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SPATIAL AND TEMPORAL VARIATIONS OF METHANE FLUX FROM SUBARCTIC/NORTHERN BOREAL FENS

Tim Moore

Department of Geography, McGill University, Montreal, Quebec, Canada

Nigel Roulet

Department of Geography, York University, North York, Ontario, Canada

Roger Knowles

Department of Microbiology, Macdonald College of McGill University, Sainte Anne de Bellevue, Quebec, Canada

Abstract. Emissions of CH_4 were measured by a static chamber technique (five chambers/site) at 23 sites in four fens near Schefferville, subarctic Quebec. At three intensively-monitored sites along a transect from fen margin to central and flooded sites, mean CH_4 fluxes from June to August, 1989 were 65, 125, and 36 mg m^{-2} d^{-1}, respectively. Pore water CH_4 concentrations in the peat profiles to a depth of 1 m averaged 125 to 200 μM, with lower concentrations (generally <50 μM) at 0.1 m. Total, depth-integrated storage of CH_4 in the peat profiles ranged from 3.5 to 4.3 g m^{-2}. Although CH_4 flux was only weakly correlated with either peat temperature at 0.1 m or water table position within each site, there was a strong association of flux and these variables among the three sites, indicating the value of ecological attributes in identifying patterns of CH_4 flux. A pulse of CH_4 was recorded at two of the three sites in mid-August, associated with a degassing of the peat profile, based on pore water CH_4 concentrations. This pulse appeared to be initiated by the lowering of the water table by between 5 and 10 cm during a 3-week period of low rainfall and is estimated to have contributed 18 to 65% of the seasonal CH_4 emission, depending on the location of the site. An estimate of the regional CH_4 flux from 130 km^2 of the Schefferville area was based on CH_4 flux measurements at 23 sites in the area, stratified by fen type (forested margin, margin, central, flooded, ridge, and pool). June to August regional CH_4 flux was 18 mg m^{-2} d^{-1}, for an area in which fen coverage was 29%. When extrapolated to the global scale, these results indicate that northern fens may contribute about 14 Tg yr^{-1}, somewhat lower than other recent estimates.

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INTRODUCTION

The concentration of atmospheric methane has nearly tripled in the last 400 years and continues to rise at slightly less than 1% $year^{-1}$ [Khalil et al., 1989]. Atmospheric methane is important as a radiative gas, absorbing in the 7.66 μm band, and as an atmospheric constituent involved in oxidant chemistry [Cicerone and Oremland, 1988]. Wetlands, rice paddies, and ruminants are the major biogenic sources of methane, while biomass burning, coal mining, and natural gas are the major abiogenic sources. Determining the significance of each source is difficult, in part because of the dearth of actual flux measurements at each source and, at least in the case of wetlands and rice paddies, the large spatial and

temporal variability in production, oxidation, and mode of transport of methane.

Cicerone and Oremland [1988], using several constraints, suggest that the annual release from all sources is approximately 540 Tg CH_4 yr^{-1}. Radiocarbon isotope analysis, however, indicates that between 15 and 30% of the CH_4 contains old carbon (i.e., >50,000 years), making the annual release difficult to reconcile with current source information unless (1) some of the isotopic signatures attributed to a given source are incorrect, (2) the net flux estimates are incorrect, and/or (3) some of the current biogenic emissions of CH_4 contain older isotopic signatures. If CH_4 is produced in the uppers layers of a peatlands as suggested by Crill et al. [1988] and Moore and Knowles [1990], then the signature would be that of new carbon. If, however, a portion of the methane is derived from depths below 0.5 m in some northern peatlands, it could contain an older fraction. Northern fens generally have less vertical differentiation in structure through the peat profile than do bogs [National Wetlands Working Group, 1988]. This increases the possibility of CH_4 release from depth, in contrast to the limited potential for gas release from bogs [Brown et al., 1990] which have very small pore structure below about 0.25 m [Ingram, 1983].

Cicerone and Oremland [1988] estimate that wetlands, excluding rice paddies, emit 115 Tg CH_4 yr^{-1}, or 21% of the annual source of atmospheric methane, based on the estimates of Matthews and Fung [1987]. Aselmann and Crutzen [1989] have recently suggested a smaller contribution of 80 Tg CH_4 yr^{-1}. The difference in estimates results from differences in areal coverage of wetland types, mean flux rate for each wetland type, and the length of flux period.

It has been postulated that wetland CH_4 emissions may increase in the future if the boreal forest and subarctic regions become warmer [e.g., Aselmann and Crutzen, 1989]. During the Little Ice Age, concentration of atmospheric CH_4 decreased [Khalil and Rasmussen, 1989], presumably in response to reduced net primary production and microbial activity in a cooler northern environment. However, there are many attributes of wetlands that correlate with CH_4 flux such as redox potential [Svensson and Rosswall, 1984], net primary production [Aselmann and Crutzen, 1989], wetland saturation [Harriss et al., 1982; Moore and Knowles, 1989; Sebacher et al., 1986], and wetland soil temperature [Moore and Knowles, 1987; Svensson and Rosswall, 1984]. With a warmer northern environment, it is probable that the northern wetlands will initially become drier, which would, directly and indirectly, affect many of the variables listed above.

In this paper we examine the spatial variability of CH_4 flux within and between wetlands and the temporal variability of fluxes over the snow-free period for subarctic/boreal forest fens in the area around Schefferville, Quebec, Canada. Previous studies have examined the CH_4 flux from wetlands in this area [Moore and Knowles 1987; 1990]. In the present study we (1) extend this work by examining the change in CH_4 flux and storage over time in relation to the thermal and moisture regime of the fens and (2) place the measured fluxes in a regional and ecological context to derive an estimate of an annual flux of CH_4 from this subarctic area. To this end, we recalculate several of the estimates of northern wetlands as a source of atmospheric CH_4 [Aselmann and Crutzen, 1989; Matthews and Fung, 1987].

DESCRIPTION OF THE SCHEFFERVILLE AREA

The study was conducted on several fens in the Schefferville, Quebec area, Canada (54°48'N, 66°49'W). The 35-year mean annual temperature for Schefferville is -4.9°C, and total precipitation is 790.7 mm, of which 48% falls as snow (D.R. Barr, Manager, McGill Subarctic Research Station, unpublished data, 1990).

The wetlands of the Schefferville area lie in the low subarctic peatland region of Canada [National Wetlands Working Group, 1988]. The underlying rocks are derived from the sedimentary Labrador Trough and include dolomite, shale, and quartzite. The variety of rock types produces variations in peat water chemistry and plant assemblages: very rich fens occur where dolomite is dominant, and very poor fens occur where shale or quartzite is the substrate [Sjörs, 1952; Waterway et al., 1984]. The fens, with very few exceptions, are open flat or patterned, mineral-poor fens, typically surrounded by a narrow, forested margin. The open fens have a wider, nonforested margin and a large, flat, extensive

central portion that is covered with *Carex* spp. In some open fens, portions of the central area are ephemerally flooded or have small, shallow ponds. The patterned fens usually have a nonforested margin around the perimeter of a central pool and ridge (string) complex. The fens are generally 1-2 m deep and are not underlain by permafrost, though there are palsa features in wetlands located near the upland tundra areas.

METHODS

Two levels of sampling on four fens (Figure 1), called Capricorn, Ares, NASA Fen, and Runway, were used in this study (names of the fens are unofficial). In the Capricorn fen, measurements of the CH_4 flux were made about once a week from mid-June to mid-September at three sites representative of the fen nonforested margins (C-M), central (C-C), and flooded areas (C-F). The water table, peat surface elevation, and soil temperature at a depth of 0.1 m were continuously monitored. An elevated boardwalk was installed in this fen to access the three sites without disturbing the fen surface. In the Ares, Runway, and NASA fens, at a total of 14 sites, and at four additional sites in the Capricorn fen, CH_4 flux was measured less frequently over the same period, to develop a regional estimate of total methane emissions from the Schefferville wetlands. These sites include more fen margins, central and flooded areas, as well as forested fen margins and string fen pools and ridges. With each CH_4 flux measurement at these sites, peat temperature at 0.1 m and the water table elevation were measured manually. For the regional estimate calculation, the results obtained

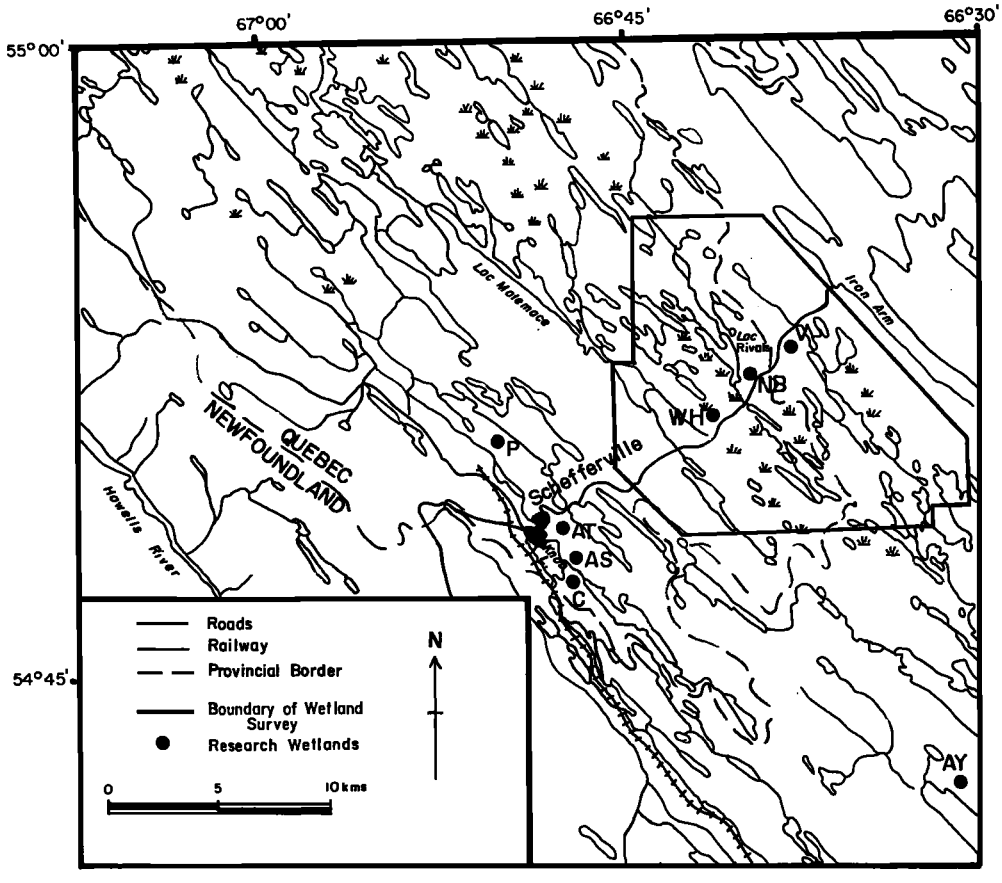

Fig. 1. Location of the fens studied and the boundary of the wetland survey (see Figure 9). The fens examined in this study were Capricorn (C), Ares (As), Runway (AT), and NASA (NB). In addition, data from Pelletier (P) were used in the regional extrapolation.

previously from a patterned fen were also used [Moore and Knowles, 1990].

At each site on each sample date, the mean CH_4 flux was computed from at least five static chambers (area, 0.053 m^2; volume 0.018 m^3). The chambers were placed on the peat surface with their rims approximately 2 cm into the peat. Ambient air was sampled when the chambers were installed and the air inside the chamber was sampled after 24 hours. Eight-milliliter samples were stored in nonsterilized, 8-mL Vacutainers, shipped to Montreal and analyzed generally within 2 weeks of sampling on a Perkin Elmer 3920 gas chromatograph with H_2 flame ionization detector [Chan and Knowles, 1979], using a Union Carbide methane standard of 550 ppm from which lower concentrations were prepared. The CH_4 flux was calculated as the difference in concentration in the two samples, corrected for the volume of air in the chamber. It is possible that the data represent the lower limits of emission rates if the increase in CH_4 concentration in the chambers stimulated CH_4 oxidation by methanotrophs. Most chamber concentrations were below 100 ppm CH_4, which is well below the range of reported apparent K_m values for CH_4 oxidation [Bédard and Knowles, 1989]. There is little evidence for nonlinearity in methane emissions over a 24-hour period or leakage from Vacutainers [Moore and Roulet, 1990].

The concentration of CH_4 in the surface water of the Capricorn fen pond was measured by first drawing 30 mL of water and then 30 mL of air into a 60-mL syringe, closing the valve, and degassing by shaking vigorously for 2 min. The CH_4 concentration in the headspace was determined as described above and converted to concentration in the peat water. The flux of CH_4 from the pond was then calculated using a simple transfer model [$F = k (C_s - C_a)$], where F is the flux of CH_4 (mg m^{-2} t^{-1}), k is the CH_4 transfer coefficient derived using the empirical function of Sebacher et al. [1983], and C_s and C_a are the concentration of CH_4 in the surface water and air above the pond surface.

The concentration of CH_4 in the peat column was determined by withdrawing water from depths of 0.10, 0.25, 0.50, 0.75, and 1.00 m at each of the three Capricorn sites five times during the summer. Water was drawn up through a metal tube, perforated at the base, with a vacuum exerted by a hand pump at 0.2 bars. After discarding turbid water caused by the disturbance of the tube insertion, 30 mL of peat pore water was drawn into a syringe through a septum on the side of the tube head, and degassing conducted as was described above for pond water.

At three Capricorn sites, peat temperature was measured using Campbell 107 thermistor probes, and the water level and peat surface elevations were determined with a float potentiometer system. From the latter, the water table elevation, defined as the elevation of the water surface in hydrostatic equilibrium with atmospheric pressure relative to the elevation of the peatland surface, was determined. Air temperature was monitored with an aspirated thermocouple 1.5 m above the peatland surface, and rainfall was recorded using a tipping bucket rain gauge. Wind speed at 1.0 m above the central pond in Capricorn was determined with a R. M. Young Sentry anemometer. All sensors were read every minute and averaged half hourly. At all other sites, Fenwall bead thermistors, calibrated to 0.25°C, were used to determine peat temperature and the location of water table measured relative to an arbitrary datum.

RESULTS

In this section, we examine the flux from and the storage of CH_4 in the Capricorn fen. We also examine the relationship between the flux of CH_4 and the moisture and thermal regimes of the fen sites. We conclude the results with an areal survey of Schefferville wetlands and a comparison of the results from this study with the estimates of northern wetlands as a source of CH_4 by Matthews and Fung [1987] and Aselmann and Crutzen [1989].

The climate of the thawed season during the study was reasonably normal (Figure 2). Precipitation in May and August was slightly less than normal, while September was slightly greater, and total precipitation for May through September was 0.93 of normal. Summer temperatures were also normal: a mean of 8.3°C for the thawed season, compared to the normal mean of 7.6°C. However, record air temperatures were established in late June, so that there was no pronounced evolution of the thermal regime at the surface (0.10 m) depth of the peat, as has

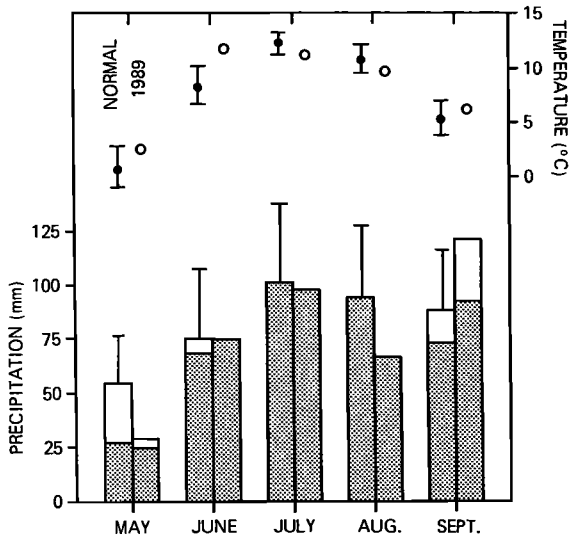

Fig. 2. May to September normal precipitation and temperature and that recorded for 1989, in Schefferville, Quebec. Shaded section represents rainfall and open section represents snowfall. Bars indicate standard deviation around the mean.

been observed previously [Moore, 1987]. Maximum surface peat temperatures were recorded in late June (Figures 3 and 4). An unusually early, permanent snow cover developed by late September.

Time Series of the Methane Flux and Storage

Methane flux was highest at the central site (mean of 125 mg m^{-2} d^{-1}), and lower at the margin and flooded sites (means of 65 and 36 mg m^{-2} d^{-1}, respectively) (Figure 4). As in previous studies of methane emissions from northern wetlands [e.g., Moore and Knowles, 1987, 1990], a very large temporal and spatial variability in methane emissions was observed. The range in mean daily flux from the flooded, central and margin sites were 10.2 to 110.0, 53.9 to 158.8, and 4.9 to 262.0 mg m^{-2} d^{-1}, respectively. The ranges in coefficient of variation for the daily samples at these three sites were 0.43 to 1.99, 0.26 to 0.9, and 0.23 to 2.0, respectively.

A large part of the temporal variation in emissions was due to a short duration, episodic flux at each site. The largest mean daily flux, 262 ± 205 mg m^{-2} d^{-1}, was observed at the margin site on August 12 (Figure 4). The largest daily flux at the flooded site, 110 ± 220 mg m^{-2} d^{-1}, was observed on the same day. These large fluxes initially appear anomalous, but they correspond to a long period of sustained drop in water table of between 5 and 10 cm, associated with little rainfall in the previous 22 days (Figure 3), and also to a very large negative change in stored CH_4 in the peat (Figure 5). At 9 of the 18 regional sampling sites, including two Capricorn forested margin sites, the largest flux of CH_4 was recorded between August 9 and 17. While these sites would have had a different hydrology, and therefore different water table elevations, a reduction in water table would have been regional, since it is controlled primarily by rainfall and evaporation in these wetlands (N. Roulet, Surface adjustment in northern peatlands: The maintenance of effective surface saturation, submitted to *Arctic and Alpine Research*, 1990, hereinafter referred to as Roulet (1990)).

The concentration of CH_4 in the peat pore water dropped from generally over 125 μM to under 50 μM at the flooded and central site from July 31 to August 14, while a similar drop occurred at the margin site, but there it was more prolonged. A previous loss at the latter site occurred between July 3 and 31. The largest flux at the central site occurred on June 27 and corresponds to the release of methane as the peatland thaws.

At the central and flooded sites, the CH_4 concentration in the peat decreased slowly from late June to late July. While the continuity between storage and flux during this time period was transient, it was only marginally so. The mean CH_4 concentration during this period was 210 and 147 μM at the central and flooded sites. Multiplying these concentrations by the average depth of peat at these two sites (1.4 and 1.6 m, respectively), and the mean volumetric soil moisture of 0.92 per m^3 column of peat (N. Roulet, unpublished data, 1990), the mean CH_4 storage at each site was 4.3 and 3.5 g m^{-2}. The mean flux of CH_4 between July 3 and 31 at the central and flooded site was 104 and 29 mg m^{-2} d^{-1}, resulting in storage:daily flux ratios of 42 and 118 days, respectively.

The mean calculated CH_4 flux from the pond for days when the surface water concentration was measured was 33.1 ± 31.8 mg m^{-2} d^{-1}. This flux is not statistically

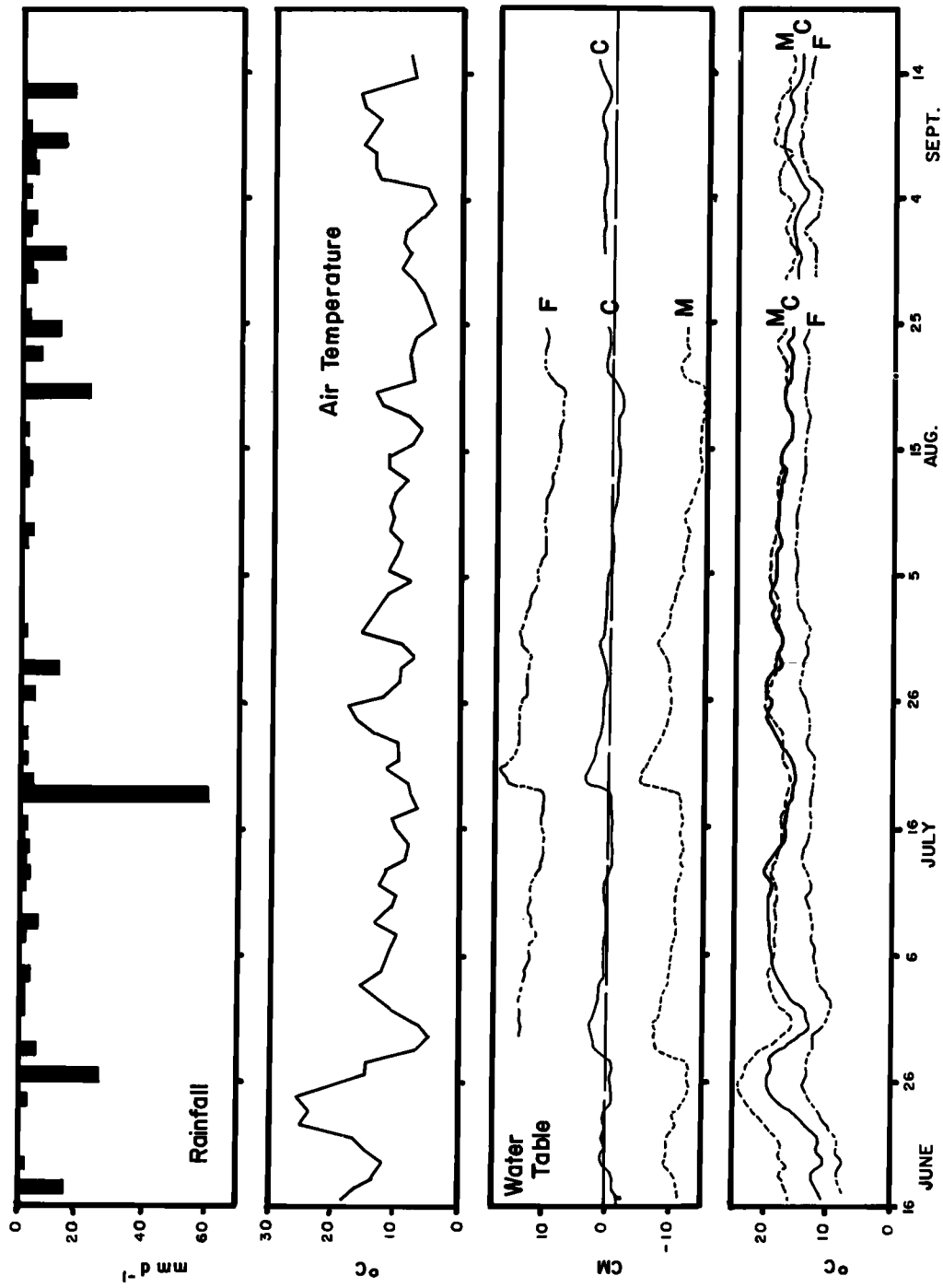

Fig. 3. Precipitation and air temperature at the Capricorn wetland and the position of the water table and the peat temperature at a depth of -10 cm at the margin (M), central (C) and flooded (F) sites, June-September 1989.

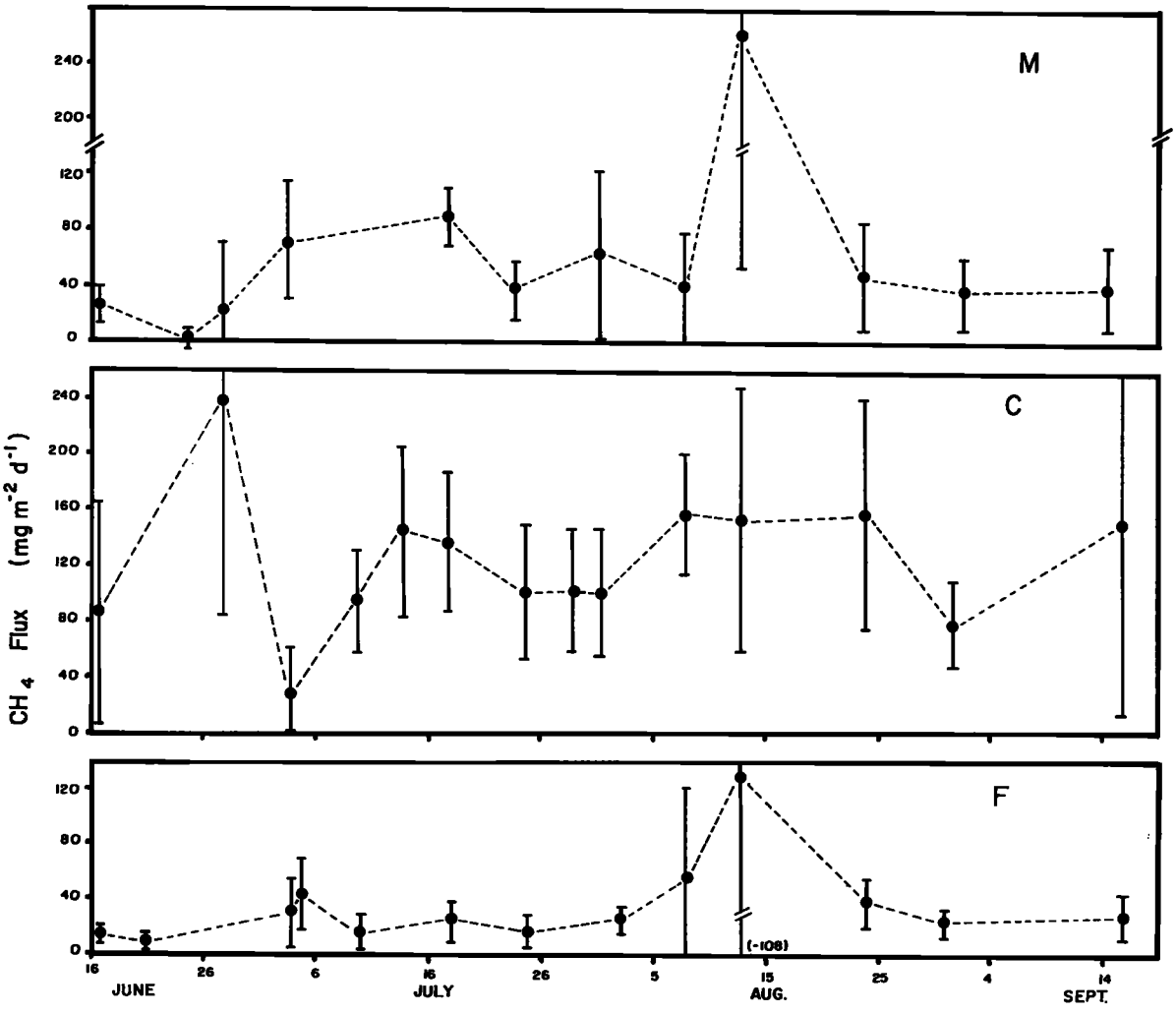

Fig. 4. Methane flux from the margin (M), central (C), and flooded (F) sites at the Capricorn wetland, June-August 1989.

different from the mean flux at the flooded site (36 mg m^{-2} d^{-1}). It was anticipated that the transfer calculations would yield a larger flux than that measured in the chambers because the chambers interfere with the surface exchange process. Sebacher et al. [1983] showed that the CH_4 flux increases exponentially with wind velocities above 1.4 m s^{-1}. However, the net CH_4 flux across the atmosphere-water interface is ultimately controlled by the flux of CH_4 across the peat-water interface, and the concentration of CH_4 in the surface waters is a reflection of difference between the peat-water and water-atmosphere exchange rates. Thus the exchange across the peat-water interface is likely to be the limiting flux, and the averages of chamber-derived fluxes are not likely to differ much from those calculated by a turbulent exchange function, if several samples over time were taken. In addition, the chambers may trap CH_4 released by ebullition, which would not be represented in the surface water analysis.

In the Capricorn fen, the water that floods the peat surface is contiguous with the pond. The CH_4 concentration in surface water ranged from 30.7 ± 36.8 to 194.6 ± 104.3 $\mu g\ L^{-1}$, with a mean concentration of 74.8 $\mu g\ L^{-1}$ (Figure 6). The lowest concentration was observed on August 12, corresponding with the low concentrations observed in the peat pore water at the other sites. The spatial variability in CH_4

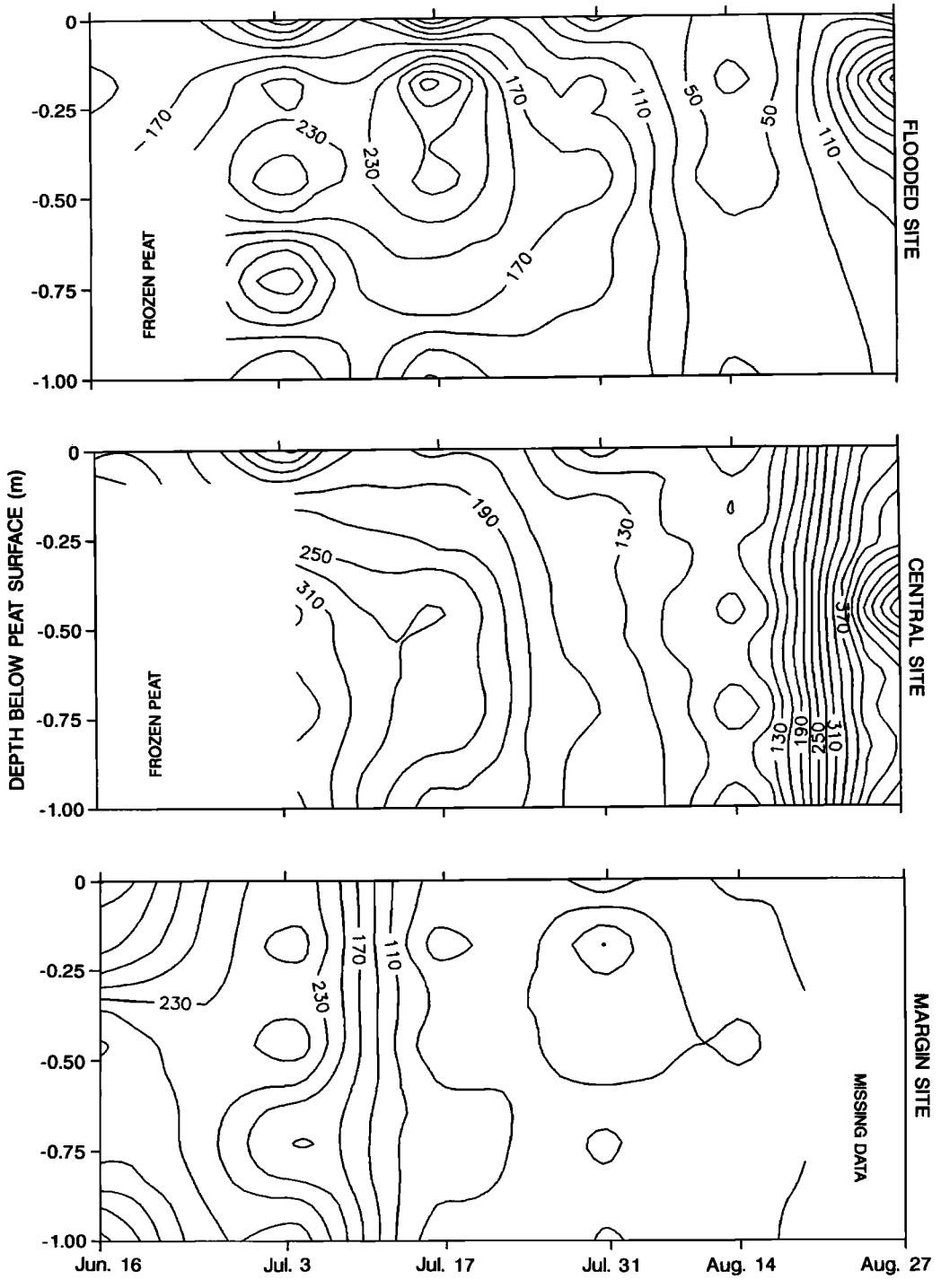

Fig. 5. Pore water methane concentrations (μM) at the Capricorn margin (M), central (C), and flooded (F) sites, June-August 1989, based on samples from 0.1, 0.25, 0.5, 0.75, and 1.0 m.

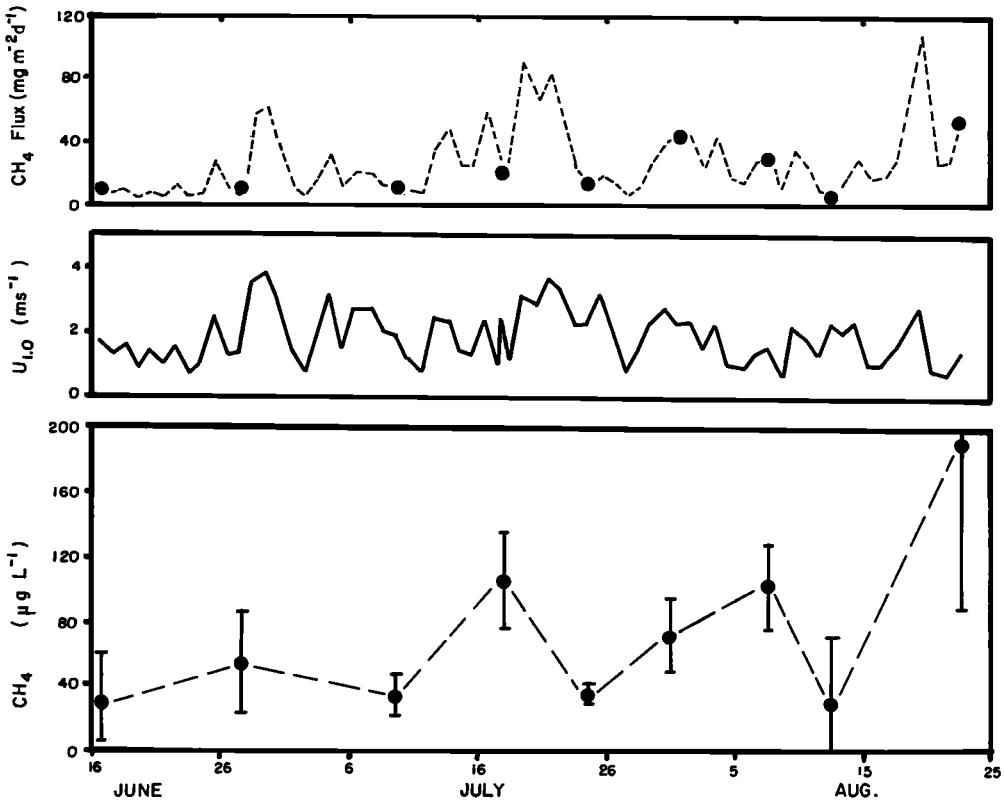

Fig. 6. Surface water methane concentrations at the Capricorn pool, wind speed at 1 m, and calculated methane flux assuming turbulent diffusion, June-August 1989.

concentration (mean coefficient of variation, 0.5; range, 0.06-1.2), was lower than that of the fluxes observed at the other sites. The pond was 1.6 m deep, and assuming the CH_4 concentration near the surface is representative of the entire water profile, on average the pond stores 118 mg m^{-2}, and this CH_4 pool could turn over approximately every 3.6 days.

Relationship Between Methane Flux and Site Moisture and Temperature

In general, the changes in CH_4 flux and storage were related to temperature and degree of saturation at each site. At the end of the summer, when the temperature of the overall peat column was highest, the production of CH_4, as indicated by the build up of CH_4 in the peat in late August, was greatest (Figures 3 and 5). CH_4 flux was exponentially related to 0.1 m peat temperature (Figure 7; $r^2 = 0.46$, significant at $p = 0.01$). There was also an inverse parabolic relationship between the elevation of the water table and CH_4 flux (Figure 8). At the central site, the water table varied little relative to the peat surface, and the flux was highest. Where the water table was continuously below the surface, as at the margin site, or above the surface as at the flooded site, the fluxes were lower.

While the relationships indicate a correlation between the environmental variables of a peatland and CH_4 emission, the relationships may, in part, be specious. The variables of water table and peat temperature are themselves correlated: the flooded site has the lowest temperature because there is a layer of water above the peat surface that acts as a thermal reservoir of large heat capacity, and it loses latent heat through evaporation, thus reducing heat conduction into the peat. Therefore any relationship between CH_4 flux and these two variables cannot be viewed as being independent.

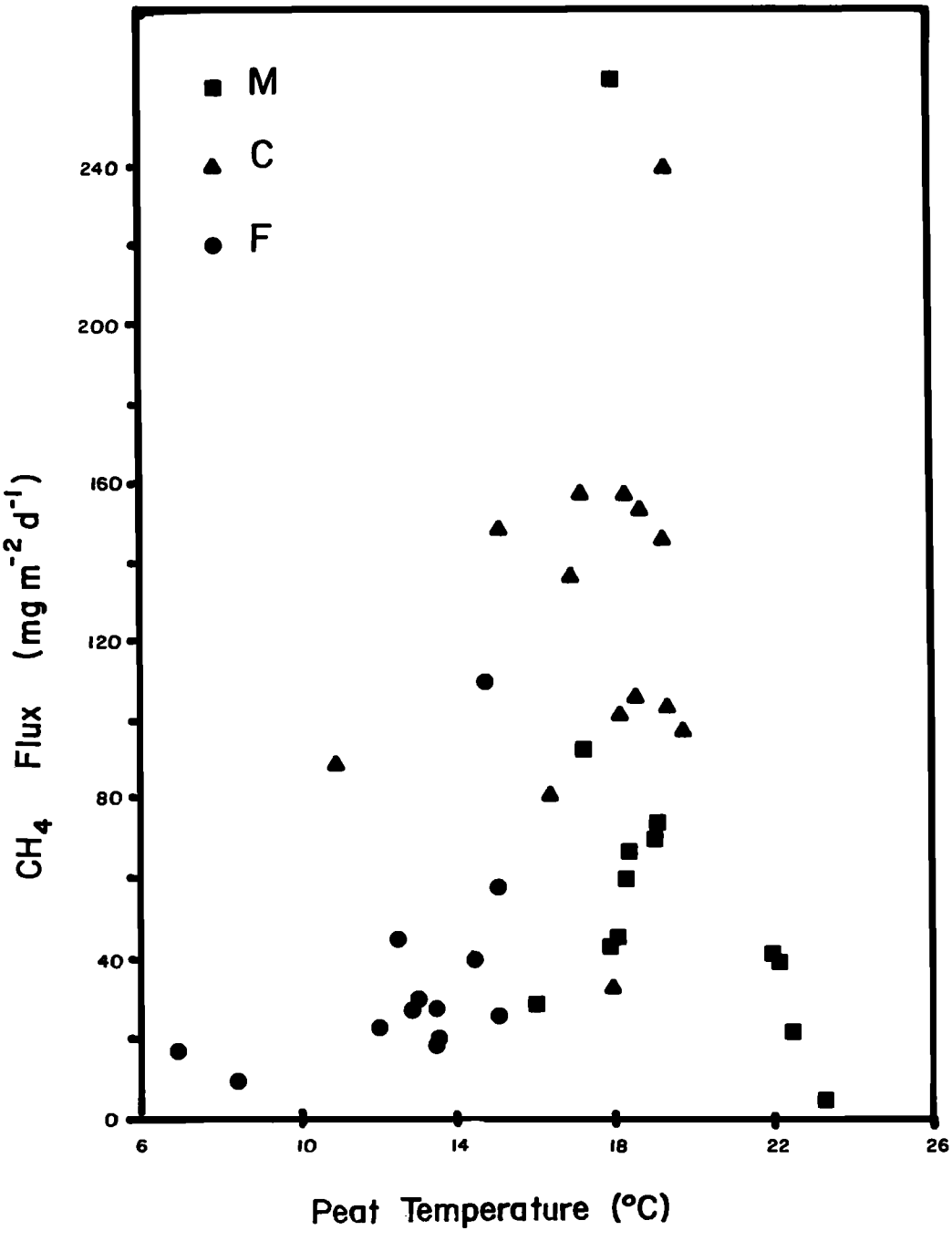

Fig. 7. Relationship between methane flux and peat temperature at a depth of -10 cm at the Capricorn margin (M), central (C), and flooded (F) sites.

The relationship between CH_4 flux and water table can be explained from two perspectives. It indicates that sites across the Capricorn fen that are generally surface-saturated, but not flooded, consistently yield the largest flux. The exception to this was the episodic large fluxes. At the margin and flooded sites, CH_4 flux was related to water table elevation. In the margin there was a positive relationship between flux and water table ($r^2 = 0.43$, $p = 0.05$, and

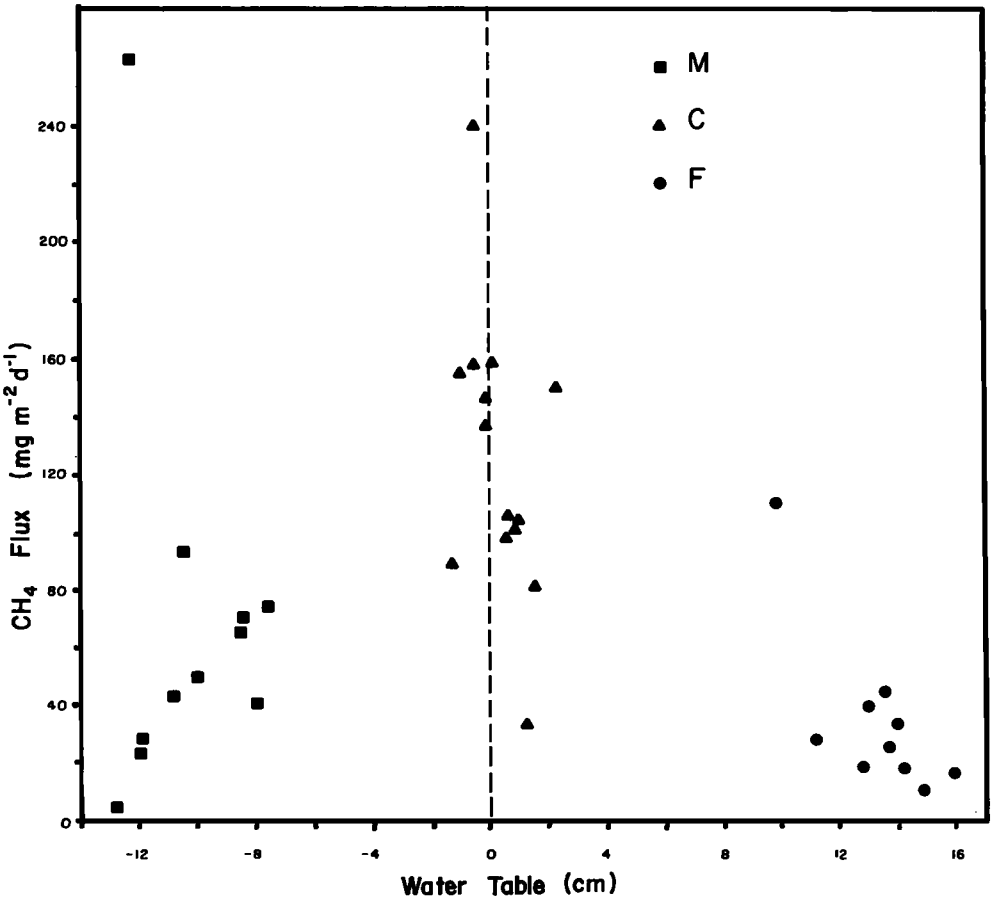

Fig. 8. Relationship between methane flux and the position of the water table relative to the peat surface at the Capricorn margin (M), central (C), and flooded (F) sites.

slope = 10.9 mg CH_4 m^{-2} d^{-1} / cm change in water table), and at the flooded site there was a negative relationship (r^2 = 0.42, p = 0.05 and slope = -5.7 mg CH_4 m^{-2} d^{-1} / cm). At the central site there was no relationship, because of the adjustment of the peat surface to the falling water level, resulting in a water table elevation that changes little throughout the summer (Roulet, 1990). The peat surface did change at the other two sites, but the change relative to a change in the water level was much smaller than at the central site.

Estimation of Regional Methane Flux From Northern Fens

To derive an estimate of the regional CH_4 flux from the Schefferville area, data from the other fens were used. The mean thawed-season CH_4 flux for each site is shown in Table 1. The sites have been categorized into six fen types: forested margins, nontreed or sparely treed fen margins, central fens, flooded fen, string fen ridges and string fen pools. The sites under each fen type have similar vegetation characteristics (Table 1), reflecting generally similar environmental conditions, such as moisture regime, nutrients, redox potential, and acidity.

The percentage of each fen type per peatland was estimated for a representative 130 km^2 area by air photographs (1:10,000 and 1:50,000) and maps of wetlands from previous studies (Roulet, 1990; also T. Moore, unpublished data, 1990) (Figure 9). The cover statistics were combined with the mean flux data to produce areally-weighted

TABLE 1. Mean Summer CH_4 Flux (mg m^{-2} d^{-1}) for Fen Types in the Schefferville Area

Fen Type	Site	N	Mean	(s.d.)	Dominant Vascular Plant Species
Forest margin	T1	50	2.1	(5.3)	*Betula pumila* (5) *Salix pedicellaris* (5), *Scirpus cespitosus* (5), *Larix laricina* (4), *Rubus chamaemorus* (4), *Carex aquatilis* (4), *Carex chordorriza* (4)
	T4	35	41.7	(49.2)	*Carex oligosperma* (5), *Empetrum hermaphoditum* (5), *L. laricina* (5), *Picea mariana* (5), *Kalmia polifolia* (4)
	T5	30	50.7	(61.7)	*E. hermaphoditum* (5), *P. mariana* (5), *Rubus chamaemorus* (5), *Vaccinium uliginosum* (5), *Betula glandulosa* (4), *Carex pauciflora* (4)
	T8	45	12.2	(9.1)	*S. cespitosus* (5), *Carex limosa* (4), *C. oligosperma* (4), *Carex rostrata* (4)
	T11	45	3.4	(2.3)	*S. cespitosus* (5), *Aster radula* (4), *L. laricina* (4), *Coptis trifolia* (4)
	T19	50	0.6	(1.5)	*C. pauciflora* (5), *L. laricina* (5), *S. pedicellaris* (5), *V. uliginosum* (5), *B. pumila* (4), *Equisetum arvense* (4), *S. cespitosus* (4), *P. mariana* (4), *R. chamaemorus* (4)
Fen margin	T2	45	11.6	(7.4)	*Andromeda glaucophylla* (5), *C. limosa* (5), *C. chordorriza* (4), *Menyantheses trifoliata* (4)
	T9	40	19.7	(22.7)	*A. glaucophylla* (4), *C. limosa* (4), *C. paupercula* (4), *Chamaedaphne calyculata* (4)
	T25	45	9.2	(4.2)	*Drosera intermedia* (5), *Carex livida* (4), *K. polifolia* (4), *M. trifoliata* (4), *S. cespitosus* (4)
	C-M	65	64.7	(63.8)	*C. limosa* (5), *C. oligosperma* (5), *C. calyculata* (4)
Fen central	T10	40	91.5	(79.1)	*C. limosa* (5), *C. rostrata* (4)
	T13	45	30.4	(24.1)	*C. limosa* (5), *C. rostrata* (5)
	T15	50	29.3	(17.9)	*C. limosa* (5), *A. glaucophylla* (4), *C. livida* (4), *M. trifoliata* (4)
	C-C	70	125.1	(48.9)	*C. limosa* (5), *C. rostrata* (5), *A. glaucophylla* (4)
Fen flooded	T3	50	24.5	(14.2)	*A. glaucophylla* (5), *C. chordorriza* (5), *M. trifoliata* (5), *C. limosa* (4), *C. livida* (4)
	T7	25	32.7	(34.5)	*C. limosa* (4), *Myrica gale* (4), *M. trifoliata* (4)
	T12	45	40.2	(28.3)	*C. limosa* (4), *C. rostrata* (4)
	C-F	65	35.9	(26.0)	*C. limosa* (5), *C. rostrata* (5)
Patterned fen	T6	30	4.9	(6.3)	*Carex exilis* (5), *S. cespitosus* (5), *A. radula* (4), *M. gale* (4)
ridges (strings)	T16	40	8.3	(7.1)	*Betula michauxii* (5), *Smilacina trifolia* (5), *C. calyculata* (4), *S. cespitosus* (4), *Vaccinium oxycoccus* (4)
	PS	40	8.6	-	*S. cespitosus* (5), *B. michauxii* (4), *C. calyculata* (4)
Patterned fen	T20	45	32.4	(13.5)	*C. limosa* (5), *Eriophorum chamissonis* (4), *M. trifoliata* (4)
(pools)	PP	40	65.9	-	*M. trifoliata* (5)

N is the number of CH_4 measurements at each site. Numbers 5 and 4 after species names indicate very common and common occurrence, respectively. Sites are as follows: C-M, C-C, C-F, T4, T5, T6, and T7, Capricorn fen; T1, T2, T3, and T25, Ares fen; T8, T9, T10, T11, T12, T13, NASA fen; T15, T16, T19, T20, Runway fen; and PS and PP, Patterned fen [Moore and Knowles, 1990].

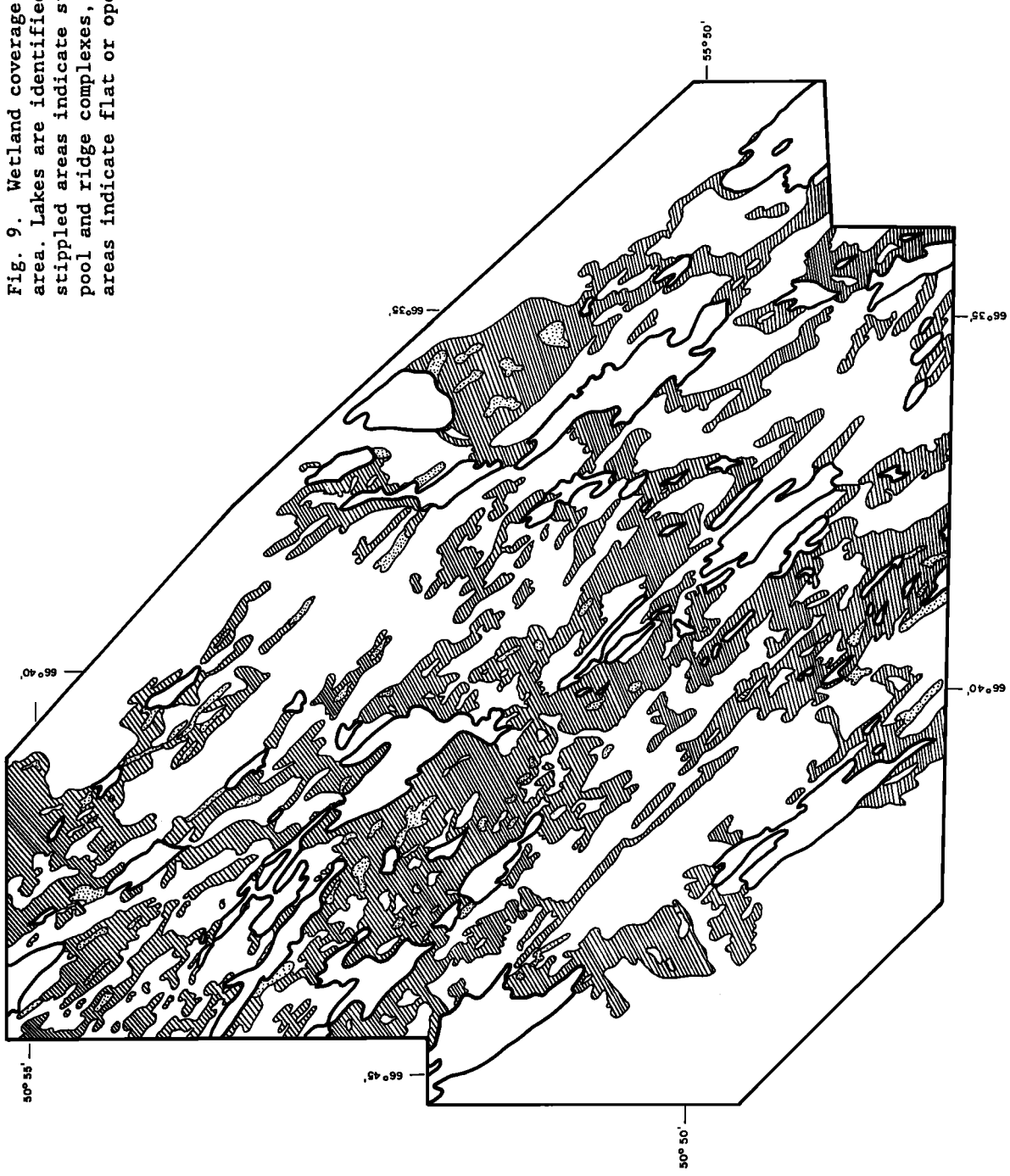

Fig. 9. Wetland coverage in the survey area. Lakes are identified by bold lines, stippled areas indicate string fens with pool and ridge complexes, and hatched areas indicate flat or open fens.

estimates of CH_4 emissions (Table 2). Two estimates were derived. The first is the estimate of the regional mean flux per square meter of wetland (sum of column 3 in Table 2) and the second is a regional mean flux per square meter of the land and lake area surveyed (i.e. total area of 130 km^2), assuming that only the peatlands generate CH_4 and that no CH_4 is consumed by the upland soils and lakes adjacent to the fens. These estimates are probably conservative, because lakes represent between 10 and 20% of the surface area in the region, though their shallowness and commonly mineral floor and low CH_4 concentrations in surface waters indicate that they are probably a minor regional source of CH_4.

The results from Table 2 cannot be directly compared with those of Matthews and Fung [1987] or Aselmann and Crutzen [1989], because of differences in length of CH_4 emission period, areal extent of wetlands, and flux values used in each calculation. For comparative purposes, we have used the duration and areal coverage of the authors above, and substituted our flux estimates (Table 3). Matthews and Fung [1987] did not differentiate bogs and fens, only forested and nonforested bogs, so their areal coverage for nonforested bogs north of 40° contains a significant proportion of fens. Aselmann and Crutzen [1989] classified fens as one wetland type, so this number was used in comparisons with their work.

Based on our studies at Schefferville, our estimates for the annual CH_4 flux from northern nonforested wetlands are approximately 3 times smaller than that of Matthews and Fung [1987]. They used flux estimates of 200 and 70 mg m^{-2} d^{-1}, which is considerably higher than our mean flux (Table 2). Our estimates are close to those of Aselmann and Crutzen [1989], especially when their fen flux is recalculated incorporating our mean flux data (means of 80 and 56 mg CH_4 m^{-2} d^{-1}, respectively). In both recalculations, the role of the northern wetlands as a source of CH_4 is reduced. In comparison with the source reconstruction of Cicerone and

TABLE 2. Estimate of the Regional Daily, Snow-Free CH_4 Flux (mg m^{-2} d^{-1}) for Fens in the Schefferville Area

Fen type	Proportional Coverage	Wetland Mean Flux[a]	Regional Weighted Wetland Flux[b]	Regional Weighted Total Flux[c]
Forest margin	0.014	28.0	1.4	0.4
Patterned fen	0.021	34.7	2.5	2.5
margin	(0.3)[d]	(30.4)[e]		
pool	(0.5)	(48.2)		
ridge	(0.2)	(7.5)		
Open fen	0.251	59.7	52.4	15.0
margin	(0.2)	(30.4)		
central	(0.7)	(71.9)		
flooded	(0.08)	(33.4)		
ponds	(0.02)	(33.2)		
Total			56.3	17.9

[a] Computed from the average flux for each wetland type listed in Table 1, weighted by sample size and variance.
[b] Calculated as the proportion of each wetland type relative to the total wetland area.
[c] Calculated as the proportion of each wetland type relative to the total 130 km^2 surveyed.
[d] Areal weighting for each wetland type.
[e] The mean flux for each wetland type listed in Table 1, weighted by sample size and variance.

TABLE 3. Comparison of Annual Global Northern Wetland CH_4 Flux Estimates

Author	Flux Period days	Area of Wetlands x 10^9 m^2	Annual Flux x 10^{12} g yr^{-1}
Matthews and Fung [1987]	150	1,914[a]	57.3
This Study			16.1
Aselmann and Crutzen [1989]	169	1,480[b]	20.0
This Study			14.0[c]
			19.0[d]

[a] Total area of non-forested bog above 40°N latitude from Matthews and Fung.
[b] Total area of fens from Aselmann and Crutzen.
[c] Substituting our mean fen flux estimate for that of Aselmann and Crutzen.
[d] Recalculation of the Aselmann and Crutzen mean fen methane flux, incorporating our estimates.

Oremland [1988], northern fens may account for 4% of the annual global emission of CH_4.

DISCUSSION

The mean snow-free period CH_4 flux obtained in this study is within the range of fluxes measured in arctic, subarctic, and boreal fens. The mean fen flux of 56 mg m^{-2} d^{-1} is very close to the 59 mg m^{-2} d^{-1} (range, 18-195) of Sebacher et al. [1986], but is higher than the 39 mg m^{-2} d^{-1} of Whalen and Reeburgh [1988], both measured from Alaskan fens. Svensson and Rosswall [1984] measured larger daily fluxes (mean, 95; range, 26-350 mg CH_4 m^{-2} d^{-1}) from a fen in Sweden, and Whalen and Reeburgh [1990] reported average fluxes of 5-90 mg CH_4 m^{-2} d^{-1} for a range of Alaskan sites. Meaningful comparison of the results is difficult, however, because of differences in the number of flux measurements made per site, the number of sites per wetland, and the number of wetlands used to develop a wetland type average. The mean flux calculated for Schefferville is from a large data set, approximately 1000 samples, that was stratified by six fen types that could be characterized by vegetation, degree of saturation, and general thermal regime, over five different fens.

The temporal variation in CH_4 flux at the Capricorn sites was small compared to that observed from other peatlands [e.g., Crill et al. 1988; Sebacher et al., 1986; Whalen and Reeburgh, 1988]. When examining the relationship between environmental variables and CH_4 flux, it is important to establish whether the data were obtained all from one site in one wetland in which ecological variability may be expected to be minor [e.g., Crill et al., 1988; Whalen and Reeburgh, 1988], or whether the data were pooled from several wetlands [e.g., Sebacher et al., 1986; Whalen and Reeburgh, 1990], where large differences in ecological factors could produce an apparent correlation. Such ecological factors include nutrient cycling, plant production, litter quality, redox potential, microbial populations of methane producers and oxidizers, and acidity.

If the central and margin of the Capricorn fen had been assumed to be representative of the two most common fen types of the area, a mean flux of 110 mg m^{-2} d^{-1} would have been estimated. This is 1.9 times higher than the areally-integrated mean obtained by using the regional sites. These results indicate the importance of multiple samples from a range of fens, or other wetlands, that can be characterized in terms of common ecological, chemical, and/or physical attributes that relate to the gas flux [e.g., Matson et al., 1989]. When the results of this study were incorporated into the global estimate of annual CH4 flux from northern fens, their role decreased considerably compared to that estimated by Matthews and Fung [1987] and marginally compared to that estimated by Aselmann and Crutzen [1989]. Comparison of methane emission measurements from

subarctic fens using static and dynamic chambers (in which the air is circulated at a speed similar to that in the open) has shown that static chambers may underestimate emission rates by about 20%, compared to dynamic chambers with a wind speed of about 2 m s^{-1} [Moore and Roulet, 1990]. Unfortunately, there is no way, with the exception of a comparison with short duration aircraft flux measurements, to test regional extrapolations, and the validity of global estimates can only be assessed relative to the constraints outlined by Cicerone and Oremland [1988].

Fens generally emit more CH_4 than bogs and Moore and Knowles [1990], Svensson and Rosswall [1984], and Whalen and Reeburgh [1988] calculated a mean flux for northern bogs of about 5 mg CH_4 m^{-2} d^{-1}, but the emissions from northern Minnesota bogs were much higher (mean of 106 mg CH_4 m^{-2} d^{-1} [Crill et al., 1988]). Bogs are generally believed to be a more significant land type in northern regions [e.g., National Wetlands Working Group, 1988]; however, the coverage data of Aselmann and Crutzen [1989] and recent surveys in the extensive wetland regions of the Hudson Bay lowland of Canada (W. A. Glooschenko and R. Protz, personal communication, 1990) indicate that fens may be an equally prevalent wetland type. The fens in the Schefferville area have vegetation assemblages similar to those reported in southeastern Labrador [Foster and King, 1984] but are different from the raised bogs in the same area [Foster and Glaser, 1986]. Although the ecological differentiation of northern wetlands has little effect on the overall coverage by northern peats, bogs and fens appear to differ considerably in CH_4 emissions, and these differences could have a significant effect on the estimate of the global role of northern wetland ecosystems as a source of atmospheric CH_4.

The time series analysis of CH_4 fluxes and storage and moisture regime of the three sites in Capricorn fen indicates several factors that would be important to consider in the design of CH_4 sampling programs, and may have important implications in the interpretation of "old" versus "new" carbon isotopic signatures of the emitted CH_4. The large CH_4 flux that was observed on August 12 at two of the Capricorn sites corresponded to a fourfold decrease in stored CH_4. A similar large flux was observed in 50% of the regional sites, but there was no consistent pattern of the large flux occurring more often in one subfen type. The common factor experienced at all sites was the period of low rainfall resulting in the lowering of the peatland water table. The decrease in hydrostatic head would have resulted in a pressure differential which may have triggered the episodic release. Large, single episodic fluxes have been recorded occasionally before [e.g., Moore and Knowles, 1990], but with the chamber approach, reliable recording is fortuitous. Based on the change in CH_4 storage in the peat at the Capricorn sites, 3 to 4 g m^{-2} of CH_4 were lost in this August episode. The seasonal total CH_4 emitted from the margin, central and flooded sites was 9.2, 17.1, and 4.6 g m^{-2}, respectively, calculated for the snow-free period of 186 days in 1989. The episodic CH_4 emission in August could account for approximately 33, 18, and 65% of the estimated seasonal emission. In addition, there may be significant emission of CH_4 as the peat thaws during the spring [Moore and Knowles, 1990]. Without time-integrated flux measurement or measurements of changes in storage to corroborate instantaneous flux measurements, the annual and mean emissions obtained using a chamber approach could be grossly underestimated.

The CH_4 released in the August pulse came from the entire peat profile. During the period of general steady state conditions, CH_4 is likely produced in the upper layers of the peat [Crill et al., 1988; Moore and Knowles, 1990] and would therefore contain predominantly modern carbon. However, the peat below a depth of 0.5 m may be several thousand years old: basal dates for peatlands in northern Quebec are approximately 5000 years BP [Richard, 1987]. The CH_4 released in August may contain a significant fraction of older carbon. To balance the budget, the radiocarbon component of CH_4 in the atmosphere requires a fraction of old carbon to be released, possibly from present-day biogenic processes [Wahlen et al., 1989]. The episodic release of CH_4 from deep within northern fens may be a mechanism to increase the fraction of "old" carbon in the atmosphere. Unfortunately, no isotopic analysis was undertaken during this study, and the isotopic studies of CH_4 from northern wetlands that have been undertaken tend to be of short duration such that episodes could, if they occur, be easily missed.

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R. Knowles, Department of Microbiology, Macdonald College of McGill University, 21111 Lakeshore Road, Sainte Anne de Bellevue, Quebec, Canada H9X 1C0.

T. Moore, Department of Geography, McGill University, 805 Sherbrooke Street West, Montreal, Quebec, Canada H3A 2K6.

N. Roulet, Department of Geography, York University, 4700 Keele Street, North York, Ontario, Canada, M3J 1P3.

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