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Regional-scale measurements of CH_4 exchange from a tall tower over a mixed temperate/boreal lowland and wetland forest

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Abstract

The biosphere–atmosphere exchange of methane (CH_4) was estimated for a temperate/boreal lowland and wetland forest ecosystem in northern Wisconsin for 1997–1999 using the modified Bowen ratio (MBR) method. Gradients of CH_4 and CO_2 and CO_2 flux were measured on the 447-m WLEF-TV tower as part of the Chequamegon Ecosystem–Atmosphere Study (ChEAS). No systematic diurnal variability was observed in regional CH_4 fluxes measured using the MBR method. In all 3 years, regional CH_4 emissions reached maximum values during June–August ($24 \pm 14.4\,mg\,m^{-2}\,day^{-1}$), coinciding with periods of maximum soil temperatures. In 1997 and 1998, the onset in CH_4 emission was coincident with increases in ground temperatures following the melting of the snow cover. The onset of emission in 1999 lagged 100 days behind the 1997 and 1998 onsets, and was likely related to postdrought recovery of the regional water table to typical levels. The net regional emissions were 3.0, 3.1, and 2.1 g $CH_4\,m^{-2}$ for 1997, 1998, and 1999, respectively. Annual emissions for wetland regions within the source area (28% of the land area) were 13.2, 13.8, and 10.3 g $CH_4\,m^{-2}$ assuming moderate rates of oxidation of CH_4 in upland regions in 1997, 1998, and 1999, respectively. Scaling these measurements to the Chequamegon Ecosystem (CNNF) and comparing with average wetland emissions between 40°N and 50°N suggests that wetlands in the CNNF emit approximately 40% less than average wetlands at this latitude. Differences in mean monthly air temperatures did not affect the magnitude of CH_4 emissions; however, reduced precipitation and water table levels suppressed CH_4 emission during 1999, suggesting that long-term climatic changes that reduce the water table will likely transform this landscape to a reduced source or possibly a sink for atmospheric CH_4.

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Introduction

Methane (CH_4) is a greenhouse gas with a global warming potential that is 23 times that of CO_2 over 100-year timescales (IPCC, 2001). Thus, it is important to recognize all global sources and sinks of atmospheric CH_4, and determine how CH_4-producing environments will respond to climate change. Natural and cultivated wetlands are estimated to contribute ~40% of the annual global emission of CH_4 to the atmosphere, yet estimates of CH_4 emissions from wetland environments can vary over orders of magnitude (Crill *et al*., 1992), making global extrapolations difficult (IPCC, 2001). Estimates of the contribution from northern temperate and boreal (>40°N latitude) wetlands to atmospheric CH_4 vary considerably (Cao *et al*., 1998; Panikov, 1999), but the contribution is likely to be significant (30–60%) when compared with global wetland sources (Bartlett & Harriss, 1993; Birkett, 1998). Multiple-year CH_4 emission estimates are needed to test the sensitivity of northern wetlands to climate change (e.g., Worthy *et al*., 2000), to assess the relative importance of winter and

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cold-period CH_4 (e.g., Sommerfeld *et al.*, 1993; Panikov, 1999), and also to test process-based models of CH_4 emissions (e.g., Walter & Heimann, 2000).

CH_4 is both produced and consumed within a soil profile by microbial activity under anaerobic and aerobic conditions, respectively (e.g., Edwards *et al.*, 1998). Variability of the CH_4 flux on various timescales (diurnal, seasonal, and interannual) has been correlated to be changes in environmental conditions specific to an area including vegetation type, soil temperature, soil moisture, and water table levels (Shannon *et al.*, 1996; MacDonald *et al.*, 1998; Friborg *et al.*, 2000). The type of vegetation in a wetland has a strong influence on how CH_4 is transported to the surface. Diurnal variability of CH_4 fluxes is often correlated to a specific plant species and to changes in light intensity or variations in daily temperature (Mikkela *et al.*, 1995; Shannon *et al.*, 1996; Whiting & Chanton, 1996). Studies conducted over periods of months to years typically show that CH_4 fluxes in wetlands increase with increasing soil temperatures and water table levels. However, relatively few studies have been conducted over multiple years including wintertime measurements. Most wintertime measurements suggest that wetlands continue to steadily emit CH_4 throughout cold or snow-covered periods (Melloh & Crill, 1996; Panikov & Dedysh, 2000). Likewise, uptake of CH_4 has been observed in grassland and alpine environments during winter periods (Mosier *et al.*, 1993; Sommerfeld *et al.*, 1993). Thus, assessing the capacity of wetland and upland environments to emit or consume CH_4 during winter periods is important for quantifying global CH_4 budgets (Sommerfeld *et al.*, 1993).

Regional variability in CH_4 emission and consumption is strongly correlated to changes in topography and also vegetation type (Moosavi & Crill, 1997). Upland forested regions have been generally documented as sinks of atmospheric CH_4 (Smith *et al.*, 2000). However, upland regions may become sources of CH_4 when soils become saturated following precipitation events (Savage *et al.*, 1997; Van den Pol-van Dasselaar *et al.*, 1998). Emissions from small wetland regions (e.g., 'hotspots', Moosavi *et al.*, 1996) within forested areas have been shown to overwhelm the low-level regional uptake of CH_4. Thus, establishing the contribution from small wetland areas within a mixed forest can be essential in assessing the total CH_4 budget of a given region (Simpson *et al.*, 1997). In such cases, micrometeorological techniques are useful for obtaining large-scale representative measurements. While chamber methods are useful in understanding the processes controlling CH_4 fluxes on small spatial scales ($\sim 1\,m^2$), the small footprint of the measurement leaves a difficult scaling problem when estimating landscape-scale fluxes in a heterogeneous terrain.

This study is unique in that the CH_4 flux measurements were performed continuously over multiple years (1997–1999) on a tall tower (447 m) in a landscape composed of both wetlands and upland forest. Because the flux measurements were made on a tall tower, they are representative of an upwind source area that is larger than most studies. Wetlands throughout the area are relatively small and discontinuous (typically $<1\,km^2$) relative to forested regions, but were expected to contribute significantly to the overall CH_4 exchange in the area. The main objectives of this study were to establish the magnitude of CH_4 emission or uptake by the landscape, to evaluate the temporal variability of CH_4 (diurnal, seasonal, interannual), and to assess the correlation of CH_4 flux with environmental factors such as soil and air temperature, precipitation, and the level of the water table.

Site description

The results presented here are part of the Chequamegon Ecosystem–Atmosphere Study (ChEAS), a multi-organizational research effort studying biosphere/atmosphere interactions within a mixed forest in northern Wisconsin (also a part of AmeriFlux and FLUXNET). The primary goal of ChEAS is to obtain long-term measurements of CO_2, water vapor, trace gases, and energy exchange to help constrain the global carbon budget (see Davis *et al.*, this issue).

The ChEAS research area is located in the Chequamegon-Nicolet National Forest (CNNF), which covers approximately 325 000 ha. Within the CNNF, dominant forest types include mixed northern hardwoods (85 000 ha, 26%), aspen (75 000 ha, 23%), and lowlands and wetlands (60 000 ha, 18%); human population density in the area is sparse (approximately 5 people per km^2). The climate is cool continental, with a mean annual temperature of 4.1 °C (−12.9 °C in January, 18.9 °C in July), and the annual average precipitation is 818 mm (http://mcc.sws.uiuc.edu).

Detailed land cover maps were produced by the State of Wisconsin Department of Natural Resources, Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data (WISCLAND) project (http://www.dnr.state.wi.us/org/at/et/geo/data/wlc.htm). Land cover was interpreted in 30-m grid cells derived from LANDSAT Thematic Mapper (TM) satellite imagery acquired during August 1991; May, July, September, and October 1992; and May 1993. Vegetation within a 3-km radius region surrounding the ChEAS tall tower site includes lowland shrub and forested wetland (28%), broad-leaved deciduous forest (56%), and conifer forest (16%). Winds were distributed relatively equally about the WLEF tower during

1997–1999; winds from the south to southwest were approximately 10% more common than other directions, whereas winds from the northeast to east were approximately 5% less common than other directions.

Instrumentation and methods

Measurements were made at the 447-m-tall WLEF-TV transmitter tower located 15 km east of Park Falls, Wisconsin (45°56′43″N, 90°16′28″W). Ambient air was drawn from the 11-, 30-, 76-, 122-, 244-, and 396-m levels and CO_2 mixing ratios were measured five times per hour at each level using an LI-COR infrared gas analyzer (Model 6251) (Bakwin *et al*., 1998). CH_4 mixing ratios were measured from 30, 76, and 396 m once per hour using an automated gas chromatograph (Hurst *et al*., 1997; Bakwin *et al*., 1998; Hurst *et al*., 1998). Fluxes of CO_2 were measured at 30, 122, and 396 m by eddy covariance (EC) using 3D sonic anemometers (Applied Technologies, Model SAT-11/3 K or Campbell Scientific Inc., Logan, UT, USA, Model CSAT3, depending on the date and the level on the tower) to measure wind velocities and infrared gas analyzers (LI-COR, Model 6262) to measure CO_2 and water vapor mixing ratios (Berger *et al*., 2001). EC measurements were made at a rate of 5 Hz and time averaged over periods of 60 min for EC calculations. Further analysis of CO_2 flux measurements can be found in Yi *et al.* (2000) and Davis *et al*. (this issue).

Calculating CH_4 fluxes

Fluxes of CH_4 were calculated using both the modified Bowen ratio (MBR) method at 30 m and by calculating changes in the column integral up to 396 m at night. The MBR method relates the vertical flux of a constituent to its vertical gradient through the eddy diffusivity or exchange coefficient (k) (Meyers *et al*., 1996). Using the MBR method, the gradients of two gases are measured, and equality of transfer coefficients for both gases is assumed (i.e., $k_{CO_2} = k_{CH_4}$). In other words, turbulence is assumed to mix and transport the two gases, CO_2 and CH_4, indiscriminately. The flux of CH_4 at 30 m was calculated on an hourly basis from the difference in the mixing ratio of CH_4 and CO_2 between 30 and 76 m ($\delta_{CH_4}/\delta z$ and $\delta_{CO_2}/\delta z$), and the flux of CO_2 (F_{CO_2}) at 30 m as

$$F_{CH_4-30\,m} = F_{CO_2-30\,m}\left(\frac{\delta_{CH_4}/\delta z}{\delta_{CO_2}/\delta z}\right). \quad (1)$$

Measurement precision was approximately 10 ppb and 0.03 ppm for CH_4 and CO_2, respectively (Hurst *et al*., 1997). Uncertainty of the eddy covariance measurement of CO_2 at the 30-m level is typically $<$15–40% (Berger *et al*., 2001), and we expect the same order of uncertainty for CH_4 flux measurements. However, uncertainty was also introduced due to the relatively low sampling frequency in CH_4 mixing ratios.

The CH_4 fluxes were not included in our analysis when (1) CO_2 flux was anomalous ($>40\,\mu mol\,m^{-2}\,s^{-1}$), (2) the CO_2 gradient was small relative to the CH_4 gradient ($\delta_{CH_4}/\delta_{CO_2} \geq 0.15$, typically during the daytime hours with vigorous mixing of the boundary layer), and (3) the friction velocity was low ($u_* < 0.23\,m\,s^{-1}$, typically during the night-time hours). During summer periods, it was observed that fluxes should not be included in our analysis if δ_{CO_2} was ≤ 0.1 ppm due to the instability of (1). However, during winter periods when CO_2 fluxes and gradients were low during both daytime and night-time hours (Fig. 1), using this constraint eliminated $>90\%$ of the data. Small CO_2 fluxes and CH_4 gradients in winter make (1) more stable, despite small CO_2 gradients. Thus, the above constraint was not applied in winter periods. After applying the above constraints, trends in CH_4 flux were generally smooth (no erratic increases or decreases in flux), and daytime and night-time fluxes were consistent over periods of weeks. The fraction of data retained after eliminating data as above was 71%, 66%, and 54% for 1997, 1998, and 1999, respectively. In 1998 and 1999, CH_4 gradients were corrected for systematic offsets in mid-day CH_4 gradients between 30 and 76 m, which were 1.1 and -1.4 ppb, respectively. These offsets resulted from small systematic measurement errors that differed between tower levels. No offset was observed in CH_4 during 1997, and no mean correction was made for this year. For the purpose of obtaining cumulative CH_4 emissions over each year, missing hours of CH_4 flux data were filled with the monthly median value for the missing hour (for example, see Fig. 1). The median was used because the distribution of fluxes for a given hour of a month was often skewed such that the mean was not considered representative, and because diurnal variability of the median was more systematic than the mean. However, for periods with little missing data, the median and mean values were often similar. Cumulative emissions were calculated as the sum of the hourly values over a period of the year.

In order to obtain flux estimates using a method independent of CO_2 gradients and fluxes, CH_4 fluxes were also calculated for night-time periods from the rate of change of the column integral up to 396 m as in

$$F_{CH_4} = \frac{\partial}{\partial t}\int_0^h CH_4\,\partial z, \quad (2)$$

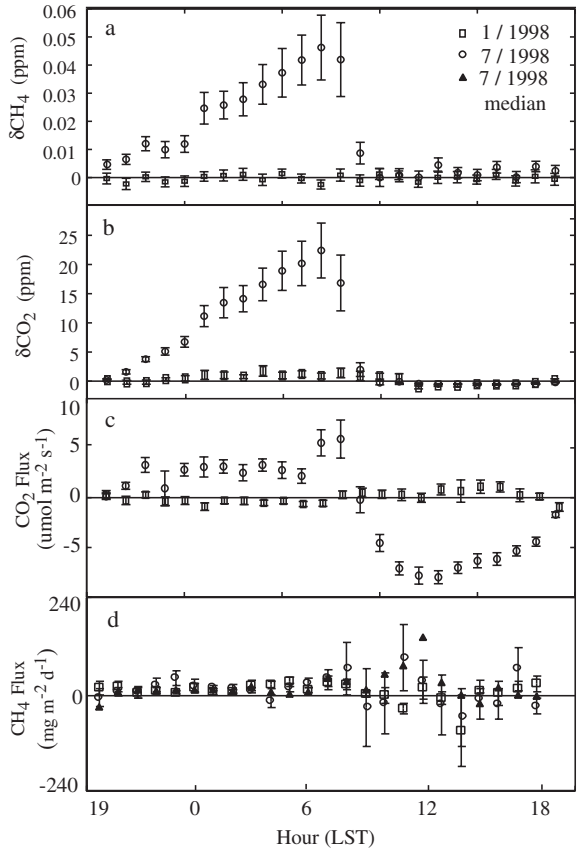

Fig. 1 Diurnal pattern of mean hourly fluxes (±standard error) for January and July 1998. CH_4 (a) and CO_2 (b) gradients (defined as the 30-m level minus the 76-m level) show increases during night-time hours (19:00–06:00 LST) and near-zero values during the day due to turbulent mixing (hours 07:00–18:00 LST). Gradients are strongest during the summer season during the height of biogenic activity. CO_2 fluxes (c) are positive during night-time hours and negative during daytime hours, reflecting respiration and photosynthesis, respectively. CH_4 fluxes (d) show no consistent diurnal variability except that daytime fluxes have a larger standard error. Daytime and night-time means were not statistically different based on *t*-tests. Mid-day median fluxes potentially exceed other hourly median values by up to a factor of two.

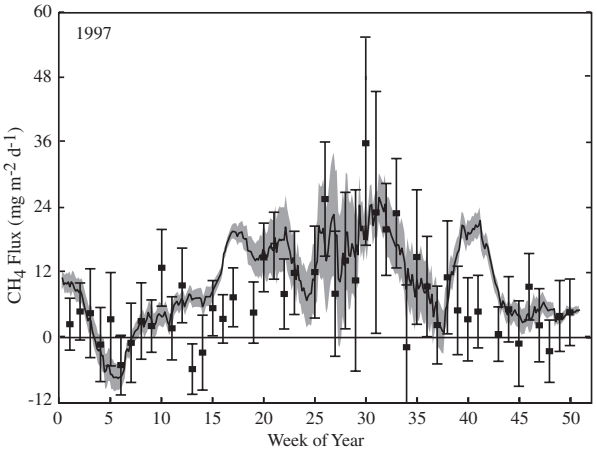

Fig. 2 A 2-week running average (the black line)±standard error (shown in dark gray shading) of the time series of CH_4 fluxes measured using the modified Bowen ratio approach, and the flux calculated from the night-time column storage up to 396 m in 1-week means (±standard error) for 1997. The two independent methods of calculating flux give similar results. The night-time storage measurements have larger error than the MBR technique because fewer measurements are included in the average, and because accurate storage cannot be calculated on windy nights. See text for discussion.

where *h* refers to the 396-m measurement height. Hence, we assume that there is no transfer of CH_4 through the 396-m level at night. Fluxes from (2) were averaged for weekly periods and compared with fluxes calculated using the MBR method (e.g., 1997 in Fig. 2). While fluxes calculated using the different methods should not be identical due to the differences in source areas for the time periods used in each calculation (i.e., only night-time data were used in flux estimates from (2), while both daytime and night-time hours were used in the MBR flux calculations), the two methods should show general agreement, thereby acting as an independent check on the results from (1). The large standard error ($6\,mg\,m^{-2}\,day^{-1}$ in winter and up to $18\,mg\,m^{-2}\,day^{-1}$ in summer months, Fig. 2) observed in weekly mean fluxes from (2) is in part a result of including windy night-time periods when strong gradients do not develop. On windy nights, CH_4 is mixed above the 396-m upper measurement level; thus, (2) results in a systematic underestimate of CH_4 emissions on windy nights. This method is also subject to error due to advection.

Results

Comparison of flux calculations

Night-time fluxes calculated from (2) and averaged over 7 days were consistent within error with CH_4 fluxes calculated using (1) for 38 out of 47 weeks, or for 81% of the available observations (Fig. 2). The general pattern of seasonal variability was observed in both calculation techniques with lowest fluxes (uptake) occurring in February and highest fluxes in July–August. Because the storage flux calculation is independent of the CO_2 gradient and CO_2 flux measurements, calculating fluxes with similar magnitude and variability with each method lends confidence to fluxes calculated using the MBR method. However,

fluxes calculated using (2) can only be calculated for night-time periods and the technique only works on fairly calm nights when the 396-m measurement level is above the top of the stable boundary layer. Therefore, we preferred the MBR approach over night-time storage calculations for the assessment of CH_4 flux in this study.

Diurnal variability

Diurnal variability of CH_4 and CO_2 gradients (Fig. 1a and b) and CO_2 fluxes (Fig. 1c) was most pronounced during the summer months. Gradients of both trace gases increased during night-time hours under stable meteorological conditions (hours 19:00–07:00), and approached zero during daytime hours when convective mixing occurred (hours 08:00–18:00) (Fig. 1a,b). CO_2 fluxes were positive during the night (net respiration) and negative during the day (net photosynthesis) in summer months (Fig. 1c), and typically produced CO_2 gradients with the same sign (Fig. 1b). CH_4 fluxes measured using the MBR technique did not display systematic diurnal variability (Fig. 1d). Mean and median hourly CH_4 fluxes displayed less variability during the night-time hours, when gradients of both CO_2 and CH_4 were large. During daytime hours, CH_4 fluxes displayed more variability when the gradients of CH_4 and CO_2 approached zero due to turbulent mixing of the atmosphere.

Seasonal and interannual variability

In all three years, CH_4 fluxes increased seasonally with increasing soil temperatures (Fig. 3a,b). In 1997 and 1998, average regional emissions of CH_4 during January and March were $<6 \pm 3.6\,mg\,m^{-2}\,day^{-1}$ (Fig. 3). Emissions reached a maximum of $24 \pm 14.4\,mg\,m^{-2}\,day^{-1}$ during the growing season (July–August) in all three years. In 1997 and 1998, negative fluxes calculated using the MBR method were observed in February during a period of snowcover, in November of 1998, and in May of 1999. However, negative fluxes were within an error of zero during these same periods when calculated using (2) (for example, see February 1997 in Fig. 2). In 1997 and 1998, the flux increased significantly following the soil thaw in March or April (Fig. 4). In 1999, the CH_4 flux did not increase until after a significant precipitation (>200 mm at WLEF) in June (Fig. 3e), and a rise in the regional water table (Fig. 3c,d).

Regional net CH_4 emission was observed in all 3 years (Fig. 4). In 1997 and 1998, the annual ecosystem emission was 3.0 and $3.1\,g\,CH_4\,m^{-2}$, respectively. The total CH_4 release during 1999 is uncertain due to missing data; yet, the region had emitted $1.8\,g\,CH_4\,m^{-2}$ by August. Fluxes of CH_4 are missing after day 274 in 1999 due to instrumental problems. If we assume that the emissions after this date can be represented by the average of 1997 and 1998 emissions during the same time period, then the total emission during 1999 was approximately $2.1\,g\,CH_4\,m^{-2}$ (Fig. 4). Within the error of the measurement, accumulated annual emissions were not significantly different for any of the years. However, a lag of approximately 100 days was observed in the onset of increasing CH_4 emission in 1999 relative to 1997 and 1998 (Fig. 4).

Discussion

Diurnal variability of CH_4 flux

Diurnal variability in soil and air temperatures, photosynthetic activity, plant type, and meteorological parameters have been suggested to affect both the production and transport of CH_4 in wetlands (Waddington & Roulet, 1996; Roulet *et al.*, 1997; Hargreaves & Fowler, 1998). Yet, diurnal variability CH_4 flux is not ubiquitous (Moosavi & Crill, 1997). Typically, a lack of diurnal variability is attributed to either a lack of response of microbes to diurnal variability in soil temperatures, inadequate transport by vascular plants out of the production zone, or insensitivity of the measurement technique. Daytime CH_4 fluxes have been observed at 25–100% higher than night-time fluxes in some studies using continuous measurement techniques (Hargreaves & Fowler, 1998; Moncrieff *et al.*, 1998). However, other studies have also observed night-time emission rates exceeding those during the day, depending on plant communities (Mikkela *et al.*, 1995).

In this study, the differences in atmospheric mixing and transport between night and day make the study of diurnal variability of emissions difficult when using the MBR method, especially due to small daytime CO_2 gradients. Hourly CH_4 flux shows no consistent or systematic diurnal variability, which is most likely related to the inherent variability in using the MBR method. Variability in hourly median CH_4 fluxes suggests that daytime CH_4 fluxes could potentially exceed night-time fluxes by a factor of two (Fig. 1); however, daytime and night-time means were significantly different for only three days out of three years using *t*-tests.

Footprint considerations

The flux measurements in this study represent the whole ecosystem CH_4 exchange with the atmosphere. The measured ecosystem fluxes represent both the

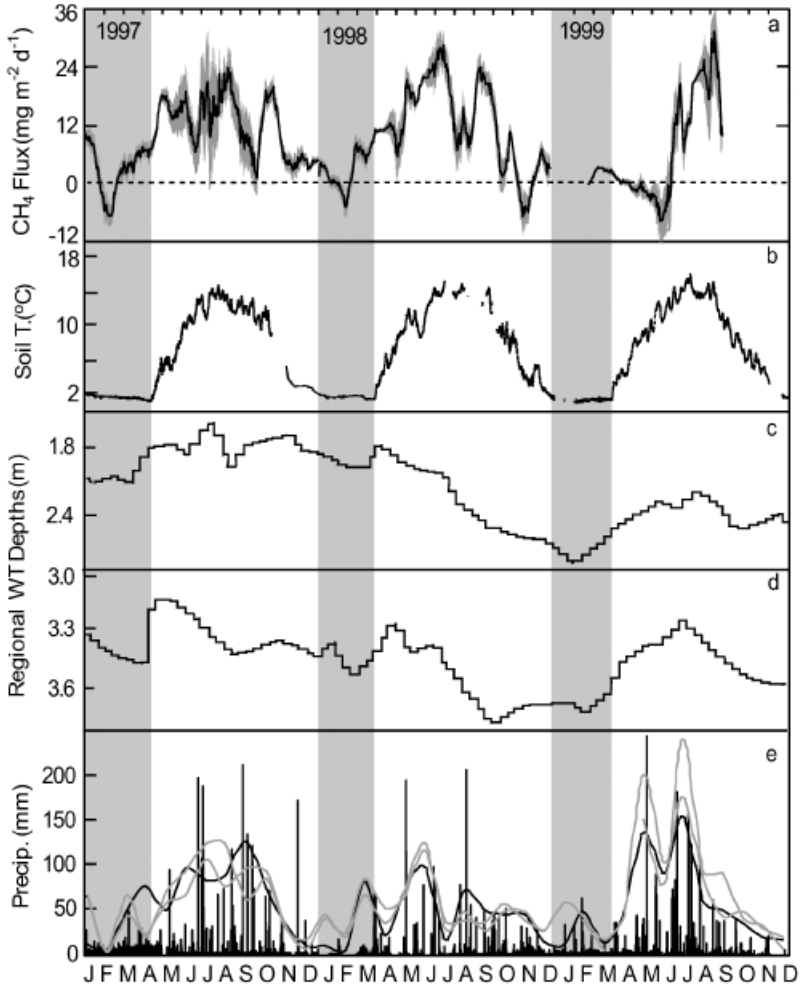

Fig. 3 (a) A 2-week running average (the black line) ± standard error (shown in dark gray shading) of the time series of CH_4 fluxes measured using MBR for 1997–1999. Light gray shaded bars indicate periods where the soil temperatures at 20 cm were $<1\,^{\circ}C$. Only a partial record of CH_4 flux exists for 1999 due to instrumental problems. (b) Record of soil temperatures at 20 cm depth at the ChEAS site. (c, d) Water table level measured at two wells in the USGS groundwater observation network for the state of Wisconsin (data obtained through http://wwwdwimdn.er.usgs.gov/gw/index.html). Well PR-0065 (c) was located 50 km southeast, and AS-0054 (d) was approximately 30 km northwest of WLEF. In both records, a lowering of the water table was observed in 1998. (e) Hourly precipitation measured at the WLEF for the three years shown in bars. Also shown is the daily average precipitation at WLEF (black line) as well as two locations near Park Falls, WI (gray lines).

wetland and upland with a certain upwind area defined by the footprint. The footprint is a model prediction of both the upwind spatial extent and the relative weight applied to upwind CH_4 sources contributing to the flux measured on a tower based on meteorological parameters (Schuepp *et al.*, 1990). Thus, the possibility of surface CH_4 flux in the upwind area contributing to the measured CH_4 flux on the tower depends on both the separation between the CH_4 source and the tower location, and the meteorological conditions during the measurement. In order to examine how much wetland (or upland) accounts for the measured ecosystem CH_4 fluxes and emissions, we assume that the footprint function is a step function. In other words, surface CH_4 fluxes at any point within the area surrounding the tower (3-km radius) contribute equally to the measured CH_4 flux on the tower, and no contribution comes from the area beyond a 3-km radius. For measurements made between 30 and 76 m above the surface, previous studies suggest that the upwind source area likely extends a minimum of 3 km from the tower (e.g. Simpson *et al.*, 1997). Within the 3 km radius of the WLEF tower, the landscape includes approximately 28% wetland, 56% hardwoods, and 16% conifer forest based on satellite imagery (http://www.dnr.state.wi.us/org/at/et/geo/data/wlc.htm).

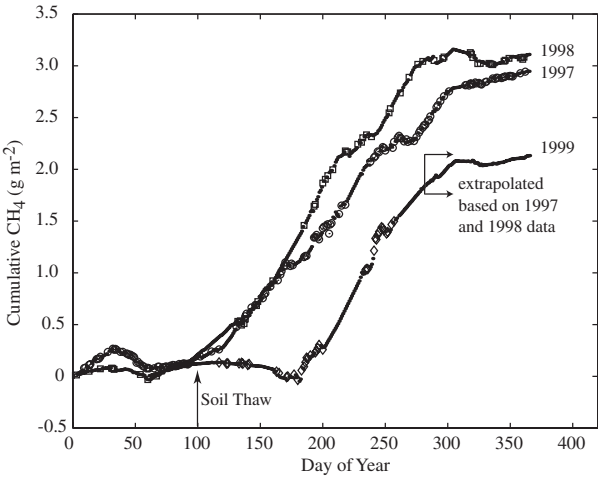

Fig. 4 Cumulative CH_4 emitted at WLEF for 1997–1999 is shown with respect to the approximate time that soil temperatures increased above zero. Increases in 1997 and 1998 emission occurred following the soilthaw in March–April. Emissions in 1999 lagged the 1997 and 1998 records by approximately 100 days and was likely related to drought conditions in 1998, causing low water tables in late 1998 and early 1999. Flux of CH_4 recovered to rates typical of 1997 and 1998 coincident with the rise of the water table in June 1999. Accumulated flux of CH_4 at the end of 1999 was estimated based on the average fluxes in 1997 and 1998 during the same time period. Within the error of the measurement, accumulated year-end emissions for all three years were not significantly different.

Seasonal variability

The seasonal variability observed over multiple years in regional CH_4 fluxes at WLEF was similar to that observed for individual wetlands using either chamber (Shannon & White, 1994) or micrometeorological (Shurpali & Verma, 1998) techniques. Seasonal changes in flux were generally coincident with the rise and fall in soil temperatures, reaching a maximum regional flux of $24 \pm 14.4\,mg\,m^{-2}\,day^{-1}$ during the summer months of each year. If we assume moderate rates of oxidation (between 2.5 and $4.8\,mg\,CH_4\,m^{-2}\,day^{-1}$; e.g., Crill, 1991; Smith *et al*., 2000) in the upland regions around WLEF, this results in maximum CH_4 fluxes $\sim 95\,mg\,CH_4\,m^{-2}\,day^{-1}$ for the wetland regions in the source area (28% of the land area). This magnitude of flux from wetlands around WLEF is consistent with what would be expected based on previous studies specific to wetland environments during a similar period of the growing season (Dise *et al*., 1993; Shannon & White, 1994; Hargreaves & Fowler, 1998; Shurpali & Verma, 1998). Thus, we suggest that the seasonal correlation between regional CH_4 flux with rising soil temperatures is most likely related to the increase in the magnitude of CH_4 emissions from individual wetland areas during periods of warmer temperatures. It follows that decreases in regional CH_4 emissions are most likely related to decreases in emissions from wetlands during cooler periods rather than increases in the uptake from upland areas within the source area.

The data also suggest that water table depth and precipitation have a very strong influence on the seasonal and weekly variability in CH_4 flux. Between July and December 1998, precipitation remained between 20% and 90% below long-term (1960–1990) monthly average precipitation levels (Fig. 5a). This drought caused the water table to drop at several locations across the state of Wisconsin (Fig. 3c,d). At well location PR-0065, approximately 50 km south-southeast of the ChEAS site, the water table dropped by over a meter between July and December of 1998 (Fig. 3c) to levels not recorded in 3 years. A similar pattern was observed at well SW-0007 located 25 km north-northwest of WLEF, where water levels reached record lows (Fig. 3d). While the water table level was not available specifically at the WLEF tower, typically waterlogged regions were dry, and water stress was observed in vegetation in the region during late 1998 (P. V. Bolstad, Department of Forest Resources, University of Minnesota, personal communication). The period following the regional drought was characterized by low CH_4 fluxes and the potential uptake of CH_4 (November 1998 and May 1999) that had not been observed in previous years (Fig. 3a). It is important to note that the uptake observed using the MBR method (up to $8 \pm 3\,mg\,m^{-2}\,day^{-1}$) during February and during drought/dry periods (November 1998 and May 1999) was not validated by the fluxes calculated using (2). Furthermore, previous studies in grassland and forested environments suggest that uptake is typically $< 1.5\,mg\,m^{-2}\,day^{-1}$ during winter periods (e.g. Sommerfeld *et al*., 1993 and references therein), suggesting that further study will be necessary to validate the uptake observed using the MBR method at the ChEAS site. However, CH_4 oxidation has been shown to increase by 41–102% during controlled drought experiments in forested regions (Borken *et al*., 2000), suggesting that the observed uptake of CH_4 could be the result of increased oxidation across the landscape during dry periods. The recovery of the regional water table in June 1999 to levels typical of previous years was coincident with the onset of measured CH_4 emission. We therefore suggest that the water table exerts strong control on regional emissions of CH_4, which has been suggested in studies of individual wetland environments (Shannon & White, 1994; Moosavi *et al*., 1996; Moosavi & Crill, 1997).

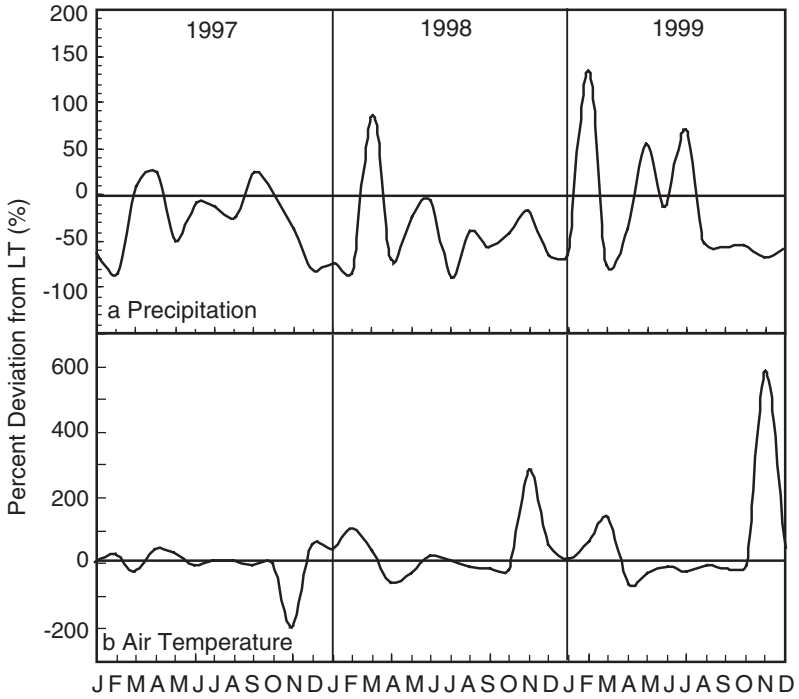

Fig. 5 Monthly deviations in precipitation (a) and mean temperature (b) relative to the long-term means (1961–1990) for Park Falls, WI, approximately 15 km west of the WLEF tower. For many months the precipitation was less than the long-term monthly averages. Monthly air temperatures did not deviate significantly from the long-term monthly average temperatures except for a few months (November 1997, November 1998, March and November 1999). Park Falls climate summary data obtained from (http://mcc.sws.uiuc.edu/Summary/Data/476398.txt).

Annual emissions from the landscape

Assuming that no emissions or uptake occurred in forested upland regions, the wetland areas within the predicted source area (28% of the 3-km radius) emitted 10.5, 11.1, and 7.6 g CH_4 m^{-2} for 1997, 1998, and 1999, respectively. These estimates are comparable to annual CH_4 emissions in central and northern Minnesota measured using both chamber and micrometeorological methods (10–30 g m^{-2} (Dise *et al.*, 1993; Shurpali *et al.*, 1993)). If we assume moderate CH_4 oxidation rates in upland regions of the forest (e.g., 2.5–4.8 mg CH_4 m^{-2} day^{-1}; Crill, 1991; Smith *et al.*, 2000), this results in an annual uptake of 0.6–0.9 g CH_4 m^{-2} in forested regions, and an annual wetland emission of 13.2, 13.8, and 10.3 g CH_4 m^{-2} in 1997, 1998, and 1999, respectively.

Finally, if we assume that the wetlands near WLEF are representative of the wetlands in the Chequamegon National Forest (CNNF; 325 000 ha, 18% wetland area), scaling the cumulative wetland emissions results in 7–10×10^9 g CH_4 annually for the CNNF. Based on these values, the wetland land area of the CNNF accounts for ~0.2% of the total natural wetland area and up to 0.16% of the CH_4 emissions, estimated between 40°N and 50°N (Cao *et al.*, 1998). This suggests that the wetlands of the CNNF contribute about 40% less than the average emission expected from natural wetlands for this latitude.

Long-term implications

The amounts of monthly precipitation during 1997–1999 at WLEF were typically less than the long-term (1961–1990) averages of monthly precipitation for Park Falls, WI (Fig. 5). The drought that occurred between July and December of 1998 resulted in deviations in precipitation between 20% and 90% below long-term monthly averages, and resulted in reductions of CH_4 emissions. Thus, if any climatic changes occur that result in further reductions of precipitation, or permanent decreases in the regional water, this will likely reduce the capacity of the region to emit CH_4, or potentially convert the CNNF from a source to a sink of atmospheric CH_4 (Crill *et al.*, 1991; Whalen *et al.*, 1992).

Monthly mean air temperatures during 1997–1999 were generally similar to the long-term average temperatures for each month, with a few significant exceptions in the spring or fall of each year (Fig. 5b).

Maximum air temperatures during summer months were not significantly different from long-term average temperatures. Likewise, maximum average CH_4 emissions were approximately the same each year ($\sim 24\,mg\,m^{-2}\,day^{-1}$, Fig. 3). Increased air temperatures were observed in November 1998, which was coincident with a period of potential uptake. However, soil temperatures did not deviate significantly during this same period (Fig. 3b), suggesting that the potential uptake was likely related to CH_4 consumption due to low water table levels rather than increased temperatures. It is difficult to assess long-term trends in CH_4 flux as a function of interannual temperature variability based on our observation period. However, the data suggest that significant short-term increases or decreases relative to the long-term mean monthly air temperature do not greatly affect the magnitude of CH_4 emission as long as water tables are sufficiently high.

Conclusions

CH_4 emissions were estimated for a temperate/boreal lowland and wetland forest in the Chequamegon National Forest in northern Wisconsin for 1997–1999 using the modified Bowen ratio MBR method. Gradients of CH_4 and CO_2 and CO_2 flux were measured at 30 and 76 m on the WLEF-TV tower. No systematic diurnal variability was observed in the CH_4 flux, which was most likely related to the inherent variability in the MBR method. Although fluxes measured during daytime hours were more variable and could have been up to a factor of two higher in magnitude than night-time fluxes, these differences were not statistically significant. In all 3 years, emissions reached a maximum during June–August ($24 \pm 14.4\,mg\,m^{-2}\,day^{-1}$), correlating with high soil temperatures and high water table levels. In 1997 and 1998, significant increases in emission were coincident with the soil thaw during March/April. The onset of emission in 1999 lagged 100 days behind the 1997 and 1998 onsets, and was likely related to postdrought recovery of the regional water table to typical levels. Because of this pattern, we suggest that the water table exerts a strong control on CH_4 emissions at the ChEAS/WLEF site. The net regional emissions for 1997, 1998, and 1999 were 3.0, 3.1, and $2.1\,g\,CH_4\,m^{-2}$, respectively. Considering the source area of the measurements contained $\sim 28\%$ wetland, net annual emissions for wetland regions in the source area would have been 10.5, 11.1, and $7.6\,g\,m^{-2}$, assuming no uptake in upland forested regions. Assuming moderate oxidation rates of CH_4 in upland regions would increase annual net emissions from wetland regions to 13.2, 13.8, and $10.3\,g\,m^{-2}$ in 1997, 1998, and 1999, respectively. Scaling these measurements to the Chequamegon Ecosystem (CNNF) and comparing with average wetland emissions between 40°N and 50°N suggests that wetlands in the CNNF emit approximately 40% less than average wetlands at this latitude. Interannual variability of CH_4 emissions during 1997–1999 with respect to long-term trends in environmental controls suggests that the water table level exerts the strongest control over the CH_4 flux. If climatic changes occur such that the water table is reduced, it is likely the CNNF would emit less or possibly become a sink for atmospheric CH_4.

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