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Abstract. A static chamber technique was used weekly from spring thaw to winter freezing to measure methane emissions from 10 sites representing subarctic fens and temperate swamps and bogs. Rates of $< 200\,\mathrm{mg\,CH_4\,m^{-2}\,d^{-1}}$ were recorded in subarctic fens: within-site emissions were primarily controlled by the evolution of the peat thermal regime, though significant releases during spring thaw were recorded at some sites. Between subarctic fens, topography and water table elevation were important controls on methane emissions, with the general sequence: pool = horizontal fen > string. Emission rates from the 2 swamp sites were lower ($< 20\,\mathrm{mg\,CH_4\,m^{-2}\,d^{-1}}$), except during the spring thaw and when the sites were saturated. The low water table (< 80 cm depth) in abnormally dry years reduced emission rates; rates were also low from a swamp site which had been drained and cleared of vegetation for horticulture. Methane emission rates were also low ($< 5\,\mathrm{mg\,CH_4\,m^{-2}\,d^{-1}}$) from 2 ombrotrophic bog sites. Laboratory measurements of rates of methane production under anaerobic conditions and methane consumption under aerobic conditions revealed that production rates were generally highest in the surface layers (0 to 25 cm depth); production was high in the fens and very low in the bogs. The swamp samples were able to produce methane under anaerobic conditions, but were also able to consume methane under aerobic conditions. Annual methane emission rates are estimated to be 1 to $10\,\mathrm{g\,CH_4\,m^{-2}}$ from the fens, 1 to $4\,\mathrm{g\,CH_4\,m^{-2}}$ from the swamps and $< 0.2\,\mathrm{g\,CH_4\,m^{-2}}$ from the bogs and drained swamp.

Introduction

Atmospheric concentrations of methane have been increasing at a rate of about 1% $\mathrm{y^{-1}}$ over the past 15 y (Ramanathan 1988) and the highest concentrations are found in latitudes north of 40°N (Steele et al. 1987). This distribution coincides with the large area of wetlands in the northern part of the northern hemisphere and suggests that peatlands in this area may make a significant contribution to the global methane budget (e.g. Aselmann & Crutzen 1989; Crill et al. 1988; Matthews & Fung 1987). However, reliable estimates of the contribution of northern peatlands and all other sources are severely limited by a paucity of field measurements of methane emissions.

Several studies have examined methane emissions from peatlands in temperate to subarctic locations. These studies show a large range of emission rates, from 0 to $0.7\,\mathrm{g\,CH_4\,m^{-2}\,d^{-1}}$, often with a strong component of seasonal and spatial variability (Baker-Blocker et al. 1977; Clymo & Reddaway 1971; Crill et al. 1988; Harriss et al. 1982, 1985; Moore & Knowles 1987; Sebacher et al. 1986;

Svensson 1980; Svensson & Rosswall 1984; Whalen & Reeburgh 1988). Measurements have often been made over only part of the season during which the peatlands were expected to produce methane. Extrapolating the daily or hourly flux measurements to annual values suggests that emission rates from peatlands in temperate and subarctic areas may range from 0.1 to 60 g CH_4 m^{-2} y^{-1}. As noted by Crill et al. (1988), adequate assessment of the contribution of peatlands to the global methane budget requires the field measurement of methane fluxes over the complete season and over a wide range of sites. These studies, as well as laboratory studies, have identified the main controls on methane production and emission as temperature, water table position and the microbial characteristics of the peat material (e.g. Moore & Knowles 1989; Svensson & Rosswall 1984; Yavitt et al. 1987).

In this paper, we report on methane emission measurements through an annual cycle at 10 sites, representing subarctic fens, temperate bogs and temperate swamps. We examine the seasonal pattern of methane emission, estimate the annual flux and evaluate the role of temperature, hydrology and peat type on emission rates. The study extends some preliminary measurements reported earlier (Moore & Knowles 1987) and examines the environmental controls on methane emission in the field and the ability of the peat profiles to produce and consume methane under anaerobic and aerobic conditions in the laboratory.

Sites and methods

Field measurements were conducted at 10 sites, representing examples of the major types of peatland found in Quebec (National Wetlands Working Group 1988; Zoltai & Pollett 1983). Five sites were located near Schefferville, northern Quebec (54° 48′N, 66° 49′W), representing subarctic horizontal and ribbed or patterned fens. The remaining five sites were located near Mt. St. Hilaire and St. Bruno in southern Quebec (45° 32′N, 73° 8′W and 45° 33′N, 73° 23′W, respectively), representing basin swamps and domed bogs, with one site drained and cleared of vegetation for horticultural purposes. Site characteristics are described in Table 1. Peat thickness at each site was 1 to 2 m.

Methane emission measurements

Methane emission measurements from each site were made using a static chamber technique. Polycarbonate bottles (6 per site) about 40 cm high and 26 cm diameter, with the base removed, were pushed about 5 cm into the peat surface to ensure a seal against the ambient atmosphere; the necks were sealed with a rubber stopper, a 10 cm glass tube and serum stopper. At the subarctic pool site, the bottles were partially submerged over the underlying peat surface and held in position with a wooden stake. The bottles were moved around the site at each sampling date. The surface of the bottles was covered with aluminum foil to minimise temperature changes within the bottle. The chambers covered

Table 1. Characteristics of the ten sites.

Site	Location[1]	Dominant vegetation	Peatland type[2]
Subarctic: Schefferville			
1	423724	*Sphagnum lindbergii*, *Carex limosa*	Horizontal poor fen
2	425728	*Sphagnum lindbergii*, *Carex rariflora*	Horizontal rich fen
3	378879	*Scirpus cespitosus*, *Chamaedaphne calyculata*, *Sphagnum spp.*, *Betula michauxii*	Northern ribbed fen – string: peat surface about 20 cm above water level
4	378879	*Carex limosa*	Northern ribbed fen – flark: peat surface close to water level
5	378879	*Menyanthes trifoliata*	Northern ribbed fen – pool: peat surface about 40 cm beneath water level
Temperate: Mt. St. Hilaire			
6	452465	*Betula alleghaniensis*, *Tsuga canadensis*	Basin swamp
St. Bruno			
7	276470	*Populus deltoides*	Basin swamp
8	274465	*Sphagnum spp.*, *Rhododendron spp.*, *Betula populifolia*	Domed bog – centre
9	273465	*Sphagnum spp.*, *Rhododendron spp.*, *Betula populifolia*	Domed bog – margin
10	276477	none	Swamp drained and cleared of vegetation for horticulture: water table 50 to 100 cm beneath peat surface

[1] Location indicated by grid reference on 1:50000 maps – 23J/15 at subarctic sites and 31H/11 at temperate sites.

[2] Classification of peatland type follows the National Wetlands Working Group (1988).

an area of 530 cm^2 and thus were comparable to those used by Whalen & Reeburgh (1988), but were larger than those used by Svensson & Rosswall (1984) and smaller than those used by Sebacher et al. (1986). A comparison of static and dynamic chambers in subarctic fens has shown that static chambers tend to underestimate emission rates, compared to dynamic chambers and there is a linear increase in methane concentration in the chamber over 24 h (Moore & Roulet, unpubl. ms.).

Ambient atmosphere samples were collected at the time the bottles were sealed and stored in 3-mL Vacutainers (Becton-Dickinson, Rutherford, NJ). Twenty-four hours later, a 3-mL sample of the air within the chamber was withdrawn with a syringe and transferred to a Vacutainer. During the spring thaw of the peat, air in the chambers was sampled every 3 or 4 d, with the chambers left in the thawing peat, with the neck sealed. The samples were sent to Montreal and analysed for methane concentrations by gas chromatography (Nelson & Knowles 1978), usually within 10 d of sampling.

There are several sources of error associated with the emission measurements. A minor source is instrumental error in the determination of methane concentrations. A second source is the variation in background concentration of methane within the sterilized Vacutainers. Leakage, however, was presumably not a problem since loss of vacuum in fully evacuated Vacutainers was negligible during 2 mo and averaged only 13% in 7 mo. The variability of emission rates recorded at each sampling date is a combination of the above two sources of error, plus that produced by the natural spatial variability in methane emissions. In most cases, coefficients of variation of methane emission measurements were about 100%. At the subarctic sites, where methane emissions are generally highest, about 85% of this variability is associated with the spatial variability between the replicate chambers. A similar variability (coefficients of variation of 50 to 100%) within sites has been reported from Alaskan tundra by Whalen & Reeburgh (1988) and from temperate swamps by Wilson et al. (1989). At the bog and swamp sites, where methane emissions are generally low, this variability appears to be about equally divided between the spatial variability and the variability in background concentrations of methane in the Vacutainers.

Methane emission measurements were made at 7 to 10 d intervals from July, 1986 to August, 1988 at the subarctic and Mt. St. Hilaire sites and from May, 1987 to August, 1988 at the other sites. The emission of methane from the sites was calculated from the difference between the ambient air and chamber concentrations and the area and volume of the chambers.

Measurements of the thermal regime at most of the sites was made by the placement of thermistors at depths from 10 to 100 cm, which were read each time an emission measurement was made. Depth to water table was measured by installing 5 cm diameter tubes at the temperate sites.

Methane production and consumption in peat samples under laboratory conditions

To establish differences in potential methane production and consumption rates of the sites under standard anaerobic and aerobic conditions, 25-cm increment samples of the peat profile at each site were collected by auger in May and June, 1988. The samples were placed in plastic bottles, saturated with peat water and stored at 4 °C.

Because of the late thaw of the peat profile at site 2 in 1988, only the surface (0–25 cm) layer was collected. Peat samples were also collected from a transitional and a very rich fen near Schefferville, whose field methane emission rates have been reported earlier (sites 1 and 2, respectively, in Moore & Knowles 1987).

For the anaerobic incubation, duplicate 5 g (wet) samples of the peat were kept under a flow of nitrogen gas to minimize exposure to oxygen and placed in 50-mL Erlenmeyer flasks. The flasks were then sealed with SubaSeals and evacuated and filled three times with nitrogen to remove any ambient air. The samples were incubated at 15 °C over a 12 d period. This temperature was chosen because it is a value close to that reached in the surface layers (0 to 25 cm depth) of most of the peat profiles during the summer.

For the aerobic incubation, duplicate 5 g (wet) samples of the peat were placed in 50-mL Erlenmeyer flasks, sealed with SubaSeals and methane added to produce a concentration of 5% inside the flask. The samples were incubated at 15 °C over a period of 12 d on a rotary shaker.

Gas samples (0.5 mL) were removed from the flasks using syringes with Teflon minivalves at 48 h intervals and analyzed for methane, as noted above. After the incubation, the weight of the sample was determined by oven drying at 105 °C.

Rates of methane production or consumption were calculated for the 12 day incubation by regressing the change of methane concentration in the flask with time. A t-test of the regression coefficient was used to determine if the rates were significantly different from zero ($p < 0.05$).

The pH of the peat samples was determined using a 0.01 M $CaCl_2$ solution and an estimate of the degree of decomposition of the samples was made using the von Post scale (Canada Soil Survey Comittee 1978).

Results

Field emission rates

Subarctic fens

The seasonal pattern of methane emission was similar at the subarctic sites (Figs. 1, 2). Emission rates were generally lower during the early summer, reaching peak values in late summer and early autumn. At the horizontal poor fen site (Fig. 1, site 1), emission rates ranged from 30 to 40 mg $CH_4\,m^{-2}\,d^{-1}$ in the early summer, rising to > 50 mg $CH_4\,m^{-2}\,d^{-1}$ later in the summer. Emission rates were lower at the rich fen site (Fig. 1, site 2). Both sites recorded a strong emission of methane during the spring thaw during 1987, probably associated with the release of methane produced during the winter and trapped within and beneath the ice.

At the ribbed or patterned fen sites (Fig. 2), similar seasonal variations were observed, but there were major differences in the magnitude of methane emissions between the string, flark and pool sites. Emissions were lowest, generally < 20 mg $CH_4\,m^{-2}\,d^{-1}$, at the string site (site 3), whose peat surface is located

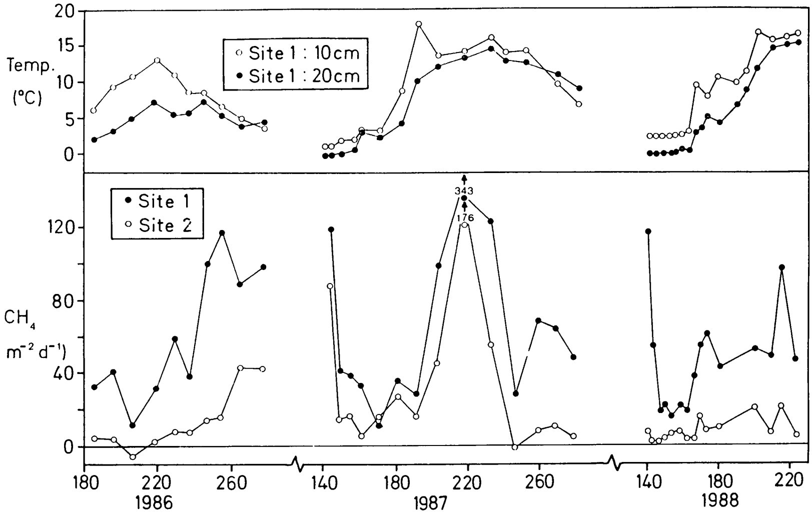

Fig. 1. Methane emission from the subarctic poor fen (1) and rich fen (2) sites, with temperature at 10 and 20 cm depths at the poor fen site.

about 20 cm above the water table and were higher (10 to 100 mg CH_4 m^{-2} d^{-1}) at the flark site (site 4), where the peat surface was generally at about the same elevation as the water surface. The highest emission rates (< 200 mg CH_4 m^{-2} d^{-1}) were recorded at the pool site (site 5), where the water surface was 30 to 50 cm above the peaty bottom of the pool. The static chamber

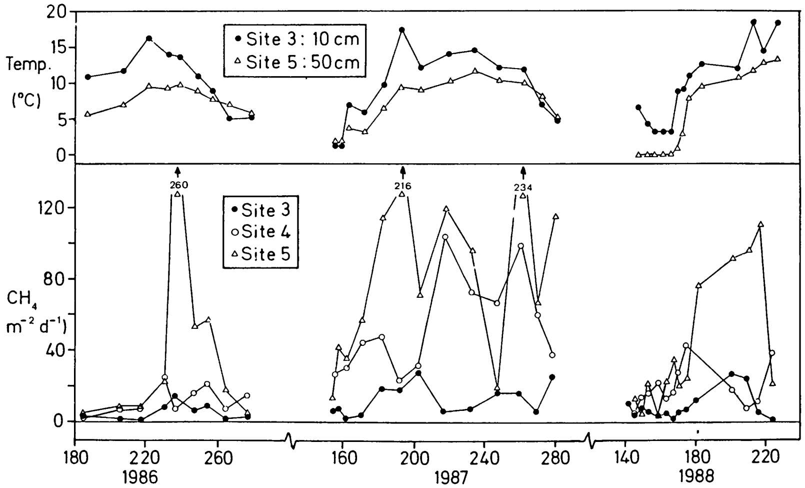

Fig. 2. Methane emission from the subarctic string (3), flark (4) and pool (5) sites, with temperature at the 10 cm depth at the string site and near the surface of the peat bottom (50 cm beneath the water surface) at the pool site.

Table 2. Relationships between methane emission rates and peatland temperature at the Schefferville sites, excluding emissions during the spring thaw. Methane emissions in $\mathrm{mg\,m^{-2}\,d^{-1}}$ and temperature in °C at the depth indicated (cm).

Site	Regression	r^2	Sig. level
1	$\log_{10}CH_4 = 0.025T_{10} + 1.44$	0.132	0.041
	$\log_{10}CH_4 = 0.035T_{20} + 1.43$	0.266	0.003
2	$\log_{10}CH_4 = 0.075T_{20} + 0.61$	0.204	0.011
3	$\log_{10}CH_4 = 0.013T_{10} + 0.57$	0.009	0.598
	$\log_{10}CH_4 = 0.000T_{25} + 0.70$	0.000	0.987
4	$\log_{10}CH_4 = 0.030T_{10} + 0.88$	0.030	0.337
	$\log_{10}CH_4 = 0.023T_{25} + 0.98$	0.027	0.362
5	$\log_{10}CH_4 = 0.065T_{50} + 1.13$	0.223	0.006

method may underestimate methane emissions from the pool, through the absence of turbulent exchange, which Sebacher et al. (1983) have shown significantly increases emissions during windy conditions. Heating of the pool floor through adsorption of solar radiation raises summer temperatures to 10 to 20 °C in the upper layers of peat at the pool site (Fig. 2). Microtopography in relation to water table elevation played an important role in controlling methane emissions in the ribbed fen. The thaw-related emissions of methane were not recorded at the ribbed fen sites.

Within each of the subarctic sites, the seasonal variation in methane emission appears to be related to the thermal evolution of the peat profile. However, because of between-year variations in wetness, the correlations between the logarithm of methane emission and the temperature in the surface layers (generally depth of 10 or 25 cm) over the measurement period are not strong, being significant ($p < 0.05$) at only three of the five sites (Table 2).

Precipitation at Schefferville in 1987 was greater than average, especially during July when the monthly precipitation was 187% of the long-term mean (Table 3). Precipitation in 1986 and 1988 was lower than average, especially in

Table 3. Monthly precipitation (mm) at St. Hubert and Schefferville airports during the sampling period. Figures in parentheses represent the percentage of the long term mean.

Month	St. Hubert			Schefferville		
	1986	1987	1988	1986	1987	1988
April		41 (55)	83 (111)		48 (96)	58 (116)
May		71 (97)	35 (48)		54 (102)	49 (92)
June		126 (147)	62 (73)		62 (82)	34 (45)
July	105 (108)	41 (40)	41 (42)	100 (100)	189 (187)	71 (70)
Aug.	140 (145)	46 (45)	107 (110)	74 (77)	98 (102)	53 (55)
Sept.	134 (148)	121 (134)		84 (95)	77 (88)	
Oct.	61 (81)	59 (79)		61 (82)	57 (77)	
Nov.	84 (94)	85 (132)		35 (55)	124 (194)	

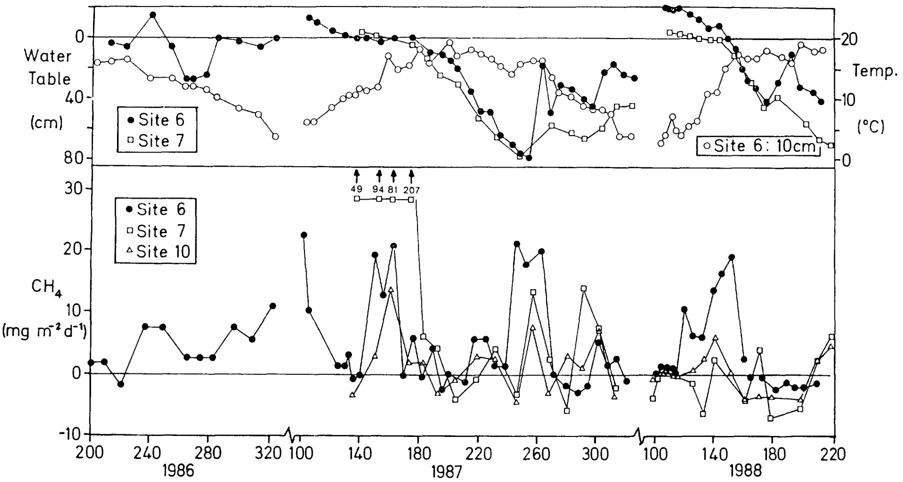

Fig. 3. Methane emission from the temperate swamp (6 and 7) and drained swamp (10) sites, with water table levels at the two swamp sites and temperature at a depth of 10 cm at the Mt. St. Hilaire swamp (site 6).

June, July and August, 1988, in which precipitation was only 63% of the long-term mean and the second driest on record. Mean monthly temperatures were close to the long term average, being within one standard deviation of the average for all but August, 1987. Average methane emissions from all the sites during 1987 were much higher (170 to 350%) than those recorded in 1986 and 1988: the largest ratios of methane emission 1987:1986/1988 were observed at the flark site (# 4), at which the water table oscillates close to the peat surface. The ratio was smallest at the two fen sites (# 1 and 2), in which there is evidence of surface adjustment of the peat and *Sphagnum* mat to changes in the water table elevation (Roulet, pers. comm.).

At each site, especially high emissions of methane were recorded on some dates, especially during the summer of 1987. The sampling frequency is not sufficiently detailed to be able to relate these emissions to specific hydrology events, such as heavy precipitation, or to the increased production of methane under generally wetter conditions, which may produce larger bubbles and create a more pronounced episodic emission pattern.

Temperate swamps

The pattern of methane emission at the two swamp sites is more complex than that of the subarctic sites (Fig. 3). During 1987, the Mt. St. Hilaire swamp (site 6) revealed a strong release of methane as the peat column thawed in early spring, though this pattern was not recorded in 1988. This was followed by very low emission rates in the spring, which rose to 10 to 20 mg CH_4 m^{-2} d^{-1} as the peat remained saturated and temperatures reached 10 to 15 °C at a depth of 10 cm. Emission rates fell to very low values (< 5 mg CH_4 m^{-2} d^{-1}) during the summer and autumn, associated with a fall in the depth of the water table from

30 to 80 cm. The results collected at the end of 1986 at site 6 suggest that methane emission rates rise in the autumn if the water table reaches the peat surface.

The second swamp site (# 7) also recorded high methane emission rates (50 to 200 mg $CH_4\,m^{-2}\,d^{-1}$) in spring, 1987, when the water table was close to the peat surface, but emission rates dropped dramatically (to < 5 mg $CH_4\,m^{-2}\,d^{-1}$) when the water table fell 20 cm or more beneath the surface.

Both 1987 and 1988 were drier than average in the Montreal area, whereas 1986 received about average precipitation (Table 3). The results suggest that water table position is of critical importance in controlling methane emission rates from swamps, with temperature being significant only if the water table remains at or close to the surface. An individual example of the importance of hydrological changes on methane emissions is shown by the high emissions recorded at site 6 between days 245 and 260, 1987. In the 30 days prior to day 245, only 28 mm of rain fell, with the water table at a depth of about 80 cm. Seventeen mm of rain fell on days 246–248, 26 mm on days 251–253 and 75 mm on days 256–257. The occurrence of increased methane emission rates before the observed rise in water table from 80 to 18 cm suggests either that, after a dry period, rewetting the surface layers may stimulate methanogenesis or, more probably, methane stored in pores is expelled. A similar, but less pronounced, response in both water table and methane emissions was observed at site 7 during the same period in 1987. The complex relationship between temperature, water table position and methane emission failed to produce any statistically-significant relationship, through either single or multiple regression ($p > 0.10$).

During the dry summer, with water table depths of 50 cm or more, there appeared to be small amounts of methane consumption by the swamps, < 5 mg $CH_4\,m^{-2}\,d^{-1}$, though the significance of this may be questioned, given the high variability of methane concentrations in the chambers and Vacutainers.

At the drained swamp site (10), methane emissions were always low, associated with the water table at a depth of 50 cm or more.

Temperate bogs

At the two bog sites (Fig. 4, sites 8 and 9), methane emissions were very small (generally < 5 mg $CH_4\,m^{-2}\,d^{-1}$) and water tables were at depths of 30 to 60 cm for much of the sampling period, associated with the dry summers in 1987 and 1988. The sites were close to saturation only during the spring of 1988, though at this time, low temperatures (5 to 10 °C) may have lowered methane production rates.

Annual emissions

Integration of the seasonal pattern of methane emission at the sites allows an estimate of annual fluxes to be made. Measurements were not attempted during the winter and measurements in the late fall and spring melt may underestimate emission rates (Whalen & Reeburgh 1988). The high spatial and temporal variability in the methane emission measurements add further uncertainty to the

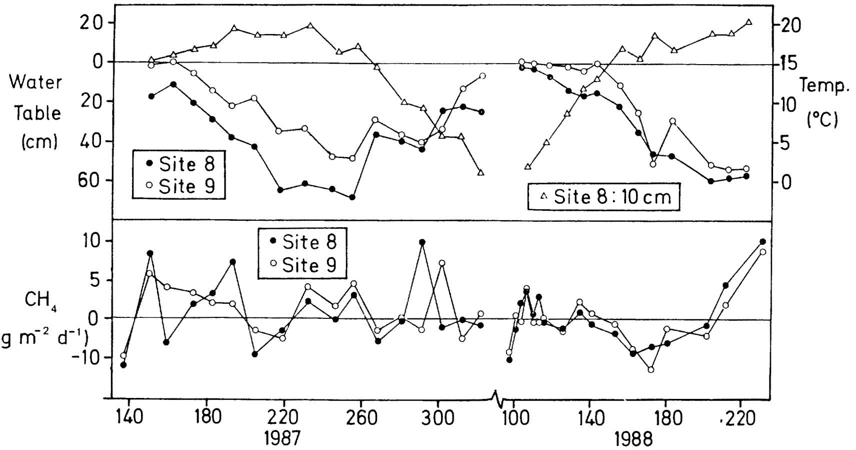

Fig. 4. Methane emission from the temperate bog sites (8 and 9), with water table levels and the temperature at a depth of 10 cm at site 8.

estimates, which range from 1.3 to 9.9 g CH_4 $m^{-2}y^{-1}$ for the subarctic fens, to 1.2 to 4.2 g CH_4 $m^{-2}y^{-1}$ for the swamps and 0.1 g CH_4 $m^{-2}y^{-1}$ for the bogs (Table 4). It must also be recognised that these estimates are based on data from one wet and one dry year at the subarctic sites and two dry years at the swamp and bog sites, so that the swamp and bog values, in particular, may be underestimates of long-term emission rates.

Methane production and consumption under laboratory conditions

The highest rates of methane production under anaerobic conditions (up to 182 nmol g^{-1} d^{-1}) were recorded in the surface samples (0 to 25 cm depth) from the subarctic poor fen site (# 1) and a transitional fen (Table 5), which had been

Table 4. Estimated annual emission of methane from the 10 sites, based on observed emissions.

Site	Methane emission ($g m^{-2} y^{-1}$)
Subarctic	
1 Poor fen	9.8
2 Rich fen	3.0
3 String	1.3
4 Flark	4.5
5 Pool	9.9
Temperate	
6 Swamp	1.2
7 Swamp	4.2
8 Bog	0.1
9 Bog	0.1
10 Drained swamp	0.2

Table 5. Methane production under anaerobic conditions and methane consumption under aerobic conditions of samples collected from the peat profile at each site, plus samples collected from a transitional fen and a very rich fen in the Schefferville area (Moore & Knowles 1987).

Site	Depth (cm)	CH_4 Production (nmol g^{-1} d^{-1})	CH_4 Consumption (μmol g^{-1} d^{-1})	pH	Decomposition
Subarctic					
1	0–25	182	6.54	3.1	2
	25–50	100	ns	4.0	3
	50–75	51	2.22	4.4	4
	75–100	28	3.88	4.3	4
2	0–25	22	10.74	4.9	3
3	0–25	52	ns	3.7	4
	25–50	16	ns	3.7	5
	50–75	16	ns	3.5	5
	75–100	13	ns	3.3	6
4	0–25	32	ns	3.6	5
	25–50	15	ns	3.6	5
	50–75	33	ns	3.8	5
	75–100	18	2.47	3.8	5
5	0–25	77	ns	3.9	6
	25–50	40	ns	3.8	5
	50–75	18	ns	3.4	5
	75–100	19	ns	3.2	5
Transitional fen*	0–25	168	ns	3.5	4
	25–50	16	ns	3.8	5
	50–75	39	2.18	4.6	5
	75–100	9	ns	4.8	5
Very rich fen*	0–25	12	4.62	5.7	5
	25–50	10	ns	5.9	6
	50–75	122	ns	6.0	6
	75–100	10	3.50	6.1	6
Temperate					
6	0–25	4	13.08	5.2	5
	25–50	6	15.59	5.0	6
	50–75	ns	ns	4.7	6
	75–100	1	ns	4.9	6
7	0–25	89	11.53	5.3	6
	25–50	5	11.10	5.4	7
	50–75	ns	ns	5.2	7
	75–100	ns	ns	5.1	7
8	0–25	4	ns	2.9	3
	25–50	5	2.64	3.3	4
	50–75	ns	ns	3.3	4
	75–100	2	ns	3.1	4
9	0–25	4	3.04	3.0	3
	25–50	6	5.97	2.8	4
	50–75	3	6.71	2.8	4
	75–100	3	5.22	2.9	4
10	0–25	5	ns	4.4	5
	25–50	7	ns	4.7	5
	50–75	ns	ns	4.9	5
	75–100	ns	ns	4.9	5

* Site 1 and 2 from Moore & Knowles (1987). Samples were incubated at 15 °C over a 12 day period and rates calculated for that period; ns means that the regression coefficient was not significantly different from zero ($p > 0.05$).

studied previously (Moore & Knowles 1987). In nearly all cases, there was a decrease in methane production with depth at each site, though most of the subarctic samples were able to produce substantial amounts of methane (10 to 30 nmol $g^{-1} d^{-1}$) at depths from 50 to 100 cm.

The Mt. St. Hilaire swamp (site 6) exhibited very low rates of methane production throughout the profile (< 10 nmol $g^{-1} d^{-1}$), a pattern also shown by the other swamp (site 7), except for the surface layer (0 to 25 cm), which recorded high rates of methane production of 89 nmol $g^{-1} d^{-1}$. The drained swamp (site 10) also showed very low rates of methane production throughout the profile.

Both the bog profiles (sites 8 and 9) showed extremely low rates of methane production under anaerobic conditions throughout the profile (< 10 nmol $g^{-1} d^{-1}$).

Many of the peat samples showed insignificant rates of methane consumption. The highest rates were observed in the surface (0 to 50 cm) layers of the two swamp profiles (11 to 16 μmol CH_4 $g^{-1} d^{-1}$). Significant but lower rates of methane consumption (< 6 μmol $g^{-1} d^{-1}$) were also observed at the string and bog sites (# 1 and 9).

Although the pH of the samples ranged from 2.9 to 6.1, there appears to be no strong relationship between acidity and either methane production or consumption. The most acidic samples at the bog sites (pH $<$ 3.3, sites 8 and 9) recorded the lowest rates of methane production, yet the highest rates were recorded in the surface layers of the poor and transitional fens in which the pH fell between 3.1 and 3.5. There were low rates of methane production in the surface samples with the highest pH, such as the swamps and the very rich fen. Similarly, there does not appear to be a strong relationship between the degree of decomposition and methane production, with the weakly decomposed, *Sphagnum* fen and bog samples exhibiting the range of methane production rates. There appears to be no association between either soil pH or degree of decomposition and rates of methane consumption.

Discussion

Estimates of methane flux from soils, such as peatlands, suffer from two main problems. One problem concerns ensuring that the environment within the measurement chambers is similar to that above the peatland surface, in terms of temperature, wind speed and methane concentration. The second problem involves a sampling strategy to allow for the high variability in methane emissions, both spatially within and between sites and temporally, as the methane flux from wetlands can occur as episodic events, such as bubbles (e.g. Bartlett et al. 1988; Crill et al. 1988; Devol et al. 1988) or as diffusion (Barber et al. 1988; Whalen & Reeburgh 1988).

The results from this study show there can be up to two orders of magnitude difference in daily methane emissions, both within and between sites. The range of summer methane emissions of 10 to 300 mg $CH_4 m^{-2} d^{-1}$ from the subarctic peatlands is similar to those reported for other subarctic peatlands (Moore & Knowles 1987; Sebacher et al. 1986; Svensson 1976, 1980; Whalen & Reeburgh 1988) for a tundra pond by Hobbie et al. (1980) and for Minnesota fens (Harriss et al. 1985; Crill et al. 1988). The results confirm the importance of local variations in topography as they reflect differences in water table elevation, as illustrated by the string-flark-pool sequence at Schefferville. Small waterlogged depressions and pools, a common feature of many subarctic landscapes (e.g. Foster et al. 1983), may be important regional sources of methane emission, rather than the better-drained sections of wetlands. Poorly-consolidated, lower-lying fens may also be important because of their ability to adjust the *Sphagnum*-peat surface to seasonal changes in the water table elevation, as suggested by the results from the poor fen at Schefferville. The influence of wetness is further illustrated by the differences in methane emissions from the subarctic sites in wet and dry years, and the differential response to this between the sites.

Within the year, the main influence on methane emission rates from the subarctic fen sites is temperature, especially in the upper (top 25 cm) layers of the profile (Moore 1987). The importance of temperature on methane production has been noted by several other investigators (e.g. Crill et al. 1988; Svensson 1984; Whalen & Reeburgh 1988; Williams & Crawford 1984). The weak statistical relationship between methane emissions and temperature at the subarctic sites probably reflects the high spatial variability in emission rates at the sites, fluctuations in water table position, seasonal changes in vegetation cover, substrate quality and methanogen populations and lag time between methane production and transport and emission.

There is evidence of significant release of methane during the spring thaw, especially at the fen sites. Whalen & Reeburgh (1988) also noted an increase in methane emissions from Alaskan wetlands, and, at a moss-covered site, release during the winter as the freezing front moved downwards to permafrost. In the Schefferville study, no attempt was made to measure over-winter emissions of methane, which may produce underestimates of annual emissions but the Schefferville fens are not underlain by permafrost.

The summer methane emission rates from the two swamps are similar to those reported for the Great Dismal Swamp (Harriss et al. 1982), but lower than those from other temperate swamps (Harriss & Sebacher 1981; Baker-Blocker et al. 1977; Wilson et al. 1989). The low annual emission rates must be viewed within the context of the abnormally dry years of measurement. In the swamps, although there may be significant methane production under waterlogged conditions, the rapid reduction in methane emissions with a fall in the water table (substantiated by the laboratory experiment reported by Moore & Knowles 1989) appears to be related to the ability of the swamp peats to oxidise methane. The occurrence of small net methane consumption fluxes during summer periods of low water table has been observed in the Great Dismal Swamp (Harriss & Sebacher 1981). Swamps in southern Canada frequently have a water table beneath the peat surface during the summer (National Wetlands Working Group 1988).

The low seasonal and annual emission rates of methane from the two bog sites appears to be related to the inability of these very acidic peats to produce methane. Although the bogs had an acrotelm for much of the summer, Moore & Knowles (1989) reported very low emission rates from laboratory columns of peat from site 8 kept under inundated and saturated conditions and the laboratory anaerobic incubations reported here revealed very low rates of methane production. The low methane producing capacity of the two bog sites may be related to the microbiological and chemical properties of the very acid, fibric peat. Substantial emissions of methane have been reported from other bog peats, though summer emission rates tend to be low (e.g. Clymo & Reddaway 1971; Crill et al. 1988; Harriss et al. 1985; Svensson 1976). Given the extensive area of acid, ombrotrophic bogs in North America and elsewhere, methane emission rates from this wetland type deserve further study, as does a more detailed examination of the microbiological controls on methane production and consumption in a range of peats.

It is unclear how much influence the gradient from ombrotrophic, acidic to minerotrophic, neutral conditions in the peatland has on methane emissions, and most field studies involve sites at which other factors, such as water table, thermal regime and rate of water movement also vary among the sites (e.g. Crill et al. 1988; Svensson 1976; Svensson & Rosswall 1984). From the present study, it appears that degree of ombrotrophy or decomposition is not a good indication of relative rates of methane production and emission. In Minnesota peatlands, Crill et al. (1988) have observed higher methane masses in minerotrophic than ombrotrophic sections, which they relate to higher porewater pH values associated with the influx of groundwater rich in nutrients. The occurrence of acid-tolerant methanogens and an increase in methane production with an increase in pH has been reported (e.g. Williams & Crawford 1985). Microbial processes leading to methane production and consumption are complex and it is important that these processes be examined in a wider range of peats, to allow the development of predictive models of methane emissions, using simple peat characteristics.

An estimate of the proportion of net primary plant production (NPP) emitted as methane can be made for the sites. NPP at the subarctic sites range between 50 and 100 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ for the poor and rich fens and 150, 50 and 5 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ at the string, flark and pool sites (Bartsch & Moore 1985; Moore 1989a, b). Litterfall at the Mont St. Hilaire swamp site totals about 100 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ and the NPP of boreal bogs ranges from 100 to 200 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ (Bartsch & Moore 1985). Using these figures, annual methane emissions from the subarctic peatlands ranged from 1% of NPP-C at the string site to 5–14% at the fen and flark sites and over 100% at the pool site, where the high flux probably represents anaerobic degradation of the underlying peat (Foster et al. 1983). These figures are similar to the 1–11% reported by Svensson (1983) and 5.5% by Sebacher et al. (1986) from subarctic mires. At the swamp and bog sites, the methane emissions represent only 0.1 to 3% of NPP, lower than the figures of 1–7.5% reported by Clymo & Reddaway (1971) and Crill et al. (1988).

This study has identified the importance of temperature, water table elevation and peat characteristics on rates of methane emission from wetlands. The results, however, suggest that the relationships between these variables and methane emission are complex and vary between sites. Extrapolations of regional methane fluxes may be made from frequent and spatially diverse measurements from sites representing a wide range of wetland types and scaling up wetland class and period during the year.

Aselmann & Crutzen (1989) have recently attempted to produce a global methane budget, using global wetland coverage and emission rates from representative wetlands. Their estimated geometric means were 15, 80 and 84 $mg\,CH_4\,m^{-2}\,d^{-1}$ for bogs, fens and swamps, respectively. The present study has revealed the wide range in emission rates and suggests that the above figures may be over-estimates. Within Canada, swamps, bogs and fens cover about 14, 673 and 531 × $10^3\,km^2$ (Aselmann & Crutzen 1989, from Zoltai & Pollett 1983). Based on the observed emissions of 1 to 10 $g\,CH_4\,m^{-2}\,y^{-1}$ reported here, Canadian wetlands contribute about 5 × $10^{12}\,g\,CH_4\,y^{-1}$ to the atmosphere, mostly from subarctic fens. Although this flux may be regionally important, it forms a small proportion of the estimated annual total global emission of about 500 × $10^{12}\,g\,CH_4$ (Aselmann & Crutzen 1989; Cicerone & Oremland 1988).

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References

Aselmann I & Crutzen PJ (1989) Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. J Atmos. Chem. 8: 307–359

Baker-Blocker A, Donahue TM & Mancy KH (1977) Methane flux from wetland areas. Tellus 29: 245–250

Barber TR, Burke RA Jr & Sackett WA (1988) Diffusive flux of methane from warm wetlands. Global Biogeochem. Cycles 2: 411–425

Bartlett KB, Crill PM, Sebacher DI, Harriss RC, Wilson JO & Melack JM (1988) Methane flux from the central Amazonian floodplain. J. Geophys. Res. 93: 1571–1582

Bartsch I & Moore TR (1985) A preliminary investigation of primary production and decomposition in four peatlands near Schefferville, Quebec. Can. J. Botany 63: 1241–1248

Canadian Soil Survey Committee, Subcommittee on Soil Classification (1978) The Canadian System of Soil Classification. Canadian Department of Agriculture, Publication 1646, Supply and Services Canada, Ottawa

Cicerone RJ & Oremland RS (1988) Biogeochemical aspects of atmospheric methane. Global Biogeochem. Cycles 2: 299–327

Clymo RS & Reddaway (1971) A tentative dry matter balance sheet for the wet blanket bog on Burnt Hill, Moor House NNR. Aspects of the Ecology of the Northern Pennines. Moor House Occasional Paper No. 3, Nature Conservancy Council, London

Crill PM, Bartlett KB, Harriss RC, Gorham E, Verry ES, Sebacher DI, Madzar L & Sanner W (1988) Methane flux from Minnesota peatlands. Global Biogeochem. Cycles 2: 371–384

Devol AH, Richey JE, Clark WA, King SL & Martinez LA (1988) Methane emissions to the troposphere from the Amazon floodplain. J. Geophys. Res. 93: 1583–1592

Foster DR, King GA, Glaser PH & Wright HE Jr (1983) Origin of string patterns in boreal peatlands. Nature 306: 256–258

Harriss RC & Sebacher DI (1981) Methane flux in forested freshwater swamps of the southeastern United States. Geophys. Res. Lett. 8: 1002–1004

Harriss RC, Sebacher DI & Day FP Jr (1982) Methane flux from the Great Dismal Swamp. Nature 297: 673–674

Harriss RC, Gorham E, Sebacher DI, Bartlett KB & Flebbe PA (1985) Methane flux from northern peatlands. Nature 315: 652–654

Hobbie JE, Traaen T, Rublee P, Reed JP, Miller MC & Fenichel T (1980) Decomposers, bacteria and micro-benthos. In: Hobbie JE (Ed) Limnology of Tundra Ponds (pp 340–387). Dowden, Hutchinson and Ross, Stroudsburg, Penn

Matthews E & Fung I (1987) Methane emissions from natural wetlands: global distribution, area and environmental characteristics of sources. Global Biogeochem. Cycles 1: 61–86

Moore TR (1987) The thermal regime of peatlands in subarctic eastern Canada. Can. J. Earth Sci. 24: 1352–1359

Moore TR (1989a) Growth and net primary production of *Sphagnum* at five fen sites, subarctic eastern Canada. Can. J. Botany 67: 1203–1207

Moore TR (1989b) Plant production and decomposition and carbon efflux in a subarctic patterned fen. Arctic and Alpine Research 21: 156–162

Moore TR & Knowles R (1987) Methane and carbon dioxide evolution from subarctic fens. Can. J. Soil Sci. 67: 77–81

Moore TR & Knowles R (1989) The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Can. J. Soil Sci. 69: 33–3

Moore TR & Roulet NT A comparison of static and dynamic chambers for methane emission measurements from subarctic fens (unpubl. ms.)

National Wetlands Working Group (1988) Wetlands of Canada. Ecological Land Classification Series, No. 24. Sustainable Development Branch, Environment Canada, Ottawa and Polyscience Publications, Montreal, 452 pp

Nelson LM & Knowles R (1978) Effect of oxygen and nitrate on nitrogen fixation and denitrification by *Azospirillum brasilense* grown in continuous culture. Can. J. Microbiol. 24: 1395–1403

Ramanathan V (1988) The greenhouse theory of climatic change: a test by an inadvertant global experiment. Science 240: 293–299

Sebacher DI, Harriss RC & Bartlett KB (1983) Methane flux across the air–water interface: Air velocity effects. Tellus 35B: 103–109

Sebacher DI, Harriss RC, Bartlett KB, Sebacher SM & Grice SS (1986) Atmospheric methane sources: Alaskan tundra bogs, an alpine fen, and a subarctic boreal marsh. Tellus 36B: 1–10

Steele LP, Fraser JP, Rasmussen RA, Khalil MAK, Conway TJ, Crawford AJ, Gammon RH, Maserie KA & Thoning KW (1987) The global distribution of methane in the troposphere. J. Atmos. Chem. 5: 125–172

Svensson BH (1976) Methane production in tundra peat. In: Schlegel HG, Gottschalk G & Pfennig N (Eds) Microbial Production and Utilization of Gases (pp 135–139). Goltze KG, Gottingen, FRG

Svensson BH (1980) Carbon dioxide and methane fluxes from the ombrotrophic parts of a subarctic mire. Ecol. Bull. (Stockholm) 30: 235–250

Svensson BH (1983) Carbon fluxes from acid peat of a subarctic mire with emphasis on methane. Report 20, Department of Microbiology, Swedish University of Agricultural Sciences, Uppsala, Sweden

Svensson BH (1984) Different temperature optima for methane formation when enrichments are supplemented with acetate or hydrogen. Appl. Environ. Microbiol. 48: 389-394

Svensson BH & Rosswall T (1980) Energy flow through the subarctic mire at Stordalen. Ecol. Bull. (Stockholm) 30: 283-301

Svensson BH & Rosswall T (1984) In situ methane production from acid peat in plant communities with different moisture regimes in a subartic mire. Oikos 43: 341-350

Whalen SC & Reeburgh WS (1988) A methane flux time series for tundra environments. Global Biogeochem. Cycles 2: 399-409

Williams RT & Crawford RL (1984) Methane production in Minnesota peatlands. Appl. Environ. Microbiol. 47: 1266-1271

Williams RT & Crawford RL (1985) Methanogenic bacteria, including an acid-tolerant strain, from peatlands. Appl. Environ. Microbiol. 50: 1542-1544

Wilson JO, Crill PM, Bartlett KB, Sebacher DI, Harriss RC & Sass RL (1989) Seasonal variation of methane emissions from a temperate swamp. Biogeochemistry 7: 55-71

Yavitt JB, Lang GE & Wieder RK (1987) Control of carbon mineralization to CH_4 and CO_2 in anaerobic, *Sphagnum*-derived peat from Big Run Bog, West Virginia. Biogeochemistry 4: 141-157

Zoltai SC & Pollett FC (1983) Wetlands in Canada: their classification, distribution and use. In: Gore AJP (Ed) Mires: Swamp, Bog, Fen and Moor, B (pp 245-268). Regional Studies. Elsevier, Amsterdam, The Netherlands