stream inflow to the pond. Sites B and C were located on the main boardwalk near the pond edge and the wetland edge respectively. All three sites were part of the 'open bog' vegetation community dominated by *Chamaedaphne* shrub surrounding the central water body of 979 as described in Dyck (1998). Following flooding, site A was under more than 1 m of water whereas sites B and C were under approximately 0.5 m of water.

Site B was particularly interesting because it floated to the reservoir surface during the third year of flooding (1995) becoming a 'floating peat island'. In addition to site B, four other floating peat island sites (FP-1, 2, 3 and 4) were studied in 1995 (Figure 1).

All of the peat was flooded at the same time, but areas within the peatland floated at different times. This resulted in varying degrees of regrowth of vegetation on the floating peat sites by 1995. Sites FP-3 and FP-4 lifted almost immediately following flooding in 1993 with no death of vegetation. FP-1 also lifted in 1993, however, there was very little regrowth at this site in the

Table 1. CH_4 fluxes from undisturbed peat surfaces at wetlands 979 and 632, standard error of the mean (SE) and average water table depth from the peat surface.

Site	Wetland 979				Wetland 632			
	Avg water table position (cm)	Pre-flood CH_4 fluxes (1991-mid 1993)			Avg water table position (cm)	Avg CH_4 fluxes (1991–1994)		
		$mg\ m^{-2}\ d^{-1}$	(SE)	n		$mg\ m^{-2}\ d^{-1}$	(SE)	n
A	+2.40	176	(24)	26	−13.3	32	(3.7)	37
B	−23.0	2.5	(0.59)	24	−19.3	1.1	(0.25)	36
C	−28.2	−0.09	(0.03)	21	−37.5	−0.03	(0.01)	35
D					−5.90	53	(10)	17

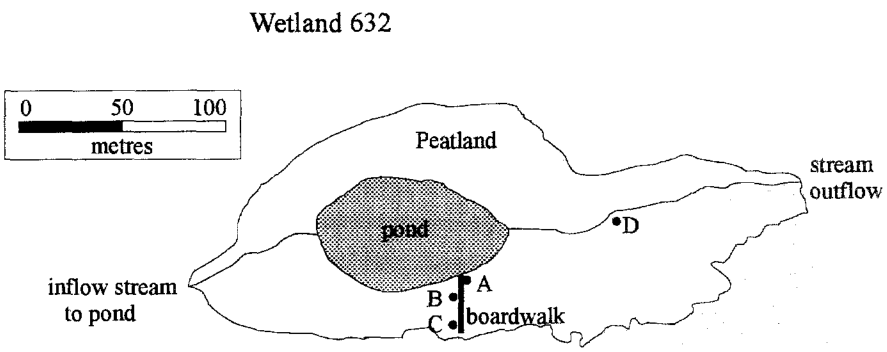


Figure 2. Map of wetland 632. Static chamber sites A, B, C, D.

subsequent years of the study. Site FP-2 lifted in 1994 after complete die-off of the vegetation. Some regrowth occurred at this site in 1995 but it was not as abundant as sites FP-3 and 4. When site B lifted in 1995, the vegetation had died completely and no regrowth occurred during the field season.

At wetland 632, three sites (A, B, and C) followed a transect which ran from the pond edge to the wetland edge (Figure 2). The depth from the peat surface to the water table increased at sites along this transect with site A being the wettest, followed by site B and then site C (Table 1). These sites fell within the 'open bog' vegetation community type dominated by *Carix oligosperma* (Dyck 1998). A fourth site, D, was located at the stream outflow of the central pond. This site was also within the 'open bog' community, however, the dominant vegetation types were *Chamaedaphne/Ledum* shrub (Dyck 1998).

Methane flux measurements

At wetland 979, CH_4 fluxes from undisturbed peat sites were measured before flooding in 1991, 1992, and until June of 1993, using static chambers (Moore & Knowles 1990). After flooding in 1993, 1994, and 1995, the same sites were sampled but submerged chambers were used to measure fluxes from the flooded peat surface to the water column. Fluxes from the floating peat island surfaces were measured using static chambers. At wetland 632, CH_4 fluxes were measured between 1991 and 1994 from undisturbed peat surfaces using static chambers.

Static chambers were made from 18 L polycarbonate bottles. At each site, there were three permanent collars inserted about 20 cm into the peat, which allowed placement of the chambers without disturbing the peat. Duplicate samples were taken from each chamber by syringe at dusk and then at dawn of the following day. Chambers used on the floating peat at wetland 979 were in place for 30 to 108 minutes (58 minutes on average) because fluxes were high. Samples were analyzed for CH_4 concentrations using a Varian series 3700 gas chromatograph within 12 hours of collection. The detection limit was 0.2 ppm.

Submerged chambers consisted of weighted, 9 L polycarbonate bottles and a 9 volt battery operated motor and propeller system which turned at 1 rpm inside the chamber to prevent concentration gradients from forming. Duplicate water samples were taken three times over a 24 hr period (dawn, dusk, and dawn of the following day) using evacuated 40 ml serum bottles. 10 ml of nitrogen (N_2) was added to the serum bottles before sampling to provide a head-space for equilibration of dissolved CH_4. Samples were killed by acidifying with 0.5 ml of 85% w/w phosphoric acid and analyzed for CH_4 concentrations using a Shimadzu mini-2 gas chromatograph with a flame detector.

Dissolved methane measurements

Depth profiles of dissolved CH_4 concentrations in peat pore water were taken four times throughout the field season in 1995 at sites FP-2 and FP-3. Samplers made from 6 mm polyethylene tubing were inserted into the peat at depth intervals of 0.1 m and left for the entire ice-free season. About 5 ml of pore water were collected from each depth using a 10 ml plastic syringe equipped with a 3-way valve. An 18-gauge needle placed on the 3-way valve allowed the transfer of the sample from the syringe to an evacuated 9 ml serum bottle. Prior to this transfer, CH_4 bubbles collected along with the pore water were discarded from the syringe because their presence was highly variable, both spatially and in time. Thus, measurements were of dissolved

CH_4 only, not total CH_4 (dissolved and bubbles). The samples were acidified with 0.2 ml of 85% w/w phosphoric acid and analyzed for CH_4 concentrations using a Carle series 100 gas chromatograph with a thermal conductivity detector.

Results

Methane fluxes from undisturbed peat at wetlands 632 and 979

At both wetlands, on a single sampling date, the variability of CH_4 flux measurements between the three collars at each site was high. Coefficients of variation ranged between 0 and 150% with the majority below 50%. The largest coefficients of variation occurred at the sites which consumed CH_4 and where absolute fluxes were very low and/or negative. This large within-site variability in CH_4 flux measurements from peat surfaces is common (Roulet et al. 1992; Whalen & Reeburgh 1992; Bubier et al. 1993).

Site-to-site differences in CH_4 flux rates were apparent among the undisturbed sites, and were related to the depth of the water table (Tables 1 and 2). The distinct character of each site (whether it had high, low, or negative flux rates) remained consistent during all four years of measurements at wetland 632 and during the three pre-flood time periods at wetland 979 (Figure 3; Table 2).

There was a pronounced seasonal trend in flux rates at undisturbed sites producing CH_4, with peak fluxes generally occurring in August (Figure 3). Because of the shape of the seasonal distribution, mean CH_4 fluxes from undisturbed peat surfaces were on the whole higher than the median values (Table 2) indicating a skewed distribution toward higher rates. At sites where CH_4 fluxes were very low and often negative (sites C at both wetlands), there was no distinct seasonal pattern (Figure 3).

Interannual variability in the average CH_4 flux was less than two-fold at all sites at both wetlands with a few exceptions (Table 2). The largest % variation occurred at the low fluxing and CH_4 consuming sites (B and C).

Methane fluxes from flooded peat at wetland 979

After flooding, fluxes from the peat surfaces to the water column changed at all sites. Site C changed from being a net consumer of CH_4 to a net producer (Table 2, Figure 4). CH_4 emissions at site B increased 22-fold (Table 2, Figure 5). At site A, average CH_4 flux rates from the peat surface to the water column decreased by about a third relative to pre-flood fluxes (Table 1, Figure 4). Unlike the other sites, site A had a high water table prior to flooding (Table

Table 2. Pre- and post-flood average methane fluxes (in bold), median, and standard error of the mean (SE) for undisturbed peat at wetlands 632 and 979, and for post-flood submerged and floating peat surfaces at wetland 979.

Wetland	Year	Average methane flux (mg CH_4 m^{-2} d^{-1}) (median) (SE)						
632		Site A	Site B	Site C	Site D			
	1991	30 (17) (9.5)	0.09 (0.05) (0.08)	−0.04 (−0.01) (0.03)	–			
	1992	43 (44) (7.1)	1.3 (0.67) (0.6)	−0.02 (−0.03) (0.01)	–			
	1993	35 (32) (6.4)	1.3 (0.90) (0.36)	−0.03 (−0.03) (0.03)	67 (46) (17)			
	1994	17 (15) (2.0)	1.5 (1.1) (0.49)	−0.01 (−0.01) (0.01)	37 (30) (5.9)			
979		Site A	Site B*	Site C	Site FP-1	Site FP-2	Site FP-3	Site FP-4
Preflood	1991	210 (149) (47)	0.41 (0.46) (0.16)	−0.07 (−0.13) (0.03)	–	–	–	–
	1992	164 (183) (26)	4.1 (3.6) (0.95)	−0.12 (−0.12) (0.02)	–	–	–	–
	1993	97 (71) (41)	2.3 (2.46) (0.24)	−0.03 (−0.04) (0.01)	–	–	–	–
Postflood	1993	218 (242) (48)	55 (29) (27)	38 (9.9) (27)	–	–	–	–
	1994	105 (91) (13)	53 (56) (9.2)	7.7 (5.6) (4.6)	–	–	–	–
	1995	88 (81) (29)	644 (535) (148)	18 (17) (8.5)	268 (237) (55)	709 (676) (153)	244 (131) (84)	344 (189) (108)

* This site became a floating peat island in 1995.

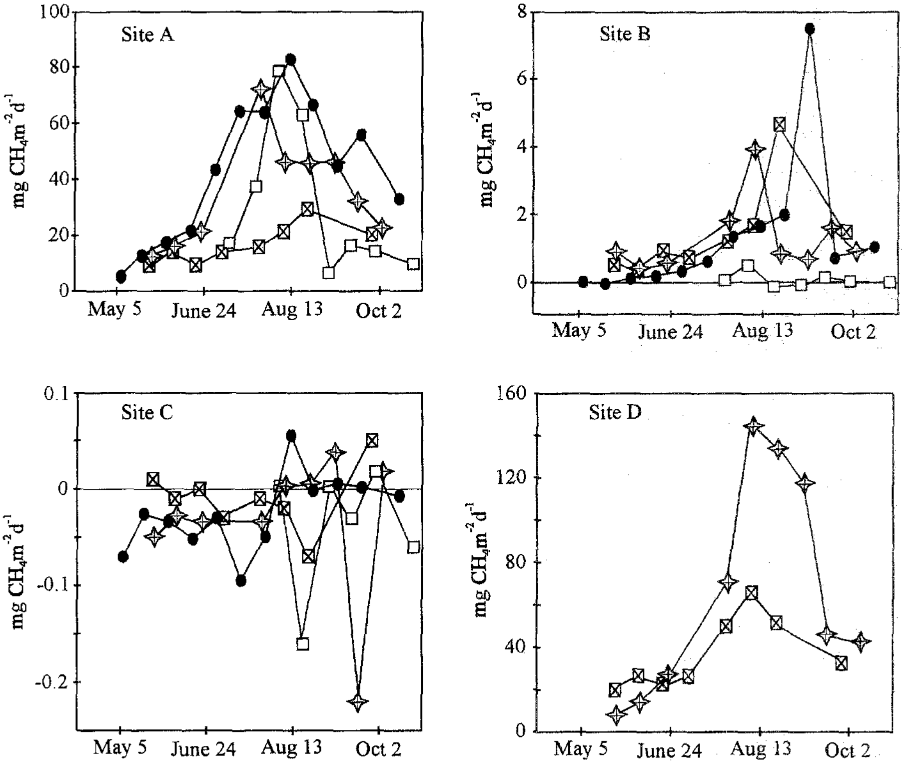


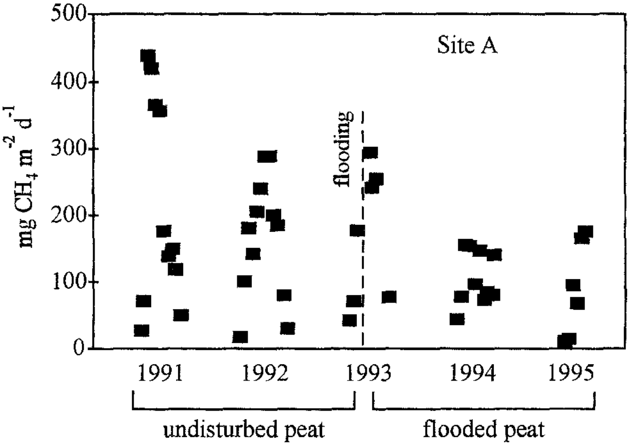
Figure 3. CH_4 fluxes from undisturbed peat at wetland 632, 1991–1994. (1991 □, 1992 ●, 1993 ✧, 1994 ⊠).

1) and pre-flood flux rates were high. Sites B and C, on the other hand, both had low water tables before flooding (Table 1) and experienced a more drastic change in habitat following flooding.

Methane fluxes from floating peat at wetland 979

CH_4 production within the flooded peat resulted in bubble formation, which caused many areas of the peatland to float. Site B became a floating peat island in 1995 and flux rates from the peat surface increased substantially: 12-fold greater than the flooded surface, or 260-fold when compared to pre-flood emissions (Figure 5). In addition to site B above, fluxes from the other peat islands were also high, and were greater than fluxes from all other surfaces at the reservoir (Tables 2 and 3).

A seasonal pattern was evident at all floating peat sites except site FP-1 (Figure 6), with the highest fluxes occurring in mid-July to early August. The sites that retained vegetation when they floated in 1993 (FP-3 and FP-4) had lower fluxes than the less vegetated site FP-2 (lifted in 1994) and the



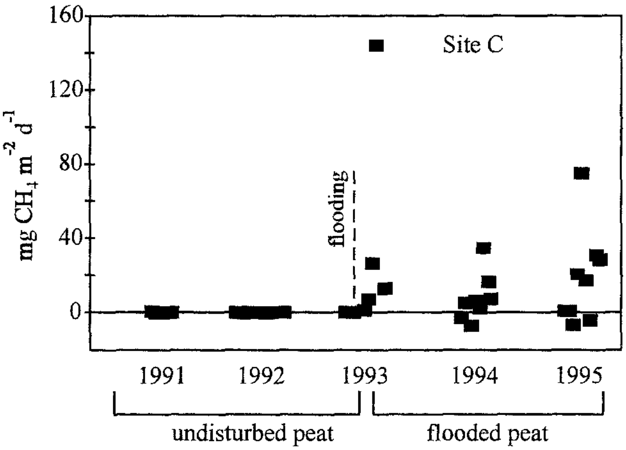


Figure 4. CH_4 fluxes from sites A and C at wetland 979 – from undisturbed (pre-flood) peat and inundated (post-flood) peat surfaces (1991 to 1995).

unvegetated site B which lifted in 1995. Site FP-1 lifted in 1993 yet had no regrowth on it by 1995. Fluxes from this site were lower than from all of the other floating peat sites (Figure 6).

Dissolved methane profiles within peat islands

Dissolved CH_4 concentrations within the peat islands were consistently higher at site FP-2 than at site FP-3 (Figure 7), which correlated with the higher fluxes to the atmosphere from site FP-2 (Table 2; Figure 6). One particularly high value at FP-2 on June 13 (0.4 m) may have been due to the accidental inclusion of a bubble in the sample.

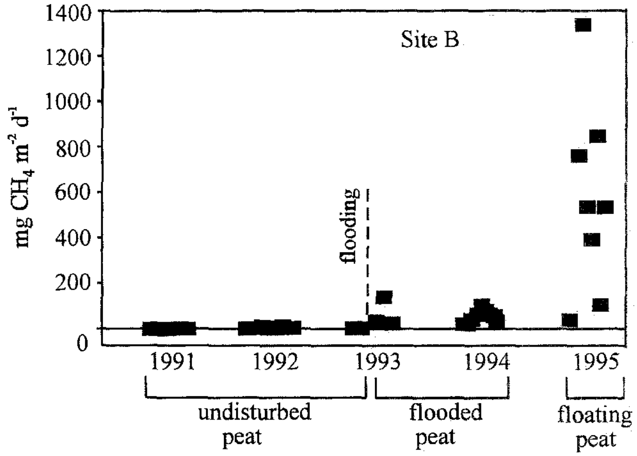


Figure 5. CH_4 fluxes from site B at wetland 979 – from undisturbed (pre-flood), post-flood inundated and floating peat surfaces (1991–1995).

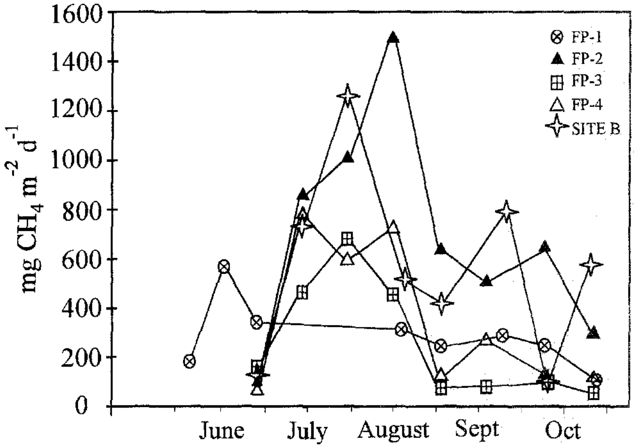


Figure 6. CH_4 fluxes from five different floating peat islands at wetland 979, 1995. Site B lifted in 1995 becoming a floating peat island.

The maximum possible concentration of dissolved CH_4, assuming 1 atmosphere for the partial pressure of CH_4 at 20 °C, is 1,473 μmol L^{-1}. In reality, however, CO_2 and N_2 should also be present and CH_4 bubble formation would therefore occur at less than this value. Because bubble formation did occur, the dissolved concentrations at the mid-depths of the peat islands were probably the saturation values for CH_4 at the time of sampling.

There were occasions when bubbles of CH_4 were intentionally included in the samples for comparison purposes. Concentrations between depths varied tremendously due to the spatial variability of the occluded bubbles, however,

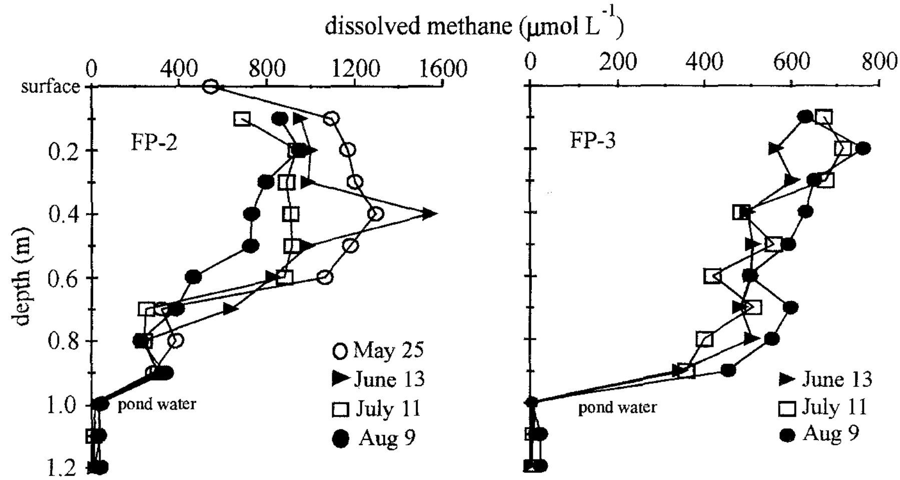


Figure 7. Depth profile of dissolved CH_4 in floating peat island sites FP-2 and 3, 1995.

values over 6,000 μmol CH_4 L^{-1} were not uncommon and reached as high as 15,000 to 20,000 μmol CH_4 L^{-1} at some depths (data not shown).

Discussion

The floating peat islands at wetland 979 were essentially large chunks of peat, approximately 1 m thick, that had become detached from the pond sediment after the wetland was flooded. The flux from floating peat averaged 440 mg CH_4 m^{-2} d^{-1}; nearly nine times greater than from flooded, submerged peat, and over 400 times greater than from the surface of undisturbed peat (Table 3, Figures 4, 5) excluding site A, near the stream inflow (Figure 4). Flux rates from the floating peat also exceeded those from the surface of the flooded pond (88 mg CH_4 m^{-2} d^{-1}, Kelly et al. 1997) by a factor of five.

The CH_4 fluxes measured from the undisturbed peat at wetlands 979 (pre-flood) and 632 in this study were within the range of those measured from other boreal fens and bogs (Table 4). This is not surprising since the range of CH_4 flux rates from the boreal region is large and includes some sites with high water tables. However, flux rates measured from the floating peat sites at wetland 979 generally exceeded those measured from undisturbed boreal sites and were more similar in magnitude to flux rates measured from beaver bonds (Table 4).

A number of conditions that are characteristic of floating peat islands, compared to intact peat, likely contributed to the high flux rates. These conditions, discussed below, include increased anoxia in the near surface peat,

Table 3. Average methane fluxes from peat surfaces to the atmosphere or to the water column (*) and standard error of the mean (SE) from wetland 979.

Fluxing surface	Years sampled	*n*	Avg CH_4 flux mg m^{-2} d^{-1} (SE)
Pre-flood			
Undisturbed peat	1991–1993	59	1.0 (0.29)
Post-flood			
Flooded peat*	1993–1995	56	64 (9.3)
Floating peat	1995	39	440 (58)

Table 4. Methane fluxes from boreal wetlands and beaver impoundments in North America.

Site	Lat.	Habitat	Average flux mg m^{-2} d^{-1}	Range	Reference
		Temperate			
W. Virginia	39°	Beaver ponds	300	1–1400	Yavitt et al. 1990†
New York	43°	Beaver ponds	150	–	Yavitt et al. 1992
		Boreal			
S. Ontario	45°	Beaver ponds	30–90	0.2–400	Roulet et al. 1992
		Bogs/fens	3–21	−0.2–140	
N. Minnesota	47°	Forested bog	10–38	2–246	Dise 1993†
(Marcell Forest)		Open bog/poor fen	118–180	0–1056	
		Fen lagg	35	−1–482	
(Marcell Forest)		Bogs/fens	207	11–866	Crill et al. 1988
Cochrane, Ont.	47–50°	Peatlands	0.4–67.5	0.1–156	Bubier et al. 1993
		Beaver ponds	290	136–919	
		Marshes	91–350	4.4–350	
ELA, NW Ont.	49°	Wetlands 632, 979	1.0–176	−0.37–439	This study
		Floating peat 979	440	42–1,458	
Sept-Iles, Que.	50°	Beaver ponds	18.7–21.6	–	Ford & Naiman 1988
		Boreal/subarctic			
Schefferville, Que.	54°	Fens	36–125	4.9–159	Moore et al. 1990
C. Alberta	54–55°	Beaver ponds	518	0–12,068	Vitt et al. 1990

Measurement periods were all seasonal except for † which were annual studies.

decreased oxidation of CH_4 by methanotrophic bacteria, and increased peat temperature. All of these factors are related to the position of the water table which, in floating peat, is at or near the peat surface.

Increased anoxia occurs in floating peat islands because they are saturated with water, which restricts the diffusion of oxygen (O_2) from the atmosphere into the surface peat. This is in contrast to undisturbed peat where the water table may fluctuate, creating an aerobic zone in the upper layers (Moore & Roulet 1993). When surface peat was incubated with and without additions of water, the overall rate of decomposition at 20 °C was somewhat lower under anoxic, water-saturated conditions than under aerobic, unsaturated conditions. However, the ratio of CH_4 to CO_2 produced increased, leading to an increase in net CH_4 production under conditions mimicking those in the floating peat (V. St. Louis pers. comm.).

The high water table common to floating peat restricts the extent of the aerobic zone and allows much of the CH_4 produced within the islands to flux directly to the atmosphere, with minimal oxidation by methanotrophic bacteria. In undisturbed peatlands, considerable CH_4 oxidation can take place in the aerobic zone above the water table (Whalen & Reeburgh 1990). The elimination of this zone in floating peat reduces the habitat available for CH_4 oxidizers, and increases the habitat for CH_4 producers. This was shown by $\delta\ ^{13}C$ measurements taken prior to and following flooding of wetland 979. CH_4 samples from undisturbed peat prior to flooding were highly oxidized, with a $\delta\ ^{13}C$ value of −28‰ (Kelly et al. 1997). Flooded peat was less oxidized ($\delta\ ^{13}C$ = −38‰) (Kelly et al. 1997) and floating peat surfaces showed the least oxidation ($\delta\ ^{13}C$ = −56‰) (Scott et al. 1997).

In an undisturbed peat profile, temperature generally decreases with depth due to the insulating effect of the overlying unsaturated peat. Following flooding of wetland 979, the average annual temperature of the submerged peat increased by 1 to 4 °C (Kelly et al. 1997). Midsummer temperatures ranged from 19 °C at the surface of the submerged peat to approximately 10 °C at a depth of 1.0 m. Temperatures in the bulk of the floating peat were even higher (18–24 °C) reflecting the temperature of the pond. The highest temperatures (up to 35 °C) occurred at the surface of the floating peat in response to diel changes in air temperature (Poschadel et al. in press).

Increased temperature results in increased CH_4 production in laboratory incubations of lake sediments (Zeikus & Winfrey 1976; Kelly & Chynoweth 1981) and in peat (Williams & Crawford 1984; Dunfield et al. 1993). The optimum temperatures for CH_4 production in peat soils were between 25 and 30 °C (Williams & Crawford 1984; Dunfield et al. 1993). Thus, the temperatures in the floating peat islands were approaching the optima for methanogenesis.

The presence or absence of plant cover was not a consistent predictor of CH_4 fluxes from floating peat. The lowest fluxes were measured at the well vegetated sites (FP-3 and 4) and one unvegetated site (FP-1, Table 1). The highest emissions were at another unvegetated site (site B) and a poorly vegetated site (FP-2). Concentration profiles of dissolved CH_4 showed overall lower values throughout the vegetated peat island profile (FP-3) suggesting either lower rates of production or greater rates of oxidation perhaps due to roots. However, given that sites FP-1, 3, and 4 all lifted in the first year of the study and had lower fluxes than the newly lifted peat islands (FP-2 and site B), it is possible that the extremely high fluxes associated with newly lifted peat might decrease somewhat as the islands age regardless of the degree of recolonization by plants.

CH_4 fluxes associated with beaver ponds are generally high (Table 4). Although 'castorigenic' flooding (i.e. by beavers, *Castor canadensis*) comprises a small percentage of the total landscape, it still contributes significantly to CH_4 fluxes to the atmosphere (Bridgham et al. 1995). Similarly, peat islands in reservoirs may also be small areas that are important sources of CH_4 to the atmosphere. For example, if only 1% of the total area of hydroelectric complexes such as La Grande-2 and Laforge-1 in northern Quebec experienced uplifting of peat, annual flux rates from the reservoir areas as a whole (based on 150 ice-free days) would increase from roughly 1.5 g CH_4 m^{-2} yr^{-1} (10 mg CH_4 m^{-2} d^{-1}, Duchemin et al. 1995) to 2.1 g CH_4 m^{-2} yr^{-1} or by 43%. Considering that approximately 20,000 km^2 of peatland and upland areas in Canada alone are presently covered by hydroelectric reservoirs (Rosenberg et al. 1987) and a further 10,000 km^2 are planned for northern Quebec (Rougerie 1990), floating peat may be an important yet previously unidentified source of CH_4 to the atmosphere.

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