12-1-1993

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GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 7, NO. 4, PAGES 749-769, DECEMBER 1993

METHANE FLUX FROM DRAINED NORTHERN PEATLANDS: EFFECT OF A PERSISTENT WATER TABLE LOWERING ON FLUX

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Abstract. Measurements of CH_4 flux from drained and undrained sites in three northern Ontario peatlands (a treed fen, a forested bog, and a treed bog) were made from the beginning of May to the end of October 1991. In the drained portions, the water table had been lowered between 0.1 and 0.5 m, compared to the water table of the undrained portion of the peatlands. The mean seasonal CH_4 flux from the undrained portions of three peatlands was small, ranging from 0 to 8 mg m^{-2} d^{-1}, but similar to the CH_4 flux from other treed and forested northern peatlands. The mean seasonal CH_4 flux from the drained portion of the peatlands was either near zero or slightly negative (i.e., uptake): fluxes ranged from 0.1 to -0.4 mg m^{-2} d^{-1}. Profiles of CH_4 in the air-filled pores in the unsaturated zone, and the water-filled pores of the saturated zone of the peat at the undrained sites, showed that all the CH_4 produced at depth was consumed within 0.2 m of the water table and that atmospheric CH_4 was consumed in the upper 0.15 m of the peatland. On the basis of laboratory incubations of peat slurries to determine CH_4 production and consumption potentials, the lowering of the water table eliminated the near-surface zone of CH_4 production that existed in the undrained peatland. However, drainage did not alter significantly the potential for CH_4 oxidation between the water table and peatland surface but increased the thickness of the layer over which CH_4 oxidation could take place. These changes occurred with a drop in the mean summer water table of only 0.1 m (from -0.2 to -0.3 m) suggesting that only a small negative change in soil moisture would be required to significantly reduce CH_4 flux from northern peatlands.

Paper number 93GB01931.
0886-6236/93/93GB-01931$10.00

INTRODUCTION

Wetlands north of 40° N are estimated to contribute ~ 35 Tg CH_4 yr^{-1} to the atmosphere or 8% of the annual atmospheric burden [Fung et al., 1991]. Several studies based on the positive correlation between CH_4 flux from wetlands and substrate temperature have suggested that future emissions would be greater if the northern latitudes were to become warmer [Hameed and Cess, 1983; Khalil and Rasmussen, 1989; Lashof, 1989]. However, CH_4 flux from wetlands is also positively correlated with the position of the water table [e.g., Crill et al., 1988; Moore and Roulet, 1993; Moore et al., 1990; Roulet et al., 1992a; Sebacher et al., 1986]. If warmer northern climates were associated with a drier soil water regime, then emissions could possibly decrease. The results of almost all 2 x CO_2 scenarios from general circulation models (GCM) predict a 3° to 5° increase in June, July, and August (JJA) surface temperatures, but there is less agreement over the predicted changes in precipitation and soil moisture [Intergovernmental Panel of Climate Change (IPCC), 1990]. Roulet et al. [1992b], using conservative 2 x CO_2 climate predictions of an increase in summer temperature and rainfall of 3°C and 1 mm d^{-1} respectively and a simple thermal and hydrological model for a northern fen, estimated a water table drop that was sufficient to reduce CH_4 emissions to 20% of those in a 1 x CO_2 climate scenario. However, the assessment of the impact of changing climate on CH_4 flux from northern wetlands is also complicated by the presence or absence of permafrost [Gorham, 1991]. Permafrost degradation could lead to collapse scars which would increase peatland wetness, or contrastingly, thermokarst erosion could make drainage more effective, reducing peatland wetness. In this paper we present empirical results of the effect of drainage of wetlands on CH_4 flux. This paper examines only peatlands, which comprise over 85% of all wetlands in Canada [National Wetlands Working Group (NWWG), 1988], and most of the wetlands north of 45° N in the northern hemisphere [Matthews and Fung, 1987]. Gorham [1991] estimated that 1.2×10^5 km^2 (or 3.5%) of boreal and subarctic peatlands have been drained, and Armentano and Menges [1986] calculated the area of drained temperate peatlands as 2.0×10^5 km^2 (or 5.7%).

Below the water table, decomposition in peatlands occurs under anaerobic conditions. If the peat is saturated, most of the CH_4 produced is emitted to the atmosphere, and high CH_4 fluxes can be sustained [e.g., Crill et al., 1988; Moore et al., 1990]. However, if the water table is well below the surface (i.e., > -0.25 m), aerobic conditions can exist, slowing the production of CH_4 and significantly enhancing the oxidation of CH_4 produced in the anaerobic zone deeper in the peat. Other variables are important in the control of CH_4 flux, but the maintenance of an anaerobic environment and the absence of a significant oxidation zone are of primary importance.

The correlation between CH_4 flux and the position of the water table has been established by using measurements over time in individual wetlands [e.g. Crill et al., 1988; Moore et al., 1990] or by comparing fluxes and water tables among many peatlands [Moore and Roulet, 1993; Roulet et al., 1992a; Sebacher et al., 1986]. These relationships therefore encompass the range of natural water table fluctuations under normal climate conditions. However, they cannot necessarily be expected to represent the flux - water table relations under climate conditions that might exist if peatlands became much drier. The water table of small plots can be regulated to simulate such a condition, but unless the normal fluctuation and duration of water table at a given location can be approximated, which is unlikely, the experimental situation is highly unrealistic from a biogeochemical perspective.

The use of peatlands that have been drained by ditching to increase forest productivity presents an ideal experimental situation. The water table is not greatly lowered, usually between 0.3 and 0.4 m [Päivänen, 1991] and therefore is a fair representation of what might be expected in a warmer-drier climate [Roulet et al., 1992b]. Equally important is that the day-to-day and seasonal fluctuations in water table are retained through the free vertical and lateral exchange of water. Finally, as the degree of water table drawdown decreases with distance from a drainage ditch [Boelter, 1972], CH_4 flux can be measured over a range of drier conditions.

In the study reported here, we used a forest drainage site in northern Ontario to examine the effect of lowering the average water table on daily and seasonal CH_4 fluxes from northern peatlands. The objectives of the present study were to (1) examine the effect of a persistent water table lowering on the spring, summer, and fall CH_4 flux; (2) establish that the water table, although lowered for forestry drainage, continues to respond to the natural day-to-day and seasonal changes in precipitation and evapotranspiration; (3) examine the concentrations of CH_4 stored in the peat profile under different water tables; and (4) determine the effect of water table lowering on the relative rates of CH_4 production and consumption in the peat profile.

METHODS

Field Sites and Experimental Design

The research was conducted from May to October 1991, in the Wally Creek experimental forest drainage site [Jeglum, 1991], located in the midhumid boreal wetland region of Canada [NWWG, 1988] 27 km east of Cochrane, Ontario, Canada (49° 3'N, 80° 40'W). Over 77% of the peatlands in the Cochrane area are treed [Riley, 1987]. The two most common peatlands are conifer swamps, (53%) and treed bogs (23%). Open bogs and fens, treed fens, thicket swamps and marshes account for the remaining 24% of peatland types in the region. The Wally Creek site consists of 306 ha of lowland black spruce (Picea mariana) forest, drained by 87 km of open ditches which are between 0.7 and 1.2 m deep [Jeglum, 1991]. Drainage at the site began in 1984.

On the basis of 30 years of climate record, Cochrane receives 885 mm of precipitation annually, 33% of which falls as snow [Environment Canada, 1988] (Table 1). Approximately 80 mm month^{-1} of rain falls each month from May through October. The mean annual temperature is 0.6°C, and the mean daily temperatures for January and June are -18.3° and 16.5°C, respectively. The May to October 1991 climate for Cochrane was normal with the following exceptions (Table 1): May and June were warmer than normal and the August rainfall was ~ 50% of normal.

Three peatland types were selected to study the influence of water table on CH_4 flux (Table 2): a treed fen, a treed bog, and, a forested bog. The water in the peat at the treed fen had the largest Ca and Mg concentrations, and a circumneutral pH (Table 2). The other locations were more acid and had smaller Ca and Mg concentrations and lower electrical conductance (K_{CORR}). The tree density on all three locations was relatively low: ~ 4000, 8000, and 2000 stems ha^{-1} for the treed fen, forested bog, and treed bog, respectively.

The experiments were designed to take advantage of the parabolic distribution of location of the water table which develops between two drainage ditches [Boelter, 1972]. The maximum water table drawdown occurs adjacent to a ditch and the degree of water table lowering decreases exponentially to some mimimum level at the midpoint between the ditches. Three transects, one at each of the peatland types, were established perpendicular to the lateral ditches along the perimeter of the drainage complex. A reference site was located at 30 m beyond the perimeter ditch. This is > 10 m beyond the lateral extent of lowering of the water table observed by Berry and Jeglum [1988] in the same peatland and is

TABLE 1. The 1991 May to October Monthly Temperature and Precipitation (Snow) Summaries for Cochrane, Ontario

Variable	May	June	July	Aug.	Sept.	Oct.
			Daily Temperature			
Mean (°C)	10.9$^+$	16.2$^+$	17.3	16.7	9.2	3.4
Maximum (°C)	31.0	29.0	33.0	33.0	25.0	22.0
Minimum (°C)	-6.0	-1.0	1.0	7.0	-3.0	-5.0
			Precipitation			
Total (mm)	62.4	82.9	66.2	47.6*	107.7 (1.2)	84.8 (12.0)
24 hour Maximum (mm)	22.6	26.0	13.4	8.2	27.2	16.3

Data are from Environment Canada [1988]. The crosses and asterisks indicate monthly value is 1 standard deviation above or below the 30 year mean. The precipitation values enclosed in parenthesis indicates snowfall.

TABLE 2. Plant Composition and General Characteristics of the Wally Creek Reference Sites

Location	Dominant Plant Species	pH	K_{corr}, µS cm^{-1}	Ca, mg L^{-1}	Mg, mg L^{-1}
Treed Fen	Hummocks Sphagnum fuscum Juniperus communuis J. horizontalis Hollows Warnstorfia exannulates S. wanstorfii Lawn S. russowii Potentilla fruticosa Scirpus hudsonianus Larix occidentalis	6.3 ± 0.3	45.1 ± 4.3	7.17 ± 1.12	1.50 ± 0.22
Forested bog	Hummocks S. fuscum Chamaedaphne calyculata Hollows S. angustifolium Carex oligosperma C. exilis Lawn S. angustifolium Pleurozium shreberi Ledum groenlandicum P. mariana	4.6 ± 0.2	30.2 ± 1.1	3.11 ± 1.10	0.57 ± 0.15
Treed bog	Hummock S. fuscum C. calyculata Hollow S. angustifolium C. oligosperma Lawn Pleurozium shreberi S. fuscum Picea mariana	4.5 ± 0.3	28.4 ± 1.3	1.50 ± 0.74	0.49 ± 0.31

Data are from J. Bubier et al. (Methane emissions from wetlands in the boreal region of northern Ontario, Ecology, submitted to Ecology, in press, 1993)

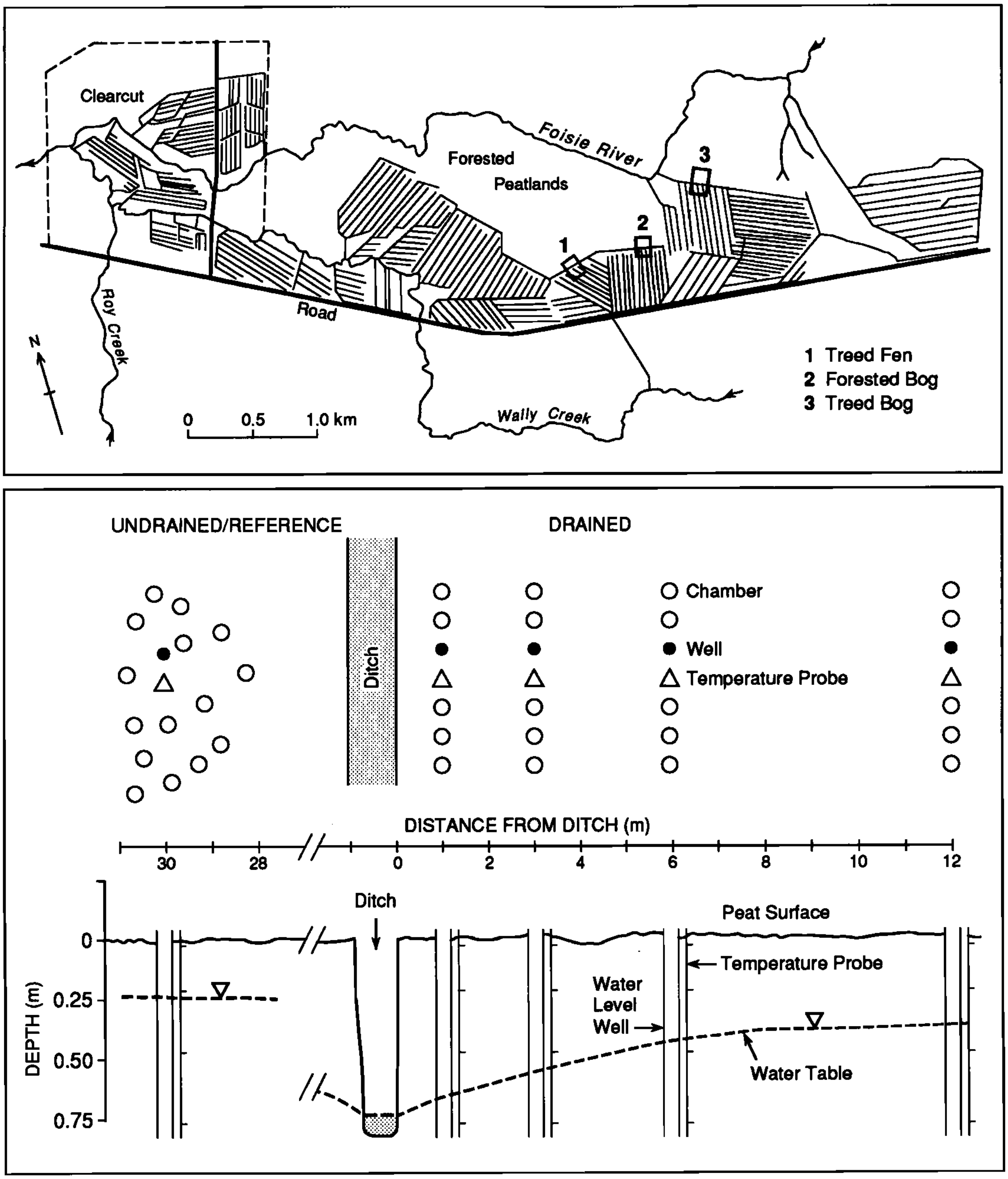

Fig. 1. The experimental design at the forested bog. The setup was exactly the same at the other two locations with the exception of that CH_4 storage measurements and peat cores were only taken from the forest bog.

therefore considered undrained. On the inside of the perimeter ditch CH_4 flux was measured at 1, 3, 6, and 12 m from the ditch (Figure 1). These distances were selected because they represented a range in water table lowering of over 0.4 m at 1 m from the ditch to less than 0.1 m, 12 m from the ditch [Berry and Jeglum, 1988]. Comparison between the water table depths presented in the present study and those observed by Berry and Jeglum [1988] suggest the water levels have reached an equilibrium with the rate of drainage. Three subsites were established at the reference sites to incorporate the local variability in microtopography and vegetation: hummocks, hollows, and lawns. No distinction was necessary for the drained sites since the fluxes did not vary in relation to topography or vegetation. At each site along the transect at each peatland location, CH_4 flux was measured every 10 days, and the elevation of the water table and peat temperatures down to 1.5 m were measured continuously. The flux, water table, and temperature measurements were made from May 12 to August 16 at the treed bog and forested bog locations and from May 12 to October 23 at the treed fen location. The shorter period represents the bulk of the growing period, while the latter represents the snow-free period.

The concentration of CH_4 stored above and below the water table was measured at four sites on two occasions in the forested bog location. Peat samples were extracted from the 6 m and reference sites in the forested bog location, and these were used for incubations in CH_4 production and consumption studies.

Determination of the Flux, Subsurface Storage, Production, and Consumption of CH_4

At each of the five sites along each transect, CH_4 flux was measured using at least five static chambers per site. At the reference sites a minimum of 10 chambers were used. The sampling procedures used are outlined in detail by Moore and Roulet [1991]. The static chambers were made of 18-L polycarbonate bottles (26 cm diameter; 40 cm height; area of exposure 0.053 m^2), from which the base was removed. The bottle neck was sealed with a rubber stopper that contained a glass tube with a rubber septum stopper. Chambers were covered with aluminum foil to minimize heating. The chambers were carefully inserted 2 cm into the peat for each run. The same locations were used for several runs, but the chambers were removed from the site between runs. The volume of air in the chamber was corrected for the displacement caused by the insertion of the chambers. Initial and final concentrations were taken and the flux was calculated as the difference between the two over time. If initial concentrations were elevated above ambient concentrations (> 2 ppmv) the run was rejected. Less than 2% of the fluxes were rejected.

Chambers were set up for a 2-hour run in both the morning and afternoon on each sampling day. Air samples were obtained from the chambers by inserting a needle attached to a 10-mL plastic syringe into the septum stopper. The piston of the syringe was pumped 5 times to mix the air in the chamber before a 10-mL sample was drawn. Samples were analyzed either the same day or the following morning (i.e., < 16 hours after sampling). No significant loss of CH_4 from the syringes was observed to occur over this period.

The concentration of methane was measured in the peat profile at the reference, 1, 6, and 12 m at the forested bog once in August and again in September. Samples were obtained from the unsaturated zone using the approach described by Fechner and Hemond [1992]. A 1.0-m-long, 3-mm I.D., stainless steel needle, with 20 small holes drilled in the crimped bottom, was inserted in the peat at 0.05 m intervals from 0.05 to a maximum of 0.55-m. The deepest sample was dependent on the elevation of the water table. A 30 mL sample of air was drawn through the needle and discarded and then a 10-mL sample was taken. During the flushing and sampling, the needle was kept closed to the atmosphere by a three-way valve attached to the top of the needle inserted in the ground. Fechner and Hemond [1992] estimate the sphere of influence of this sampling device is ~ 0.03 m radius. Samples from below the water table were taken using the water extraction device described by Moore et al. [1990]. A 3-mm stainless steel tube was inserted in the peat to depths of 1.0 m. The top of the tube had two two-way valves in series. With both valves open, water was drawn up the tube using a small pump. Once water had passed both valves, the lower valve was closed and a 30-mL sample was drawn into a 60-mL syringe from the water stored in the tubing. The second valve was then closed to keep the sample isolated from the atmosphere. This valve system eliminated any significant bubbling of the sample. After the 30-mL sample was obtained, 30-mL of ambient air was drawn into the syringe, and the sample was shaken vigorously for 2 min. to degas the water. The CH_4 concentration in the head space of the syringe was then measured.

The concentration of CH_4 from all samples was determined by gas chromatography using a

1-mL injection into a Shimadzu Mini-2 Gas Chromatograph using He as the carrier gas, a Poropaq Q column (80/100 mesh) and a flame ionization detector. Calibration gases of nominally 2, 100, and 2000 ppmv were used depending on the samples being analyzed. For the unsaturated zone gas samples, the calibrations were checked for reproducibility after every five samples by injecting five standards in a row. The accuracy was ± 50 ppbv. Fluxes between 0.1 and -0.1 mg m^{-2} d^{-1} were not detectable.

To assess CH_4 consumption and production potentials, cores from the reference and 6-m sites at the forested bog location were collected in mid-August. The cores were divided into 0.1-m increments, stored at 4°C in sealed plastic bottles at field moisture contents (i.e., saturated beneath the water table) and incubated as follows. To determine the anaerobic production rate of CH_4, 5 g of wet peat was placed in triplicate 50-mL Erlenmeyer flasks. The flasks were evacuated 3 times and back-filled with N_2. Several 5-mL air samples were extracted from the flasks at various intervals for up to 5 days with N_2 back - filling. The rate of CH_4 production was interpreted as the slope of the volume-corrected CH_4 concentrations over time. CH_4 consumption under aerobic conditions was measured by placing 5 g of wet peat in distilled water (5 ml of water per 5 ml of peat) in triplicate 50-mL Erlenmeyer flasks, injecting pure CH_4 to produce an initial concentration of ~ 1000 ppmv in the flask, and incubating with continuous shaking to inhibit the development of anaerobic pockets within the slurry. As in the production studies, 5-mL of air from the flask was removed every 24 hours for 5 days. The rate of consumption was calculated as the change in concentration over time. At the end of the experiment the mass of oven-dried peat in each flask was determined, and the rates of consumption and production are expressed in mass of CH_4 to the mass of dry peat.

Determination of the Water Table and Peat Temperature

Continuous measurements of the water table and peat temperatures were made at all five sites at the three locations from May 12 to August 16. Measurements continued until October 22 at the forested bog. The elevation of the water table was determined using a potentiometric water level recorder [Roulet et al., 1991] which was read every minute and averaged every half hour. The peat temperature was measured every 5 min. at 0.02, 0.2, 0.4, 0.8, and 1.5 m, using differential thermocouples connected to a multiplexer and data logger. The temperatures were averaged every 2 hours.

RESULTS

Patterns in CH_4 Flux

The mean CH_4 flux, water table, and peat temperatures for the reference and drained sites at all three locations are presented in Table 3. The temporal patterns of CH_4 flux, water table, and peat temperatures for all the sites at the three locations are shown in Figures 2, 3, and 4, respectively. Approximately 350 of the more than 2800 flux measurements made in this study fell between the detection limits of 0.1 and -0.1 mg m^{-2} d^{-1}. In total, 15, 16, and 21% of measurements from the drained sites, and 1, 4, and 7% of measurements from the reference sites at the treed fen, forested bog, and treed bog, respectively were undetectable. The undetectable fluxes were set to 0 mg m^{-2} d^{-1}.

Comparison of the Mean Summer CH_4 Flux Among Sites

Comparison of the mean summer CH_4 flux among the reference sites, and between the reference site and the drained sites at each location, indicates that the wetter sites had a positive flux, while the drier sites had a 0 or a slightly negative flux (Table 3). The treed fen and forested bog reference sites had the highest mean water tables (-24 and -20 cm) and the largest mean fluxes (6.2 and 3.6 mg m^{-2} d^{-1}; this is the areally weighted mean of the hummock, hollow, and lawn measurements). The treed bog reference site had a very small, but still positive, flux (0.3 mg m^{-2} d^{-1}) and a correspondingly low mean water table (-49 cm).

The mean fluxes from the 1- to 12-m sites inclusive (0.1 to -0.3 mg m^{-2} d^{-1}) at the treed fen and forested bog locations were significantly smaller ($p=0.01$) than that of their

TABLE 3. Seasonal Methane Flux, Water Table, and -20 cm Depth Peat Temperature for the Wally Creek Transects

Location/ Site	Mean CH_4 Flux, $mg\ m^{-2}\ d^{-1}$			N	WT, cm			T_{-20cm}, °C		
	Mean	Max	Min		Mean	Max	Min	Mean	Max	Min
Treed fen										
Reference										
Hummock	1.8 ± 3.9	37.8	-1.6	143						
Hollow	11.4 ± 1.2	65.5	2.8	103	-24.4	-18.6	-28.9	13.9	16.8	9.6
Lawn	7.3 ± 9.9	56.1	-0.2	81						
1 m	-0.3 ± 1.0	5.4	-3.4	173	-83.7 Δ -59.3	-55.0	-109.3	12.0 Δ -1.9	16.4	1.3
3 m	-0.1 ± 1.0	6.8	-3.5	168	-49.1 Δ -24.7	-26.5	-63.5	12.8 Δ -1.1	16.9	4.1
6 m	0.1 ± 0.8	3.6	-2.0	170	-63.8 Δ -39.4	-41.2	-80.3	12.2 Δ -1.7	15.6	4.6
12 m	0.1 ± 0.8	4.2	-4.8	167	-34.4 Δ -10.0	-13.8	-57.5	9.6 Δ -4.3	14.1	0.2
Forested bog										
Reference										
Hummock	1.2 ± 3.8	37.7	-4.0	118						
Hollow	4.6 ± 6.2	32.9	-5.6	105	-20.8	-12.8	-38.0	13.0	15.3	10.0
Lawn	5.2 ± 8.1	40.6	-2.8	120						

Table 3. (continued)

Location/ Site	Mean CH_4 Flux, $mg\ m^{-2}\ d^{-1}$				WT, cm			T_{-20cm}, °C		
	Mean	Max	Min	N	Mean	Max	Min	Mean	Max	Min
1 m	0.1 ± 0.9	4.5	-2.2	175	-48.2 Δ -27.4	-28.9	-62.6	12.5 Δ -0.5	17.3	0.5
3 m	-0.2 ± 0.5	1.8	-1.9	184	-46.0 Δ -25.2	-21.9	-69.0	10.3 Δ -2.7	16.4	0.3
6 m	-0.2 ± 0.7	4.7	-1.9	179	-40.0 Δ -19.2	-18.4	-69.0	11.2 Δ -1.8	15.6	1.2
12 m	-0.1 ± 0.7	3.7	-1.8	177	-31.5 Δ -10.7	-11.0	-69.5	10.5 Δ -2.5	13.5	3.4
Treed bog										
Reference										
Hummock	0.1 ± 0.8	2.4	-1.5	82						
Hollows	0.5 ± 1.4	6.0	-2.2	77	-48.7	-69.5	-56.5	13.1	15.2	8.9
Lawn	0.3 ± 0.8	2.8	-1.3	66						
1 m	-0.3 ± 1.0	4.0	-2.6	123	-77.6 Δ -28.9	-118.6	-85.7	11.3 Δ -1.8	15.3	1.4
3 m	-0.3 ± 1.0	2.8	-5.3	130	-119.3 Δ -70.6	-74.9	-120.6	16.2 Δ -3.1	21.1	3.4
6 m	-0.3 ± 0.9	3.2	-2.6	129	-85.1 Δ -36.4	-74.9	-95.4	11.6 Δ -1.5	15.0	2.9
12 m	-0.4 ± 0.9	2.0	-2.4	130	-90.0 Δ -41.7	-76.7	-102.4	12.1 Δ -1.0	16.2	2.2

Δ indicates the change relative to the reference site.

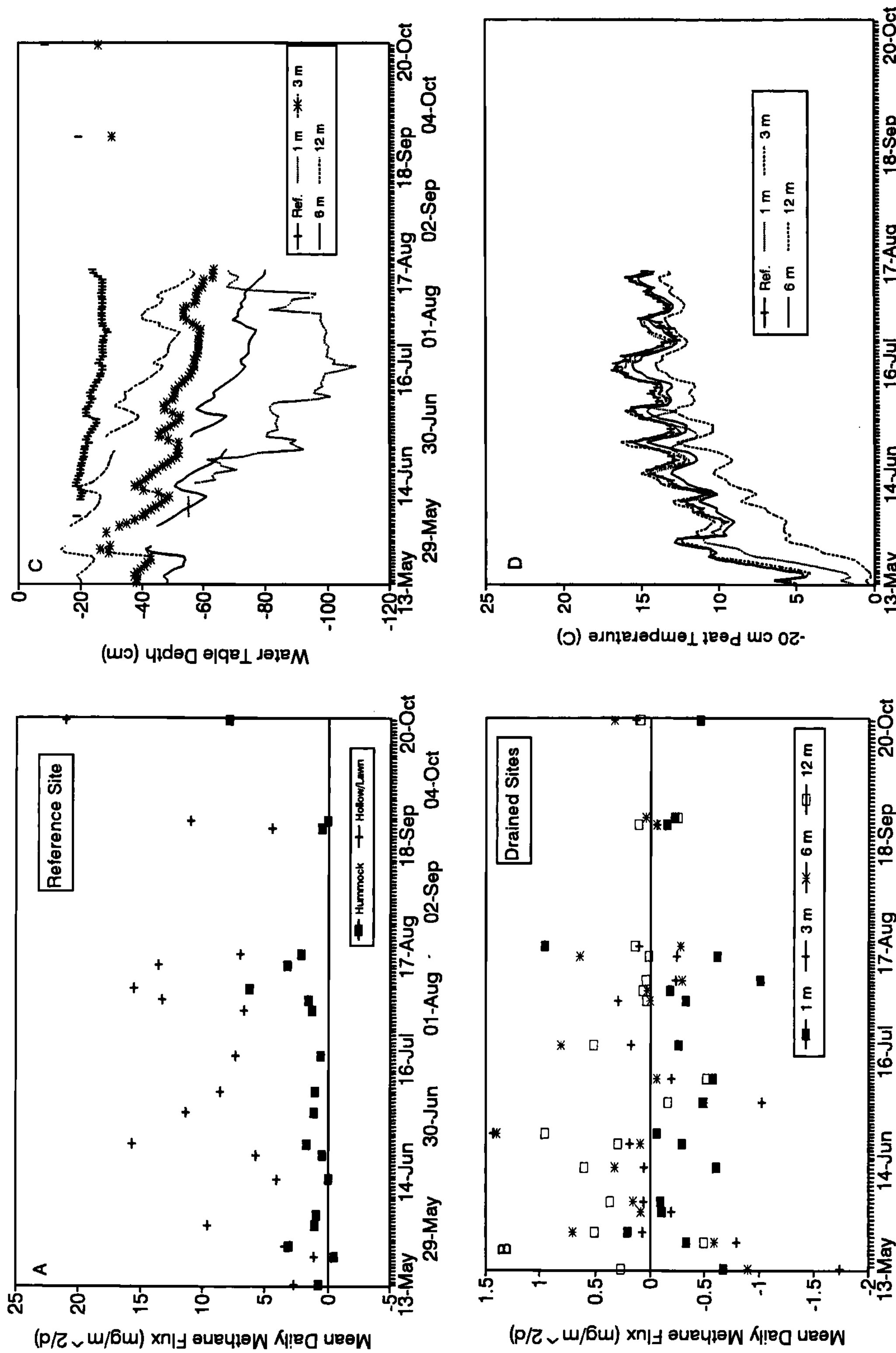

Fig. 2. CH_4 flux from (a) the reference site, (b) the drained sites, (c) water table, and (d) -0.2-m peat temperatures at the treed fen.

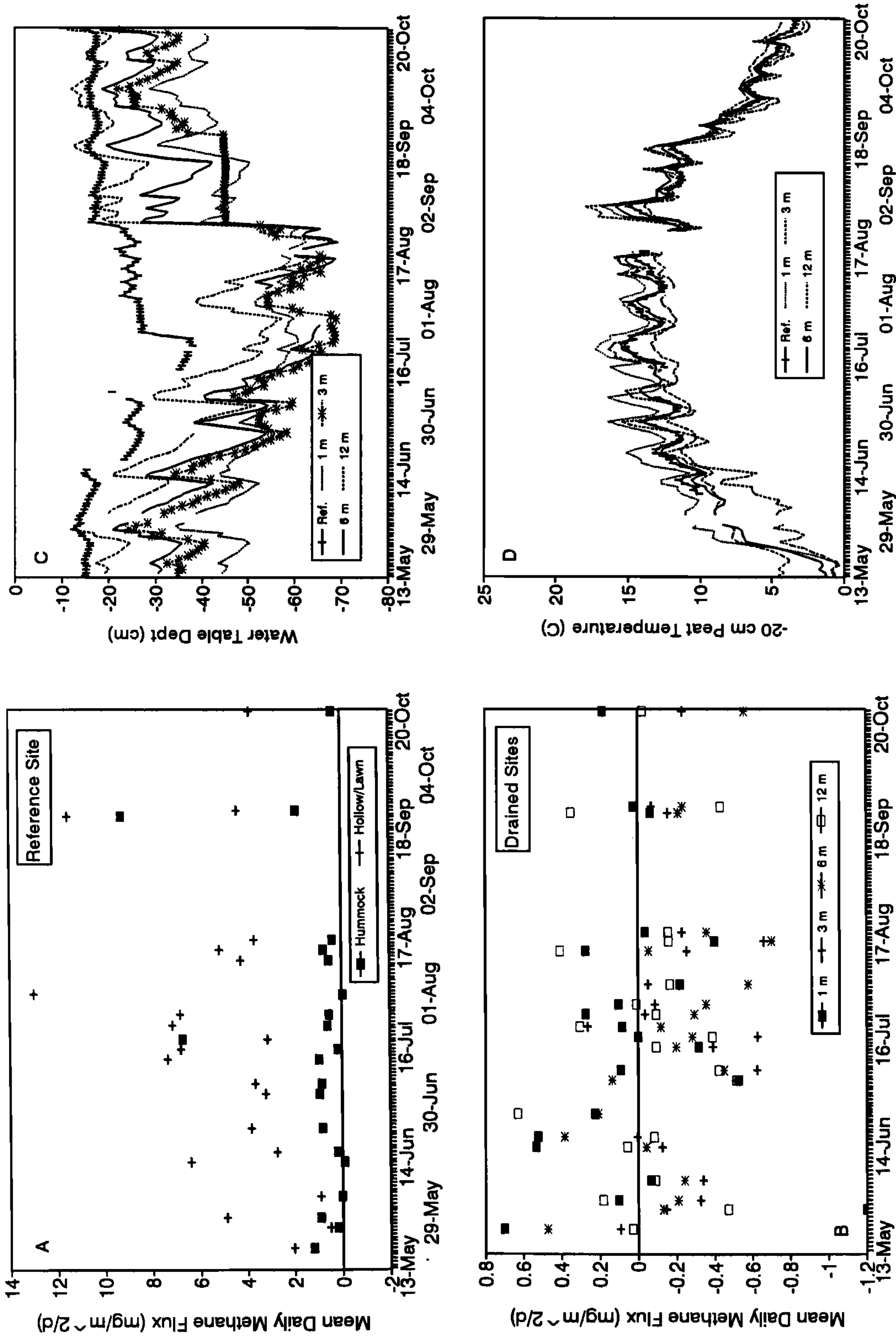

Fig. 3. CH_4 flux from (a) the reference site, (b) the drained sites, (c) water table, and (d) -0.2-m peat temperatures at the forested bog.

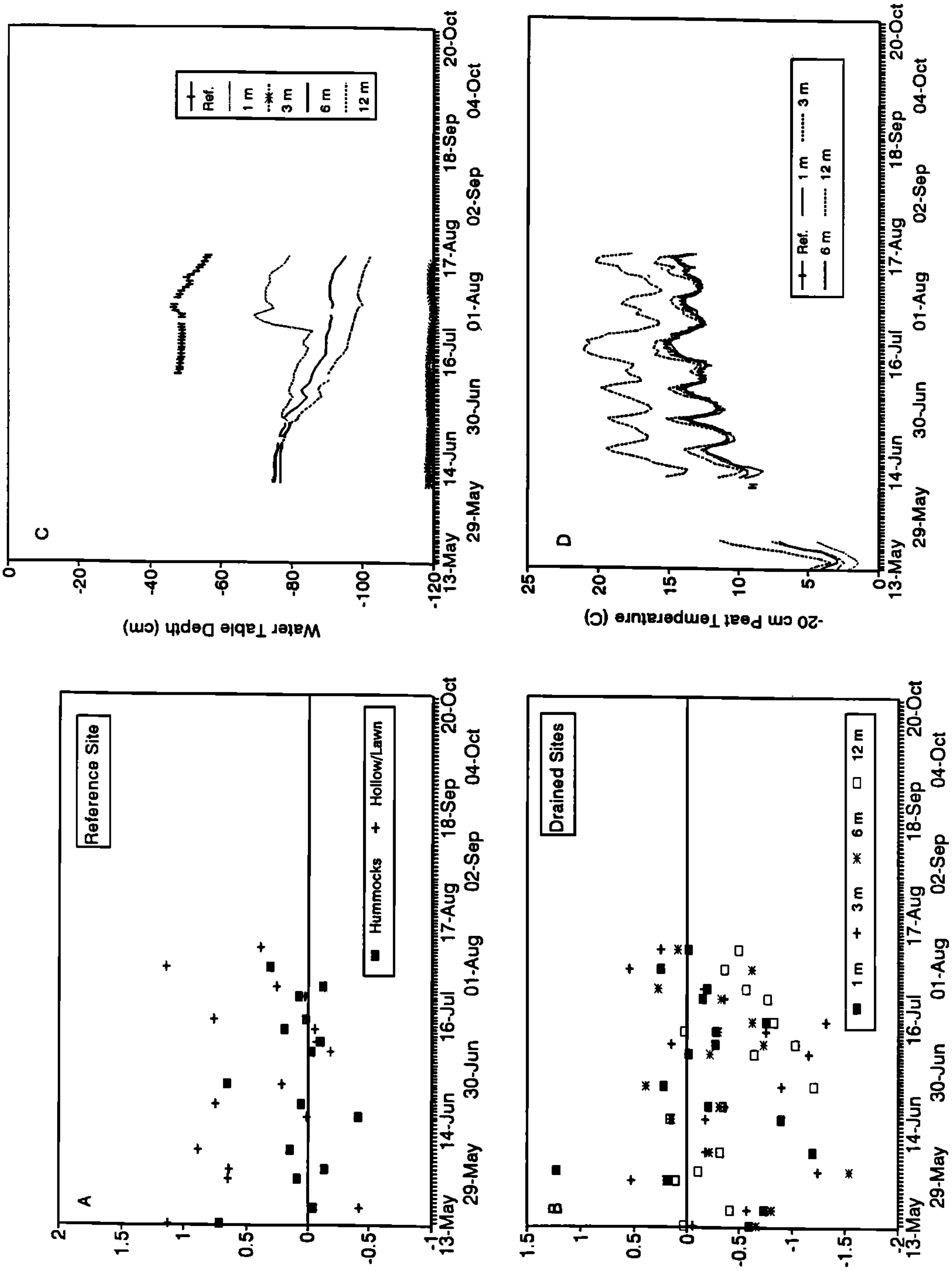

Fig. 4. CH_4 flux from (a) the reference site, (b) the drained sites, (c) water table, and (d) -0.2-m peat temperatures at the treed bog.

respective reference site (Table 3). Sites where the mean water table was > -30 cm had zero to slightly negative fluxes. The difference in flux between the reference sites and the 12 m drained site at the treed fen and forested bog locations demonstrates that a change of only -10 cm is sufficient to eliminate CH_4 flux to the atmosphere from these peatlands. However, lowering the mean water table an additional -60 cm produced little increase in CH_4 uptake.

There was a relatively small, but consistent decrease in mean peat temperature (represented by the temperature at -20 cm in Table 3) with a lowering of the water table. The difference in temperature among the reference sites was 0.9°C, while the difference between the reference site and the drained sites at a location was between -1.4° and -2.3°C. In all the drained sites, with the exception of the treed bog 6-m site, the peat temperature was lower than that of the corresponding reference site. No explanation can be provided for the treed bog 6-m site having a consistently warmer temperature.

Temporal Trends in Mean Daily CH_4 Flux Among Sites

Comparison of the day-to-day variability between the mean daily CH_4 flux from the reference site (Figures 2a, 3a, and 4a) and the drained sites (Figures 2b, 3b, and 4b) indicates the role the position of the water table played in determining the direction of the flux. The range in fluxes from the reference site at the treed fen was from -0.1 to 8, and 1 to 22 mg m^{-2} d^{-1}, for the hummocks, and hollow/lawn, respectively. Only 5% of the mean daily fluxes were negative at the reference site. In contrast, the mean daily fluxes from the drained sites were smaller (1.5 to -1.5 mg m^{-2} d^{-1}) and often negative. The daily flux was negative 89% of the time at the 1 m site where the water table was < -80 cm, and occasionally reached -110 cm, while only 22% of the daily fluxes were negative at the 12-m site where the range was between -15 and -55 cm.

Similar patterns were observed at the forested bog and treed bog location. The daily fluxes from the reference site at the forested bog were from -0.1 to 9, and 0.5 to 13 mg m^{-2} d^{-1} from the hummock, and hollow/lawns, respectively, and the water table was between -15 and -35 cm. At the drained sites, daily fluxes were between 0.8 and -1.2 mg m^{-2} d^{-1}, but there was not as big a difference in the number of negative daily fluxes between the 1-m site (38%) and the 12-m site (57%) at this location as there was at the treed bog location. This is the result of the difference in water table being not large at this site: -35 to -65 at 1 m, and -10 to -60 cm at 12 m. The 1-m site at the forested bog location did not experience the extreme low that was observed at the treed bog. The period of flux measurement for the treed bog location was shorter than that of the other two locations. The pattern of daily fluxes at the treed fen reference site is not overly different from that observed at the 12-m sites at the treed fen and forested bog locations: 0.8 to -0.4 mg m^{-2} d^{-1} and 40% negative fluxes for the hummocks, and 1.2 to -0.4 mg m^{-2} d^{-1} and 20% negative fluxes for the hollows/lawns. All the drained sites at this location experienced the largest proportion of negative fluxes (> 80%) and the lowest water tables (-65 to -85 cm with daily fluxes between 1.3 and -1.2 mg m^{-2} d^{-1} at the 1-m site, and -75 to -100 cm and between 0.2 and -1.2 mg m^{-2} d^{-1} at the 12-m site).

There was no temporal pattern in the daily CH_4 flux at any of the sites, both reference and drained, at the three locations, that could be related to water table, peat temperature, or both. At one reference site, the treed bog (Figure 2a), the highest CH_4 flux did correspond to periods when the water table had risen, but the changes in water table were very small, - i.e., < 5 cm (Figure 2c). There was no statistically significant relationship between the mean daily CH_4 flux and water table, or peat temperature, for any of the sites. The mean summer CH_4 flux was weakly correlated with both the mean water table and -20-cm peat temperature, but the significance of these relationships is mainly a function of the small sample size (N=6) and not a strong association between the variables.

The day-to-day variability in the depth of the water table at the drained sites was similar to that of the reference sites (Figure 2c, 3c, and 4c). The water table at the drained sites was more responsive (i.e., greater increase and decrease for a given input of loss of water

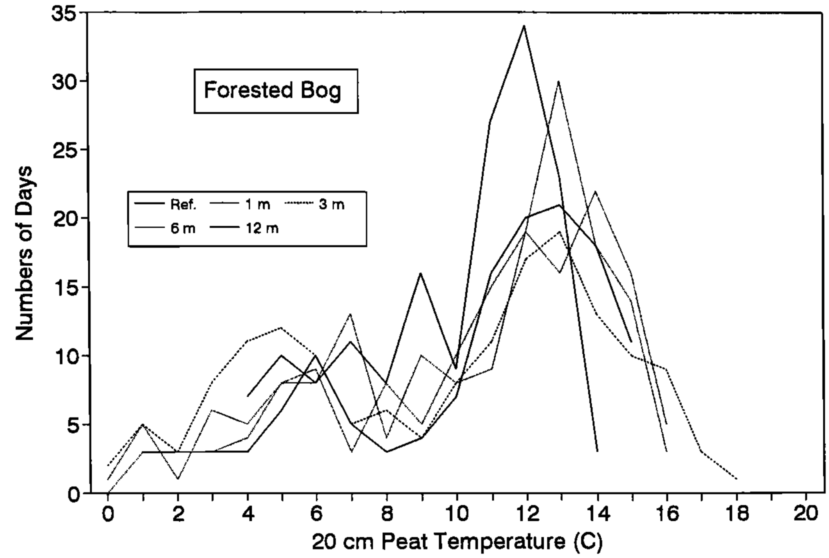

Fig. 5. Water table occupancy curves for the reference and drained sites of the forested bog for the period May 12 to October 22, 1991.

compared to that of the reference sites). This was expected because the specific yield (gravity drainage) and hydraulic conductivity in peats decrease with depth [Boelter, 1966]. There was a downward shift of the most frequently occurring depth of the water table (Figure 5). The frequency distribution for the forested bog reference site was bimodal: the two nodes occurred at ~ -0.18 and -0.25 to -0.27 m. The most frequent occurrences of the water table at the forested bog drained sites were -0.20, -0.28,-0.45,and -0.42 m at the 12-, 6-, 3-, and 1-m sites, respectively.

The temporal patterns of the peat temperatures were very similar among the reference sites, and between the reference sites and the drained sites at each location, with the exception of the 6-m site at the treed bog. At all sites, -20 cm temperatures between 11° and 15°C occurred most frequently (Figure 6).

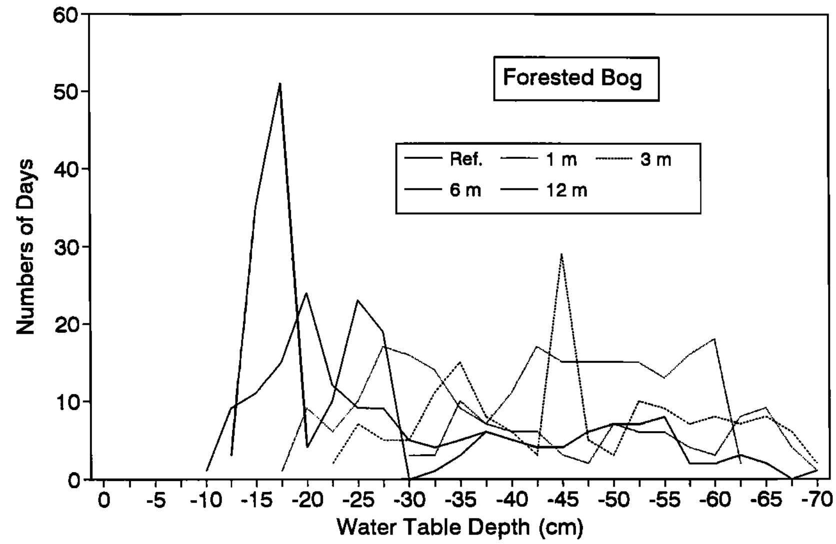

Fig. 6. Frequency temperature curves for the -0.2-m depth for the reference and drained site of the forested bog for May 12 to October 22, 1991.

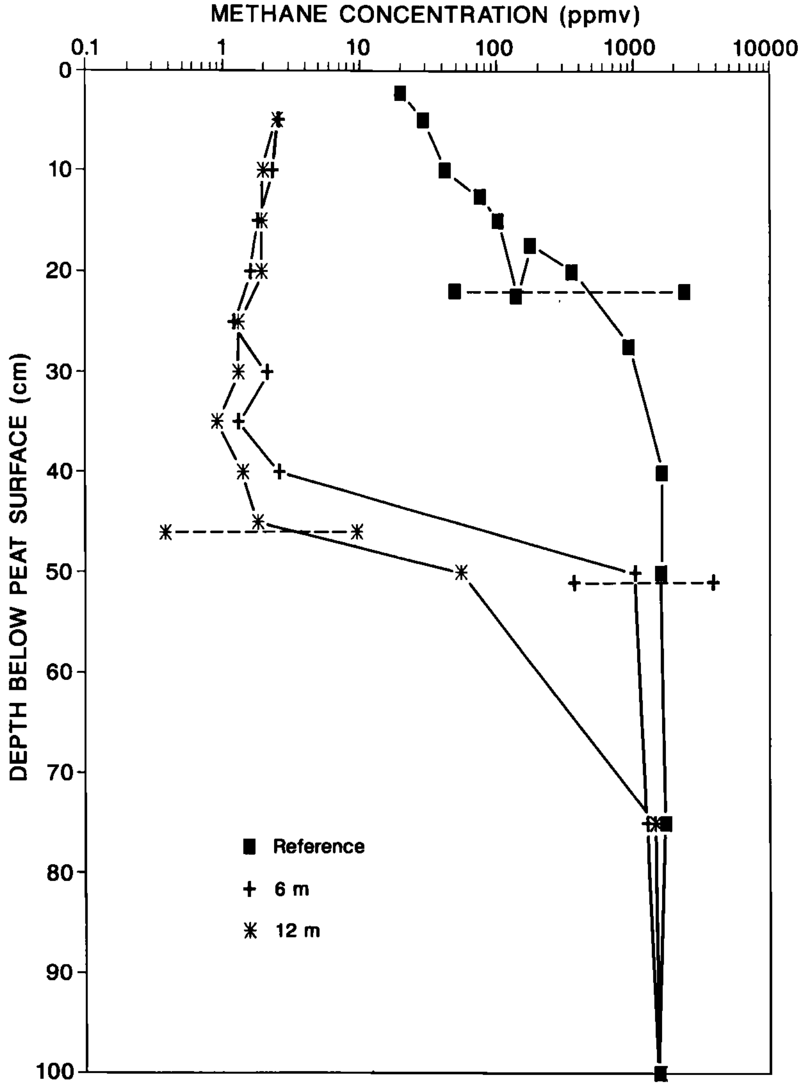

Fig. 7. CH_4 profile for the forested bog reference site, and the 6-m and 12-m drained sites on August 8, 1991. The dashed horizontal lines indicate the depth of the water table at the time of the measurements.

Unlike the distribution of the depth occurrence of the water table, the frequency distributions for temperature were not altered greatly by drainage.

Storage of CH_4 in the Peat at Undrained and Drained Sites

The concentrations of CH_4 in air filled pore spaces of the unsaturated zone and in the pore water of the saturated zone show strongly contrasting patterns for the reference, 6- and 12-m sites of the forested bog in August (Figures 7). CH_4 concentration at the reference site increased from near atmospheric concentrations at the surface (~ 2 ppmv) to 200 ppmv at the water table, and then increased to ~ 1600 ppmv below the water table, where the concentration remained reasonably constant. At the 6-m site, the concentrations decrease from near ambient at the surface to 1.2 ppmv, 0.25 and 0.35 m below the surface and then rise to > 2 ppmv immediately above the water table. At the 12-m site, the concentrations decreased to < 1.0 ppmv by 0.35 m below the surface and increased toward the water table.

The September profiles were measured only in the unsaturated zone of the reference and 12-m sites of the forested bog location. In contrast to the August profiles, there was little difference between the reference and drained sites: there was no vertical gradient from the surface to water table. Concentrations were ≈ 2 ppmv.

CH_4 Production and Consumption Potentials of the Peat Profile

On the basis of laboratory incubations of peat slurries maximum CH_4 maximum production potential occurred 0.35 m beneath the peat surface at the forested bog reference site core (Figure 8), which corresponds to the upper depth of permanent saturation (Table 3, Figure 5). The maximum CH_4 consumption potential for the same reference site occurred at 0.15 m beneath the surface, which corresponds to the lower depth of permanent unsaturation (Table 3, Figure 5). The zone of CH_4 consumption potential is less distinct than that of production potential.

At the 6-m drained site the persistent lowering of the water table effectively eliminated the production potential of CH_4 in the upper 0.45 m of the core. However, the consumption potential revealed a similar pattern to that from the reference core.

DISCUSSION

These results indicate that a small, (≈ 0.1 m) but persistent, lowering of the water table can

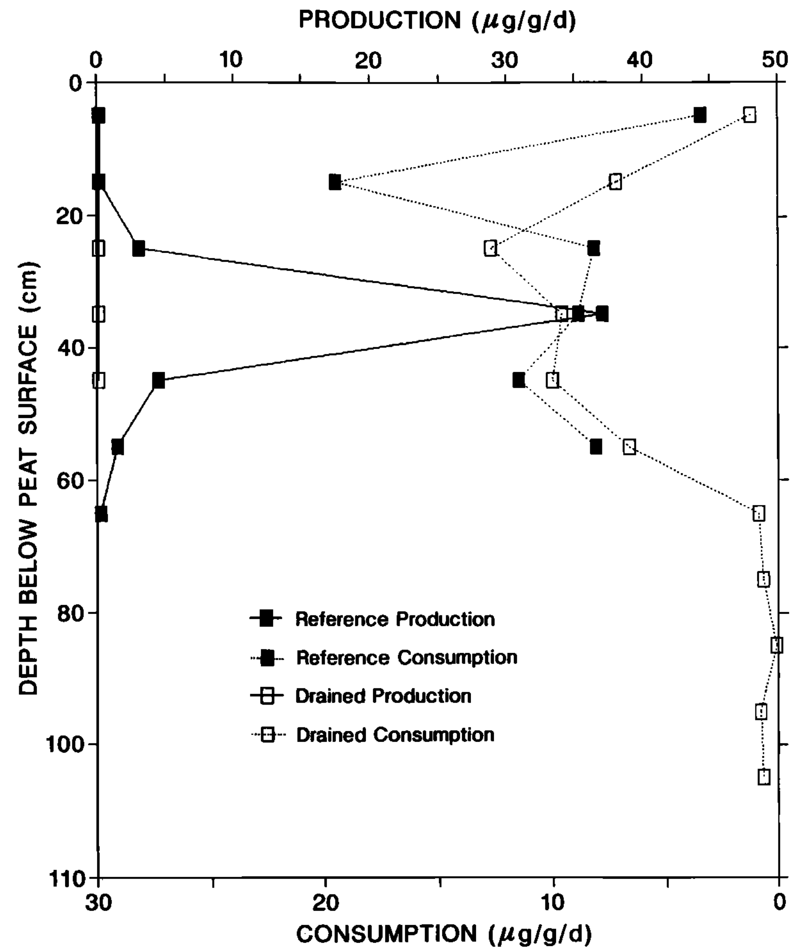

Fig. 8. The potential for CH_4 production and consumption in the peat profile derived from incubation of peat from the reference and 6-m site at the forested bog.

convert a peatland from a source to a sink of atmospheric CH_4. Since there was little change (< 2.3°C decrease at -20 cm) in thermal regime, it can be concluded that the differences in CH_4 flux between the reference and drained sites are the result of changes in the moisture regime, or the indirect result of secondary changes induced by an initial change in the moisture regime. The critical water table at which these peatlands convert from a source to a sink is between -0.25 and -0.30 m. Other studies have shown that when the water table drops to these levels CH_4 flux to the atmosphere either stops or reverses [e.g. Harriss et al., 1982; Moore and Knowles, 1989]. As the water table drops, the thickness of the zone of methanotrophic activity increases and a greater proportion of CH_4 produced at depth in the peat is oxidized before it reaches the peat surface [Sundh et al., 1992; Whalen et al., 1993]. The incubation data show a distinct consumption maximum at -15 cm at the reference site, whereas a less distinct maximum at the drained site, but similar potential with depth.

Typical average summer time water tables for open bogs and fens range between 0 and -0.25 m and 0 and -0.15 m, respectively [e.g. Ingram, 1983]. There are few observations from forested peatlands, but the summer averages appear to be ~ 0.05 to 0.1 m lower [Verry, 1988]. This means a water table lowering of between only 0.1 m may be sufficient to induce this conversion. Using a liberal specific yield for peat of 0.3, this water table drawdown could be attained with a persistent net negative storage change of only 30 to 45 mm. This change in storage is similar to the change in soil moisture predicted for some northern regions by GCMs [IPCC, 1990] and less than the water loss predicted by Roulet et al. [1992b] for northern fens.

CH_4 flux from the reference sites, i.e. the undisturbed peatland condition with natural water tables, was lower than the fluxes reported for most boreal northern peatlands: < 10 mg m^{-2} d^{-1} in this study compared to generally > 40 mg m^{-2} d^{-1} from other studies [e.g. Crill et al., 1988; Moore and Knowles, 1990; Moore et al., 1990; Sebacher et al., 1986]. However, most of the published fluxes are for open peatlands. Fluxes from treed and forested peatlands tend be much lower [Bubier et al., 1993; Moore and Knowles, 1990, Roulet et al., 1992a]. The exception is the high fluxes measured from forested peatlands in Minnesota [Crill et al., 1988]. The open peatlands generally have higher water tables than treed peatlands since the establishment and maintenance of trees requires a minimal level of soil aeration [Päivänen, 1991].

Since the flux is already quite low from the peatlands observed in the present study a large drop in water table was not required to effectively stop the net CH_4 emissions to the atmosphere. Comparison between the reference site and the 12 m site in the treed fen and forested bog shows a difference in water table of only 0.1 m, yet the flux dropped to 0 mg m^{-2} d^{-1}. The flux from the reference site at the treed bog was initially near 0, but the drop of 0.4 m in water table between the reference site and that at the 12-m site resulted in a flux of -0.4 mg m^{-2} d^{-1}.

The production of CH_4 was clearly affected by the persistent lowering of the water table. The zone of maximum CH_4 production potential occurs just beneath the zone of permanent saturation at the forested bog location (cf. Figure 5 and 8). This is where the optimum balance between constant anaerobic conditions and the newest peat substrate is first found. A persistent lowering of the water table, even as small as 0.1 m (e.g. 6-m site core) eliminated production in this zone. Production may have continued below this point, but unfortunately no peat samples for production studies were obtained below -0.55 m. The maximum zone of consumption in the reference peat occurred at 0.15 m which is the zone immediately above the water table (cf. Figures 5 and 8). Since the CH_4 profiles at the three sites below the water table were not different a lowering of the water table does not necessarily affect the production and storage of CH_4 deeper in the peats. However, all CH_4 diffusing upward from the deeper peats is effectively oxidized within 0.2 m of the water table. Maximum oxidation rates have been found to occur immediately above the water table in other studies [Sundh et al., 1992].

While there was a clear spatial relationship between CH_4 flux and water table location, there was no relationship between temporal changes in water table and CH_4 flux at any one site. With the low mean fluxes and the high variance, the noise to signal ratio is large, and this could possibly hide this relationship. However, Moore and Roulet [1993] suggest other factors that may affect this relationship. In laboratory experiments they found a strong hysteresis between fluxes observed wiht a falling water table compared to fluxes when the water table was rising, suggesting a differential lag time between the response of methanogens and methanontrophs. In addition, the fluxes on the falling limb is not only maintained by the production of CH_4, but also the release of stored CH_4 can contribute to the flux [Windsor et al., 1992].

The speculations that drier northern peatlands could convert from sources to sinks for atmospheric CH_4 [e.g. Whalen and Reeburgh, 1990] is based on CH_4 uptake studies from mineral and humus soils, but not peat. Uptake rates for CH_4 in forest and grassland soils [Crill, 1991; Mosier et al., 1991] are an order of magnitude higher than the rates measured in the present study. Measurements of the profile of CH_4 in forest soils show a decrease of ~ 1.6 ppmv in the top 0.15 m or a gradient of -10 ppmv m^{-1} [Crill, 1991]. The gradients in the drained peat were ~ -1.7 to -2.6 ppmv m^{-1} down to 0.35 m. Beneath this depth, CH_4 concentrations increase, indicating a compensation depth between -0.25 and -0.35 m where the source of CH_4 to the oxidizers switches from atmospheric to CH_4 produced in the anaerobic zone beneath the water table. Therefore, unlike the forest soils, there is not an infinite depth in the drained peat in which the uptake of atmospheric CH_4 can take place. However, the thickness of this upper layer should not be a limiting factor if there is a sufficient oxidizing community. The rates of CH_4 uptake observed by Whalen and Reeburgh [1990] suggest a thickness of 0.25 m should be ample for a high uptake.

The main limitation on the uptake rate is probably the rate of diffusion of CH_4 into the peat soil. This is controlled by the CH_4 gradient and molecular diffusion of CH_4 in the air-filled pores, which is controlled by the soil moisture retention capacity of the peat. Soil moisture characteristics curves developed by Boelter [1966] for peat soils indicate that peat can retain a large amount of water under small matric potentials if the peat is humified. The peat soils of the Wally Creek area are humified (B. Warner, personal communication, 1992), hence the air-filled porosity in the unsaturated zone may be quite limited (~ 10 to 20%). The difference in the volumetric soil moisture content from drained and undrained Wally Creek peat where the water table normally resides, 0.2 to 0.3 m, was 14 to 15% for samples taken in June [Rothwell, 1991]. The effective molecular diffusion, D^*, for CH_4 in peat can be calculated as $Dn^{4/3}$, where D is the molecular diffusion coefficient, 0.20 $cm^2\ s^{-1}$ at 0°C and 101.7 kPa for CH_4 in still air, and n is air-filled porosity [Fechner and Hemond, 1992]. Assuming a mean air-filled porosity of 0.1 for the upper 0.3 m of the drained peat, the diffusion coefficient would be ~ 0.009 $cm^2\ s^{-1}$. Using Fick's first law of diffusion, $J = D^*$ (dc/dz), where J is the flux of CH_4, and the observed gradients (dc/dz) of between -1.7 and -2.6 ppmv m^{-1} (-1.2 to -1.8 g $m^{-3}\ m^{-1}$), the maximum diffusional transport of CH_4 into the peat from the atmosphere would be between -0.10 and -0.14 mg $m^{-2}\ d^{-1}$. If it is assumed the air porosity is 0.3, probably an unrealistically large value, the diffusional flux increases to between -0.4 and -0.6 mg $m^{-2}\ d^{-1}$. The measured fluxes agree well with these estimates and, therefore, it appears reasonable to assume that the very low uptake rates observed in the present study are diffusional limited. However, the gradient of CH_4 in the upper layers is controlled not only by the flux, but also by the consumption of CH_4. Since the gradients are very shallow in the drained peat compared to that of forest soils, a lack of consumption in the upper layers probably plays an equally important role in reducing the uptake rates.

The results of this study support the conclusions of Roulet et al. [1992b] who estimated a drop in the water table would reduce CH_4 flux to the atmosphere from fens in certain locations in the north. It appears that in a drier northern environment the net CH_4 flux to the atmosphere from peatlands would decrease. This contrasts with other studies that have suggested CH_4 fluxes from northern wetlands might increase [Hameed and Cess, 1983; Khalil and Rasmussen, 1989; Lashof, 1989] based on an increase in methanogensis with a temperature increase. However, the climate scenario of wetter, warmer northern peatlands has not yet been examined.

The ability of northern peatlands to become a significant sink also appears to be limited. Hence they should not become an important portion of the soil sink term in global budgets. If the drying was severe enough to increase CH_4 uptake to the point that it did become significant, much of the surface peat itself would probably also be oxidized, altering the storage of carbon in the peatland [Armentano and Menges, 1986; Gorham, 1991].

Acknowledgments. The authors would like to thank Kathleen Savage, Andrew Costello, and Andrew Heyes for their assistance in the field and Mike Dalva for his work in the laboratory. We would like to thank the Ontario Ministry of Natural Resources and Forestry Canada, especially J. Jeglum, for their permission, and encouragement to use the Wally Creek site. P. Crill, K. Roulet, I. Sundh, and B. Svensson provided useful criticisms of early drafts of this manuscript. This manuscript was written while NTR was a Visiting Professor of Naturagrafi, Geografiska Institut, University of Umeå, Umeå, Sweden. Their generousity is acknowledged. This project was funded by NSERC Canada (STR 0045266).

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(Received March 10, 1993;
revised June 10, 1993;
accepted July 12, 1993.)