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Relating chamber measurements to eddy correlation measurements of methane flux

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Abstract. Methane fluxes were measured using eddy correlation and chamber techniques during 1991 and 1992 at a peatland in north central Minnesota. Comparisons of the two techniques were made using averages of methane flux data available during 1-week periods. The seasonal patterns of fluxes measured by the two techniques compared well. Chamber flux, in 1991, was about 1.8 mg m^{-2} hr^{-1} greater than the flux obtained by the eddy correlation technique. In 1992, the chamber flux was about 1.5 mg m^{-2} hr^{-1} higher than the eddy correlation flux prior to midseason and 1.0 mg m^{-2} hr^{-1} lower than the eddy correlation flux after midseason. Chamber data from individual hummock and hollow pairs were used to calculate the averaged dF/dZ (rate of change of methane flux with surface height). During midseason in 1991, the magnitude of dF/dZ ranged between 10 and 100 (mg m^{-2} hr^{-1})m^{-1}. We speculate that high water table conditions caused a decrease in the magnitude of dF/dZ after midseason of 1992. As compared to 1991, greater variability of dF/dZ in 1992 probably resulted from less frequent sampling. To obtain a more valid comparison of the results from the two measurement techniques, chamber data were adjusted to account for the spatial variation in methane flux. Accordingly, the chamber flux values were "scaled up" using the dF/dZ values and distributions of surface heights representative of the footprint of the eddy correlation sensors. The scaling procedure reduced the chamber fluxes by an average of 1.8 mg m^{-2} hr^{-1} in 1991 and 1.0 mg m^{-2} hr^{-1} in 1992. The comparison of eddy correlation and chamber fluxes was improved both before and after midseason in 1991. The slope of the linear regression between eddy correlation and chamber fluxes decreased from 1.49 to 1.14 (r^2 increased from 0.53 to 0.75). During 1992, the scaling of chamber fluxes slightly improved their comparison with eddy correlation fluxes only prior to midseason. The lack of improvement after midseason in 1992 is likely the result of scaling assumptions when the water table was above the hollow surface. Results suggest that the adjustment of chamber flux data for spatial variations on microtopographical scales does provide fluxes more representative of a larger area. However, more information is needed on factors controlling spatial variation of methane flux to help refine the assumptions involved in the scaling procedure.

Introduction

Accurate predictions of future atmospheric methane concentrations and their consequences are contingent on our ability to model methane sinks and sources. However, without reliable measurements of methane flux our capability of modeling methane dynamics is greatly limited. One step toward obtaining accurate methane flux measurements is to compare the results from available methods.

Trace gas fluxes, including methane, have traditionally been measured using chambers. Chambers are inexpensive, portable, and well suited for process level studies. Their size, however, allows characterization of only small areas (~1 m^2). Only recently have micrometeorological techniques, such as eddy correlation [e.g., *Fan et al.*, 1992; *Verma et al.*, 1992; *Edwards et al.*, 1994], become feasible for making measurements of methane flux. This noninvasive technique provides continuous, spatially integrated fluxes representative of relatively large areas (10^2 – 10^4 m^2) [e.g., *Hicks*, 1989; *Schuepp et al.*, 1990; *Horst and Weil*, 1994]. Successful intercomparison of chamber and micrometeorological techniques has been accomplished for carbon dioxide, [e.g., *Norman et al.*, 1992; *Dugas*, 1993]. In a comparison of methane fluxes from a heterogeneous wetland area, scaled-up chamber measurements differed by about a factor of 2 in comparison with tower eddy correlation measurements [*Fan et al.*, 1992; *Bartlett et al.*, 1992]. Improved methods of scaling methane fluxes are needed to establish proper comparisons between these measurement techniques.

In comparing methane fluxes measured with eddy correlation and chamber methods it is necessary to recognize the great variability in biological, chemical, and physical characteristics of wetlands. These characteristics vary not only on regional scales or between sites [*Vitt and Chee*, 1990; *Glaser*,

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Table 1. Monthly Averages of Temperature and Precipitation for 1991, 1992 and for the Period 1961 to 1993

Month	April	May	June	July	Aug	Sept	Oct	Annual
				Temperature				
1991	7.1	15.1	18.4	19.2	19.9	11.4	3.5	4.3
1992	2.9	13	14.3	15.1	15.5	11.3	4.5	3.4
1961–1993	4.1	11.3	15.9	18.8	17.3	11.8	5.7	3.2
				Precipitation				
1991	70.1	76.2	104.9	74.7	65.3	85.6	45.0	715.8
1992	42.2	85.3	199.6	114.3	143.0	93.7	5.8	837.9
1961–1993	58.7	84.3	107.4	110.0	98.6	87.6	64.5	773.9

1992], but also within sites [*Vitt et al.*, 1975; *Karlin and Bliss*, 1984; *Kenkle*, 1988]. The production of methane has been observed to be controlled by such factors as substrate and nutrient levels, temperature, and pH [e.g., *Ferguson and Mah*, 1987; *Yavitt et al.*, 1987; *Oremland*, 1988]. More commonly however, the emission of methane has been related to temperature and water table position [e.g., *Crill et al.*, 1988; *Moore et al.*, 1990; *Moore and Dalva*, 1993]. To produce representative measurements, a method should be able to incorporate the spatial variability of relevant factors. With proper placement of sensors, the eddy correlation technique integrates these spatial variations. Chamber measurements, if made at a variety of locations, can address the ranges of characteristics relevant to methane flux [*Moore et al.*, 1990]. However, without an adequate spatial characterization of the surface being studied, comparison of techniques may be subject to large scaling-related differences [*Fan et al.*, 1992].

A study was conducted at a peatland in north central Minnesota, in which methane flux was measured by chamber and eddy correlation methods. The objective of this paper is to examine the results from the two techniques and present a procedure for scaling up of chamber flux data to allow a proper comparison with the eddy correlation results.

Materials and Methods

Site

The experiment was conducted at the Bog Lake peatland (47° 32′N 93° 28′W), which is a wetland area of approximately 200,000 m^2 located adjacent to the Marcell Experimental Forest in north central Minnesota. The Marcell Experimental Forest is underlain by slightly calcareous glacial debris and is thinly overlain with upland soils over 74% of its surface area, with the remaining low-lying areas covered by lowland organic (peat) soils (21%) and open water (5%). The climate of this site places it in the southern boreal forest.

The Bog Lake peatland is transitional between poorly minerotrophic fen and an oligotrophic bog. Its water has a specific conductance of 36 μS and a pH of 4.6. The peatland receives water from adjoining higher peatlands, the surrounding upland mineral soil, and precipitation. It is estimated that approximately 65% of annual precipitation is lost through evapotranspiration and the remaining precipitation is lost to groundwater seepage [*Smith*, 1993]. Initial survey data indicate a level water table from east to west across the wetland and a decrease in water table elevation of about 0.20 m km^{-1} from north to south. There is no surface water outlet, and the downward trend from north to south results from seepage outflow at the southern end.

The Bog Lake peatland's surface is mostly concave with indications of dome formation in certain areas. The dominant spatial surface variation appears to correspond to hummock/hollow microtopography. The hollow/hummock spacing is 1–2 m, which is similar to that of a weakly minerotrophic mire in the southern boreal forest of Ontario, Canada [*Kenkel*, 1988].

Mosses, dominated by *Sphagnum papillosum*, cover about 60% of the surface. In wetter hollows, *Sphagnum majus* dominates, while *Polytrichum strictum* occurs on about 5% of the taller hummocks. Other *Sphagnum* mosses include: *S. warnstorfii*, *S. russowii*, and *S. angustifolium*. The dominant emergents are *Scheuchzeria palustris* and *Rhynchospora alba*. *Saracenia purpurea* is well distributed, and other emergents include the following: *Carex paupercula, Carex oligosperma, Kalmia polifolia, Andromeda glaucophylla, Chamaedaphne calyculata*, and *Glyceria spp.* Widely scattered *Larix larcina* (tamarack), 1 to 3 m tall, also occur. Upland vegetation consists primarily of *Populus tremuloides* (trembling aspen), and *Pinus resinosa* (red pine) in the overstory and *Corylus cornuta* (beaked hazel) in the understory.

Annual average temperatures in 1991 (4.3°C) and 1992 (3.4°C) were warmer than the 1961 to 1993 mean of 3.2°C (Table 1). During the growing season (April to October) the monthly average temperatures in 1991 were higher than the corresponding long-term average values. The 1992 growing season, except during May, was cooler.

As compared to the 1961 to 1993 mean annual precipitation of 774 mm, 1991 was drier (precipitation = 716 mm) and 1992 was wetter (precipitation = 838 mm). The growing season was also drier in 1991 and wetter in 1992 than the long-term mean. The water table position was near the hollow surfaces before midseason in both 1991 and 1992 (Figure 1). The water table after midseason was about 0.15 m below the hollow surfaces in 1991 and about 0.10 m above the hollow surfaces in 1992.

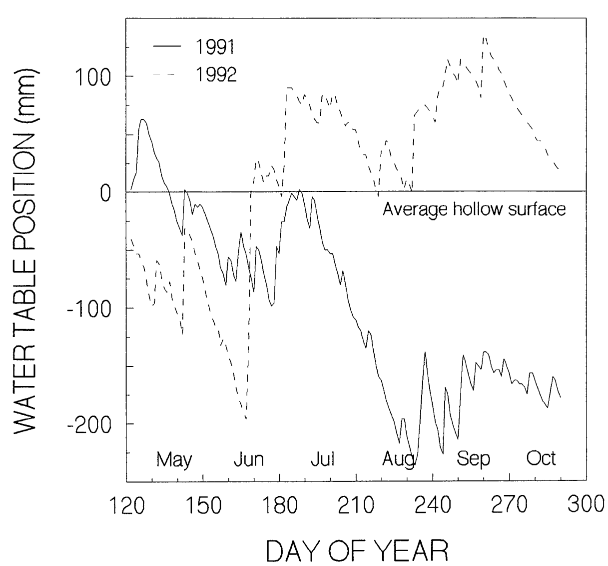

Figure 1. Water table heights versus day of year during the main experimental periods of 1991 and 1992. The water table position is measured with respect to an average hollow surface.

Eddy Correlation Flux Measurements

The eddy correlation technique provides a measure of the vertical transport (i.e., flux) of an entity at a point in the atmosphere. A flux is determined by calculating the covariance between the concentration fluctuations of that entity and the fluctuations in vertical wind speed [e.g., *Businger*, 1986]. A map showing the area upwind of the instrument mast is shown in Figure 2. Wind directions from 200° to 30° (SSW–NNE) provided reasonable upwind fetch.

Wind velocity fluctuations were measured with one-dimensional sonic anemometers (CA27T, Campbell Scientific, Logan, Utah), and a three-dimensional sonic anemometer (model DAT-310 TR-61A, Kaijo Denki Company, Tokyo, Japan). Temperature fluctuations were measured with fine-wire thermocouples (Campbell Scientific, Logan, Utah). A krypton hygrometer (model KH20, Campbell Scientific) and a Lyman-alpha hygrometer (model AIR-LA-1, A.I.R. Inc., Boulder, Colo.) were used to measure humidity fluctuations. A closed cell, tunable diode laser absorption spectrometer (TDLS) (Unisearch Associates, Inc., Concord, Ontario, Canada) was used to measure fluctuations in methane concentration. (see e.g., *Hastie et al.* [1983] for details of the TDLS measurement principle).

Air samples for the TDLS were drawn through 8 m of 7.75-mm ID stainless steel tubing at 25 SLM (standard liters per minute). A delay time, of about 1.0 s, due to the separation between the TDLS sensor and its intake point adjacent to the sonic anemometer, was determined by examining the cross correlation of the methane signal with vertical wind velocity using a procedure described by *Chahuneau et al.* [1989]. The effect of the delay time was eliminated by lagging the corresponding vertical velocity signal. The TDLS was calibrated using bottled gas of known concentrations at the beginning of the day, after optical realignment, and at the end of the day.

The eddy correlation sensors were mounted at 2.5 m, with the exception of the three-dimensional sonic anemometer, fine-wire thermocouple and krypton hygrometer which were mounted at 3.5 m above the peat surface. Information on the sensors and computational procedures is available in the literature and in our previous reports [e.g., *Verma*, 1990; *Verma et al.*, 1992; *Suyker and Verma*, 1993; *Shurpali et al.*, 1993]. Footprint calculations using the procedures of *Gash* [1986] and *Schuepp et al.* [1990] indicate that under neutral and unstable conditions, more than 90% of the measured flux was from the peatland.

The data were low-pass filtered using 8-pole Butterworth active filters with 12.5 Hz cutoff frequency and were sampled at 25 Hz. Sampling, recording, and near real time data processing were done with a microcomputer. Fluxes were computed over 30-min periods. Methane flux was computed using the band-pass covariance technique (details are given in *Verma et al.* [1992]).

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}.

Values of methane 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 and Moncrieff*, 1990].

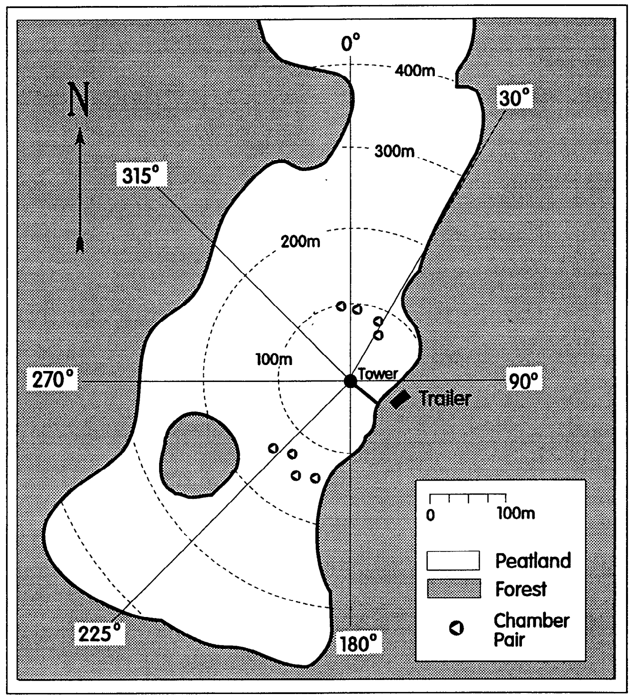

Figure 2. Map of site showing the location of the eddy correlation tower and chamber (hummock/hollow) pair locations.

Chamber Flux Measurements

Methane flux chamber collars were placed at 16 locations in 1991 and 8 locations in 1992. One half of the chamber locations were northwest of the eddy correlation tower and the other half were located southwest of the tower; all locations were within 200 m of the eddy correlation tower (Figure 2). Chamber locations were paired, with one chamber collar positioned on a hummock and the second positioned on a hollow. The chamber collars (with 8-cm deep sides) were pushed into the peat after cutting a slit. The height of the surface (i.e., the surface of the peat or living moss) relative to the water table was determined for each chamber collar. Platforms were located next to the chamber collars to minimize disturbance during measurement.

Chamber sampling was done at various times during daylight hours. Using a procedure similar to *Smith* [1993] (assuming a level of significance, $\alpha = 0.05$ and a standard deviation, s = 4.3 mg m^{-2} hr^{-1}), we determined that at least seven chamber flux samples were required to produce a representative midseason flux. Generally eight chambers (i.e., four hummock/hollow pairs) were sampled in a day. During sampling, an aluminum chamber (0.624 × 0.624 × 0.370 m) was placed in a groove of the aluminum collars and sealed with wet moss or packed with snow. In a method similar to *Crill et al.* [1988], 60 mL samples (using a 75 mL syringe) were taken at the time of chamber placement and every 4 min for a total of five samples over 20 min. The air samples were analyzed with a Shimadzu GC-8A gas chromatograph equipped with a flame ionization detector (FID-GC). The FID-GC was equipped with a 1-m Poropak Q

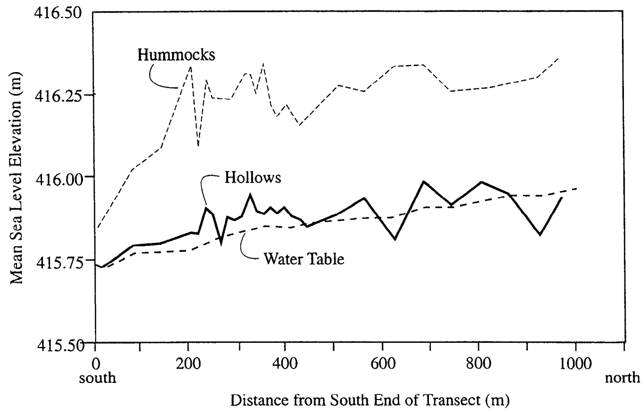

Figure 3. Water table heights and peat hollow and hummock heights for a north-south transect measured in July, 1991. Results from the east-west transects were similar.

column set at 125°C. The FID and injector temperature was 150°C. Nitrogen was used as a carrier gas. The FID-GC peaks were quantified with a Shimadzu CR601 recording integrator. The FID-GC was calibrated with 4.831 ppm, National Institute of Standards and Technology (NIST) traceable standards between each set of chamber sample analyses [*Smith*, 1993].

Samples from each syringe were analyzed in two parts, providing 10 data points. The concentration change of the first six to eight data points with time was linear, except during periods with high fluxes. Regressions were only accepted if they were linear and the r^2 value exceeded 0.85. Methane flux was calculated using the effective chamber volume, the temperature of air in the chamber, and the slope of methane concentration against time. The sensitivity of the GC-FID is given as 10 parts per billion by volume (ppbv) CH_4 which gives a theoretical minimum detectable flux of 0.01 mg m^{-2} hr^{-1} [*Bartlet et al.*, 1988]. However, the average standard deviation of multiple measurements made at one location on a few days was approximately 1.4 mg m^{-2} hr^{-1}.

Data Averaging

Eddy correlation flux data were collected from mid-May through mid-October, 1991 and 1992, while the chamber flux data were gathered from January 1991 through October 1992. Eddy correlation measurements were generally made 2 to 3 days per week. Chamber measurements were made on 2 to 3 days per week in 1991 and on 1 day per week in 1992. The number of chamber samples per week ranged from 6 to 52 (average of 18) in 1991 and from 5 to 8 (average of 8) in 1992. Because the days of eddy correlation and chamber flux measurements did not necessarily coincide, we used 1-week periods to group the available flux data for averaging. Eddy correlation data were not used for calm conditions (mean horizontal wind speed at 2.5 m < 1.0 m/s), and for wind directions with insufficient fetch (i.e., < 250 m). Methane flux data for days of episodic emissions [*Shurpali et al.*, 1993] were also not included in the data averages.

Surface Height Distributions

In July 1991, a theodolite was used to survey surface (hollow and hummock) and water table heights along a north-south transect (Figure 3) and three east-west transects, in the vicinity of the eddy correlation tower. The transect heights agreed within 0.008 m at intersecting locations. The heights of hummocks and hollows relative to the water table did not vary greatly along the transects, suggesting that the peatland did not have large regions of consistently higher or lower microtopography.

On October 13, 1991, a more detailed survey was conducted using an electronic theodolite (Geodetic Electronic Total Station, Sokkia Corporation, Overland Park, Kansas). The benchmark elevation used was the same as in the July survey. Errors in the elevation measurement of the electronic theodolite were approximately ±0.002 m at a distance of 43 m. Surface and water table elevations were measured every 2 m and 10 m, respectively, along six radial vectors (210°, 240°, 260°, 300°, 340°, and 20°, where 0° = north) originating at the eddy correlation tower.

A histogram was constructed for each transect of the October survey. Values of the height of the surface above the water table (hereafter referred to as surface height) data were separated into 0.03-m interval classes (Z_i). The value of the histogram classes (g_i, Figure 4) represent the fraction of the transect surface area in each height interval. A comparison of the mean surface heights of the transects indicated that the mean of some transects were similar ($\alpha = 0.05$). Data for statistically similar transects were combined, resulting in three distinct patterns. These results indicate that locations closer to the eastern edge of the fen (320° through 0° to 220°) had a mean surface height of approximately 0.25 m. The areas to the west and southwest (220° to 280°) had a slightly lower mean surface height of 0.21 m while the mean height of region to the northwest (280° to 320°) was slightly higher at 0.33 m. A mean surface height for all data combined was 0.26 m. For use on dates other than October 13, 1991, values of Z_i were adjusted

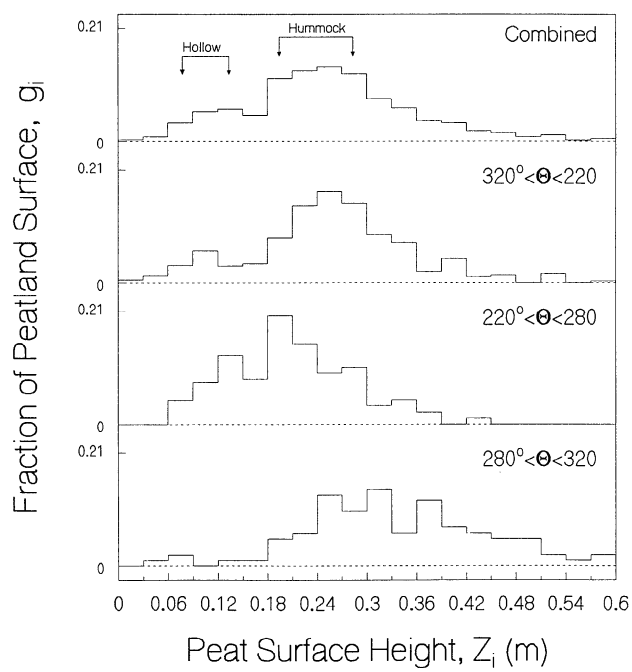

Figure 4. Distributions of peat surface height (relative to the water table) measured on October 13, 1991. Distribution patterns for three wind direction (Θ) regimes (320° < Θ < 220°, 220° < Θ < 280°, and 280° < Θ < 320°, where Θ = 0° is a northerly wind), and for all combined data sets are shown. The range of surface heights are shown for hollow and hummock chamber collars.

for changes in the water table. A recording well, referenced to mean sea level, was installed near the instrument tower to provide daily values of water table elevation. It was assumed that water table changes were similar at all locations in the tower footprint and were well represented by the recording well.

The range of positions of hummock and hollow chamber collars relative to the total surface height distribution curve are also shown in Figure 4. Hollow collars were located approximately 0.1 m below the distribution peak. Hummock collars were located at about the distribution peak.

Results and Discussion

Seasonal Patterns

Methane flux data (averages of available data over 1-week periods, as explained previously), measured during 1991 and 1992, are shown in Figures 5a and 5b. The methane flux measured with the eddy correlation technique reached a maximum (6 mg m^{-2} hr^{-1} in 1991 and 7 mg m^{-2} hr^{-1} in 1992) in late July to early August, (a detailed description of the eddy correlation data can be found in *Shurpali et al.* [1993]). The chamber flux (i.e., the average of all available hummock and hollow data over 1-week periods) increased from near zero in early April to a peak in late July (10 mg m^{-2} hr^{-1} in 1991, and 8 mg m^{-2} hr^{-1} in 1992), then decreased to near zero by early November. These patterns are similar to those observed by *Dise* [1991] from nearby peatlands.

The seasonal patterns measured with the two techniques were similar in both years (Figure 5). However, the averaged chamber flux magnitudes were significantly ($\alpha = 0.05$) greater than the averaged eddy correlation flux magnitudes during 8 of 15 comparison weeks, and significantly less during 1 week in 1991. On the average, chamber flux values were higher than the eddy correlation values by 2.6 mg m^{-2} hr^{-1} before midseason and 1.3 mg m^{-2} hr^{-1} after midseason (and by 1.8 mg m^{-2} hr^{-1} for the entire season) (Table 2). A regression through the origin, relating chamber to eddy correlation data, gave a slope of 1.63 ($r^2 = 0.37$) before midseason and 1.27 ($r^2 = 0.58$) after midseason. The slope for the entire year was 1.41 ($r^2 = 0.53$).

In contrast to 1991, chamber flux magnitudes were higher than eddy correlation flux magnitudes (by 1.5 mg m^{-2} hr^{-1}, on average) only before midseason in 1992. After midseason, the chamber flux was less than the eddy correlation flux by about 1.0 mg m^{-2} hr^{-1} (Table 2). The chamber flux in 1992 was significantly greater ($\alpha = 0.05$) than the eddy correlation flux on 4 of 17 comparison weeks, and significantly less on 5 weeks. Over the entire season in 1992, the chamber flux was on average 0.2 mg m^{-2} hr^{-1} greater than eddy correlation flux. A regression through the origin, relating chamber to eddy correlation data, gave a slope for the entire year of 0.97 ($r^2 = 0.26$). The slope before midseason was 1.35 ($r^2 = 0.02$) and 0.83 ($r^2 = 0.62$) after midseason.

In both years the chamber and eddy correlation values compared better after midseason. This may be related to the positions of the water table observed after midseason. It has been suggested by *Bubier et al.* [1993] that methane flux decreases dramatically when the water table is more than 0.18 to 0.2 m below the local surface. A similar effect has also been shown for a falling water table in a laboratory column of peat by *Moore and Dalva* [1993]. Prior to midseason in both years, the water table was near the hollow surfaces, while being 0.2 m from a majority of the hummock surfaces. Therefore it is likely that prior to midseason the methane flux from hollows remained high because of their close proximity to the water table while the flux from hummocks was low. These conditions likely account for larger microtopographic variability in methane flux prior to midseason. The lower water table after midseason in 1991 resulted in both hummocks and hollows being more than 0.20 m above the water table. This condition helped produce low fluxes from both hummocks and hollows, and hence less microtopographic variability in methane emission. The high water table after midseason in 1992 caused high flux from both hollows and hummocks because both surfaces were close to the water table. This situation may also have resulted in less microtopographic variability in methane emission. Our specula-

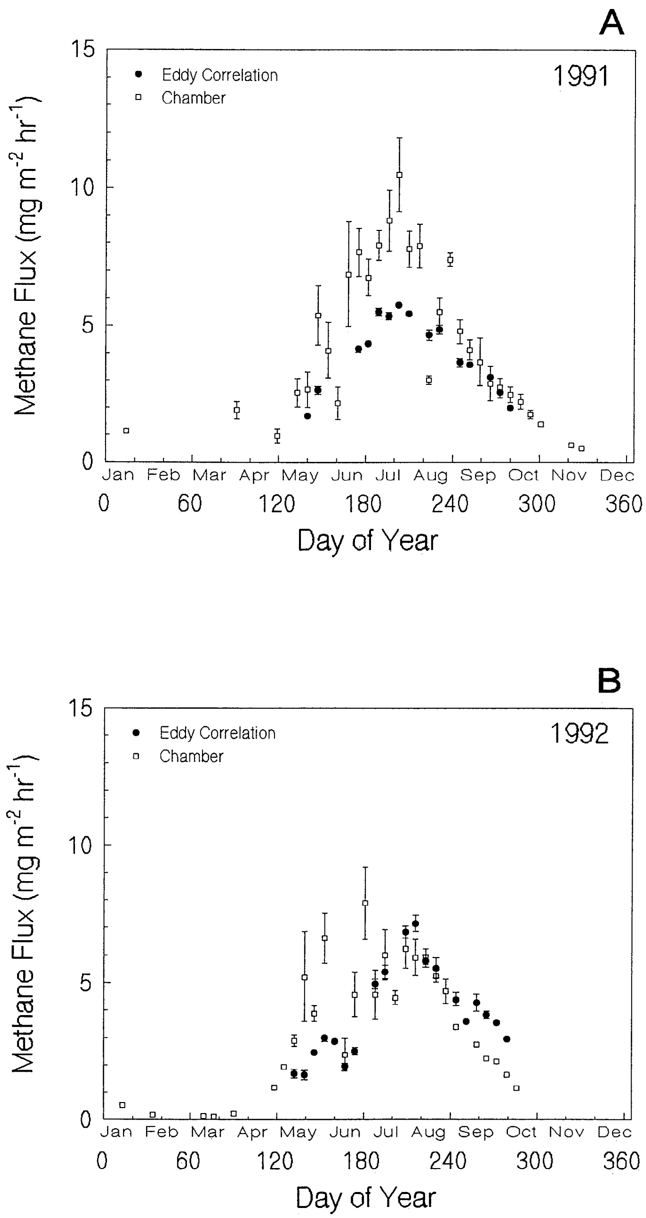

Figure 5. Methane fluxes measured by eddy correlation and chamber (average of hummock and hollow data) techniques during (a) 1991 and (b) 1992. Points indicate averages of data available over 1-week periods. Error bars indicate ± one standard error.

Table 2. Comparison of Linear Regression Analysis (Through Origin) of Chamber and Eddy Correlation Flux Values

	Mean Flux Difference, mg m^{-2} hr^{-1}		Slope of Linear Regression		Correlation Coefficient, r^2	
	Unadjusted	Scaled Up	Unadjusted	Scaled Up	Unadjusted	Scaled Up
			1991			
DOY < 200	2.6	1.0	1.63	1.27	0.37	0.66
DOY > 200	1.3	0.0	1.38	1.04	0.58	0.73
All Season	1.8	0.5	1.49	1.14	0.53	0.75
			1992			
DOY < 200	1.5	1.1	1.35	1.29	0.02	0.18
DOY > 200	−1.0	−1.3	0.83	0.73	0.62	0.29
All Season	0.2	−0.2	0.97	0.88	0.26	0.21

Chamber flux was used as the dependent variable and the eddy correlation flux was used as the independent variable. Mean flux difference equals chamber flux minus eddy correlation flux.

tion is that prior to midseason in both years the water table position resulted in a greater effect of microtopography on methane flux.

Microtopographical Dependence of Methane Flux

Because direct measurements of many of the controlling factors of methane emission are not available in this study, we assume that the spatial variation of these factors, and hence methane flux, is related to the observed hummock/hollow microtopography. The survey data indicate a slight variation in the mean surface heights for different transects. However, site inspection and aerial photos of the peatland suggest that, within the tower's footprint areas, obvious vegetative or morphological variations do not exist at scales greater than 1 to 2 m (the primary scale of microtopographic variation). Individual transect measurements (e.g., Figure 3) also suggest that large regions of atypical surface heights (relative to the water table) do not exist.

Methane fluxes from hummock and hollow chambers (i.e., averages of available data over 1-week periods) are compared in Figures 6a and 6b. Although the seasonal patterns are similar to those for combined hummock and hollow chamber data (Figure 5), the magnitudes of fluxes from the hollows were greater than those from the hummocks. In 1991, this difference is near zero until late April and increased to 3.5 mg m^{-2} hr^{-1} in July and decreased to near zero by mid-October. A similar pattern was observed in 1992 with a midseason difference in magnitudes of 1.2 mg m^{-2} hr^{-1}. When the flux was more than 2 mg m^{-2} hr^{-1}, the hollow flux was greater than the hummock flux on all comparison weeks in 1991 and 60% of the comparison weeks in 1992. The hollow flux was significantly greater ($\alpha = 0.05$) than the hummock flux on 30% of the comparison weeks in 1991 and 20% of the comparison weeks in 1992. These patterns of hummock/hollow differences are similar to those observed by *Bubier et al.* [1993a] for an open low shrub bog in northern Ontario, Canada.

Individual measurements of methane flux from colocated hollow and hummock chambers (F_{hollow} and F_{hummock}) were used to calculate the change of flux with surface height

$$dF/dZ = \frac{(F_{\text{hummock}} - F_{\text{hollow}})}{(Z_{\text{hummock}} - Z_{\text{hollow}})} \tag{1}$$

It was assumed that the production of methane per unit area is the same below adjacent hummocks and hollows, and that the horizontal advection of methane is negligible. A linear variation in flux with respect to height was assumed (1) because the range of Z was small (≈0.25 m). The values of dF/dZ, averaged over 1-week periods, are shown in Figure 7.

The values of dF/dZ were negative throughout most of 1991. The magnitude of dF/dZ increased from near zero in early May to a peak in late June or early July and decreased to near zero by mid-October. The magnitude of dF/dZ ranged from 10 to 100 (±6 SE) (mg m^{-2} hr^{-1})m^{-1} during midseason. The increase in the magnitude of dF/dZ during May and June appeared to be more rapid than its decline from July through October. In 1992, the magnitude of dF/dZ was near zero until May and peaked in July. Greater variability during midseason of 1992 (during day of year (DOY) = 180 to 250, the coefficient of variation was 1.12 as compared to 0.38 in 1991) is likely related to the less frequent chamber sampling. The magnitude of dF/dZ declined to near zero by early September 1992, 2 months earlier than in 1991. We speculate that the early decline of dF/dZ may have been the result of smaller microtopographic variability in emission caused by the higher water table conditions.

For a low subarctic fen margin in Quebec, Canada, *Moore et al.* [1990] determined a value of 45 (mg m^{-2} hr^{-1})m^{-1} for the rate of change of methane flux with water table depth for mid-June to mid-September. In boreal wetlands in Canada, *Moore and Roulet* [1993] and *Bubier et al.* [1993b] found the logarithm of seasonally averaged methane flux to be linearly related to the mean water table. These relationships are based on differences in water table heights (relative to the surface) of up to 0.9 m occurring over several months and at several sites. The relationships of *Moore and Roulet* [1993] and *Bubier et al.* [1993b] yield magnitudes of dF/dZ ranging between 10 and 71 (mg m^{-2} hr^{-1})m^{-1} for the range of fluxes observed at our site during mid-June to mid-September. As indicated in Figure 7, the magnitude of dF/dZ from our calculation ranged from about 10 to 100 (mg m^{-2} hr^{-1})m^{-1} over the same period in 1991.

Scaling Up of Chamber Fluxes

The eddy correlation flux measurement technique integrates the emissions from a variety of surfaces within the footprint of the tower sensors [e.g., *Schuepp et al.*, 1990], while the chamber measured flux represents a small area (≈0.25 m^2 each). To appropriately compare results from the two techniques, the chamber measurements must be incorporated with the spatial variation in methane flux within the tower footprint. In the following, we estimate a spatially integrated methane flux using chamber data and surface height distributions corresponding to the eddy correlation flux measurement footprint.

Chamber methane flux (F_m), measured at a given surface height (Z_m), and dF/dZ data (Figure 7) were used to calculate the flux magnitude (F_i) for all height intervals (Z_i shown in Figure 4):

$$F_i = F_m + dF/dZ(Z_i - Z_m) \tag{2}$$

On the basis of the chamber data (Figure 6), dF/dZ in this calculation was assumed to be negligible when the average chamber flux was below 2 mg m^{-2} hr^{-1}. We also assumed that there was no net uptake of methane occurring at the site (i.e.,

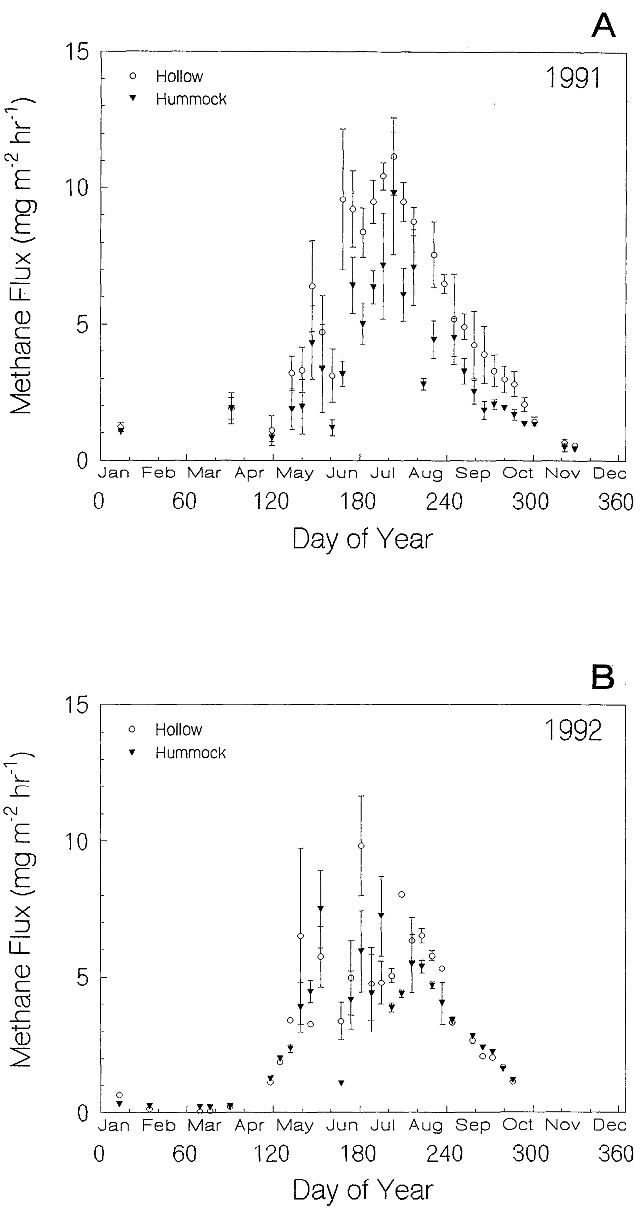

Figure 6. Methane fluxes from hummocks and hollows measured with the chamber technique during (a) 1991 and (b) 1992. Points indicate averages of data available over 1-week periods. Error bars indicate ± one standard error.

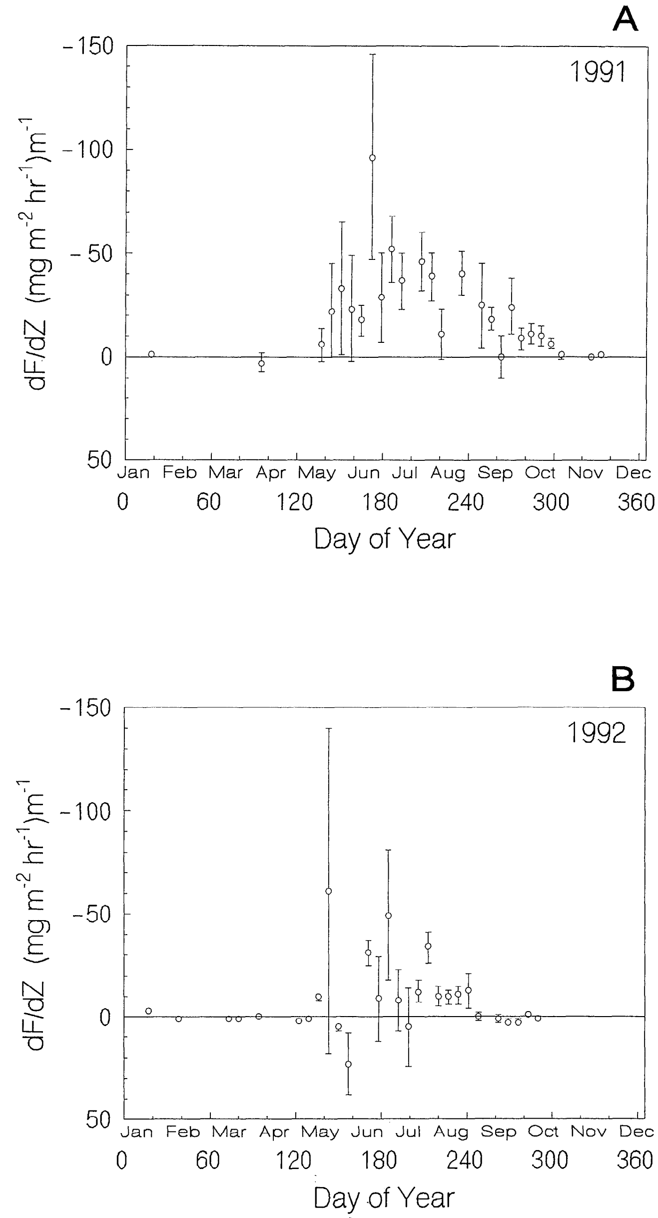

Figure 7. Seasonal distributions of dF/dZ. These values were calculated using the fluxes measured from hummock and hollow chamber pairs during (a) 1991 and (b) 1992. Points indicate averages of dF/dZ data available over 1-week periods. Error bars indicate ± one standard error.

$F_i \geq 0$). The scaled-up (area-adjusted chamber) flux (F_a) was then calculated as the sum of the products of flux (F_i) for each height (Z_i) and the corresponding fraction (g_i) of the surface at that height:

$$F_a = \sum_i F_i g_i \tag{3}$$

The height distribution (Figure 4) corresponding to the prevailing wind direction on the day of flux measurement was used in these calculations. If no wind direction data were available, the distribution for the combined data set was used. Using typical midseason values the propagated measurement error in the scaled-up chamber flux magnitudes was approximately ±0.8 mg

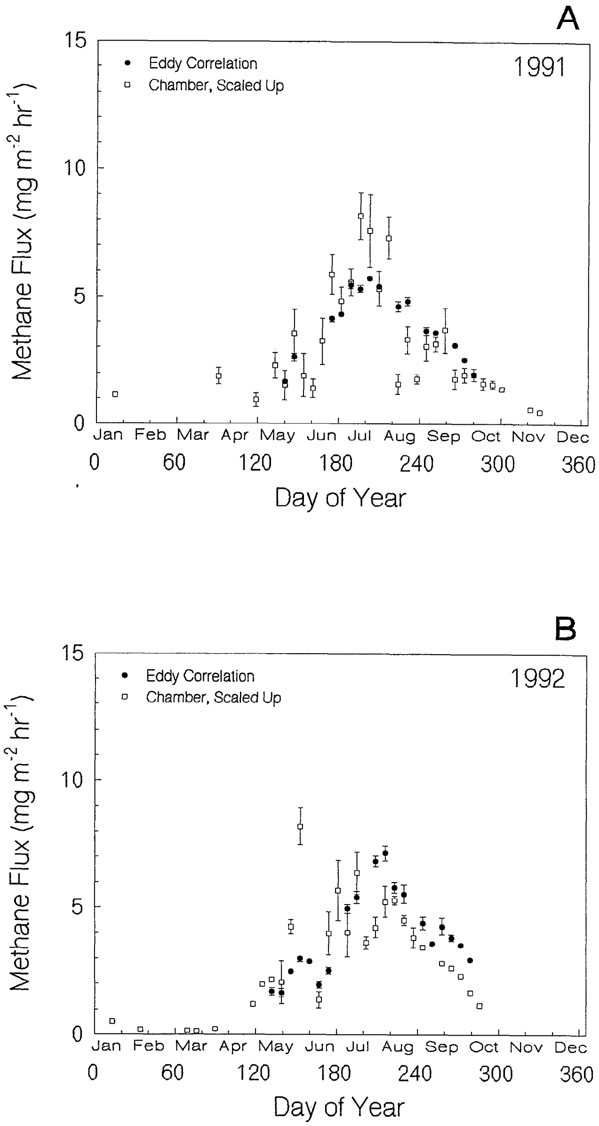

Figure 8. Comparison of the scaled-up chamber methane flux values (combined hummock and hollow data) with the eddy correlation data in (a) 1991 and (b) 1992. Points indicate averages of data available over 1-week periods. Error bars indicate ± one standard error.

m^{-2} hr^{-1}, which is on the same order as the observed standard error of the scaled-up chamber flux (Figures 8a and 8b).

Comparison of Scaled-Up Chamber Data with Eddy Correlation Fluxes

The seasonal patterns of scaled-up chamber fluxes (F_a) (Figures 8a and 8b) remained similar to those of the unadjusted fluxes (Figure 5) (i.e., both peak in late July and are near zero before May and after October). Magnitudes of F_a, however, were usually smaller than those of unadjusted chamber fluxes. The scaling procedure resulted in an average reduction in the midseason (DOY 170 to 230) chamber flux from 6.6 to 4.8 mg m^{-2} hr^{-1} in 1991 and from 5.7 to 4.7 mg m^{-2} hr^{-1} in 1992. Significant reductions ($\alpha = 0.05$) in chamber fluxes, due to scaling, were observed on 8 out of 23 weeks in 1991 and 4 out of 21 weeks in 1992, while significant increases in chamber flux were seen on 2 out of 21 weeks in 1992.

As seen in Table 2, the scaling of chamber fluxes reduced the mean difference between flux magnitudes measured by the two techniques from 1.8 to 0.5 mg m^{-2} hr^{-1} during the 1991 season. The mean difference showed similar reductions due to scaling both before midseason (2.6 to 1.0 mg m^{-2} hr^{-1}) and after midseason (1.3 to 0.0 mg m^{-2} hr^{-1}). The number of weeks with chamber fluxes significantly higher than eddy correlation decreased from 8 to 2 (out of 15) and the number of weeks with significantly higher eddy correlation fluxes increased from 1 to 3. The slope of the regression line passing through the origin (relating chamber and eddy correlation fluxes) decreased from 1.49 to 1.14 with an improvement in r^2 from 0.53 to 0.75. Comparable improvements were observed in regressions both before and after midseason (Table 2).

Scaling of chamber values in 1992 changed the seasonal mean difference between the two techniques only slightly. Before midseason, the scaling of chamber fluxes reduced the mean difference between the two techniques from 1.5 to 1.1 mg m^{-2} hr^{-1}. However, scaling after midseason resulted in a poorer correspondence between the two techniques with an increase in the difference from −1.0 to −1.3 mg m^{-2} hr^{-1} (Table 2). Both the slope and r^2 values of the regression line passing through the origin (relating chamber and eddy correlation fluxes) showed slight declines (Table 2). The number of weeks with chamber fluxes significantly higher than eddy correlation decreased from 4 to 3 (of a possible 17), and the number of weeks with significantly higher eddy correlation fluxes increased from 5 to 8.

Summary and Conclusions

In this study, chamber and eddy correlation techniques were employed to characterize methane flux from a peatland in north central Minnesota. Chamber flux measurements were made between January of 1991 and October of 1992. Chamber collars were placed at 16 locations in 1991 and at 8 locations in 1992. Eddy correlation measurements were made during mid-May through mid-October of each year. Available data from 1-week periods were averaged for comparison. Chamber flux sample size for the averaging periods ranged from 6 to 52 (average = 18) in 1991 and from 5 to 8 (average = 8) in 1992.

Averaged methane flux values from both measurement techniques showed similar seasonal patterns in both years. Chamber values in 1991 were typically 1.8 mg m^{-2} hr^{-1} greater than the eddy correlation values. In 1992, the chamber data was about 1.5 mg m^{-2} hr^{-1} greater than eddy correlation data before midseason and 1.0 mg m^{-2} hr^{-1} less than eddy correlation data after midseason.

The flux of methane varied with the peat surface height. Using the chamber data from individual hummock and hollow pairs, the rate (dF/dZ) of change of flux with surface height was calculated. The magnitude of dF/dZ in 1991 ranged from about 10 to 100 (mg m^{-2} hr^{-1})m^{-1} during midseason. These results are similar to the range of magnitudes, 10 to 71 (mg m^{-2} hr^{-1})m^{-1}, observed in boreal wetlands in Canada [*Moore et al.*, 1990; *Bubier et al.*, 1993b; *Moore and Roulet*, 1993]. The values of dF/dZ were more variable in 1992, likely as a result of fewer chamber sampling locations and less frequent sampling. An earlier decline of dF/dZ after midseason in 1992, as compared to 1991, was probably the result of a smaller spatial variability in methane emission caused by the higher water table conditions.

To incorporate the spatial variability of methane flux measured with chambers, chamber flux values were scaled up using the dF/dZ data and the surface height distributions. The scaling of a chamber flux value (see (2) and (3)) was affected by the chamber's placement (relative to the surface height distribution curve) and the rate of change of methane flux with respect to surface height (dF/dZ). Because chambers in our study were, coincidentally, placed near or below the mean of the surface height distribution (see Figure 4) and because the flux decreased with distance from the water table (i.e., dF/dZ is negative), the scaled chamber values were lower than the unadjusted values. If chambers had been located following the distribution of the surface height, the need for scaling could have been avoided. The scaled-up chamber fluxes in 1991 caused an average reduction in magnitude of about 1.8 mg m^{-2} hr^{-1} and improvement in the regression slope of about 1.49 to 1.14 (r^2 0.53 to 0.75). These results were consistent both before and after midseason. In 1992, the scaling-up procedure produced a slight improvement in the comparison of chamber and eddy correlation flux values before midseason, but a poorer comparison after midseason. We speculate that the poorer comparison after midseason was related to assumptions of the scaling process for high water table conditions.

This study suggests that the effects of spatial variations of flux, on microtopographic scales, can be incorporated to make chamber measurements representative of large areas. The scaling procedure adequately addressed the discrepancies between chamber and eddy correlation flux values when the water table was at or below the surface. When the water table was above the surface, our scaling procedure did not seem to be effective. The scaling assumptions under such conditions need further evaluation. The scaling procedure may also be improved by the placement of chambers to specifically address the range of spatial variability. The scaling-up approach used in this study is preliminary. A more complete extrapolation to larger scales would require a better understanding of the controlling factors (e.g., production, oxidation, transport) and their spatial and temporal variability in the wetlands being studied.

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