

Methane emissions from wetlands, southern Hudson Bay lowland

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Methane emissions were measured by a static chamber technique at 39 sites along a transect from the James Bay coast at the southeastern tip of Hudson Bay to Kinosheo Lake, northwest of Moosonee, Ontario, Canada. These sites represented five major wetland ecosystems along a successional gradient from the coast inland. Measurements were made at ≈ 10 -day intervals from early June to mid-August, and once in mid-September and mid-October 1990. Seasonal CH_4 fluxes were small ($< 2 \text{ g m}^{-2}$) at the recently emerged coastal marsh, coastal fen, tamarack fen, and interior fen ecosystems, except where there were shallow ponds and pools, which emitted $2 - 5 \text{ g CH}_4 \text{ m}^{-2}$. At the more complex bog ecosystem locations, CH_4 fluxes were small ($0.3 - 2.0 \text{ g m}^{-2}$) from hummock/hollow microtopography in the raised bogs and from the forested margin. The largest CH_4 fluxes were recorded from the degrading peat sections forming shallow pools and the moss/sedge mats which were always close to saturation ($1.8 - 16.6 \text{ g m}^{-2}$). A deeper (1-m water depth) pool emitted less CH_4 (1.4 g m^{-2}). In terms of ecological succession along the transect, covering emergence over $\approx 4000 \text{ yr}$, CH_4 emission rates increase from marsh to fen and bog, primarily through the development of peat degradation and the formation of moss/sedge lawns and pools. There were very weak statistical relationships at each site between the daily CH_4 flux and peat temperature and water table. However, there was a significant ($r^2 = 0.44$, $p < 0.001$) correlation between the seasonal CH_4 flux and the mean position of the water table over the complete range of sites, emphasizing the overall importance of hydrology in determining CH_4 flux. Laboratory incubation experiments were conducted to determine the capacity of the surface (0 - 20 cm depth) peat samples to produce CH_4 anaerobically and consume CH_4 aerobically. They revealed that many samples exhibited high CH_4 consumption rates, suggesting that although CH_4 production in the subsurface peat is high, CH_4 emissions from these wetlands to the atmosphere are limited to a large extent by CH_4 oxidation in the surface layers of the peat. Trophic status of the peat appeared to have little influence on emission rates, with the highest fluxes in the most acid ($\text{pH} < 3.5$) samples.

INTRODUCTION

Current global methane budgets estimate between 22 and 70 Tg $\text{CH}_4 \text{ yr}^{-1}$, or 4 to 16 % of the annual atmospheric burden, is emitted from wetlands north of 40° N [Asefmann and Crutzen, 1989; Fung *et al.*, 1991; Matthews and Fung, 1987]. This wide range in possible source strength results from the lack of measurements of CH_4 flux from such large areas ($\approx 3.0 \times 10^6 \text{ km}^2$ [Asefmann and Crutzen, 1989]), the diversity of wetland types in any one region and the poor knowledge of the areal extent of any one wetland type. Compounding the problem of obtaining regional estimates of CH_4 emissions is the large intrasite and intersite spatial variability in CH_4 flux, even within wetlands that are classified as ecologically similar [Bartlett *et al.*, 1992; Moore *et al.*, 1990; Morrissey and Livingston, 1992].

A major uncertainty in the estimation of the northern wetland source of CH_4 , however, comes from the complete lack of flux

measurements from the large, extensive, semicontinuous peatlands of the Hudson Bay lowland ($\approx 0.32 \times 10^6 \text{ km}^2$) and the western Siberian lowland ($\approx 0.54 \times 10^6 \text{ km}^2$). These two peatlands alone comprise 30 % of all wetlands north of 40° N . In the global estimates of CH_4 flux, it has been assumed that the flux from relatively small, isolated wetlands is representative of fluxes from the wetlands of these vast regions.

The evolution and present-day ecology of the wetlands of the Hudson Bay Lowland is considerably different from that of more isolated systems [National Wetlands Working Group, 1988]. The southern section of the Hudson Bay lowland possesses a great diversity of wetland types and is an area that is almost entirely covered by wetlands or lakes and rivers [Glooschenko *et al.*, this issue]. Within this diversity, there is a pattern of landscape evolution that is related to the emergence of the lowland from the Tyrrell Sea and the Bay, over the past 8000 years. This emergence has resulted in the development of a complex pattern of wetland types, representing a succession from the youngest wetlands near the coast to the oldest in the interior [Mortsch, 1990; Riley, 1982].

Methane emission from wetlands is controlled by a number of variables, including the rates of methane production and consumption by the soil microbial community and the ability of the

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soil and plant system to transport methane to the atmosphere. In turn, these variables are affected by factors such as the wetland hydrological and thermal regime and components of ecosystem functioning, such as rates of plant production and substrate quality. As wetlands evolve through time, through vegetation change and succession, so may the patterns of methane emission change. Thus by examining the patterns of methane emission both within each of the wetland ecosystems and along the successional gradient, the influence of ecosystem dynamics on methane emissions can be established.

The objective of the research reported in this paper was to examine the intrawetland and interwetland spatial and temporal variability of CH_4 flux from wetlands along a 100-km transect of the southern section of the Hudson Bay lowland, Ontario, Canada. This transect was chosen as the study site of the Northern Wetlands Study (NOWES) because it represents 5000 years of peatland evolution [Glooschenko *et al.*, this issue]. In addition to determining the fluxes of CH_4 and the seasonal pattern, environmental variables that relate to the fluxes, such as hydrological and thermal regimes and edaphic and ecological factors, were also examined. This study, among others [Hamilton *et al.*, this issue; Holland, 1991; Klinger *et al.*, this issue], provided the basis for the estimation of the Hudson Bay lowland as a source of atmospheric CH_4 [Roulet *et al.*, this issue].

METHODS

Field Locations

Five major ecosystems were sampled along a 100-km transect from the emerging James Bay coastline near North Point to the interior, at five main locations (Figure 1). In this paper, location is used to indicate position along the North Point to Kinosheo Lake transect, while the term site indicates an ecologically distinct area. A wetland type, such as bog, fen, etc., is defined using the classification system of Riley [1982]. Individual sites may represent single wetland types, or several types may represent a gradient of units within one wetland type (Table 1). Sixteen wetland types were classified, and the areal extent calculated by Roulet *et al.* [this issue]. The relative importance of each type is presented in Table 2. The following major ecosystems were sampled:

Coastal marsh. Five sites were established at the coastal marsh location ($51^\circ 29' \text{N}$, $80^\circ 28' \text{W}$) near North Point, representing recently emerged salt marshes and supertidal meadow marshes and pools [Glooschenko, 1978; Glooschenko and Clarke, 1982]. Organic matter accumulation is shallow ($< 0.2 \text{ m}$) and vascular plant species diversity is high.

Coastal fen. The coastal fen location ($51^\circ 28' \text{N}$, $80^\circ 37' \text{W}$), approximately 15 km inland from the coast, represents an open graminoid fen. One site was located in a wet fen with a dense cover of sedges (mainly *Scirpus caespitosus*, *Carex limosa*, *Carex chordorhiza* and *Carex livida*), another on a small ridge or string covered by shrubs (mainly birch, *Betula pumila*), rising 15 cm above the sedge fen. Peat accumulation averages 0.7 m in this ecosystem. Two sites were located in a series of shallow ponds. In the coastal fen, about 70 % of the area is covered by wet sedge, about 20 % by the ridges, about 5 % by pools, and about 5 % by open/treed low-shrub islands. This location represents approximately 1000 years since emergence [Klinger *et al.*, this issue].

Tamarack fen. The tamarack fens, generally covering the area of emergence of the estuarine sediments of the Moose River, were sampled at the coastal fen location and at a location 1 km northwest of the town of Moosonee ($51^\circ 18' \text{N}$, $80^\circ 38' \text{W}$). In this ecosystem there is strong microtopography of hummocks and hollows, with a cover of larch (*Larix laricina*), black spruce (*Picea mariana*), alder (*Alnus rugosa*) and shrubs such as Labrador tea (*Ledum groenlandicum*), and birch (*B. pumila*) and mosses (*Sphagnum spp.*) in the hummocks and hollows. At the coastal fen location, two sites represented the hummocks and hollows and at the location near Moosonee, four sites represented *L. laricina* and *A. rugosa* hummocks and hollows. Peat accumulation is variable but averages 0.6 m, with 1500 year since emergence.

Interior fen. This ecosystem, sampled at a location 27 km from the coast ($51^\circ 31' \text{N}$, $80^\circ 27' \text{W}$), represents the initial stage of the increasing diversity within the wetland landscape, with the formation of treed mounds, underlain by permafrost, wet fen areas dominated by sedges, shrubs and *Sphagnum spp.*, as well as pools and ponds, occasionally containing palsa-type mounds. Seven sites were selected to represent a sequence from a treed mound through a sedge/shrub area to two pools and a small emergent palsa within one of the

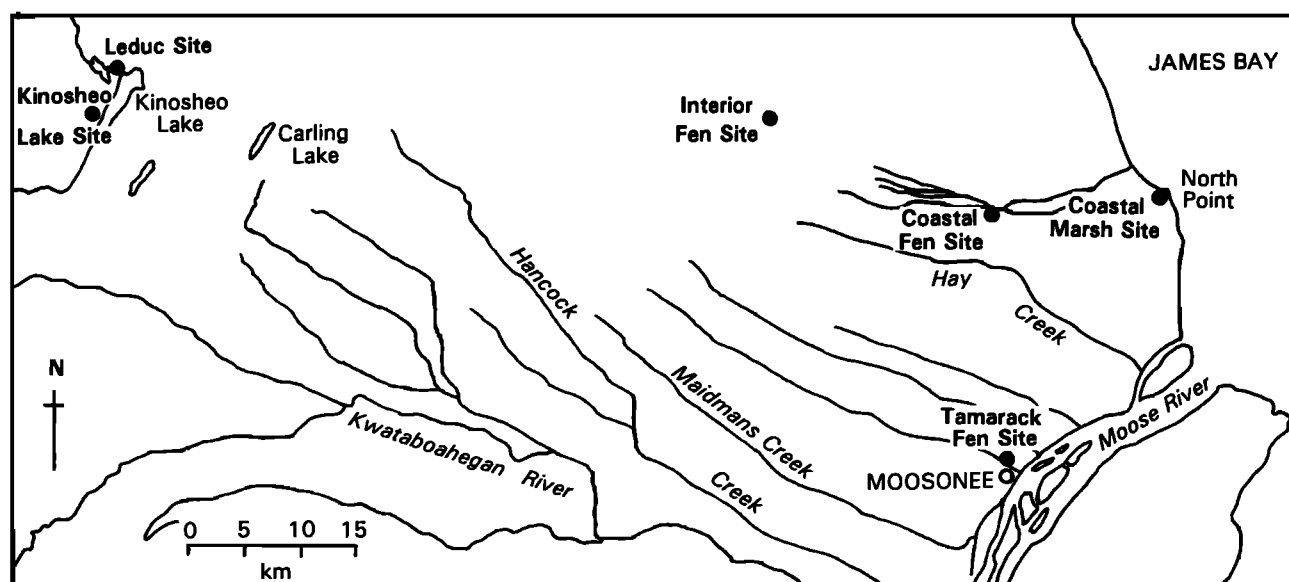


Fig. 1. The locations at which CH_4 emission measurements were made in the southern part of the Hudson Bay lowland.

TABLE 1. Ecological Types Represented by the 39 Sites Used for Methane Flux Measurements, Estimated Seasonal (June - October) CH₄ Flux, Using Temporally Weighted Means and a 130-day Season, and Average Water Table Depth and Temperature at 20 cm

Site & No.	Ecological Type	Major Plant Species	Seasonal CH ₄ Flux g m ⁻²	Water Table Depth cm	T ₂₀ ° C
<i>Coastal Marsh</i>					
1	Coastal supertidal meadow marsh (MM) panne	<i>Scirpus americanus</i> , <i>Festuca rubra</i>	0.65	0	10.3
2	Coastal supertidal meadow marsh (MM) sward	<i>Carex palacea</i> , <i>Eleocharis palustris</i> , <i>Juncus balticus</i>	0.63	-5	8.8
3	Coastal supertidal meadow marsh (MM)	<i>C. palacea</i> , <i>E. palustris</i>	0.81	-5	9.1
4	Coastal supertidal meadow marsh (MM) pool margin	<i>C. glareosa</i> , <i>M. trifoliata</i>	4.01	-2	10.3
5	Coastal supertidal meadow marsh (MM) pool	<i>M. trifoliata</i> , <i>C. palacea</i>	5.46	-10	10.7
<i>Coastal Fen</i>					
6	Open low-shrub fen ridges (OLsF)	<i>B. pumila</i> , <i>Myrica gale</i> <i>Andromeda glaucophylla</i> , <i>Sphagnum warnstorffii</i>	0.42	-16	12.3
7	Open graminoid fen (OGrF)	<i>S. caespitosus</i> , <i>C. limosa</i> <i>C. chordorrhiza</i> , <i>S. scorpioides</i>	1.44	-1	11.9
8	Pool fen (PoF)	<i>M. trifoliata</i> , <i>C. limosa</i> , <i>C. chordorrhiza</i> , <i>S. scorpioides</i>	0.97	-4	11.9
9	Pool fen (PoF)	"	2.08	-4	11.9
<i>Tamarack Fen, Moosonee</i>					
10	Treed low-shrub fen (TLsF): hummock,	<i>L. laricina</i> , <i>Picea mariana</i> <i>S. fuscum</i>	0.62	-15	8.2
11	(TLsF): hollow	-	2.21	-1	6.3
12	Treed low-shrub fen (TLsF): hummock,	<i>Alnus rugosa</i> , <i>L. laricina</i>	0.59	-20	7.0
13	(TLsF): hollow	-	2.03	-1	6.0
<i>Tamarack Fen, Coastal Fen</i>					
14	Treed low-shrub fen (TLsF): hummock,	<i>L. laricina</i> , <i>B. pumila</i> <i>C. calyculata</i> , <i>S. fuscum</i>	0.13	-8	10.5
15	(TLsF): hollow	<i>M. gale</i> , <i>Equisetum fluviatile</i> , <i>S. warnstorffii</i>	0.45	-2	12.1
<i>Interior Fen</i>					
16	Treed low-shrub bog (TLsB): hummock	<i>P. mariana</i> , <i>L. groenlandicum</i>	0.05	-30	7.1
17	Open low-shrub fen (OLsF)	<i>B. pumila</i> , <i>Salix pedicellaris</i> <i>P. mariana</i>	0.82	-11	13.6
18	Open graminoid fen (OGrF)	<i>C. lasiocarpa</i> , <i>S. caespitosus</i> <i>S. pedicellaris</i> , <i>M. gale</i>	0.89	-8	12.7
19	Open graminoid fen (OGrF)	<i>C. chordorrhiza</i> , <i>C. livida</i> <i>C. limosa</i> , <i>M. trifoliata</i>	1.67	-5	13.3
20	Pool fen (PoF)	<i>M. trifoliata</i> , <i>C. livida</i>	1.60	-4	10.9
21	Pool fen (PoF)	<i>S. scorpioides</i>	1.52	-4	10.9
22	Incipient palsa (IP)	Dark brown peat surface	0.44	-6	8.3

Site & No.	Ecological Type	Major Plant Species	Seasonal CH ₄ Flux g m ⁻²	Water Table Depth cm	T ₂₀ ° C
<i>Bog, Leduc</i>					
23	Conifer feather -moss forest	<i>P. mariana</i> , <i>L. groenlandicum</i> , <i>Pleurozium schreberi</i>	0.33	-20	9.5
24	Open lichen-rich low-shrub bog (OLrLsB)	<i>C. calyculata</i> , <i>S. fuscum</i> , <i>Cladina stygia</i>	0.46	-21	10.6
25	" : hummock				
26	" : hollow	<i>S. capillifolium</i> , <i>C. stellaris</i>	0.37	-5	7.8
26	Pool fen (PoF) & open graminoid bog (OGrB) of pools	<i>S. scorpioides</i> , <i>S. hudsonianus</i>	3.26	-8	11.4
27	Pool fen (PoF) & open graminoid bog (OGrB) margin of pools	<i>S. capillifolium</i> , <i>C. limosa</i>	1.79	-16	12.7
28	Pool fen (PoF) & margin	<i>M. trifoliata</i> , <i>S. scorpioides</i>	4.81	+3	12.5
29	Pool fen (PoF)	<i>S. scorpioides</i>	4.11	0	9.4
30	Pool fen (PoF)	Black peat surface	7.45	+29	12.6
<i>Bog, Kinosheo Lake</i>					
31	Treed low-shrub lichen-rich bog (TLrLsB)	<i>P. mariana</i> , <i>L. groenlandicum</i> <i>C. stellaris</i>	0.81	-15	9.3
32	Open lichen-rich, low- shrub bog (OLrLsB)	<i>C. calyculata</i> , <i>S. fuscum</i>	1.05	-20	10.4
33	" : hummock				
34	" : hollow	<i>S. capillifolium</i> , <i>C. stellaris</i>	2.00	-5	9.7
34	Open pool fen margin (PoF)	<i>Gymnocolea inflata</i> , <i>Sphagnum lenense</i> , <i>Carex oligosperma</i>	16.61	0	12.1
35	Open pool fen margin (PoF)	<i>S. scorpioides</i> , <i>C. oligosperma</i>	2.29	0	10.4
36	Deep pool	Peat bottom	1.38	+100	13.0
37	Open sphagnum bog (OSpB)	<i>S. capillifolium</i> , <i>S. tenellum</i> , <i>C. oligosperma</i>	4.12	-10	13.0
38	Open graminoid bog (OGrB)	<i>Scheuchzeria palustris</i> , <i>C. oligosperma</i> , <i>S. capillifolium</i>	13.62	+5	12.0
39	Open graminoid bog at pool edge	<i>C. limosa</i> , <i>Kalmia polifolia</i>	7.13	0	12.8

The site notation follows that of Riley [1982].

TABLE 2. Relative Coverage (%) of Major Wetland Types of the North Point to Kinosheo Lake
Transect As Determined by LANDSAT Thematic Mapper

Land Class	Site No.	Transect	0-30, km	31-60, km	61-90, km	91-120, km
Water		8.6	1.3	1.4	2.4	5.1
Marsh	1-5	1.3	5.5	0.0	0.0	0.0
Shrub fen	6,16	22.5	26.3	21.6	20.9	19.2
Open fen	7,8,9,17,18, 19,20,21,22,26, 27,28,29,30	18.0	16.7	27.1	17.5	12.1
Treed fen	10-15	12.4	7.9	18.3	14.4	8.0
Open bog	24,25,36-39	13.4	0.3	8.6	16.9	26.6
Treed bog	31,33,34	14.7	2.4	12.7	22.2	20.2
Conifer forest/swamp	23	5.9	6.1	9.8	4.9	3.9
Other		3.2	33.5	0.5	0.8	4.9

pools. Peat accumulation varies from 0.8 to 1.9 m and represents about 2000 years since emergence.

Bog. This is the most diverse wetland landscape and was sampled near Kinosheo Lake, 114 km from the coast. The dominant wetland vegetation is open, lichen-rich, low-shrub bog, in which there is a strongly developed microtopography of hummocks and hollows. Mats of sedges and *Sphagnum* spp. surround pools with degrading floors of bare peat and brown moss (*S. scorpioides*). Deeper ponds also occur, with an organic floor, and lakes commonly have a mineral floor. In better drained areas, feathermoss and mixed forests occur and these grade into treed low-shrub bogs dominated by *P. mariana*. Seventeen sites were sampled in the Kinosheo Lake area, eight at the Leduc location, 1 km northwest of the NOWES camp, and nine near the main NOWES tower location. Peat thicknesses are very variable, ranging from 1.0 to 3.5 m in the center of the raised bogs. Similarly, the average age of the peatland varies from the youngest at 2500 years to the oldest at 4100 years [Klinger et al., this issue].

Within each of these locations, there is a complex assemblage of wetland types, but the whole represents the ecological succession of wetlands from the coastal marsh to the interior bog [Riley, 1982](Figure 2). A total of 39 sites were sampled for methane emission measurements.

Methane Emission Measurements

Methane emissions at each site were made by a static chamber method. The chambers were made from polycarbonate 18-L bottles

(basal area 0.053 m²) from which the base had been removed. The neck of the chamber was sealed with a rubber stopper, containing a glass tube and rubber septum, through which air samples were collected with a 10-mL syringe. The chambers were covered by aluminum foil to reduce heating. Chambers were gently inserted into the peat or down to the peat surface at flooded sites. At some of the larger pools the chambers were floated with styrofoam collars. Between two and five replicate chambers were employed at each site, with movement of the position of the chambers within the site. Studies of methane emission from subarctic fens has shown that methane concentrations inside the chamber increase linearly over 24 hours and that these static chambers generally underestimate flux compared to dynamic chambers, in which the air is circulated, by about 20 %, though there is a high spatial variability in emission rates within sites [Moore and Roulet, 1991].

The static chamber technique involves some disturbance of the surface layers of the peat during chamber insertion and prevents interaction of the ambient air with the peat surface. However, CH₄ fluxes measured at the Kinosheo Lake location by static chambers compared well with areal estimates of flux derived from tower and aircraft measurements [Roulet, 1991]. Other studies have also found a good relationship between enclosures, tower and aircraft measurements [e.g., Bartlett et al., 1989a, 1992].

Air samples were extracted from the chamber when it was inserted and after an exposure period ranging from 2 to 3 hours, except for some overnight exposures during sampling in September and October. Methane concentrations were determined within 12 hours of collection (occasionally up to 48 hours) on a Shimadzu

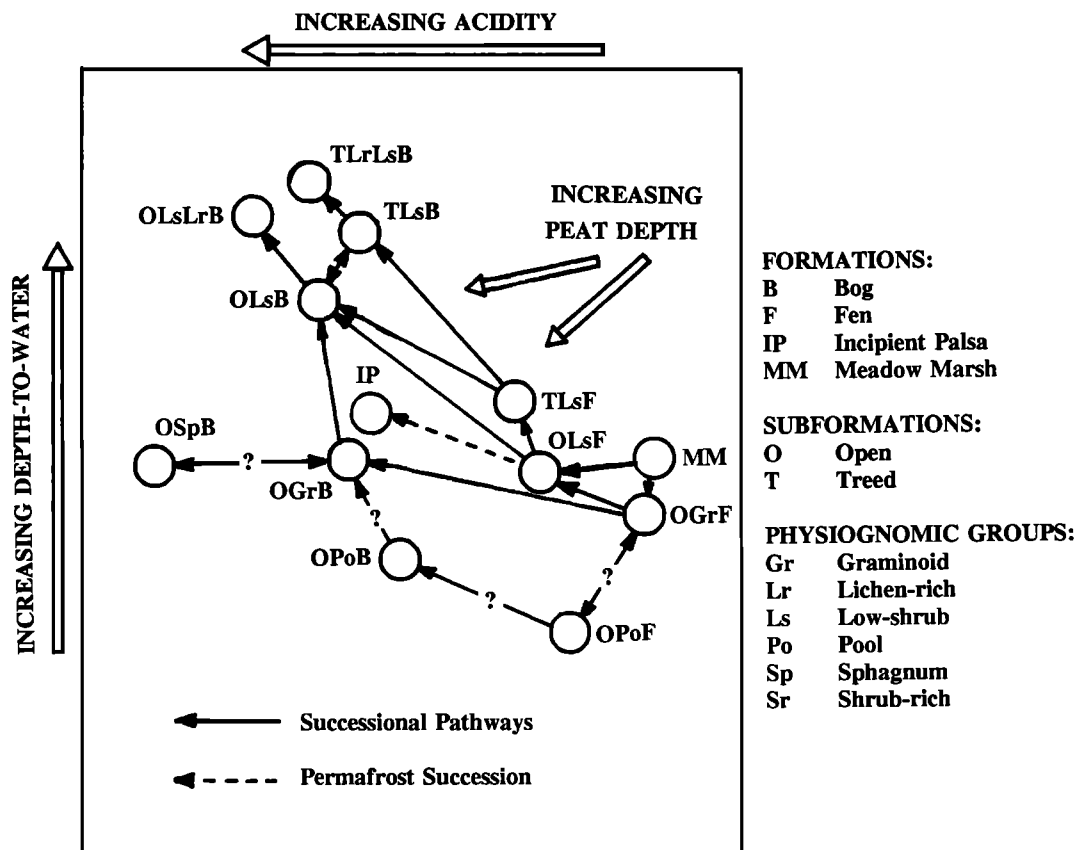


Fig. 2. The ecological succession pathways of the major wet types in the southern section of the Hudson Bay lowland [after Riley, 1982]. The ecological classification scheme is based on the plant species assemblage, including the formation and subformation and the physiognomic group. At the formation level, successional trends progress from meadow marsh through fen to bog and, dependent on climate, to palsa formations. These trends generally involve an increase in the peat depth, the depth-to-water and in peat acidity, though successional trends can be multidirectional at the level of physiognomic group.

Mini 2 gas chromatograph, using a 5-mL sample, a 1-mL injection loop, and a Poropak-Q column (80/100 mesh, 3m x 3 mm) at 40° C. Helium was used as the carrier gas at a flow rate of 30 mL min⁻¹. No detectable leakage occurred in samples stored for up to 24 hours. Methane standards of nominally 2 and 200 parts per million by volume (ppmv) were used at the beginning of each analysis run. Methane fluxes were calculated from the change in the initial and final sample concentrations, corrected for the volume of air in the chamber and the exposure period. When the initial methane concentration exceeded 3 ppmv, the chamber was rejected, amounting to approximately 10 % of the chamber measurements. Using the analytical error of the gas chromatograph (± 0.5 ppmv) and the volume and exposure period, the minimal detectable flux was 0.5 mg CH₄ m⁻² d⁻¹.

Measurements of methane flux were made at ≈ 10 -day intervals from early June to mid-August and once in late September and mid-October. At most sites, the position of the water table was recorded in boreholes and the temperature of the peat profile was measured down to 100 cm with a thermistor probe.

During late September, 250 to 500-mL samples of the 0 to 10- and 10 to 20-cm depths of the peat profile were collected from selected sites, for laboratory incubations to determine the rates of methane production and consumption. Samples were stored at 4° C at moisture contents near to that at which they were collected: where samples were collected from beneath the water table, the collection bottle was filled with peat water. Methane production under anaerobic conditions was determined by placing 5 g of wet peat into triplicate 50-mL Erlenmeyer flasks, evacuating the air under vacuum, backfilling with nitrogen and incubating at 15° C. Concentrations of methane in the flask were determined on samples taken by a syringe through a Subaseal in the flask mouth and the methane production over 5 days was calculated. Methane consumption rates were determined by placing 5 g of wet peat into 50-mL Erlenmeyer flasks, adding methane to produce an initial concentration of 1000 ppm in the flask and then incubating at 15° C under continuous shaking to avoid the development of anaerobic pockets in the peat. The methane consumption rate was calculated from the average decrease in methane concentration in the flask over a 5-day period.

RESULTS AND DISCUSSION

Climatic Context

It has been documented that there can be significant year-to-year variations in CH₄ flux from northern wetlands, associated with differences in temperature, precipitation, and resultant water table position [e.g., Dise, 1992; Holland, 1991; Moore and Knowles, 1990; Whalen and Reeburgh, 1988; 1992]. As reported by Mortsch [this issue], the 1990 climate at Moosonee was characterized by mean daily temperatures of 11.5, 16.9, 14.5, 7.9, and 3.0° C for June, July, August, September, and October, respectively. With the exception of July (which was 1.6° C warmer than the 1951-1980 average) these values are all within one standard deviation of the 1951-1980 average.

Mean monthly precipitation in 1990 was 163, 67, 88, 100, and 61 mm in the June to October months, representing 207, 69, 110, 124, and 82 % of the 1951-1980 mean value. June was about twice as wet as normal, mainly because of the 64 mm of precipitation which fell on June 3, 1990, before the chamber measurements were started. Thus compared to an average year, the Moosonee section of the lowland received average temperatures and a much wetter than average June and drier than average July, with the other months

being close to the normal. Based on year-to-year variations in CH₄ flux from other northern wetlands [e.g., Moore and Knowles, 1990; Whalen and Reeburgh, 1992], the fluxes measured from the Hudson Bay lowland sites in 1990 may be larger than normal.

Spatial Variability of Methane Emissions Within Sites

As has been observed before [e.g., Moore and Knowles, 1990; Moore and Roulet, 1991; Whalen and Reeburgh, 1988, 1992], within-site spatial variability in CH₄ flux is high, with coefficients of variation (standard deviation/mean) within visually uniform sites commonly falling between 50 and 100 %. This means that estimates of average CH₄ emissions from a site have a high statistical error associated with them. Within visually uniform sites, 30 to 40 chambers are required to attain a precision < 15 %, as illustrated by the change in the ratio of the standard error/mean for measurements at two subarctic fen sites near Schefferville, randomly selected and sequentially added (Figure 3). This pattern is similar to that which has been found in wetlands in the Everglades, Florida [Bartlett et al., 1989b]. Within each of the locations in the present study (comprising between six and nine sites), CH₄ flux variability is high, so that, even with 40 chambers, the precision of the mean commonly falls between ± 30 and 60 % (Figure 3).

Temporal Patterns of Methane Emission

Visual examination of the seasonal pattern of CH₄ emission from the 39 sites suggests that there are six types, which are illustrated by representative sites in Figure 4. (1) Three sites showed a pattern which alternates between small negative and positive fluxes of CH₄. These sites are the relatively well-drained forested sites at the bog and interior fen locations (sites 16, 23, and 31 in Table 1). (2) six sites (5, 6, 18, 29, 32, and 38) showed a summer peak emission of CH₄, which may be associated with temperature as the major control. (3) eight sites (7, 8, 9, 17, 19, 20, 24, and 27) showed a

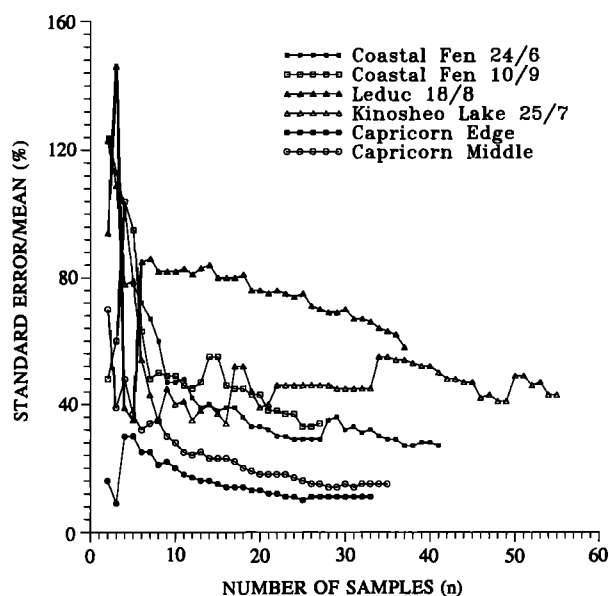


Fig. 3. Within-location variability in methane flux, for coastal fen, Leduc and Kinosheo locations, and within two visually uniform subarctic fens (Capricorn edge and middle) near Schefferville [from Moore and Roulet, 1990]. The ratios for the Hudson Bay lowland locations were generated by pooling all the data from the sites at that location, resulting in a sample size ranging from 28 to 58.

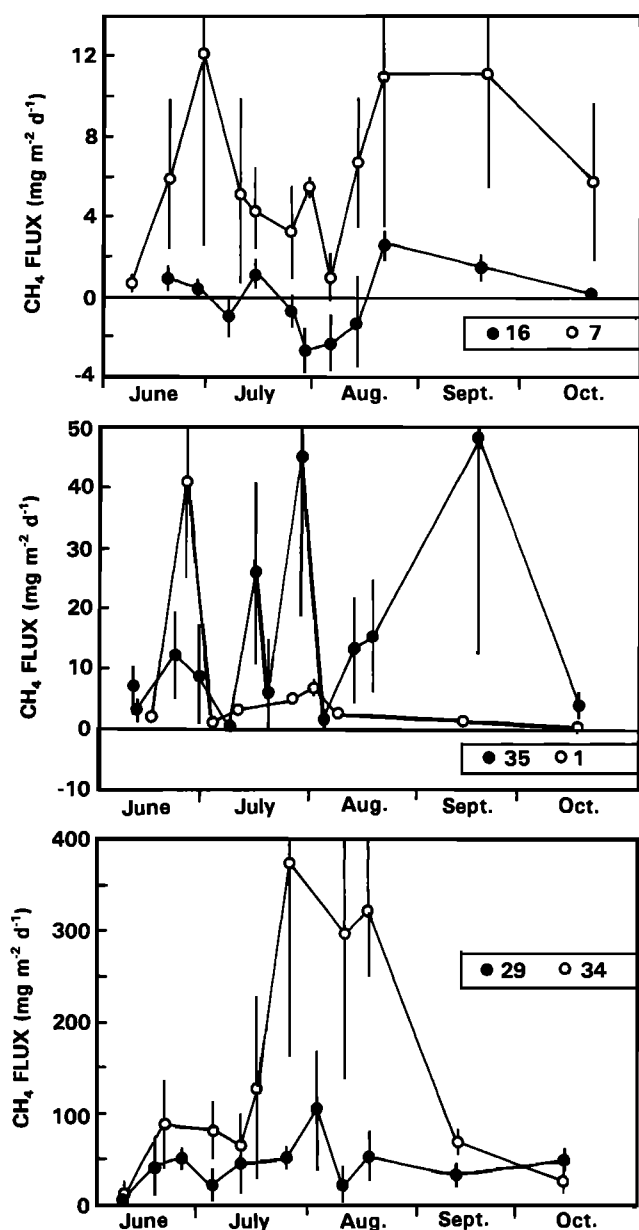


Fig. 4. The seasonal pattern of methane emission from selected sites: sites 7 (open graminoid fen, coastal fen) and 16 (treed low shrub bog hummock, interior fen); sites 29 (pool fen, Leduc bog) and 34 (open pool fen margin, Kinoshoe Lake bog); sites 1 (meadow marsh, coastal marsh) and 35 (open pool fen margin, Kinoshoe Lake bog). Vertical lines represent the standard deviation around the mean, based on replicate chamber measurements.

pattern of larger CH₄ emissions in spring and early summer, a decrease during the summer and an increase in the fall. (4) six sites (25, 26, 30, 33, 34, and 37) showed a gradual increase toward late summer and fall, when the sites were both warm and waterlogged. (5) four sites (1, 3, 28 and 36) showed a decrease in CH₄ emissions from spring to fall. (6) six sites showed no discernible pattern (sites 2, 14, 15, 21, 22 and 35).

The change in CH₄ flux over the study period is the result of a series of covarying processes that are impossible to assess individually. While there is no direct evidence of which factors are dominant at a particular site, there is sufficient knowledge of the controls on the production, oxidation, and transport of CH₄ to conjecture about the possible source of these patterns. In pattern 1,

small fluxes, both emission and uptake, were dominated by a thick unsaturated layer with a high potential for oxidation. Sites where increasing fluxes (pattern 4) or summer peak flux (pattern 2) had little capacity to oxidize the produced CH₄ because of a high level of saturation; therefore the seasonal pattern of temperature was important. Sites that experienced a mid-summer decrease in flux (pattern 3) had a high potential for oxidation because a thick unsaturated zone had developed with a drop in the water table. A large spring flux followed by small fluxes (pattern 5) may be caused by the release of stored CH₄, trapped beneath the ice cover.

From the seasonal pattern of CH₄ emissions, an estimate was made of the seasonal flux from each of the sites, by taking the temporally integrated mean value and applying a season length of 130 days. This is likely to be an underestimate of the annual flux of CH₄ from the wetland sites, for a number of reasons. Short-duration, episodic fluxes of CH₄ have been noted from several northern fens, associated with the buildup of pore-water CH₄ concentrations and small falls in the position of the water table [e.g., Moore *et al.*, 1990; Windsor *et al.*, 1992]. These episodic events are unlikely to have been caught by the weekly sampling scheme employed in the Hudson Bay lowland, and may result in an underestimate of the seasonal CH₄ flux [Windsor *et al.*, 1992]. Secondly, it has been shown that there can be significant emissions of CH₄ during the winter and during the spring thaw, as CH₄ trapped within and beneath the ice is released [e.g., Dise, 1992; Moore and Knowles, 1990; Moore *et al.*, 1990; Whalen and Reeburgh, 1988, 1992]. In addition, the absence of wind movement within the static chambers results in a lower flux than if the air was circulated at speeds similar to that outside the chamber [e.g., Moore and Roulet, 1991; Sebacher *et al.*, 1983]. The combination of these phenomena mean that the seasonal flux estimate may underestimate the annual flux by 20 %.

At the coastal marsh location, recently emerged from the Bay, seasonal CH₄ emission rates were low at the three raised sites underlain by primarily inorganic sediment, even though the water table was high, with fluxes estimated to range from 0.6 to 0.8 g m⁻² (Table 1). Emission rates were much larger at two small pool sites, with a vegetation of sedges and buckbean and water 0–10 cm above the organic sediment surface, amounting to seasonal emissions of 4.0 and 5.5 g m⁻².

At the coastal fen location the shrub-covered ridges were raised about 15 cm above the water table and showed small CH₄ fluxes, resulting in a seasonal emission of 0.4 g m⁻² (Table 1). The lower-lying, sedge-covered sections had a water table close to the peat surface for most of the time (average water depth 3 cm) and a seasonal CH₄ flux of 1.4 g m⁻². The shallow pools within the coastal fen also showed small CH₄ fluxes, 1.0 to 2.1 g m⁻².

At the two tamarack fen locations the hummocks, located 10 to 20 cm above the water table and containing ice for much of the summer, exhibited small CH₄ fluxes with seasonal CH₄ emissions of 0.1 to 0.6 g m⁻² (Table 1). The adjacent hollows, where the water table was always close to the peat surface, showed larger CH₄ fluxes, with seasonal emissions of 0.5 to 2.2 g m⁻².

At the interior fen location the raised hummock, covered by trees and mosses and with a permafrost core, exhibited very low rates of CH₄ emission and occasional CH₄ uptake, resulting in a very small seasonal CH₄ flux of 0.1 g m⁻² (Table 1). Along a hydrological gradient from a dominantly shrub-covered upper site to a lower site adjacent to a pool and vegetated with sedges and buckbean, CH₄ emission rates increased with seasonal fluxes of 0.8 to 1.7 g m⁻². Two pool sites sampled emitted 1.5–1.6 g CH₄ m⁻² and an incipient palisade emerging from one of the pools, with a bare peat surface about 20 cm above the water surface, emitted 0.4 g CH₄ m⁻².

The two bog locations showed the greatest within-location

variations in CH_4 flux. The two forest sites emitted small amounts of CH_4 (0.3 and 0.8 g m^{-2}), as did the hummocks covered with mixtures of shrubs, lichens, and mosses (0.5 to 1.0 g m^{-2}), and both sets of sites had water tables lower than 15 to 20 cm beneath the peat surface (Table 1). The hollows adjacent to the hummocks also emitted small amounts of CH_4 , 0.4 to 2.0 g m^{-2} , even though the water table was closer to the hollow peat surface for much of the summer. The sites at the Leduc location generally emitted smaller amounts of CH_4 than their equivalents at the Kinoshio Lake location, probably because of the drier, more raised nature of the former. In the graminoid and moss fen and bog sections of the locations, CH_4 emissions were greater, especially on the margin of pools, from moss mats and in sections where the peat appeared to be degrading to form incipient pools. Seasonal fluxes of CH_4 from these ecological types ranged from 1.8 to 16.6 g m^{-2} with an average of 6.4 g m^{-2} and the water table was always close to the peat surface. Seasonal CH_4 flux from the pool site at the Leduc location was also high, 7.5 g m^{-2} , but the flux from the deeper pool at Kinoshio Lake, sampled with floating chambers, was lower, 1.4 g m^{-2} .

Roulet *et al.* [this issue] determined the spatially weighted mean CH_4 flux from the five ecosystems, using the fluxes described in this paper and those from Hamilton *et al.* [this issue] and Klinger *et al.* [this issue], and the areal coverage of vegetation units derived from color air photography. In order of lowest to highest seasonal emission rates of CH_4 , they are: treed bog 0.18 g m^{-2} , treed (tamarack) fen 0.38 g m^{-2} , marsh 2.30 g m^{-2} , open fen 2.78 g m^{-2} , and open bog 4.60 g m^{-2} .

Controls on Methane Emissions

Temperature and water table. There were a few very weak statistical correlations between daily CH_4 emissions at the sites and the position of the water table and the temperature at depths of 10 and 20 cm. Most relationships were insignificant at the $p < 0.05$ level between the daily CH_4 flux (and log CH_4 flux) and these three variables. Multiple regressions between daily CH_4 flux (and log CH_4 flux) and water table and temperature also failed to produce many significant correlations, so that these variables are of little use as predictors of CH_4 emission within sites.

Weak statistical associations of this nature have been reported from other northern wetlands [e.g., Moore *et al.*, 1990; Whalen and Reeburgh, 1988; 1992], though other studies have been able to identify stronger relationships between these variables and CH_4 emissions [e.g., Crill *et al.*, 1988; Dise, 1992; Harriss *et al.*, 1992]. Part of the explanation for the weak association lies in the high spatial variability recorded for CH_4 emissions at each sampling date within the site (coefficients of variation of 50 to 100 %). Sampling the same chamber location within a site will reduce the date-to-date sampling variability. In addition, there are short-term emissions of CH_4 associated with small drops in the position of the water table, or through the release of CH_4 trapped beneath or within melting ice [e.g., Windsor *et al.*, 1992], as well as a timelag between changes in temperature and water table position and the microbial response of CH_4 production and consumption. Furthermore, the temperature responses of CH_4 production and oxidation are different [Dunfield *et al.*, 1993]. Whalen and Reeburgh [1992] note that single environmental variables may be of limited value in predicting variations in CH_4 flux and that variables which are environmental integrators are more successful.

Although there were poor statistical relationships between CH_4 emission rates and temperature and water table at sites during the sampling season, these two variables were strongly correlated with the seasonal flux of CH_4 from the sites. There was a significant correlation ($r^2 = 0.44$, $p < 0.001$) between the logarithm of the

seasonal CH_4 flux at the sites and the mean depth to the water table, when the outlier deep pond site at Kinoshio Lake was excluded (Figure 5). The relationship between seasonal CH_4 flux and mean temperature at a depth of either 10 or 20 cm was weaker but still significant ($r^2 = 0.13$ and 0.15 , $p = 0.024$ and 0.016 , respectively, Figure 5). Combination of the water table and temperature variable (T_{20}) into a step-wise regression accounted for 48 % of the variation in the logarithm of the seasonal CH_4 flux, with the T_{20} contribution insignificant. In this range of peatland types there is an insignificant relationship between seasonal mean water table position and mean temperature at 10 or 20 cm ($r^2 = 0.04$ to 0.08), probably because of the great diversity in peat physical characteristics, which control the movement of energy into and out of the peat profile.

These overall relationships emphasize the importance of the hydrologic regime, especially the position of the water table, in controlling overall CH_4 emissions from northern wetlands. In the Alaskan tundra, Bartlett *et al.* [1992], Morrissey and Livingston [1992], and Whalen and Reeburgh [1988, 1992] have noted the importance of hydrology in controlling CH_4 emission rates. A similar relationship, with water table position assuming greater significance than temperature, has been obtained for the low boreal wetlands of southern Ontario by Roulet *et al.* [1992]. Moore and Roulet [1993] have also shown that this regional relationship between seasonal CH_4 emissions and water table position is characterized by regressions with a similar slope yet a different constant.

The cold thermal regime of these northern peatlands may play an overall role in the small CH_4 emission rates. Although the surface of the peat can become warm during the summer ($> 20^\circ \text{C}$), there are strong thermal gradients down from the surface, especially at the drier sites, so that beneath 20 cm, the peat remains cool ($< 10^\circ \text{C}$), as has been found in other subarctic fens [e.g., Moore, 1987]. Using peat samples from the coastal fen and Kinoshio Lake sites, Dunfield *et al.* [1993] showed in laboratory incubations that methanogenesis was weak at $< 10^\circ \text{C}$, there was an absence of psychrophilic methanogenesis, and that the temperature dependence of methanogenesis was strong, with Q_{10} values between 3 and 7. In contrast, CH_4 consumption rates showed a weaker temperature dependence, with Q_{10} values falling between 1 and 2. Thus at low temperatures ($5^\circ - 10^\circ \text{C}$), CH_4 production is slow and CH_4 consumption is fast, compared to rates at higher temperatures.

Edaphic Factors. Although water table and temperature provide some explanation for the variations in CH_4 flux from the wetland sites, there is still considerable unexplained variability. As noted in the introduction, the ability of the soil to support CH_4 production and consumption may be an important control. To evaluate the range in abilities of the peats to produce and consume CH_4 , we incubated samples of the 0 to 10- and 10 to 20-cm layers of the profile under laboratory conditions of 15°C and anaerobic and aerobic atmospheres, respectively. Previous work with laboratory incubations has revealed that the largest rates of CH_4 production and consumption generally occur in the surface layers [Moore and Knowles, 1990], and the surface layers also attain the highest summer temperatures. Using samples collected in September and kept cool, the ability of the peat sample to produce and consume CH_4 reflects the populations of methanogens and methanotrophs at the time of collection and changes during storage, as well as the substrate characteristics of the sample that promote methane production and oxidation. There may be seasonal variations in the CH_4 production rate of the peat, as observed by Yavitt *et al.* [1987] in a temperate peatland.

The results of the laboratory incubations illustrate the wide range of production and consumption rates found in the peat samples,

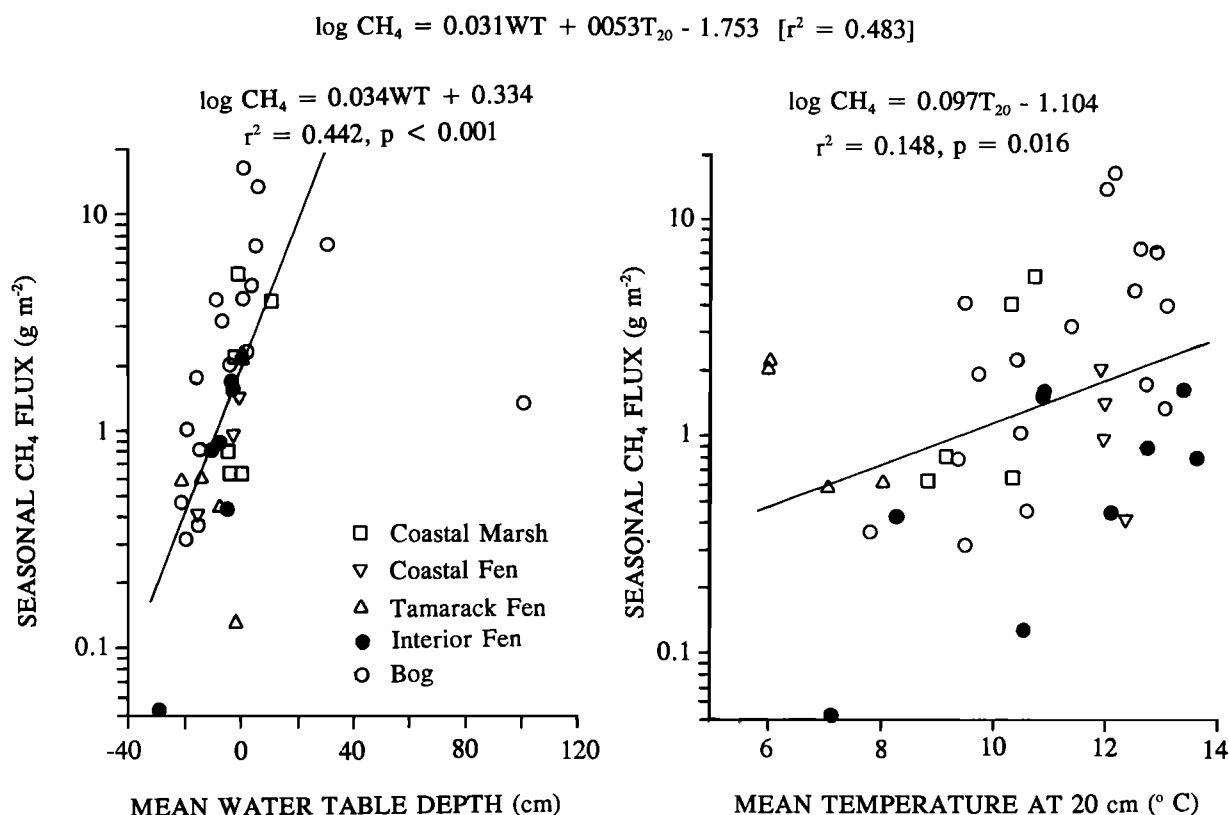


Fig. 5. Relationship between seasonal methane flux and mean water table position and temperature at 20 cm from all the sites in the Moosonee area. For the water table relationship, the outlier, representing a deep pond, has been excluded from the regression depicted.

covering 3 orders of magnitude (Figure 6). Although the absolute values are of little importance, aerobic CH_4 consumption rates ranged from 0.1 to $50 \mu\text{g g}^{-1} \text{peat d}^{-1}$ and anaerobic CH_4 production rates ranged from 0.02 to $8 \mu\text{g g}^{-1} \text{d}^{-1}$. In all cases, consumption rates exceeded production rates, though this is a function of the laboratory conditions in which aerobic consumption was measured as the decrease in CH_4 from an initial concentration of 1000 ppmv.

The 30 peat samples analyzed generally fall into three main types. Some samples had very low production and consumption rates (<0.1 and $5 \mu\text{g g}^{-1} \text{d}^{-1}$, respectively). These mainly include the samples collected from the hummocks at the interior fen and bog, which are located well above the water table and which had very low CH_4 fluxes and, in some cases, occasionally exhibited CH_4 consumption in the field. The majority of the samples fell into the second group, characterized by low rates of CH_4 production ($<0.5 \mu\text{g g}^{-1} \text{d}^{-1}$) and moderate to high rates of aerobic CH_4 consumption (5 to $20 \mu\text{g g}^{-1} \text{d}^{-1}$). These include sites with a wide range of field CH_4 flux, and both 0 to 10- and 10 to 20-cm depth increments. The third group consisted of a small number of samples, mainly from the 10- to the 20-cm depth, which exhibited high rates of both CH_4 production and consumption. None of the peat samples showed high rates of CH_4 production and low rates of CH_4 consumption. A high aerobic CH_4 consumption rate is coupled with a high anaerobic CH_4 production rate.

The incubation results help to explain some of the field flux patterns. For example, despite the high water table and the dense sedge cover, possibly leading to plant-mediated CH_4 emission [Whiting and Chanton, 1992], field emissions of CH_4 from the graminoid fen at the coastal fen location are small (1.4 g m^{-2} over the season). The incubation results reveal that the subsurface sample (10 to 20-cm) had the highest rates of CH_4 production and consumption observed (Figure 7). However, the surface sample (0

to 10-cm) exhibited low rates of CH_4 production and very large rates of CH_4 consumption in laboratory incubations, suggesting that the surface layer of the peat oxidizes much of the CH_4 before it can be emitted to the atmosphere. The conditions which produce a high CH_4 consumption capacity in the surface layer of the coastal fen site are unknown but may be related to high rates of oxygen production by algae at sites where the water table is at or close to the peat surface [King, 1990]. As noted by King *et al.* [1990] in wetlands of the Florida Everglades and Whalen *et al.* [1993] in Alaskan tundra, the capacity of the upper part of the soil profile to oxidize CH_4 plays an important role in determining the emission of CH_4 to the atmosphere: 50 to 90 % of the CH_4 produced in the profile may be oxidized.

On the other hand, the incubation results suggest that controls on CH_4 flux at other sites may lie beneath the surface layers of the peat. The highest seasonal CH_4 fluxes (4 to 17 g m^{-2}) were observed at the degrading pool peat sections at the Kinoshoe Lake and Leduc bog locations. The incubation experiment, however, showed that both the 0 to 10- and the 10 to 20-cm samples from these sites exhibited small rates of CH_4 production and large rates of CH_4 consumption, suggesting that the main source of CH_4 emitted from these sites was produced deeper in the peat profile.

Along the transect there were major changes in peat and pore-water chemistry, reflecting the changes in nutrient availability and removal of salt during the ecological succession (Figure 2). Successional trends involve an increasing depth of peat, an increasing depth to water table and creation of pools, and a decreasing soil pH [Riley, 1982]. The soils at the coastal marsh, coastal fen, and tamarack fen locations are circumneutral to slightly acid in the upper 20 cm, and the soil pH decreases at the sites in the interior fen and bog locations, falling to acid values (pH 3.1 - 5.2) in the upper layers of the peat (Table 3). This decrease in soil pH

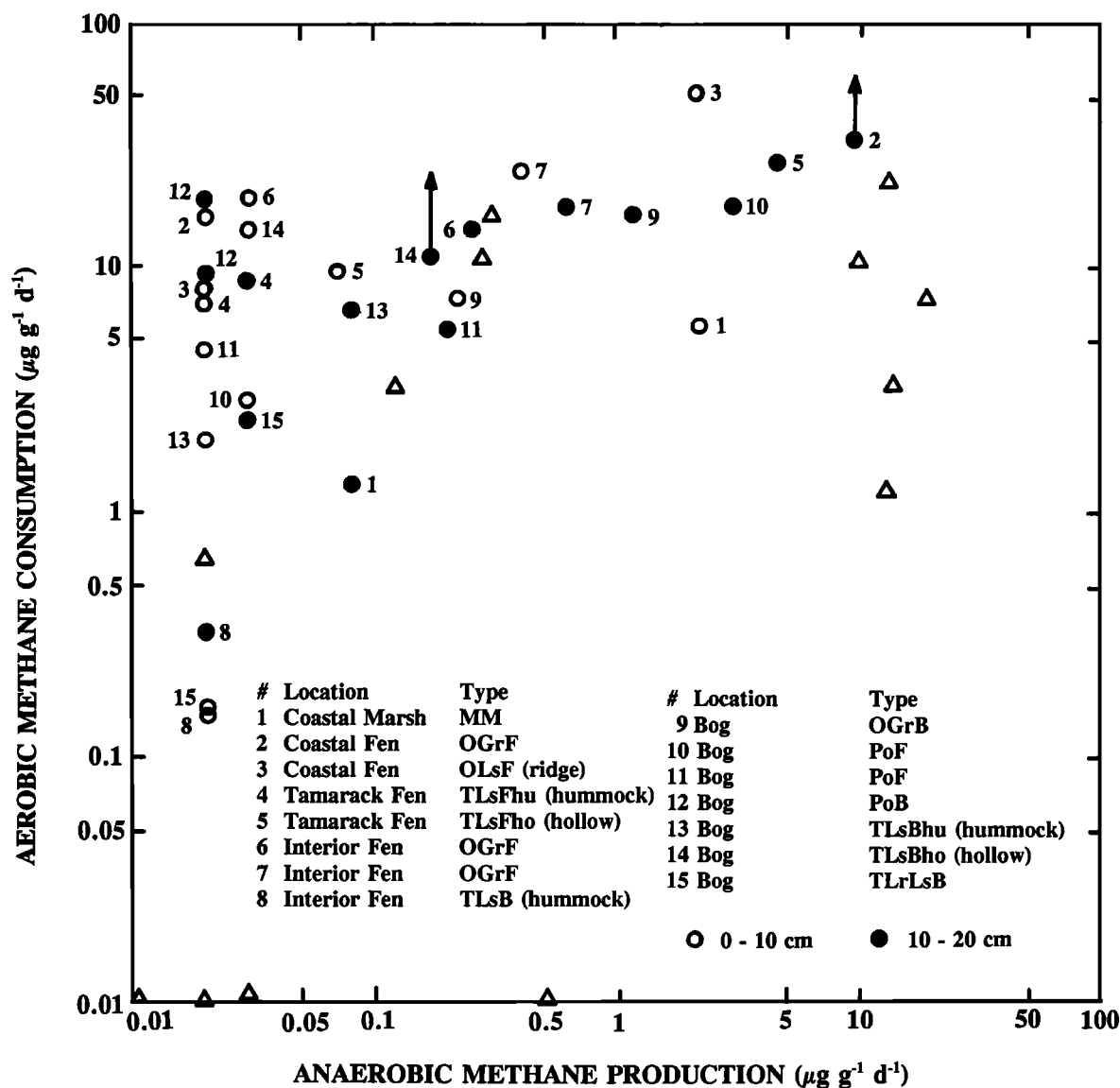


Fig. 6. Rates of methane production under anaerobic conditions and methane consumption under aerobic conditions, for the 0 to 10-cm and 10 to 20-cm samples collected from selected sites in the southern Hudson Bay Lowland. Also included are values (triangles) from 0 to 25-cm depth samples from wetlands in the Churchill area in the northern section of the Lowland [Holland, 1991]. Each point is the mean of triplicate incubations. Arrows indicate that the value used for aerobic CH_4 consumption is a minimum one, because of the fast consumption rate in the flask.

is matched by the decrease in specific conductance and cation (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) and anion (SO_4^{2-} and Cl^-) concentrations in porewater collected from the upper 50 cm of the sites (Table 3).

CH_4 emission rates from coastal wetlands are partially controlled by salinity, through the influence of SO_4^{2-} [Cicerone and Oremland, 1988], resulting in annual CH_4 emissions of < 1 to 213 g m^{-2} in eastern and southern United States [e.g., Bartlett et al., 1985; 1987]. In the Hudson Bay lowland transect, CH_4 emission rates were low (0.8 g m^{-2}) from the coastal marsh mineral soils but high (4.0 and 5.5 g m^{-2}) from small pools developing in the depressions where organic matter was beginning to accumulate. In these emerging subarctic marshes, salt is quickly removed from the upper parts of the soil by advection and diffusion [Price and Woo, 1988] and Glooschenko and Clarke [1982] noted soil saturation paste conductivities of 5 to 40 mS cm^{-1} , with a decline in conductivity over the summer. Hudson Bay has a low salinity, compared to

seawater, and the low concentrations of salt in the surface layers of sediment ($< 5 \text{ g L}^{-1}$ [Price and Woo, 1988]) suggest that SO_4^{2-} concentrations in this environment do not significantly inhibit CH_4 emission rates.

Rates of CH_4 production and consumption have been shown to be pH dependent in laboratory incubations of peat slurries. Optimum pH values of 5 to 7 have been reported for subarctic and temperate peats, the lower optimum being found in peats with a low native pH [Dunfield et al., 1993]. Acid-tolerant methanogens and methanotrophs have been reported [e.g., Patel et al., 1990; Saha and Sen, 1989; Williams and Crawford, 1985; Wolf and Hanson, 1985]. Valentine et al. [this issue] have also noted a pH dependence of CH_4 production from Kinosheo Lake peat samples. Using samples from the Kinosheo Lake bog and coastal fen locations, R. Knowles (personal communication, 1991) has shown that CH_4 production in laboratory studies of peat slurries from the upper layers is primarily

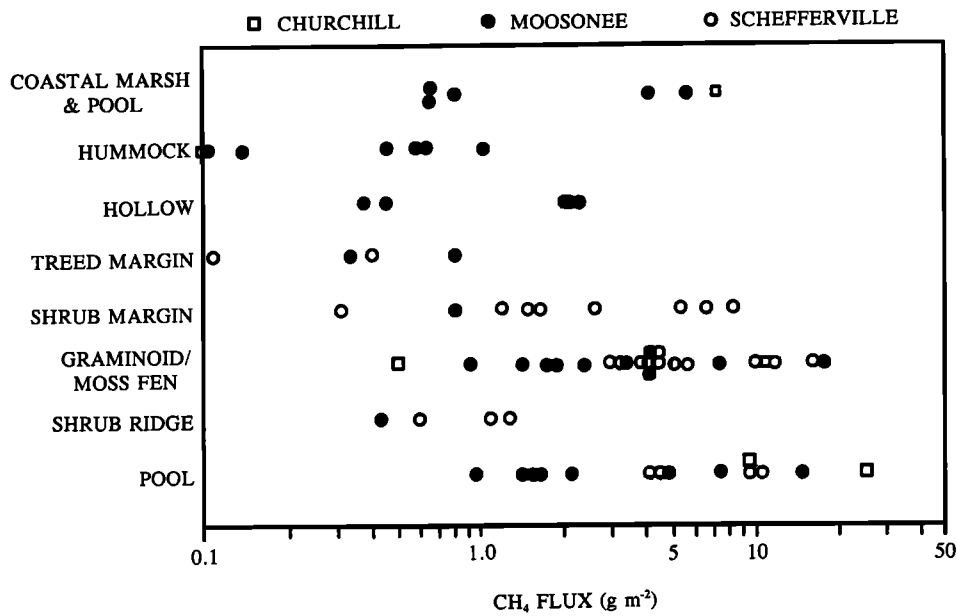


Fig. 7. Collation of estimated thaw-season CH_4 emission from Canadian subarctic wetlands, based on means. Sources: *Holland* [1991], this paper, *Moore et al.* [1990], and *Moore and Knowles* [1990].

TABLE 3. Soil pH Values in Water, of 30 Peat Samples Used in the Incubation Experiment, and pH, Specific Conductance (S.C.) and Concentrations of Ca^{2+} , Mg^{2+} , K^+ , Na^+ , SO_4^{2-} , and Cl^- , Determined on Pore-Water Samples in 0- to 25-cm depth During July and August 1990

Location & Site	Depth, cm	Soil, pH	Pore-Water Chemistry							
			pH	S.C. $\mu\text{S cm}^{-1}$	Ca^{2+}	Mg^{2+}	K^+ mg L^{-1}	Na^+	SO_4^{2-}	Cl^-
Coastal marsh MM site 5	0 - 10	3.2	7.1	410	29.3	20.1	3.3	112	17.4	157
	10 - 20	7.1								
Coastal fen OGrF site 7	0 - 10	5.6	6.3	119	23.0	3.4	2.1	5	0.2	5
	10 - 20	5.8								
Coastal fen OLsF site 6	0 - 10	4.8	7.0	65	43.6	13.9	5.7	108		166
	10 - 20	6.1								
Tamarack fen TLsF site 14 hummock	0 - 10	4.9								
	10 - 20	6.5								
Tamarack fen TLsF site 15 hollow	0 - 10	5.9	6.4	163	15.1	2.4	1.3	4	0.4	4
	10 - 20	5.3								
Interior fen OGrF site 17	0 - 10	5.3								
	10 - 20	6.5								
Interior fen OGrF site 19	0 - 10	5.3	7.0	168	27.6	4.9	0.5	7	0.3	8
	10 - 20	5.3								
Interior fen TLsB site 16	0 - 10	3.2	7.1	153	21.3	3.5	0.2	4	2.9	5
	10 - 20	7.1								
Bog OGrB site 26	0 - 10	5.2								
	10 - 20	5.1								
Bog PoF site 29	0 - 10	3.3								
	10 - 20	3.3								
Bog PoF site 27	0 - 10	3.3	4.5	27	6.3	1.4	0.5	1	4.4	2
	10 - 20	3.2								
Bog PoB site 34	0 - 10	3.1								
	10 - 20	3.3								
Bog TLsB site 32 hummock	0 - 10	3.2								
	10 - 20	3.1								
Bog TLsB site 33 hollow	0 - 10	3.2								
	10 - 20	3.1								
Bog TLrLsB site 31	0 - 10	3.3	4.5	43	9.1	2.3	0.2	1	0.9	1
	10 - 20	3.2								

TABLE 4. Comparison of Net Primary Plant Production (NPP) [From *Innanen*, 1991] and Seasonal CH₄ Emission for Various Sites

Location Site Types		Bryophyte Biomass Accumulation, g m ⁻²	Vascular Plant Biomass Accumulation, g m ⁻²	Total NPP g C m ⁻²	CH ₄ Emission g CH ₄ m ⁻²	CH ₄ -C/NPP-C
Coastal marsh	MM (1-5)	-	218 ± 54	87 ± 22	0.63 ± 0.62	0.007
Coastal fen	OLsF (6) & OGrF (7)	-	68 ± 17	27 ± 7	0.25 ± 0.20	0.009
Interior fen	OLsF (17) & OGrF (18, 19)	154 ± 55	33 ± 17	75 ± 29	0.31 ± 0.12	0.004
Leduc bog	PoF (26, 27, 29)	70 ± 40	18 ± 9	35 ± 20	0.84 ± 0.33	0.020

related to H₂ availability, rather than acetate, though *Valentine et al.* [this issue] have noted a CH₄ production response to ethyl alcohol, as an acetate precursor or electron source.

Although these laboratory studies suggest that CH₄ production and consumption should decrease with a decrease in soil pH, there is no evidence that soil pH plays an important role in determining the field emission of CH₄ to the atmosphere. The largest field emissions were recorded at the moss/sedge mats and degrading pools at the bog locations, where the surface pH values are < 4.0 and the laboratory methane production and consumption potentials were high in acidic samples.

Above ground plant net primary productivity at the wetland sites along the transect ranged from 50 to 200 g m⁻² [*Innanen*, 1991] (Table 4). Thus CH₄-C emissions are very small, ranging from 0.4 to 2.0 % when expressed as a percentage of NPP-C ratios, with most sites falling into the lower end of this range. These percentages are generally lower than those quoted by *Asekmann and Crutzen* [1989].

CONCLUSIONS

Emissions of CH₄ from wetlands in the southern section of the Hudson Bay Lowland are characterized by high variability, both spatially within and between sites, as well as temporal over the thawed season. Although CH₄ emission variations over the season were poorly related to simple variables such as water table and peat temperature, the integrated flux over the thaw season at sites was significantly related to the mean seasonal position of the water table. Seasonal fluxes ranged from 0.1 to 16.6 g CH₄ m⁻², and these are likely to underestimate the annual flux by up to 20 %. These values are generally smaller than has been assumed in the earlier construction of global CH₄ budgets [e.g., *Asekmann and Crutzen*, 1988; *Matthews and Fung*, 1987], though the high spatial and temporal variability and year-to-year variations in CH₄ flux introduce large errors into global extrapolations. *Roulet et al.* [this issue] show that the size of the northern wetlands CH₄ source, using data from this study, is similar to that attributed in the recent budget of *Fung et al.* [1991].

These Hudson Bay lowland CH₄ emission rates fall within the range observed in other northern Canadian wetlands, such as at Schefferville, Quebec and Churchill, Manitoba [*Holland*, 1991; *Moore and Knowles*, 1990; *Moore et al.*, 1990] (Figure 7), as well as those from other arctic locations [e.g., *Bartlett et al.*, 1992; *Morrissey and Livingston*, 1992; *Sebachner et al.*, 1986; *Whalen and*

Reeburgh, 1988, 1990, 1992]. Although the same overall controls of water table and temperature are dominant and with similar small-scale variability in fluxes, the Arctic fluxes tend to be larger than those observed in the subarctic locations. Within the Hudson Bay lowland the CH₄ emissions at Churchill, at the boundary between the subarctic and Arctic, are somewhat larger than those in the southern section. Fluxes are related to the evolution of the wetland ecosystems, through its control on thermal and hydrologic regimes and vegetation characteristics and productivity, with the largest fluxes observed at sites where the peat appears to be degrading to form shallow pools. Studies in the Alaskan tundra [*Bartlett et al.*, 1992; *Morrissey and Livingston*, 1992; *Whalen and Reeburgh*, 1992] also suggest that CH₄ emission rates are largest at the dynamic boundary between terrestrial peatland and aquatic ecosystems.

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