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Micrometeorological measurements of methane flux in a Minnesota peatland during two growing seasons

N.J. SHURPALI[1,2] & S.B. VERMA[1,*]
[1]*Department of Agricultural Meteorology and Center for Laser-Analytical Studies of Trace Gas Dynamics, University of Nebraska – Lincoln;* [2]*University of Antwerpen, Laboratory of Plant Ecology, Department of Biology, Wilrijk, Antwerp, Belgium (* *Corresponding author)*

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Abstract. Methane flux was measured, employing the micrometeorological eddy correlation technique, during two growing seasons (1991 and 1992) in a peatland in Minnesota. As compared to 1991, the 1992 season was wetter and cooler. Here we examine the seasonal distributions of CH_4 flux and the relationship between concurrently measured CH_4 and CO_2 fluxes. Midday CH_4 flux was low (1.5 mg m^{-2} h^{-1}) during late May in both seasons. Subsequently, the flux ranged from 2.5 to 5.5 mg m^{-2} h^{-1} during early June to early July in both years. Methane flux peaked at 6.5 mg m^{-2} h^{-1} during mid July in 1991. The peak flux (8.0 mg m^{-2} h^{-1}) in 1992 occurred 3 weeks later. A sustained drop in water table during late July to late August in 1991 may have reduced the methane emission. During mid August–mid October in 1992, the water table was consistently high and the flux ranged from 2.0 to 3.0 mg m^{-2} h^{-1}. As compared to 1991, CH_4 flux during this time in 1992 was higher by about 1.0 mg m^{-2} h^{-1} because of the overriding influence of the water table. Integration over the growing season (late May to mid October), indicated that this ecosystem released approximately 10.4 and 11.5 g C m^{-2} of CH_4 in 1991 and 1992, respectively.

We examined our concurrent measurements on methane flux and canopy photosynthesis under a variety of environmental conditions from different parts of the growing season. On a time scale of the entire season, the overall patterns of methane flux and canopy photosynthesis were similar in both years. Canopy photosynthesis, however, showed large day-to-day changes in response to variations in temperature and moisture. Corresponding changes in methane flux during these selected periods were relatively small. The slopes and correlation coefficients of linear regressions between methane flux and photosynthesis data varied widely. Accordingly, a close coupling between short-term (day to day) variations in methane flux and canopy photosynthesis was not evident.

Introduction

Natural wetlands are a major source of atmospheric methane. They account for about 20% of the total methane emissions into the atmosphere (Bartlett & Harriss 1993). Peatlands of the northern latitudes (<40° N) represent roughly half of this source (Dise 1993). The wetland soils provide anaerobic conditions conducive for the production of methane. The methane so produced is transported to the atmosphere through diffusion, ebullition (e.g., Chanton et al. 1989) and plant mediated transport (e.g., Chanton & Dacey 1991). However, a significant amount of methane may be oxidized before reaching the atmosphere (e.g., in a *Sphagnum* dominated peatland – Fechner & Hemond 1992). Thus, net methane flux is a function of factors controlling methane production, oxidation and transport. Soil/peat temperature and water table position are among the key controlling variables considered in previous studies (e.g., Crill et al. 1988; Moore & Knowles 1990; Dise 1993). Although temperature explains some of the within site variability in the methane flux data, water table has been suggested to be a better indicator of flux differences among sites (Bubier et al. 1993; Moore & Roulet 1993; Roulet et al. 1993). Precipitation and hence, water table position may also be an important indicator of year to year variability in methane emissions (e.g., Dise 1993).

Whiting et al. (1991) and Whiting & Chanton (1992) discussed the hypothesis that plant photosynthetic activity provides substrates for methanogenesis through root exudation. Their observations in a Florida Everglades marsh and a Canadian fen indicated that the spatial variations in methane flux and net ecosystem CO_2 exchange were linearly related. These measurements were made at flooded sites on a few days when the environmental conditions were generally similar. It is worthwhile to examine the relationship between these fluxes in different wetlands under a variety of environmental conditions throughout the season.

We employed the micrometeorological eddy correlation technique to measure fluxes of methane and carbon dioxide from an open fen site in north central Minnesota. The eddy correlation technique provides a measure of the vertical flux of a transported entity at a point in the atmosphere by correlating the fluctuations in the concentration of that entity with the fluctuations in the vertical wind speed (e.g., Businger 1986; Baldocchi et al. 1988). This is an *in situ* technique which causes minimal disturbance to the microenvironment being studied, and provides “spatially-integrated” fluxes (e.g., Hicks 1989; Horst & Weil 1992, 1994). Measurements were made during the 1991 and 1992 growing seasons. The 1992 season was wetter and cooler than the 1991 season. The 1991 methane flux data are discussed in Shurpali et al. (1993). In this paper, we compare methane emissions during these two seasons and examine the relationship between methane and carbon dioxide fluxes measured concurrently in a range of environmental conditions.

Study site and measurements

The study site, referred to as the Bog Lake Peatland (47°32′ N, 93°28′ W), is located in the Chippewa National Forest, adjacent to the Marcell Experimental Forest in north central Minnesota. The peatland is poorly-minerotrophic to oligotrophic with its water having a specific conductance of 36 μS and a pH of 4.6. The organic soil of the peatland consists primarily of *Sphagnum* derived peat, classified as a Greenwood series peat. This is a Dysic Typic Borohemist. Von Post Degree of Decomposition values range from H1 to H4 in the upper meter of soil. At greater depths, H5 and H6 occur. Much of the upland soil is classified as the Warba fine sandy loam series and is a Fine-loamy mixed Glossic Eutroboralf. Some of the upland soil surrounding the bottom 2/3 of the peatland is classified as the Menaga loamy sand series and is mixed, frigid, Typic Updipsamment. The vegetation at the site is dominated by *Sphagnum papillosum* and vascular species of *Scheuchzeria palustris* and *Chamaedaphne calyculata*. The maximum leaf area index of the vascular plant species was 0.6. The site provided at least 250–300 m of upwind fetch of open peatland from the instrument tower in the SSW through NNE (200–390°) directions.

Fluxes of methane, carbon dioxide, water vapor and sensible heat were measured during the 1991 and 1992 growing seasons using the eddy correlation technique. The eddy correlation system consisted of a tunable diode laser spectrometer (TDLS) (Unisearch Associates, Inc., Ontario, Canada), an infrared CO_2 gas analyzer (Model LI-6251, LI-Cor Inc., Lincoln, NE), one dimensional sonic anemometers (Campbell Scientific, Logan, Utah), a three dimensional sonic anemometer (Kaijo Denki Company, Tokyo, Japan), fine wire thermocouples and a krypton hygrometer (Campbell Scientific). The three-dimensional sonic anemometer and a fine-wire thermocouple were mounted at a height of 3.5 m above the peat surface. The rest of the instruments were mounted on a horizontal boom at a height of 2.5 m above the surface. Information on these sensors is available in Verma et al. (1992); Shurpali et al. (1993, 1995); and Suyker & Verma (1993). Footprint calculations using the procedures of Gash (1986) and Schuepp et al. (1990) indicate that under neutral and unstable conditions, more than 85% of the measured flux was from the peatland.

Eddy fluxes were calculated on a half hourly basis. Values of flux were corrected for the variation in air density due to the transfer of water vapor (Webb et al. 1980). Use of metal intake tubing for the TDLS sensor removed temperature fluctuations of the sampled gas, thus eliminating the need for the density correction term due to heat transfer (see e.g., Leuning & Moncrieff 1990). Flux values were also corrected for the effects of tube attenuation (Suyker & Verma 1993) and spatial separation of sensors (Moore 1986). The combined effect (tube attenuation and spatial sensor separation) was of the order of 10% for methane and CO_2 fluxes for daytime conditions. Because the eddy correlation method averages the products of concentration and vertical wind velocity, only those concentration fluctuations which correlate with vertical velocity fluctuations will contribute to the measured flux. Thus, the eddy correlation computation process discriminates against uncorrelated noise (e.g. Ogram et al. 1988). Measurements using bottled air of constant methane concentration indicate a minimum detectable methane flux of approximately 0.4 mg m^{-2} hr^{-1}.

Other meteorological variables such as solar and net radiation, air temperature, peat temperature (at 0.10 m depth), humidity, wind speed and direction were also measured. Moss surface temperature was measured by an infrared thermometer. Sixteen above-ground biomass samples of *Sphagnum papillosum*, *Scheuchzeria palustris* and *Chamaedaphne calyculata* were collected at random every two weeks during the measurement period. The samples were oven dried at 70 °C for 24 hours and dry weights were recorded. The daily water table position was recorded using a recording well situated near the instrument tower. The daily water table position was measured relative to an "average" hollow surface referenced at 415.84 m altitude from the mean sea level.

Results and discussion

Microclimatic conditions

The 30-year (1961–1990) average precipitation and air temperature for the May–October period are 553 mm and 13.6 °C. As compared to the long-term average, the 1991 growing season was drier and warmer and the 1992 season was wetter and slightly cooler. The total precipitation and average air temperature during May–October in 1991 were 452 mm and 14.9 °C, while in 1992 these values were 642 mm and 13.4 °C respectively. In 1991, the water table remained within the first 0.10 m below the hollow surface from late May to the third week of July (Figure 1A). There was a sustained drop in water table during the period from late July until the end of August. It fluctuated between 0.14 to 0.22 m below the hollow surface during the rest of the season. In 1992, however, the water table remained generally above the surface during most of the season (Figure 1B), except for a brief dry spell during late May–mid June (when the water table dropped from 0.03 to 0.20 m below the surface). Peat temperature was generally higher during the 1991 season except for brief periods from early to mid July and from late September to mid October (Figure 2).

Seasonal distribution of methane flux

As discussed in Shurpali et al. (1993), episodic emissions were occasionally observed during the 1991 season. These emissions were suggested to be

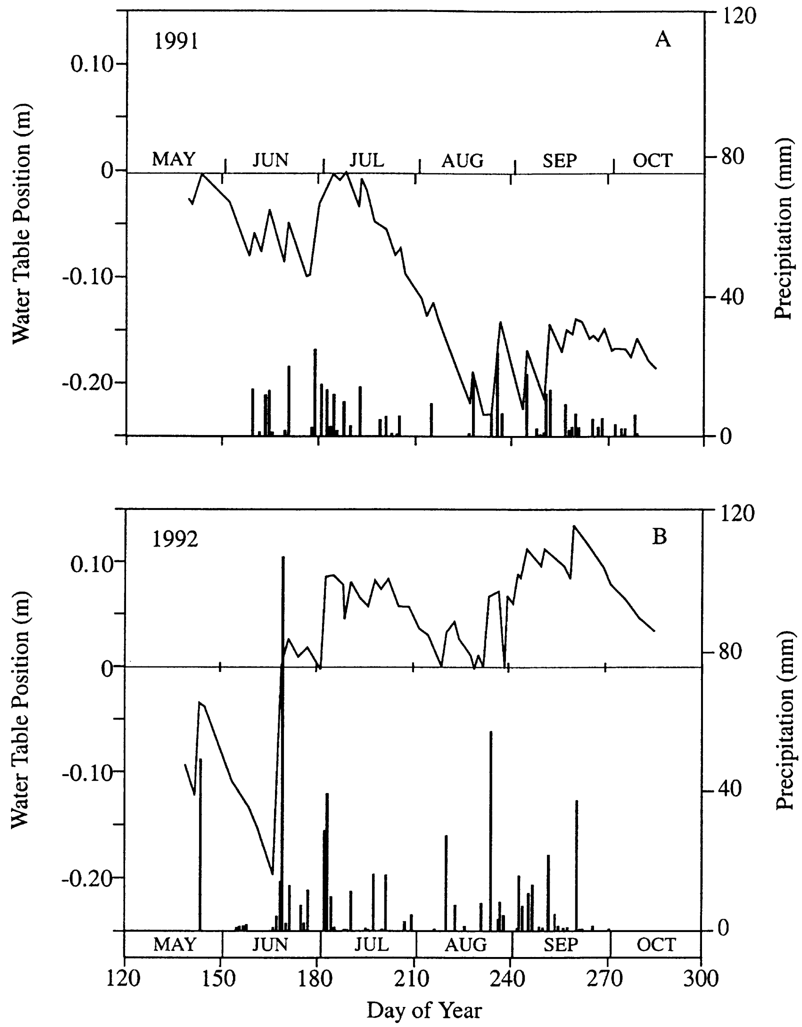

Figure 1. Seasonal distributions of precipitation and water table position in (A) 1991 and (B) 1992. Water table depth is the distance of the water table from an "average" hollow surface (referenced at 415.85 m from the mean sea level). The negative value of water table depth indicates the water table position below the hollow surface.

associated with drops in atmospheric pressure and water table. Conditions conducive to episodic emissions may have occurred during the 1992 season also, but due to some gaps in data collection periods, these emissions could have been missed. Hence, to facilitate a better comparison and minimize confusion, the 1991 episodic emissions are deleted from Figure 3.

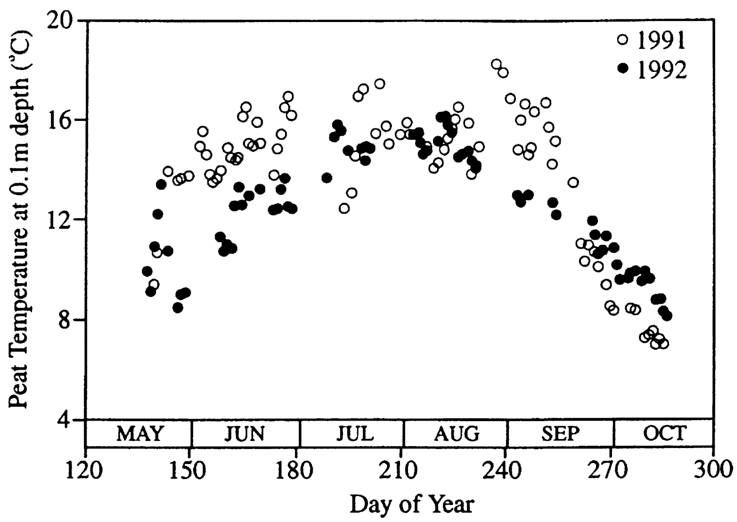

Figure 2. Seasonal distributions of midday peat temperature in 1991 and 1992.

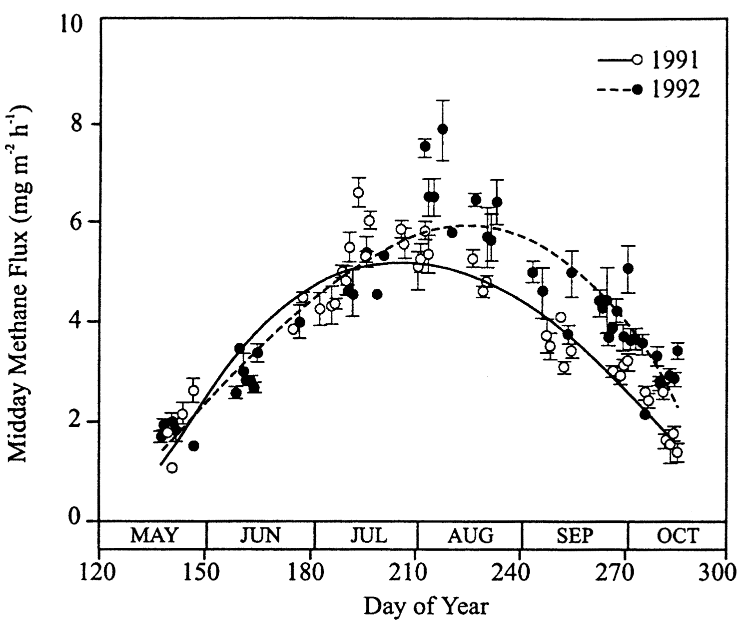

Figure 3. Seasonal distributions of midday (averaged between 1000–1400 hrs, local time) methane flux in 1991 and 1992. Error bars are shown. Third order polynomial regressions are fitted through the mean values.

In both 1991 and 1992, F_m (midday methane flux, averaged between 1000–1400 hrs, local time) was low ($\approx$1.5 mg m^{-2} h^{-1}) early in the growing season (mid-late May). Later (late May–early July) methane flux increased, primarily in response to increasing peat temperature (Figure 2). During this period in 1991, the water table was between 0.05–0.10 m below the surface. In 1992, the peat temperature was lower by 2 to 4 °C (as compared to 1991) and there were significant fluctuations in the water table during this time. A similar range (2.5 to 5.5 mg m^{-2} h^{-1}) of methane flux was observed during this time in both years.

In 1991, the peak in F_m (6.5 mg m^{-2} h^{-1}) occurred in the second week of July. At this time, the water table was close to the surface. Following the peak in F_m, the water table dropped continuously reaching 0.24 m (below the surface) by the end of August and remained between 0.14 and 0.22 m (below the surface) during the remainder of the season. The resulting aerobic layer may have favored an increase in methane oxidation preventing any further increase in F_m after mid July in 1991. During mid July and the rest of the season in 1992, however, the water table remained above the surface maintaining anaerobic conditions. It appears that the methane production continued to increase in mid July and reached its potential in the first week of August. As compared to 1991, the peak F_m in 1992 was higher by about 1.5 mg m^{-2} h^{-1} (significant at $\alpha = 0.05$) and occurred three weeks later.

Following the respective peaks, F_m in both years declined at about the same rate. Despite generally cooler temperatures in 1992, F_m was higher (by about 1.0 mg m^{-2} h^{-1}) during the period from mid August until mid October. This variation likely resulted from differences in water table positions in the two years. The decline in F_m in the later part of the 1991 season could be attributed to a combination of falling peat temperature and low water table. During this period in 1992, however, the water table remained above the surface and the decline in F_m was primarily associated with decreasing temperatures.

We compared our methane flux data against those from previous studies in the northern wetlands. The May to October average flux at our site was 3.9 mg m^{-2} h^{-1} in 1991 and 4.1 mg m^{-2} h^{-1} in 1992. Bubier et al. (1993) measured average fluxes of 0.1–1.8 mg m^{-2} h^{-1} from open and treed fens (with water table below the surface) during May through August in the midboreal region in Ontario, Canada. Moosavi et al. (1996) measured methane flux from wet, low-shrub bog in Fairbanks, Alaska during the summers of 1992 and 1993. The 1992 season was cool and wet and the 1993 season was warmer and drier. They reported average fluxes of 3.0 and 1.8 mg m^{-2} h^{-1} respectively in 1992 and 1993. Suyker et al. (1996) reported a seasonal average flux of 8.1 mg m^{-2} h^{-1} from an open fen (water table above the surface) in Saskatchewan, Canada.

Seasonal integration of methane flux

Most nights were fairly calm and did not allow accurate eddy flux measurements. On very few days, when 24-hour flux measurements were available, no significant diel pattern in methane flux seemed clear. Therefore, the midday values were assumed to represent the 24-hour averages and were used in calculating seasonal integrations of methane flux.

Integration of F_m (Figure 3) over the measurement period (late May to mid October) yielded values of 10.4 and 11.5 g C-CH_4 m^{-2} in 1991 and 1992, respectively. The thermal and hydrological regimes need to be taken into account in examining these seasonally integrated fluxes. The number of accumulated degree days (ADD = daily average peat temperature higher than the base temperature of 0 °C, at 0.10 m depth, accumulated over late May through mid October) in 1991 (ADD = 2075) was greater than that during the same period in 1992 (ADD = 1895). Thus, based on the ADD alone, the methane production potential was lower in the 1992 season. However, with the water table above the surface during most of the season, conditions remained favorable for high methane production and low methane oxidation. The two controlling factors (water table and peat temperature) seem to have somewhat counterbalanced each other, resulting in a 10% difference in the integrated seasonal flux values in the two years.

We examined our methane flux results in relation to the above-ground biomass data (available during July 5–September 21 in 1991 and June 9–August 28 in 1992) measured at the study site. During these periods, the ratio of the amount of methane released to the gain in the above-ground biomass was 0.06 in 1991 and 0.08 in 1992. Aselman & Crutzen (1989) calculated a methane flux to NPP ratio of 0.02 to 0.07 for a range of ecosystems.

Concurrently measured fluxes of methane and carbon dioxide

Whiting et al. (1991) and Whiting & Chanton (1992), using chambers, measured midday methane emissions and net CO_2 exchange at several locations in a Florida Everglades *Cladium* marsh and in a *Carex* dominated fen near Schefferville, Quebec, Canada. They reported that the spatial variations in the two variables were linearly correlated. In the following, we present an analysis of methane flux and canopy photosynthesis (P) measured at our study site. The values of P were computed from the atmospheric (eddy correlation) and soil CO_2 flux measurements (see Shurpali et al. 1995 for details).

The seasonal distributions of midday F_m and P are shown in Figure 4 (as in Figure 3, the episodic methane emissions are deleted here). Note that the F_m and P values are expressed in mg of C m^{-2} h^{-1} for consistency with Whiting et al. (1991) and Whiting & Chanton (1992). In general, the overall

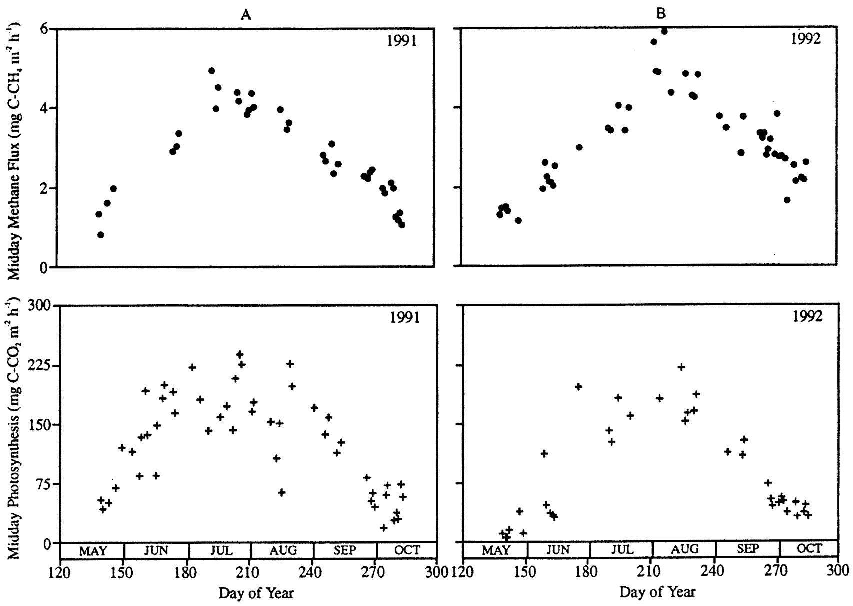

Figure 4. Seasonal distributions of midday (averaged between 1000–1400 hrs. local time) methane flux (F_m) and midday canopy photosynthesis (P) in (A) 1991 and (B) 1992.

seasonal patterns of F_m and P appear to be similar in the two seasons. On a shorter time scale (e.g., daily), however, the canopy photosynthesis values varied significantly in response to changing environmental conditions. Since methane emission is primarily controlled by belowground processes, short term variations in methane emission were not as pronounced.

To further examine the relationship between F_m and P under a variety of environmental conditions, F_m is plotted against P in Figure 5. Data from six groups (A–D in 1991 and E and F in 1992 – see Figure 5 and Table 1) of days are marked in the figure. These days are selected from different parts of the growing season with varying levels of methane emission. Canopy photosynthesis was high when the vegetation surface temperature was moderate (18–28 °C), the water table was close (within the first 0.10 m) to the surface and the vapor pressure deficit was low (0.7–1.5 kPa). (Light response of canopy photosynthesis is discussed in Shurpali et al. 1995. For the days studied here, generally the high midday light values were also associated with temperature and moisture stress conditions). A substantial reduction in P was observed when temperature was greater than 30 °C. The data in groups A, B, C, and F (Table 1) illustrate the effect of temperature on P. Photosynthesis was significantly reduced when the water table dropped 0.18 to 0.20 m below the surface and the vapor pressure deficit was high (2.2–3.0

kPa). The moisture stress effect (high vapor pressure deficit and a low water table) is evident in the data included in groups A, B, C, and F. On some occasions (e.g., on July 25 – group A and August 18 – group B), despite a water table drawdown, P was high because of rainfall a day or two prior to the measurement.

While P changed by 70% in group A, by 35% each in groups B and C and by 245% in group F, methane flux changed by about 10–15% in each of the groups (Table 1). The combined effect of the changes in peat temperature and water table (e.g., Shurpali et al. 1993) was consistent with the small changes in methane fluxes in each group of days. The data in groups D and E are from the month of September in 1991 and 1992 respectively. Vascular plants began to senesce in early September. During the period from early September to mid October, P declined with increasing vegetation senescence and the day-to-day changes in P were not associated with the changes in temperature and moisture. The values of P changed by 245% and 140% in groups D and E respectively. The corresponding decline in methane flux was about 18–20%.

Results of a linear regression analysis between midday F_m and P are shown in Table 2. A regression of the data from 1991 and 1992 suggests that, on a seasonal timescale, F_m and P are linearly related (r^2 = 0.71 and 0.69 respectively). This is similar to the results of Whiting et al. (1991) and Whiting & Chanton (1992). They reported r^2 values of 0.88 and 0.86 for the regression between methane flux and midday net CO_2 exchange for their subtropical grassland and fen sites, respectively. Their measurements were made at flooded sites in a relatively moderate range of environmental conditions (J.P. Chanton, personal communication).

Our results from the individual groups of days are quite different, however. The r^2 values from the individual groups were variable, ranging from 0.04 to 0.96 (Table 2). The slopes of the F_m-P regression for the individual groups also varied widely (-0.008 to 0.004 mg C-CH_4 m^{-2} h^{-1} per mg C-CO_2 m^{-2} h^{-1}). The data in groups B, E and F had high r^2 values, but negative slopes. These results suggest no clear evidence for a close coupling between day to day magnitudes of methane flux and canopy photosynthesis under varying conditions.

Summary and conclusions

Eddy correlation measurements of methane and CO_2 fluxes were made during the growing seasons of 1991 and 1992 at an open fen site in north central Minnesota. Peat temperature was generally higher in 1991. However, the water table was below the surface during most of this season. In 1992, the water table was generally close to or above the surface. Compared to a peak

Table 1. Midday methane flux, canopy photosynthesis and other relevant variables (a negative value of water table depth indicates the water table position below the hollow surface).

Date	Methane flux (mg C-CH_4 m^{-2} h^{-1})	Canopy photosynthesis (mg C-CO_2 m^{-2} h^{-1})	Surface temp (°C)	Vapor pressure deficit (kPa)	Peat temp (°C)	Water table position (m)	Precipitation (mm)	Photosynthetically active radiation, PAR (μEi m^{-2} s^{-1})
1991								
	A. Methane flux = 4.0–4.5 mg CH_4-C m^{-2} h^{-1}							
7/10	4.13	142	27.7	1.29	14.7	−0.02	3.1	1622
7/16	4.53	160	31.7	1.65	14.6	−0.04	–	1531
7/25	4.41	239	20.0	0.79	15.8	−0.08	5.6	1078
7/26	4.19	226	18.1	0.88	12.1	−0.09	–	1317
8/01	4.38	179	25.8	1.22	15.5	−0.13	–	1580
	B. Methane flux = 3.5–4.0 CH_4-C m^{-2} h^{-1}							
7/31	3.97	167	25.7	1.42	15.9	−0.12	–	1607
8/18	3.47	226	19.0	0.78	15.9	−0.21	19.1	1099
8/19	3.63	198	23.7	0.96	13.9	−0.22	–	1503
	C. Methane flux = 2.9–3.3 mg CH_4-C m^{-2} h^{-1}							
6/24	2.91	165	28.2	1.10	14.9	−0.08	–	1434
7/02	3.19	222	19.6	0.55	14.8	−0.01	13.2	566
7/06	3.28	182	27.3	1.33	15.4	−0.01	1.5	1668
	D. Methane flux = 2.2–2.7 mg CH_4-C m^{-2} h^{-1}							
9/06	2.66	159	9.5	0.97	16.4	−0.21	2.3	1485
9/10	2.34	113	14.9	0.49	14.6	−0.15	13.2	567
9/12	2.59	128	19.7	0.41	13.9	−0.17	–	670
9/24	2.28	82	15.0	0.77	10.1	−0.16	2.8	1209
9/26	2.22	53	8.3	0.72	9.4	−0.15	4.6	1151
9/27	2.38	62	11.7	0.71	8.6	−0.16	–	917
9/28	2.44	46	15.5	0.77	8.4	−0.17	–	1123
1992								
	E. Methane flux = 2.8–3.2 mg CH_4-C m^{-2} h^{-1}							
9/10	2.83	110	17.3	0.68	12.7	0.11	4.6	930
9/23	2.93	54	12.5	1.07	10.7	0.10	–	1516
9/24	3.18	46	19.9	1.59	10.8	0.10	–	1386
	F. Methane flux = 2.0–2.1 mg CH_4-C m^{-2} h^{-1}							
6/07	1.96	114	14.5	0.71	11.4	−0.13	2.0	949
6/10	2.14	37	29.6	2.32	11.0	−0.16	–	1635
6/11	2.12	37	30.4	2.53	12.6	−0.17	–	1517
6/12	2.04	33	29.8	2.98	13.4	−0.18	–	1497

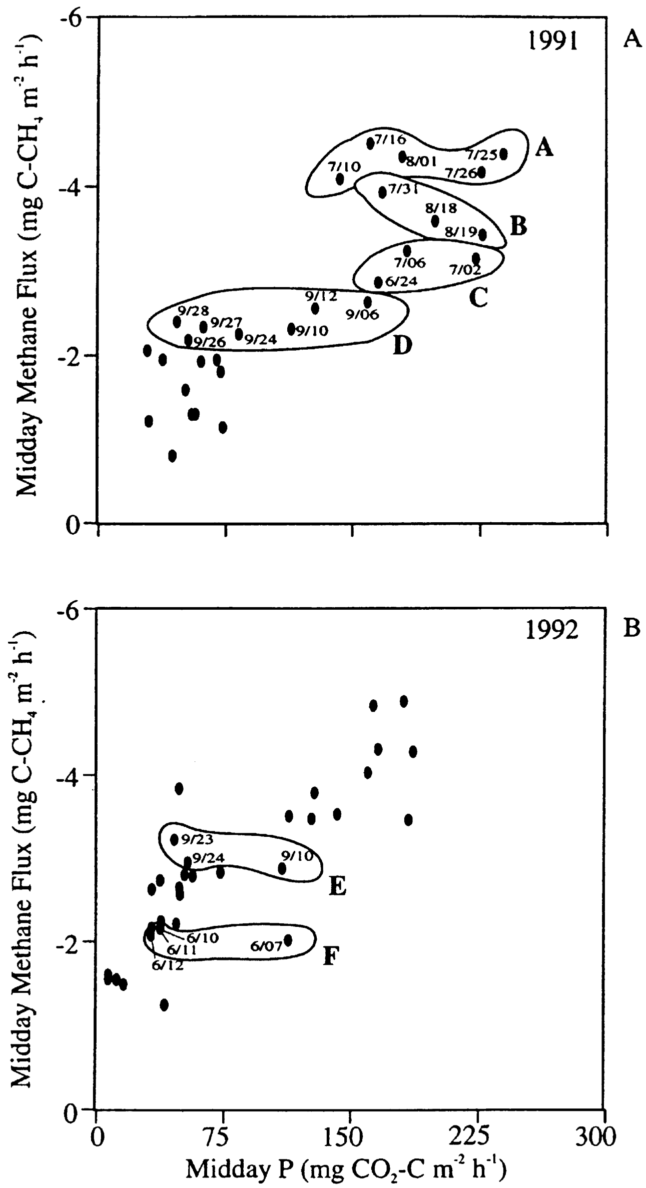

Figure 5. Midday methane flux is plotted against midday canopy photosynthesis from (A) 1991 and (B) 1992. Data from six groups (A–D in 1991 and E and F in 1992) of days from different parts of the growing season were chosen for the analysis (see text and Table 1 for details). Data points in these groups are labelled with measurement dates.

Table 2. Results of linear regressions between midday methane flux and canopy photosynthesis (Methane flux = a + b · canopy photosynthesis).

Group	(n)	b = Slope (mg C-CH_4 m^{-2} h^{-1} per mg C-CO_2 m^{-2} h^{-1})	a = Intercept (mg C-CH_4 m^{-2} h^{-1})	r^2
All season 1991	29	0.013	1.13	0.71
All season 1992	33	0.014	1.70	0.69
A	5	0.000	4.28	0.04
B	3	−0.008	5.35	0.96
C	3	0.004	2.45	0.29
D	7	0.003	2.16	0.55
E	3	−0.004	3.18	0.64
F	4	−0.002	2.16	0.69

of 6.5 mg m^{-2} h^{-1} in mid July in 1991, the peak methane flux in 1992 was higher (by about 1.5 mg m^{-2} h^{-1}) in magnitude and occurred three weeks later. A continuous drop in water table may have prevented an increase in methane flux after mid July in 1991. Integrating the midday methane flux data during the measurement period (late May to mid October) yielded seasonal emission values of 10.4 and 11.5 g C m^{-2} respectively in 1991 and 1992.

The overall seasonal patterns of CH_4 flux and canopy photosynthesis were similar. However, on a shorter time scale (e.g., daily), canopy photosynthesis showed large variations in response to the changing environmental conditions. No clear relationship between day to day values of CH_4 flux and canopy photosynthesis was found.

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