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Seasonal variation of methane emissions from a temperate swamp

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Abstract. Methane flux measurements were made at four sites in a freshwater temperate swamp over the 13 month period of April 1985 through May 1986. Emissions were highly variable both between sites and over time at any one site. Ebullition from sediments was an important component of methane release. Although release of methane through bubbling occurred in only 19% of the measurements made between April and June 1985, when instrumentation allowed us to separate diffusive and bubble fluxes, ebullition accounted for 34% of the total flux during this period. Methane release rates showed a strong seasonal variation, with highest emission rates observed in early spring and again in late summer, which was associated with changes in plant growth and physiology. Emission rates were partially correlated with sediment temperature, but the relationship was not straightforward, and resembled a step function. Emissions responded strongly to temperature change through the range of 10–16 °C. At winter sediment temperatures between 4–9 °C, CH_4 flux continued at low rates (0–28 mg CH_4 m^{-2} d^{-1}; average = 7.9 mg CH_4 m^{-2} d^{-1}) and appeared insensitive to changes in sediment temperature. Annual methane emission from three constantly flooded sites (mean water depth = 35 cm) was 43.7 +/− 7.8 g m^{-2} (standard error); annual flux from a bank site was 41.4 +/− 20.5 g m^{-2}. A comparison of flux measurements from fresh and saline wetlands in the immediate area of Newport News Swamp emphasizes the importance of edaphic factors in controlling flux.

Introduction

Methane is a trace gas, primarily of biogenic origin, which influences atmospheric chemistry and radiative transfer processes. A secular increase in methane concentration in the earth's atmosphere of 1–2% per year over the last decade has been documented and presages potential changes in atmo-

spheric chemistry and climate on a global scale (Rasmussen & Khalil 1981; Blake et al. 1982; Ehhalt 1985; Ramanathan et al. 1985). Improved assessments of the magnitude of the major sources and sinks of atmospheric methane are therefore of particular interest at this time.

Methane is a terminal product of the bacterial remineralization of organic matter under strictly anaerobic conditions. Flooded soils of natural and freshwater wetlands provide large areas of suitable anaerobic habitat that are important sources of tropospheric methane (Baker-Blocker et al. 1977; Ehhalt & Schmidt 1978). Other sources of methane include enteric fermentation in ruminants, decomposition of solid waste in landfills, biomass burning, and fossil fuel extraction and processing (Khalil & Rasmussen 1983; Ehhalt 1985; Bingemer & Crutzen 1987). Although the major sources of tropospheric methane have been identified, there is still substantial uncertainty in the estimate of the relative contributions of these various sources to the total budget. This uncertainty is illustrated by estimates of annual methane emissions from freshwater wetlands that range from 11 to 300 Tg (Ehhalt & Schmidt 1978; Seiler 1984; Holzapfel-Pschorn & Seiler 1986).

For wetlands, the wide range in estimates of annual methane emissions is due to differing assumptions about areal estimates of wetlands, the magnitude and annual duration of methane fluxes from wetlands, and from the wide variability in measured flux rates themselves. For instance, methane fluxes from different cypress habitats in freshwater wetlands during the summer (soil temperatures from 20–29 °C) ranged from 8 to 970 mg CH_4 m^{-2} day^{-1}, or over two orders of magnitude (Harriss & Sebacher 1981).

To date, few long-term studies and estimates of annual flux of methane from natural wetlands exist. In this paper, we report results of a seasonal study of methane flux from a temperate swamp located in Virginia, USA. The data show a pronounced seasonal cycle which includes a dependency on sediment temperature. Emissions were highly variable, and ebullition formed a significant component of the flux from this shallow water wetland.

Methods

Field sites

This study was conducted in Newport News Swamp, located in Newport News City Park (37°14′N, 76°30′W) near Yorktown, Virginia, in coastal southeastern U.S.A. Newport News Swamp is about 40 ha in area and was formed ca. 1862 during the American Civil War by damming Beaver Dam

Creek to impede the progress of Union Army troops. The area has been maintained as a swamp and reservoir system since that time (M. Poplawski, pers. comm.).

Dominant plants in the swamp are common cattail (*Typha latifolia* L.), arrow-arum (*Peltandra virginica* L.), lizard's tail (*Saururus cernuus* L.), swamp smartweed (*Polygonum coccineum* Muhl.), swamp loosestrife (*Decodon verticillatus* [L.] Ell.), and pumpkin ash (*Fraxinus tomentosa* Michx.). Water depth at the sites is typically less than 0.4 m and fluctuates due to evapotranspiration, precipitation, and drawdown of the adjoining city reservoir. Water generally flows slowly through the swamp and has a pH of about 7.8.

The top 20 cm of soil is organic (25–40% loss on ignition at 550 °C) and unconsolidated. Bulk density at these depths is between 0.08–0.2 g cm^{-3}. Below 20 cm, the organic layer grades into the silt and clay of the underlying Pleistocene Shirley Formation.

Flux measurements were made from a boardwalk that provides a transect across the swamp and reduced disturbance to swamp waters and soils during the measurements. Because previous work has shown that emissions of methane may vary widely among different habitats within a single wetland (Harriss & Sebacher 1981; Bartlett et al. 1988), we made flux measurements in several habitats in the swamp. One site was along the south bank of the swamp under a mixed, mesophytic stand composed of white oak (*Quercus alba*), swamp oak (*Q. bicolor*), red maple (*Acer rubrum*), and beech (*Fagus grandifolia*), but dominated by oak (Bank site). The second site (*Peltandra* site) had a stand of emergent macrophytes, with *Peltandra virginica* dominant during the early growing season and *Saururus cernuus* dominating later after the *Peltandra* had senesced. The third site (Smartweed site) had a stand of the emergent macrophyte, *Polygonum coccineum*. A fourth site (Ash tree site) was among a stand of pumpkin ash (*Fraxinus tomentosa*) but free of emergent vegetation.

Measurement techniques

A single flux measurement was made at each of the four sites at roughly two week intervals over a sampling period from April 1985 through May 1986. Methane fluxes were determined by two methods during the course of the study. From April through July 1985, we used a gas filter correlation (GFC) infrared detector coupled to an aluminum open bottom chamber (0.265 m^2 area by 0.26 m height). The chamber was placed over vegetation and water or soil surfaces; a flotation collar held the chamber stable. The rim of the chamber was generally 4 cm below the water surface. The chamber was

shaded with a mylar blanket to minimize temperature changes within the system. Air is continuously circulated between the chamber and the GFC detector while air within the chamber is mixed by a small fan. The depth at which the chamber floated was recorded to correct for chamber volume variation. Changes in methane concentration were monitored continuously, and methane flux was calculated directly from the trace of the output from the GFC detector. This system was used to distinguish bubbling events from diffusive flux, since bubble events cause a discrete shift in detector output. Measurements were typically taken in less than 20 minutes. Fluxes as low as $0.3\,mg\,CH_4\,m^{-2}\,d^{-1}$ can be detected. Description of instrument design, calibration and field testing have been published (Sebacher & Harriss 1982; Sebacher 1985).

From August 1985 to May 1986, methane flux determinations were made by taking samples of the head space of the aluminum chamber and analyzing the concentration of methane by gas chromatography. Air within the chamber was mixed continuously by a small fan during the sampling period. At four minute intervals, aliquots ($50\,cm^3$) of the headspace were withdrawn through an air sampling port in the top of the chamber fitted with a Pharmaseal three-way plastic valve into $60\,cm^3$ plastic syringes and sealed with three-way plastic stopcocks. Samples taken in this way show less than 1% loss after 48 hours. Methane mixing ratios inside the chamber increased over the measurement period, indicating that these swamp habitats acted as sources for atmospheric methane.

Methane concentrations of the gas samples were determined on a Shimadzu Mini-2 gas chromatograph fitted with a flame ionization detector. Air samples were loaded onto a Carle gas sampling valve with a $0.5\,cm^3$ sampling loop and injected onto a Poropak Q column held at 60 °C. The carrier gas was nitrogen with a flow rate of $30\,cm^3\,min^{-1}$. Methane peaks were quantified with a Hewlett-Packard 3390A integrator. Methane flux was determined from the slope of the concentration change in five samples taken over the 20 minute sampling period. This technique provides an estimate of the total net flux but does not differentiate between diffusive and bubble fluxes as the GFC detector can.

The temperature of the air, water and sediment at 10 cm depth was determined during each sampling period at each site. Water depth at the sites was also recorded.

Concentrations of dissolved methane in sediment pore water were measured at the *Peltandra* and *Fraxinus* (ash tree) sites using plexiglass close-interval dialysis samplers similar to those described by Hesslein (1976). The compartments of the samplers were filled with deionized water, covered with a Teflon membrane, and placed into the sediment for an equilibration

period of a minimum of two weeks. Upon retrieval of the sampler, samples (4 cm^3 in volume) were quickly withdrawn into 10 cm^3 disposable glass syringes fitted with gas-tight stopcocks. These samples were returned to the laboratory and analyzed within four hours. For analysis, 6 cm^3 of room air was introduced into the syringe, the sample vigorously shaken for two minutes and the methane in the headspace quantified by gas chromatography as described above (McAuliffe 1971). This method strips 98% or more of the methane from the water sample.

Methane standards were obtained from Scott Gases (Plumsteadville, PA) and were calibrated with an N.B.S. certified standard. Samples were usually analyzed within 1–4 hours following sampling. Separate sets of syringes were used for flux and porewater methane measurements. All syringes were disassembled after use to permit interior plastic and rubber plunger tip to equilibrate with ambient methane before reuse.

Results and discussion

Flux measurements

Rates of methane emission from each habitat in Newport News Swamp varied widely over the course of this study (Table 1). Similar variability of CH_4 flux has been reported from salt marshes (King & Wiebe 1978; DeLaune et al. 1983), the Great Dismal Swamp (Harriss et al. 1982), and subarctic mires (Svensson and Rosswall 1984). This variability presumably results from the complexity and heterogeneity of processes controlling the production, consumption, and release of methane from soils including seasonal temperature (Zeikus & Winfrey 1976; Baker-Blocker et al. 1977; Bartlett et al. 1985), spatial heterogeneity of microhabitats (Crill and Martens 1983), bacterial distribution in peat, and differences in substrate quality and quantity (Svensson & Rosswall 1984).

Table 1. Methane flux from four sites in Newport News Swamp.

Habitat	No.	CH_4 flux (mg CH_4 m^{-2} day^{-1})		
		Average	Median	Range
Swamp Bank	29	117	70	bd*–475
Peltandra Stand	29	155	136	4–469
Smartweed Stand	29	83	21	bd–405
Ash Tree Stand	29	152	53	bd–1005

* bd = below detection limits, between 0.3 and -0.3 mg CH_4 m^{-2} day^{-1}. These values were treated as zero in calculation of the means. No negative values were actually observed.

The distribution of all CH_4 flux measurements ranges over three orders of magnitude, with approximately 40% of the measurements falling within the range of 100–500 mg CH_4 m^{-2} d^{-1}. A frequency distribution of the measurements is non-normal (data not shown), as has been observed for methane flux in other wetlands (e.g., Harriss et al. 1985; Bartlett et al. 1988), and is the result of the combined activity of several different release processes. The observed flux includes diffusive emissions from sediment to water to air, episodic release of methane through ebullition when methane concentrations in the sediment reach saturation, and transport of methane through the stems of emergent aquatic plants.

Methane loss through ebullition

Between April and July 1985, when use of the GFC detector system permitted separation of diffusive and bubble emissions, methane release through bubbling was observed in 19% of our measurements. Bubbling events were observed on different sampling dates among sites, but bubbling frequencies were similar at all sites (observed frequencies were 18%, 18%, 27% and 20% for the bank, *Peltandra*, smartweed and ash tree sites, respectively). Analysis of gas bubbles collected with an inverted funnel indicated CH_4 mixing ratios of 30–80%, similar to values reported previously (Dacey & Klug 1979; Cicerone & Shetter 1981; Holzapfel-Pschorn & Seiler 1986). During the bubbling events, individual CH_4 release rates from ebullition ranged between 28 and 962 mg CH_4 m^{-2} d^{-1}, with an average of 180 mg CH_4 m^{-2} d^{-1}. Although bubbling events are variable both in magnitude and time, we can obtain an estimate of their contribution to the total flux by multiplying the average flux observed during bubbling events (180 mg CH_4 m^{-2} d^{-1}) by the observed bubbling frequency (19%) to obtain an average bubble flux over time from the sites of 34 mg CH_4 m^{-2} d^{-1}. Average diffusive flux was 66 mg CH_4 m^{-2} d^{-1} over the same period. Thus ebullition accounts for 34% of the total flux during this period, although it occurred in less than 20% of our measurements.

Seasonal variation

Although methane fluxes from Newport News Swamp are highly variable both in space and time, a seasonal pattern in CH_4 emission rates was observed. To reduce some of the high frequency temporal variability in the data, the study period of 13 months was broken into two week intervals and fluxes and environmental parameters were averaged within these intervals.

Seasonal changes in soil temperature and water depth are shown in Figs.

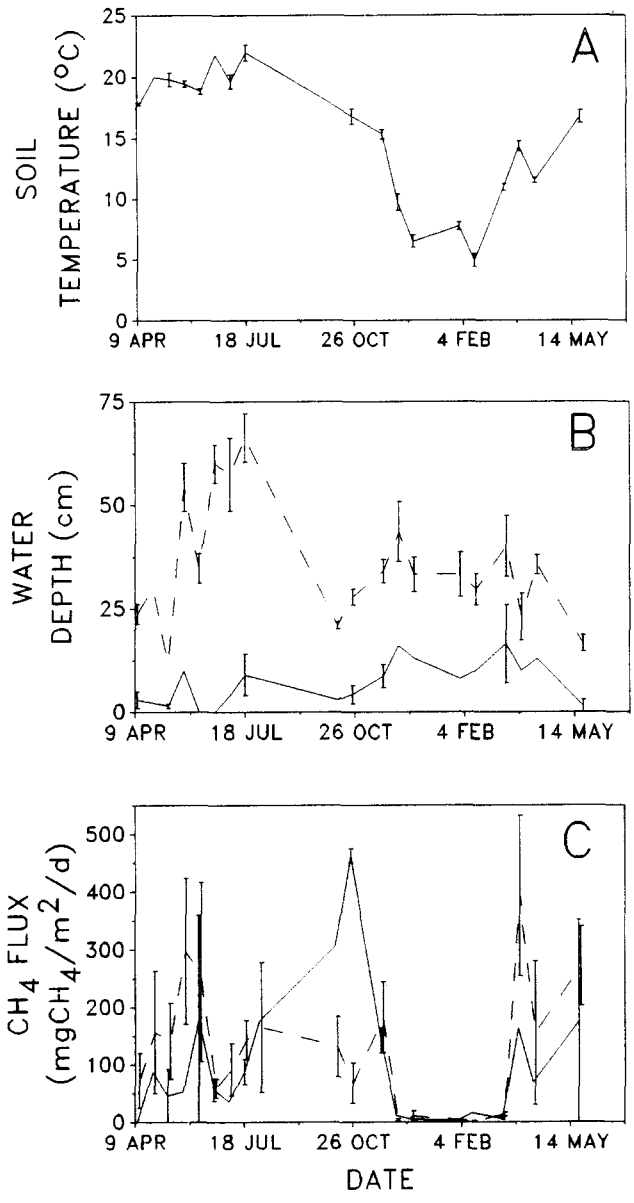

Fig. 1 A – Average sediment temperature at all four sites (10 cm depth). Error bars represented standard error of the mean. Lack of error bars indicates only a single measurement was available. *B* – Water depths at the bank site (solid line) and at the three deep sites (dashed line). Error bars indicate standard error of the mean. *C* – Methane flux at the bank site (solid line) and at deeper sites (dashed line). Error bars indicate standard error of the mean.

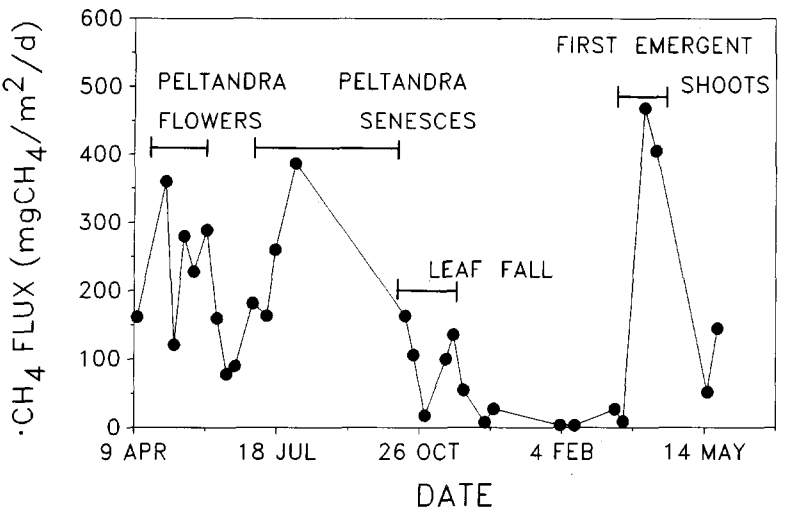

Fig. 2. Seasonal variation of CH_4 flux from the *Peltandra* site. Line connects the actual flux measurement for that sampling date.

1a and 1b, respectively. Soil temperatures were similar at all four sites and have been averaged together. Although seasonal changes in water depth follow similar trends, water depths at the bank site (mean = 7 cm) were significantly lower than those at the other three sites (mean = 35 cm; hereafter called the deep sites). Occasionally soil at the bank site was exposed to the air, especially during drawdown of the reservoir. The presence of water over a soil and its depth has been shown to be an important parameter influencing the production and subsequent release of methane (Harriss et al. 1982; Sebacher et al. 1986). For this reason, in the discussion that follows emissions at the bank site have been treated separately while those from the other three sites have been averaged together.

Methane emissions from the bank site and the deep sites showed a significant seasonal variation (Fig. 1c). The large standard errors of the mean values reflect the variability of the data on each particular sampling date. Although for most of the study period average fluxes from the deep sites are somewhat greater than those from the swamp bank, statistical analysis of these differences (Student t-test) indicated that they were not significant due to high variability.

Integration under the curves for seasonal methane emissions shown in Fig. 1c provides an estimate of annual flux from the sites. Annual release of methane at the bank site ($43.7\,g\,CH_4\,m^{-2}$ +/− a standard error of $7.8\,g\,CH_4\,m^{-2}$) was slightly higher but not significantly different from annual flux from the deeper water sites ($41.4\,g\,CH_4\,m^{-2}$ +/− $20.5\,g\,CH_4\,m^{-2}$).

Seasonal trends in methane emissions at the bank and deep sites were similar. CH_4 fluxes increased in spring, declined in early summer, then increased again in late summer. At the deep sites, emissions decreased through the autumn to low levels by the middle of December. At the bank site, however, emissions reached a seasonal maximum in the autumn before falling to similarly low levels in the winter. Autumn emissions at the bank site were significantly greater than those from the deep sites (Student–Newman–Keuls test, $p < 0.01$).

Seasonal variation of CH_4 release rates from a site with emergent vegetation (*Peltandra* site) reflects the influence of several different processes (Fig. 2). The increase in CH_4 flux rates in the spring most likely reflects mineralization of labile organic matter accumulated in the soil during the winter, when microbial activity is low. As temperature increases in the spring, this organic matter is rapidly decomposed by fermentative bacteria to produce substrates for methanogenesis. Stimulation of decomposition rates during spring has also been observed during decomposition of salt marsh litter (Wilson et al. 1986). Similar high levels of CH_4 release have been observed during early spring in the Great Dismal Swamp (Harriss et al. 1982).

High rates of CH_4 release during spring at the *Peltandra* site also coincide with the flowering stage of *Peltandra* growth. Increased rates of CH_4 release have also been observed during the flowering stage of the rice plant life cycle (Seiler et al. 1984; Holzapfel-Pschorn & Seiler 1986). The flowering stage is a physiologically active period of plant growth, during which active growth of plant roots is also occurring, with translocation of photosynthate to the root system, and concomitant release of root exudates, root lysates, and sloughing of root material. These materials can be rapidly fermented to produce substrates for methane production in soils.

The second maximum in CH_4 emission observed during the summer may also be explained by the influence of plants, through organic matter released by plant roots upon the onset of senescence (Tukey 1970; Howarth & Teal 1979).

An autumn peak of methane emissions at the sites coincided with the period of maximum leaf fall, presumably reflecting a pulse of organic substrates added to the sites. Highest fluxes at this time were observed at the bank site, which is situated at the border of a mixed stand of oak/maple and receives the greatest amount of leaf litter during leaf fall.

Minimum rates of CH_4 release were observed during winter and early spring. Since the presence of macrophytes, such as *Peltandra*, is highly seasonal, their absence during the winter removes an important pathway for methane release. Upon emergence of *Peltandra* shoots above the water level in spring, a high flux of CH_4 occurred, reflecting the diffusive transport of methane through the stems of *Peltandra* plants as previously demonstrated

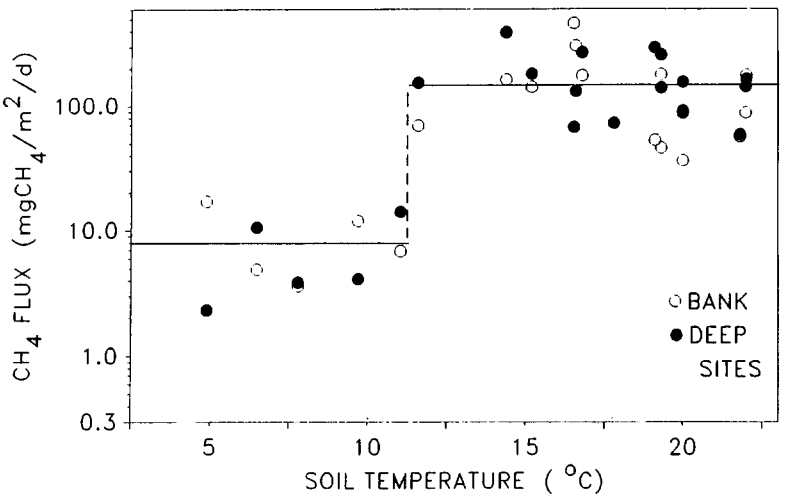

Fig. 3. Plot of methane flux versus soil temperature for measurements made at the bank site (○) and at deeper sites (●). Symbols show methane flux and soil temperatures averaged for two week sampling intervals. Line suggests a step function as discussed in the text, joining the average flux at low temperatures (7.9 mg $CH_4 m^{-2} d^{-1}$) with the average high temperature flux (155 mg $CH_4 m^{-2} d^{-1}$).

by Sebacher et al. (1985). Similar results were reported by Holzapfel-Pschorn & Seiler (1986) and Cicerone & Shetter (1981) for rice plants.

Methane flux-temperature relationship

The dependency of methane flux on temperature has been previously noted. Work in freshwater lake sediments (Zeikus & Winfrey 1976; Kelly & Chynoweth 1981), wetlands (Baker-Blocker et al. 1977), and other environments indicates a strong correlation between temperature and methanogenesis. In this study, however, this dependency was not the expected simple logarithmic function (Zeikus & Winfrey 1976), and may best be represented by a step function (Fig. 3). At both bank and deep sites, methane flux appeared to be relatively constant at temperatures below 10 °C during the winter months, and above 16 °C in the summer months. The major changes in methane flux occurred between 10 °–16 °C, during spring and fall. In contrast to observations made in some salt marsh systems (Howes et al. 1985; Bartlett et al. 1987), equivalent rates of methane emission were observed at similar temperatures in spring and autumn.

In comparing our results with those of other studies, however, it is important to note that in these previous studies, results are based on data obtained in short-term or laboratory incubations, and do not reflect seasonal

variation of CH_4 flux rates measured over an annual cycle. The seasonal response to temperature observed in this study may not only be due to the metabolic response of methanogens to temperature change, but also to increases in populations of methanogens, increases in concentrations of substrates (Zeikus & Winfrey 1976; Holzapfel-Pschorn & Seiler 1986), and changes in the physiology and presence or absence of emergent macrophytes.

Methane flux-water depth relationship

In some previous studies, water depth was an important factor regulating methane flux (Harriss et al. 1982; Sebacher et al. 1986), but in the present study flux at both bank and deep sites was poorly correlated with water level. Multiple regression analysis of methane flux with soil temperature and water level at the sites indicates that the addition of water depth to the relationship does not significantly reduce unexplained variation in flux over using soil temperature alone.

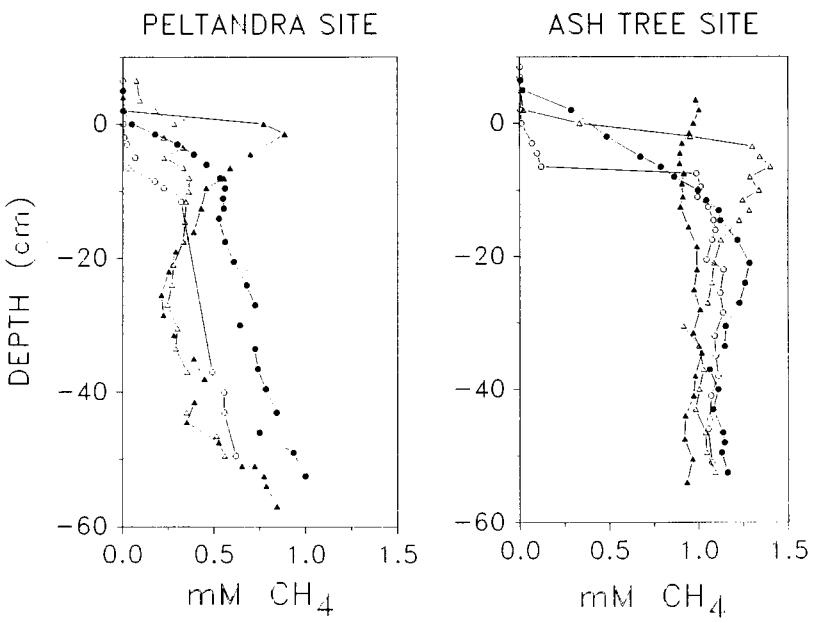

Fig. 4. Seasonal methane pore water profiles at two deeper water sites. *A* – site vegetated by *Peltandra* and *B* – the *Fraxinus* (ash tree) site. November 1985 (○); February 1986 (●); April 1986 (△); and May 1986 (▲).

Pore water methane

In wetlands, methane flux to the atmosphere is ultimately dependent on production and release of methane from anoxic sediments to the overlying water column. Pore water methane profiles measured at the *Peltandra* and *Fraxinus* (ash tree) sites (Fig. 4) suggest that significant quantities of methane are present year-round in the sediments. Porewater methane concentrations increased rapidly with depth, reaching saturation with respect to a pure methane atmosphere within 5–10 cm of the sediment/water interface.

Concentrations of methane in near-surface sediments (above about 20 cm) were more variable over time than those in sub-surface sediments. Seasonally, the lowest concentrations of porewater methane in near-surface sediments occurred in November, with high concentrations occurring in April or May. Seasonal changes in the concentration of methane would be expected to be more pronounced in near-surface sediments where both temperature change and variations in supply of organic materials such as leaf litter, root exudates, and senescing roots and rhizomes would be greatest. We note that the root zone at the *Peltandra* site was located in near-surface sediments between 6–10 cm where high methane concentrations seasonally occur.

Although the concentration gradient of methane between sediment and water has been shown to be a factor controlling rates of diffusive methane flux (Bartlett et al. 1985), in this work correlation between methane flux and the near-surface concentration gradient determined by linear regression of methane concentrations in the top 10 cm of sediment (Fig. 4) was not significant ($r = 0.52$, $n = 7$, n.s.). This poor correlation indicates the importance of other mechanisms of methane loss such as ebullition and diffusive transport of methane through plants and emphasizes the complexity of processes controlling release.

Our results and recent work in rice paddies (Cicerone et al. 1983; Holzapfel-Pschorn & Seiler 1986) demonstrate that methane fluxes from wetlands are highly variable over both daily to seasonal time scales. Other studies have shown variations in flux among different wetland habitats (Harriss & Sebacher 1981; Bartlett et al. 1988). Because methane flux is a function of a variety of processes and release mechanisms which may vary seasonally and among sites, simple correlations with factors such as temperature provide, of necessity, only approximations of the true dynamics of methane flux.

Regional variation in methane flux

The data presented in this paper on seasonal release of methane from a temperate swamp, together with data published earlier by our group on

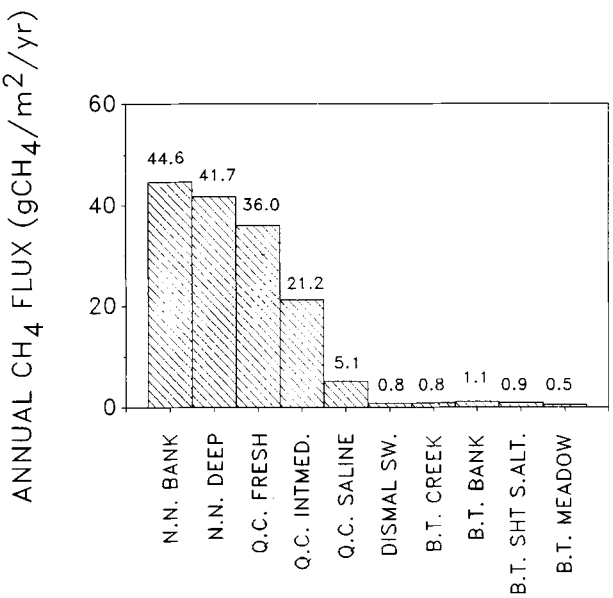

Fig. 5. Magnitude of annual methane flux from wetland sites studied in Virginia, USA. Values were obtained by integration of Fig. 6 and differ slightly from those published previously. Data adapted from Harriss et al. 1982; Bartlett et al. 1985; Bartlett et al. 1987; this study. Site abbreviations: N.N., Newport News: Q.C., Queens Creek, fresh, intermediate and saline sites; B.T., Bay Tree, creek, creek bank, short *Spartina alterniflora*, high marsh meadow sites.

methane emissions from Great Dismal Swamp (Harriss et al. 1982), and from brackish and salt marshes in Virginia (Bartlett et al. 1985; Bartlett et al. 1987), provide a unique data set for the synoptic examination of factors controlling methane emissions from temperate wetlands.

Highest annual methane emissions were found from the freshwater wetlands in this area (Fig. 5). Annual emissions from freshwater systems ranged widely, however, and annual flux of CH_4 from the Great Dismal Swamp during a drought year was only $0.5\,g\,m^{-2}$ (Harriss et al. 1982). Methane emissions above $20\,g\,CH_4\,m^{-2}\,yr^{-1}$ were observed under brackish conditions, at salinities of 8–17 ppt (Bartlett et al. 1987). Low annual emissions were reported from the more saline sites.

Comparison of measured methane emissions from these various habitats illustrates several important points relevant to understanding factors influencing methane flux in these temperate wetland systems (Fig. 6). First, in these habitats subject to pronounced annual temperature variations, emission rates showed strong seasonal cycles and a partial dependency on temperature. Second, other factors apparently affected methane flux, including supply of organic matter, hydrology, plant phenology, and soil salinities.

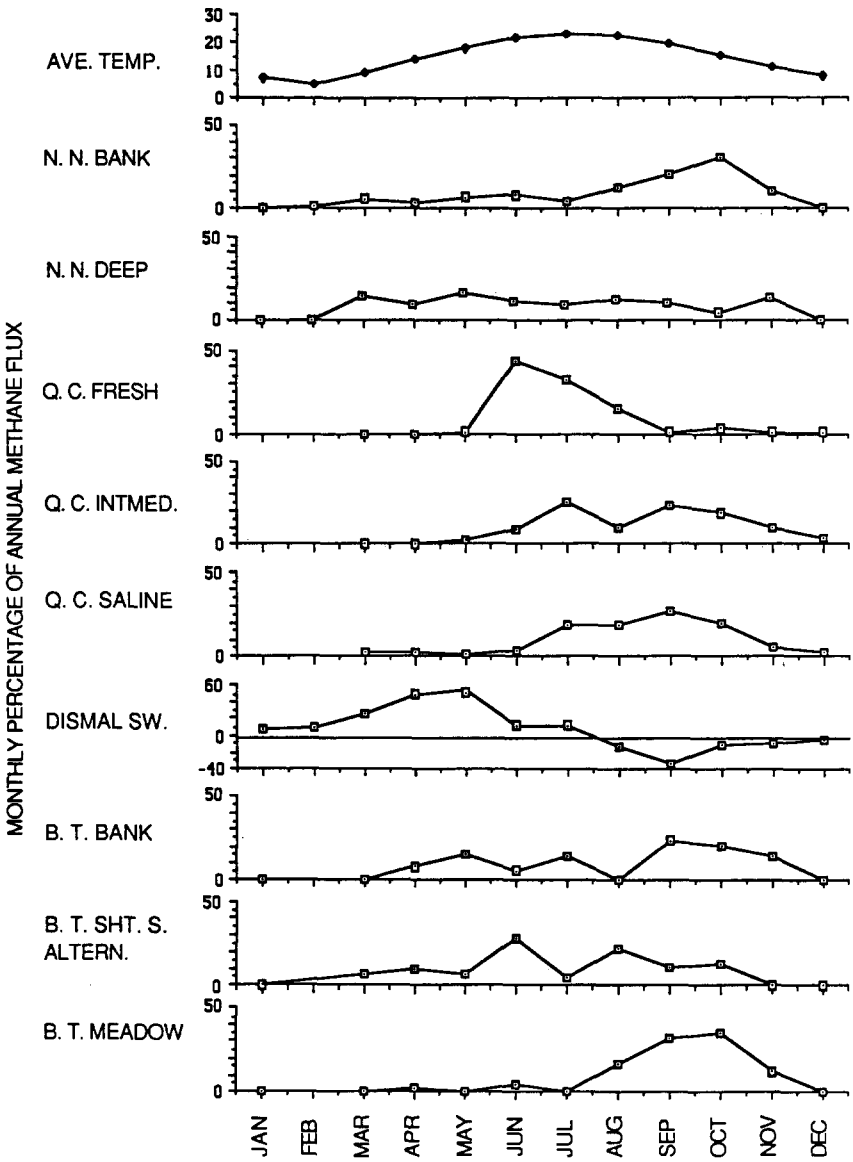

Fig. 6. Seasonal changes in methane flux from Virginia wetlands. Plotted values are monthly averages of the actual measurements. Air temperatures plotted are long-term monthly averages. Site abbreviations: N.N., Newport News; Q.C., Queens Creek, fresh, intermediate and saline sites; B.T., Bay Tree, creek, creek bank, short *Spartina alterniflora*, high marsh meadow sites. Data from Harriss et al. 1982; Bartlett et al. 1985; Bartlett et al. 1987; this study.

As shown in Fig. 6, although there is a general correspondence of flux to temperature at all of the sites studied, variation in the onset of flux, the time of highest emissions, and the duration of the period of emissions is considerable. Initiation of higher fluxes can happen anytime from March, e.g., Newport News Swamp deep sites to August, e.g., Queen's Creek Marsh saline site or Bay Tree marsh meadow site. Maximum fluxes were observed at a variety of times from May through October. Peak fluxes even occurred at different times within the same wetland, e.g., Queen's Creek. The extent of this variability under the same overall climatic setting is strong evidence for the importance of smaller scale environmental parameters controlling methane flux to the troposphere. It also suggests that latitudinally averaged methane productive seasons used in global models (Mathews & Fung 1987) may have considerable error terms, at least in temperate regions.

Our data from Virginia wetlands suggest that seasonal changes in methane flux may be closely linked to the dynamics of the vascular plant communities, although we lack quantitative data to rigorously test this hypothesis. Differences between plant communities in the timing of emergence, growth, reproduction, and senescence may account for some of the differences we observe in flux seasonality. In temperate regions like Virginia, it is clear that while the overall climatic and edaphic regime sets the bounds for fluxes of biogenic gases such as methane, biological variables can strongly influence the timing and magnitude of their flux.

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