Interannual, seasonal, and retrospective analysis of the methane and carbon dioxide budgets of a temperate peatland

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[1] Three years (2009–2011) of near-continuous methane (CH_4) and carbon dioxide (CO_2) fluxes were measured with the eddy covariance (EC) technique at a temperate peatland located within the Marcell Experimental Forest, in northern Minnesota, USA. The peatland was a net source of CH_4 and a net sink of CO_2 in each year with annual carbon budgets of -26.8 (± 18.7), -15.5 (± 14.8), and -14.6 (± 21.5) g C m^{-2} yr^{-1} for 2009–2011, respectively. Differences in the seasonal hydrometeorological conditions among the three study years were most pronounced during 2011, which was considerably warmer (+1.3°C) and wetter (+40 mm) than the 30 year average. The annual CH_4 budget was +11.8 (± 3.1), +12.2 (± 3.0), and +24.9 (± 5.6) g C m^{-2} yr^{-1} for the respective years and accounted for 23%–39% of the annual carbon budget. The larger CH_4 emission in 2011 is attributed to significant warming of the peat column coupled with a high water table position throughout the entire growing season. Historical (1991–2011) CH_4 emissions were estimated based on long-term hydrometeorological records and functional relationships derived from our 3 year field study. The predicted historical annual CH_4 budget ranged from +7.8 to +15.2 (± 2.7) g CH_4-C m^{-2} yr^{-1}. Recent (2007–2011) increases in temperature, precipitation, and rising water table at this site suggest that CH_4 emissions have been increasing, but were generally greater from 1991 to 1999 when average soil temperature and precipitation were higher than in recent years. The global warming potential (considering CO_2 and CH_4) for this peatland was calculated based on a 100 year time horizon. In all three study years, the peatland had a net positive radiative forcing on climate and was greatest (+187 g C m^{-2}) in 2011. The interannual variability in CH_4 exchange at this site suggests high sensitivity to variations in hydrometeorological conditions.

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1. Introduction

[2] Peatlands represent about 3% of the Earth's land surface but contain a disproportionate amount (300–600 Pg C) of the global soil carbon pool [*Gorham*, 1991]. The historical (i.e., last 10,000–20,000 years) carbon accumulation rate in northern peatlands has been estimated between 10 and 40 g C m^{-2} yr^{-1} [*Gorham*, 1991]. Growing interest in the contemporary carbon balance of peatlands has been motivated by concerns regarding climate warming, changes in hydrology, and the vulnerability of their stored carbon [*Bridgham et al.*, 2006; *Hargreaves et al.*, 2003; *Waddington and Roulet*, 2000].

[3] The contemporary carbon balance of peatlands and wetlands has been studied mainly with the use of flux chambers [*Hendriks et al.*, 2007; *Roulet et al.*, 2007] and, increasingly, with micrometeorological techniques [*Adkinson et al.*, 2011; *Aurela*, 2002; *Griffis et al.*, 2000; *Teklemariam et al.*, 2010]. However, annual and interannual studies of CO_2 exchange over peatlands still remain relatively rare. Eddy covariance (EC) measurements at Mer Bleue bog near Ottawa, ON, Canada, indicate that the peatland was a net sink of CO_2 with annual values ranging between 10 and 76 g C m^{-2} yr^{-1} over a 4 year period [*Lafleur et al.*, 2003]. They concluded that water table position was the single most important factor determining the interannual variations. A recent synthesis by *Lund et al.* [2009] examined the annual CO_2 budget of seven northern peatlands, including temperate and arctic sites, and showed that all sites were a net sink for CO_2 (average of all sites = 103 ± 103 g C m^{-2} yr^{-1}) and that growing season length and leaf area index best explained differences in CO_2 sink strength among sites.

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[4] To date, the vast majority of peatland carbon cycle studies have focused on the CO_2 exchange, not only because it typically represents the largest component of the carbon budget but also because of limited technologies available for making in situ CH_4 measurements at remote field sites. The vast majority of CH_4 budget investigations have been derived from chamber measurements, which have been very important for understanding the biophysical processes, but severely limited in terms of estimating annual budgets because of their relatively low spatial and temporal resolution [*Bubier et al*., 1993; *Dise*, 1993; *Moore et al*., 2011]. We are aware of only a few studies that have examined the annual and interannual variability in the CH_4 budget of peatlands using near-continuous EC measurements [*Baldocchi et al*., 2012; *Hatala et al*., 2012; *Herbst et al*., 2011; *Rinne et al*., 2007]. The smallest annual budgets were measured in a grazed degraded peatland (3.3 g CH_4-C m^{-2} yr^{-1}) and newly converted rice paddy (2.5–6.6 g CH_4-C m^{-2} yr^{-1}) [*Hatala et al*., 2012]. Similar annual budgets were measured in a restored wetland (9.5 g CH_4-C m^{-2} yr^{-1}) [*Herbst et al*., 2011], a fen (9.5 g CH_4-C m^{-2} yr^{-1}) [*Rinne et al*., 2007], and a drained and grazed peatland pasture (8.8 g CH_4-C m^{-2} yr^{-1}) [*Baldocchi et al*., 2012]. These studies found soil temperature beneath the water table, water table position, substrate availability, and vegetation type to be the dominant environmental factors controlling CH_4 emissions.

[5] In this paper, we revisit early work conducted by *Shurpali and Verma* [1998], who used tunable diode laser (TDL) spectroscopy and EC to estimate the CH_4 budget of a temperate peatland located within the Marcell Experimental Forest, in northern Minnesota, USA. Their study was limited to the growing season (late May to mid-October) in 1991 and 1992 and demonstrated a broad range of CH_4 emissions under different hydrometeorological conditions. Using a similar technical approach, we have examined the interannual variability (3 years of near-continuous measurements) of CH_4 and CO_2 exchange at this same site to address the following questions:

[6] 1. What is the contemporary carbon balance of this site and to what extent does CH_4 influence the budget and the resulting global warming potential (GWP)?

[7] 2. Does recent photosynthate production have an important influence on CH_4 emissions?

[8] 3. How sensitive is the seasonal and interannual CH_4 budget to hydrometeorological conditions and can a retrospective analysis be used to identify emerging trends?

2. Methodology

2.1. Research Site

[9] The Bog Lake Fen study site is a transitional peatland located in the south unit of the Marcell Experimental Forest, Chippewa National Forest, north central Minnesota (47.505 N, −93.489 W). The peatland is approximately 20 ha and has a slightly concave cross section. The site has been characterized previously as a poor fen, described as poorly minerotrophic to oligotrophic [*Shurpali and Verma*, 1998; *Shurpali et al*., 1993; *Verma et al*., 1992]. The water balance of this peatland is primarily determined by the difference between precipitation and evapotranspiration with no visible outflow. The site is an open peatland with few trees due to the high water table. The microtopography consists of a hummock/hollow patterned surface. Vegetation is composed mainly of sphagnum moss (*Sphagnum papillosum*), vascular plants such as sedges (*Carex* spp.), cotton grass (Eriophorum chamissonis), pitcher plants (Saracenia purpurea), leather leaf (Chamaedaphne calyculata), and Labrador tea (Rhododendron groenlandicum). Stunted tamarack (Larix laricina) and black spruce (Picea mariana) are also scattered throughout the study site.

[10] The organic soils at this site can range up to 3 m in depth. The soils are in the Greenwood series, primarily *Sphagnum*-derived peat [*Shurpali and Verma*, 1998]. The von Post degree of decomposition values ranged from H1 to H4 in the upper meter of the soil and H5 and H6 at greater depths. Upland soils are classified as Warba fine sandy loam series and Menaga loamy sand series.

2.2. Micrometeorological and Environmental Measurements

[11] EC flux measurements of CO_2 and water vapor have been ongoing at the site since June 2006. EC CH_4 flux measurements were established in April 2009. The major flux measurement instrumentation includes a tunable diode laser (TDL) absorption spectrometer for fast methane concentration measurements (TGA100A, Campbell Scientific, Inc., Logan, UT, USA), an open-path infrared gas analyzer (LI-7500, Licor Inc., Lincoln, NE, USA) for CO_2 and water vapor concentrations, and a three-dimensional sonic anemometer-thermometer for measuring wind speed and temperature (CSAT3, Campbell Scientific, Inc.). The EC instrumentation was mounted on a tower positioned 2.4 m above the peat surface. The TDL was located at the base of the tower to minimize the length of the sample tubing (3.4 m). The TDL sample tube (Synflex Hose and Tubing Products, Fairfield, OH, USA) inlet was located in close proximity of the LI-7500 analyzer and 15 cm away from the CSAT3. Air was drawn through the sample inlet at 15 standard liters per minute using a vacuum pump (Busch RB0021, Busch LLC, Virginia Beach, VA, USA) and was passed through a Nafion dryer (PD1000, Nafion® membrane, Perma Pure, Inc., Toms River, NJ, USA) prior to analysis. A TDL reference gas of 1.5% methane balanced in nitrogen was used to define the spectral shape of the CH_4 reference line. A data logger (CR5000, Campbell Scientific, Inc.) was used to collect the high-frequency data (10 Hz) from the TDL, LI-7500, CSAT3, and other supporting micrometeorological measurements (described below). The raw 10 Hz data were collected, and fluxes and data quality control were performed off-line, as discussed below.

[12] Supporting instrumentation and measurements included air temperature and relative humidity (Vaisala HMP45AC), wind speed and wind direction (05103 Young Wind Monitor), precipitation (TE525WS Texas Electronic), and soil temperature at depths of 5, 10, 20, 30, 40, 50, 100, and 200 cm belowground surface (Campbell Scientific T107). The net radiation balance (R_n) of the site was determined using a net radiometer (Kipp & Zonen CNR1, REBS Q7.1), and photosynthetically active radiation (PAR) was measured using a Licor LI-190SB sensor.

[13] Other long-term measurements made at the site include weekly soil (peat) temperatures (since 1989), daily water table position (since 1990), and biweekly peat pore water chemistry (since 1991). Water table position is recorded in a sheltered excavation pit that has a float-driven Belfort FW-1 strip-chart

recorder. This reference well is located 3.5 m southeast of the EC tower. Pore water samples are obtained from a small pool of open water located along the eastern edge of the site and analyzed for a wide range of parameters, including total organic carbon (TOC) [*Kolka et al*., 2011].

2.3. Data Processing and Quality Control

[14] CO_2 and CH_4 flux calculations were performed using custom software developed with SAS (SAS Institute, Cary, NC, USA) [*Noormets et al*., 2007, 2008]. A modification to this custom software was necessary for performing the CH_4 flux calculations to accommodate the closed-path TDL measurement system (i.e., the WPL corrections are not applied because the air sample is dried and brought to a common temperature prior to analysis). The time lag between an air sample entering the sample inlet and reaching the TDL sample cell was calculated during initial setup of the TDL instrument based on a physical test. A second test was performed based on the maximum covariance of the methane signal and vertical wind speed. The conclusion of both of these tests was that the lag was typically 0.7 s. This lag factor was used in all flux calculations.

[15] All fluxes were calculated using 30 min intervals. We have adopted a sign convention where a positive flux represents a net flux from the surface to the atmosphere. Here ecosystem respiration (R_E) has a positive sign, and gross ecosystem photosynthesis (GEP) has a negative sign ($NEE = GEP + R_E$). Missing data (i.e., power and instrument failure) accounted for 5%, 7%, and 3% of missing CO_2 and 4%, 7%, and 1% of missing CH_4 flux data collected in 2009–2011. Weak or inadequate turbulent conditions (i.e., low friction velocity, $u* < 0.12\,m\,s^{-1}$) accounted for 41%, 38%, and 36% of the data loss in 2009–2011. *Verma et al*. [1992] reported upwind fetch conditions to be at least 250–300 m in the SSW–NNE direction at the site. Wind direction associated with limited fetch accounted for 39%, 34%, and 31% 2009–2011. Methane ebullition occurs episodically and, by definition, is a nonstationary process. Our quality control processing is designed to eliminate these data by examining the nonstationarity ratios. This resulted in the removal of 46%, 49%, and 43% of the data in 2009–2011. A large fraction of this data removal overlapped with the previous screening criteria. We suspect that many episodic or ebullition events were removed by considering nonstationarity. Our budget, therefore, is a conservative estimate, and it is likely that the CH_4 budget was underestimated. Further research is required to examine the frequency and importance of such events, but is beyond the scope of our current study. The combined total data loss was similar for CO_2 (66%, 62%, and 56%) and CH_4 (65%, 62%, and 55%) in 2009–2011, respectively. The dominant factors for data loss were wind direction and periods of weak turbulence.

[16] Other quality controls applied to the CH_4 flux data included periods of laser dewar liquid nitrogen refills, loss of laser line lock, and sample cell pressure outside of the acceptable range. Select quality control criteria applied to CO_2 flux data were periods of winter time sensor heating (i.e., CO_2 uptake during $T_a < 0°C$ and high R_n). Anomalous CO_2 flux values associated with the heating of the LI-7500 analyzer [*Burba et al*., 2008] were replaced with CO_2 fluxes measured using the flux gradient approach. These data were obtained using a second TDL designed for CO_2 isotope measurements [*Griffis et al*., 2008].

2.4. Gap Filling and Budget Uncertainty

[17] Missing CO_2 fluxes were gap-filled following the Fluxnet-Canada Research Network methodology [*Barr et al*., 2004]. Briefly, net ecosystem production (F_{nep}) measurements were used to derive gross ecosystem photosynthesis (P) and ecosystem respiration (R). Data gaps F_{nep}, P, and R were filled based on annual empirical relationships, first between R and soil temperature, and second between P and PAR measurements. Time-varying parameters were calculated using a flexible window (100 consecutive, measured, nonmissing, data points) to determine the slope of the linear regression between the modeled and the measured R (and between the modeled and the measured P) and assigned to the mean time of the 100 data points. The time-varying parameters are then estimated by linear interpolation for each half-hourly period, and the adjusted relationships are used to fill data gaps.

[18] In the case of CH_4, we first plotted the average daily CH_4 flux ($\mu mol\,m^{-2}\,d^{-1}$) against the average daily soil temperature (°C) from a range of depths (5–200 cm). The best fit was observed with soil temperature at 20 cm below ground (T_{20}), which remained below the water table throughout the annual study periods similar to previous work by *Rinne et al*. [2007]. Other techniques involving data subsets [*Rinne et al*., 2007] and seasonal data sets [*Long et al*., 2009] were tested, but we did not find a significant improvement in the relationship. Next, we derived a multilinear regression (MLR) that incorporated T_{20} and water table position (WTD) using stepwise regression in MATLAB (MathWorks, Natick, MA, USA). The empirically derived MLR (Table 1) was used to fill missing CH_4 fluxes. Separate MLRs were performed for annual and combined data sets [*Carroll and Crill*, 1997; *Koch et al*., 2007; *Moore et al*., 2011; *Treat et al*., 2007; *Van Den Pol-Van Dasselaar et al*., 1999; *Walter et al*., 2001].

$$\mathrm{Ln}\,(Y) = b_0 + b_1(X_1) + b_2(X_2)$$

where

Y = mean daily CH_4 ($mg\,m^{-2}\,d^{-1}$);
X_1 = mean daily T_{20} (°C);
X_2 = mean daily WTD (m).

WTD is reported in reference to ground surface, which has been set at zero. Adopting the technique previously reported by *Shurpali and Verma* [1998], ground surface elevation is taken from an average hollow surface adjacent to Bog Lake Well referenced at 415.8 m from the mean sea level.

[19] Uncertainty in the flux measurements is associated with both systematic and random errors [*Moncrieff et al*., 1996]. We have attempted to minimize the systematic errors with routine calibration of the instrumentation and eliminating conditions when the underlying assumptions associated with the EC approach are not satisfied (i.e., weak turbulence, nonstationarity, fetch, etc. [*Foken and Wichura*, 1996]). For this study, the budget uncertainty related to random errors was calculated following *Morgenstern et al*. [2004]. The random error of the sum was based on average daily midday fluxes of half-hourly measurement periods over the entire year for both NEE and CH_4 (see Results sections). Uncertainty

Table 1. Estimating Daily Average CH_4 Emissions Using Multilinear Regression Models Derived at Various Time Intervals for Each Annual Data Set (Study Years 2009–2011) and Combined Data Sets (Study Years 2009–2011 and Study Years 2009 and 2011)[a]

Time Interval	b_0	b_1	b_2	R^2	F test	RMSE	t-statistic	p-value
Annual								
2009	2.334	0.153	0.511	0.89	1408.9	0.31	2.4	0.0159
2010	2.216	0.166	1.423	0.89	1516.3	0.31	4.9	0.0000
2011	3.186	0.122	−1.826	0.63	304.1	0.56	3.7	0.0003
2009–2011	2.607	0.162	−2.621	0.83	140.6	0.21	2.5	0.0153
[b]2009 and 2011	2.377	0.144	0.613	0.75	644.3	0.44	2.4	0.0000
Weekly								
2009	4.563	0.131	0.185	0.52	52.9	0.70	−0.1	<0.0001
2010	5.098	0.173	1.512	0.83	224.5	0.43	1.4	0.8874
2011	−4.06	0.111	−1.25	0.55	60.1	0.69	−0.8	0.4086
2009–2011	4.567	0.129	0.131	0.52	61.4	0.67	0.1	0.9113
Monthly								
2009	3.542	0.109	−1.36	0.26	1.6	1.23	−0.4	<0.0001
2010	4.928	0.152	1.569	0.91	53.6	0.29	1.1	0.0196
2011	3.929	0.092	−1.361	0.41	3.5	0.85	−0.4	0.0694
2009–2011	4.359	0.115	−0.196	0.42	25.8	0.84	−0.1	0.9118
Spring–Fall								
2009	2.168	0.168	0.519	0.87	611	0.19	2.8	0.0057
2010	2.656	0.132	2.334	0.90	839.9	0.21	7.4	0.0000
2011	2.868	0.149	−2.624	0.42	65.2	0.75	−2.5	0.0127
2009–2011	2.596	0.193	−3.86	0.95	266.4	0.15	−4.4	0.0001
June–August								
2009	2.788	0.126	−0.634	0.51	91.8	0.22	−1.1	0.2752
2010	1.476	0.209	0.405	0.92	1036.3	0.15	0.8	0.4472
2011	0.198	0.27	−3.753	0.54	89.4	0.85	−1.7	0.0845
2009–2011	3.411	0.09	0.806	0.66	61	0.11	1.4	0.1647

[a]CH_4 emissions (transformed to natural log) were predicted from variables T_{20} and WTD. The regression parameter estimates are as follows: b_0, the model intercept; b_1, the temperature coefficient; and b_2, the water table depth coefficient.
[b]Relationship used for the retrospective modeling.

associated with gap filling was determined using a Monte Carlo approach [*Griffis et al.*, 2003]. Here we randomly removed half-hourly values from the original data set using a uniform discrete random number generator in MATLAB, where artificial data gaps of up to 1000 half-hourly measurements per year were created. The process was repeated 100 times and resulted in an annual variation over the 3 year study period of 12%−14% for CH_4 and 16%−19% for NEE, respectively. The error estimates given for annual totals include the random and gap-filling uncertainty.

3. Results and Discussion

3.1. Hydrometeorology: Present and Past

[20] The hydrometeorological conditions were considerably different between annual study periods 2009 (24 April 2009 to 23 April 2010), 2010 (24 April 2010 to 23 April 2011), and 2011 (24 April 2011 to 23 April 2012). The onset of the snow-free period differed by more than a month (DOY 105, 2009; DOY 74, 2010; and DOY 123, 2011) among the years, affecting initial springtime WTD. In 2009, a positive WTD (i.e., above 0 m) was observed until early summer (75 days); the opposite trend was observed in 2010, where a negative WTD was observed until early summer (DOY 213). In 2011, a positive WTD was observed for the majority of the growing season beginning in the spring through mid-June (165 days) and then becoming positive again until late August (Figure 1). Over the 3 year period, WTD varied by 40 cm (i.e., −14 to +24 cm). Precipitation during the growing season was relatively low in 2009 (~210 mm) compared to 2010 (~400 mm) and 2011 (~450 mm). The additional precipitation received in 2010 caused WTD to rise at the beginning of August and remain positive until mid-October. In 2011, consistent rainfall events throughout the growing season sustained the elevated WTD. Annual precipitation totals were 470, 698, and 770 mm in 2009–2011, respectively.

[21] Air temperatures (T_a) ranged from −40°C to +30°C. Mean annual T_a in 2009 and 2010 was similar (3.9°C versus 3.5°C, respectively), while 2011 was 2°C warmer (5.9°C). Seasonal differences in T_a showed that the earliest spring warm up occurred in 2009, maximum peak temperature occurred in 2011, and extended fall warming was observed in 2010. Soil temperatures also differed over the 3 year period. The most pronounced difference was during the 2011 growing season when significant warming occurred in the peat column, from near-surface (T_5) to 100 cm depth (T_{100}). The peat column was saturated during the entire period in 2011.

[22] Historical hydrometeorological data (Figure 2) reveal a number of interesting patterns and trends that have potential implications for the CH_4 budget of this site (described further below). Soil temperature at T_{20} varied more than 15°C annually and exhibited a decreasing trend from 1991 to 1999, greater interannual variability during 2000 to 2007, and a rising trend from 2008 to present. Historical WTD recorded a variable seasonal response with an annual range (30 cm) consistent with current conditions. Annual precipitation varied between 600 and 900 mm. The general trend shows that from 1991 to 1999, average T_{20} and annual precipitation (7°C and 792 mm) was above the historical average (6.6°C and 758 mm), while 2000–2011 was below (6.3°C and 730 mm) the historical average.

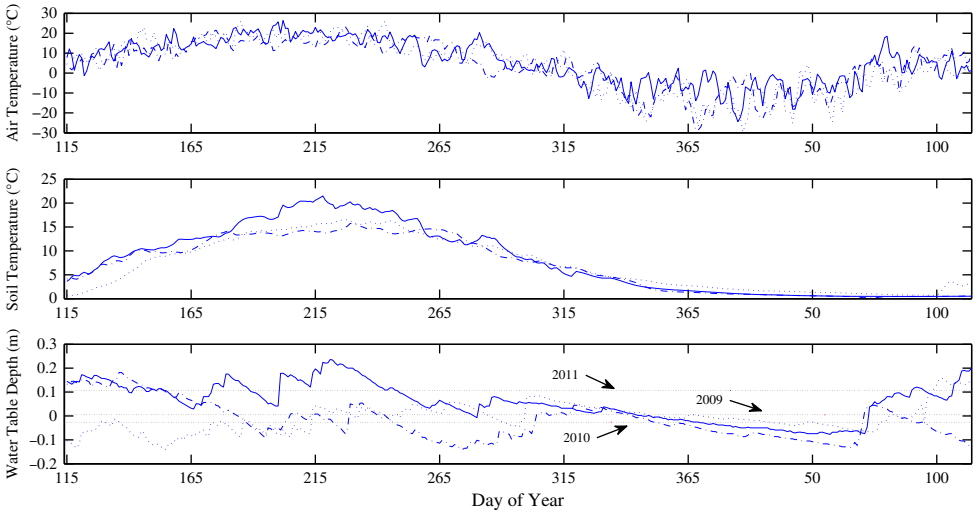

Figure 1. (top) Daily-averaged environmental parameters air temperature, (middle) soil temperature at 20 cm depth, and (bottom) water table depth for study periods (dash-dotted line) 2009, (dotted line) 2010, and (solid line) 2011. Water table depth is reported in reference to ground surface, which has been set at zero following *Shurpali and Verma* [1998]. Ground surface elevation is taken from an average hollow surface adjacent to Bog Lake Well referenced at 415.8 m from the mean sea level. The mean annual WTD for each study year (i.e., 0.0051, −0.0260, and 0.1073 m for 2009–2011, respectively) is shown as a labeled line.

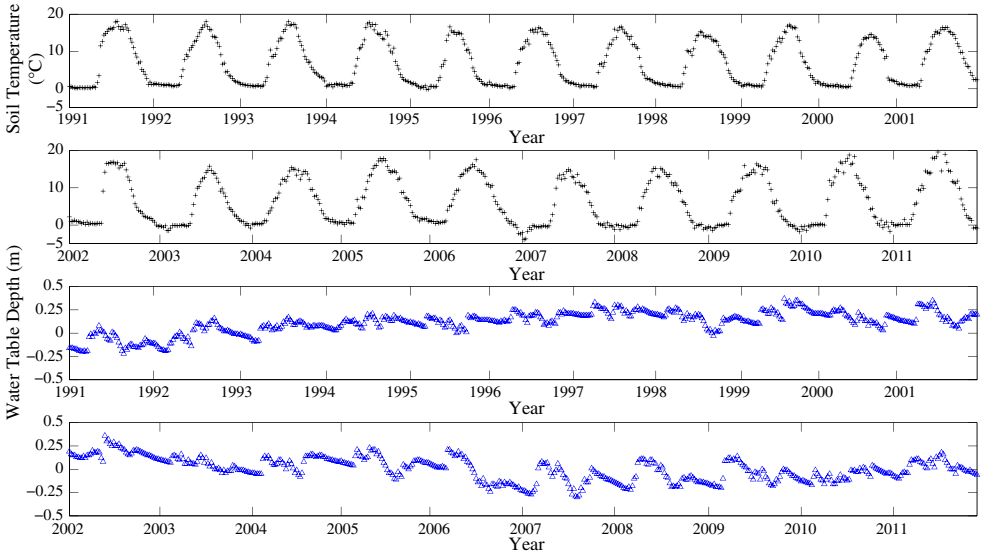

Figure 2. (black cross) Historical soil (peat) temperature at 20 cm depth is shown for (first panel) 1991–2001 and (second panel) 2002–2011. (blue triangle) Historical water table depth is shown for (third panel) 1991–2001 and (fourth panel) 1992–2011.

3.2. Seasonal and Interannual Variability in CH_4 and CO_2 Fluxes

[23] Late spring (DOY 114) CH_4 fluxes differed among the three study years (Figure 3). In 2009, CH_4 emissions increased sharply (from +40 mg to +100 mg $CH_4\,m^{-2}\,d^{-1}$) in response to rapidly rising soil temperatures and positive WTD (+17 cm) following snowmelt (DOY 105). *Shurpali et al*. [1993] reported a similar increase in methane emission (30–120 mg $m^{-2}\,d^{-1}$). In 2010, CH_4 emissions remained near 40 mg $CH_4\,m^{-2}\,d^{-1}$ due to considerably cooler soil temperatures and a negative WTD (−10 cm). In 2011, CH_4 emissions initially increased (+75 mg $CH_4\,m^{-2}\,d^{-1}$) but then declined as WTD and T_a decreased, resulting in net atmospheric methane consumption (peak flux rate −0.04 μmol $m^{-2}\,s^{-1}$). Brief periods of CH_4 consumption (at lesser rates) were also observed in study years 2009 and 2010.

[24] Maximum summertime CH_4 emissions in 2009 and 2010 were 128 and 166 mg $CH_4\,m^{-2}\,d^{-1}$, respectively, and were consistent with other studies [*Rinne et al*., 2007;

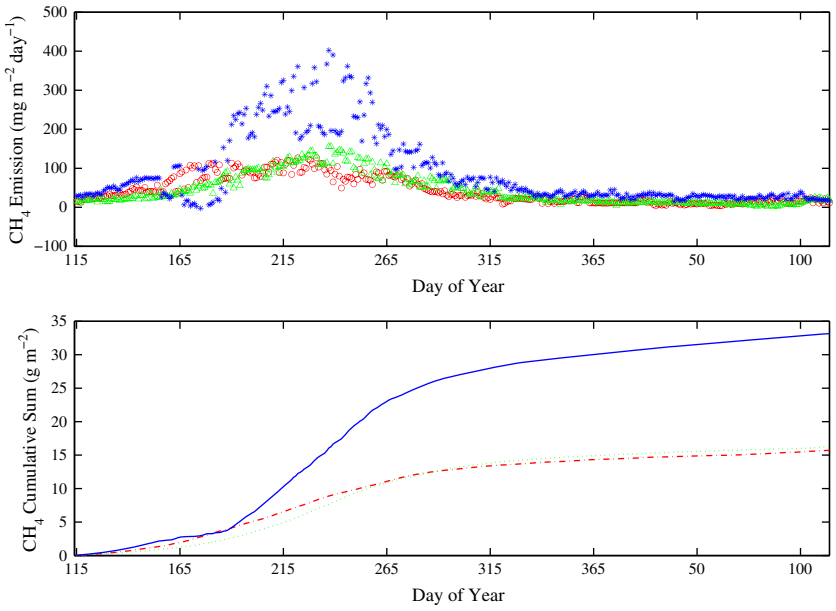

Figure 3. (top) Daily gap-filled CH_4 emission and (bottom) cumulative sum for annual study periods (red circle, dash-dotted line) 2009, (green triangle, dotted line) 2010, and (blue asterisk, solid line) 2011.

Shurpali et al., 1993] but much less than in 2011. In 2011, CH_4 emissions were dramatically larger due to warmer and wetter conditions. Beginning in July, positive WTD (up to +23 cm) and increasing peat column temperature (T_5 21.6°C and T_{100} 12.8°C) led to a remarkable increase in CH_4 emissions (≥+300 mg CH_4 m^{-2} d^{-1}) from end of July through mid-September. The high CH_4 emissions reported in 2011 are similar to findings reported in a pilot study at Bog Lake Fen during the first 2 weeks of August 1990 (+270 mg CH_4 m^{-2} d^{-1}) [*Verma et al.*, 1992] and an episodic emission in August 1991 (+400 mg CH_4 m^{-2} d^{-1}) [*Shurpali et al.*, 1993]. Although diurnal patterns in CH_4 emission from peatlands have been reported during the peak growing season [*Long et al.*, 2009], we did not observe this over the 3 year period.

[25] In 2009 and 2010, late season (September-October) CH_4 fluxes responded positively to an increase in T_5 (from 38 to +85 mg CH_4 m^{-2} d^{-1} and from 20 to +90 mg CH_4 m^{-2} d^{-1}, respectively). In 2011, CH_4 fluxes declined (from +330 to +70 mg CH_4 m^{-2} d^{-1}) but were greater than 2009 and 2011 due to positive WTD (averaging +10 cm) and a relatively warm peat column (T_5 = 8°C−18°C). Wintertime CH_4 emissions ranged from near zero up to 40 mg CH_4 m^{-2} d^{-1} and contributed approximately 14%−16% of the annual CH_4 budget in 2009–2011.

[26] Late spring (DOY 114–151) NEE was generally similar among the three study years. Half-hourly values of NEE increased to −6 μmol m^{-2} s^{-1}, while R_E increased to +1.7 μmol m^{-2} s^{-1} (Figure 4). As CH_4 fluxes decreased during this period in 2011, a notable increase was observed

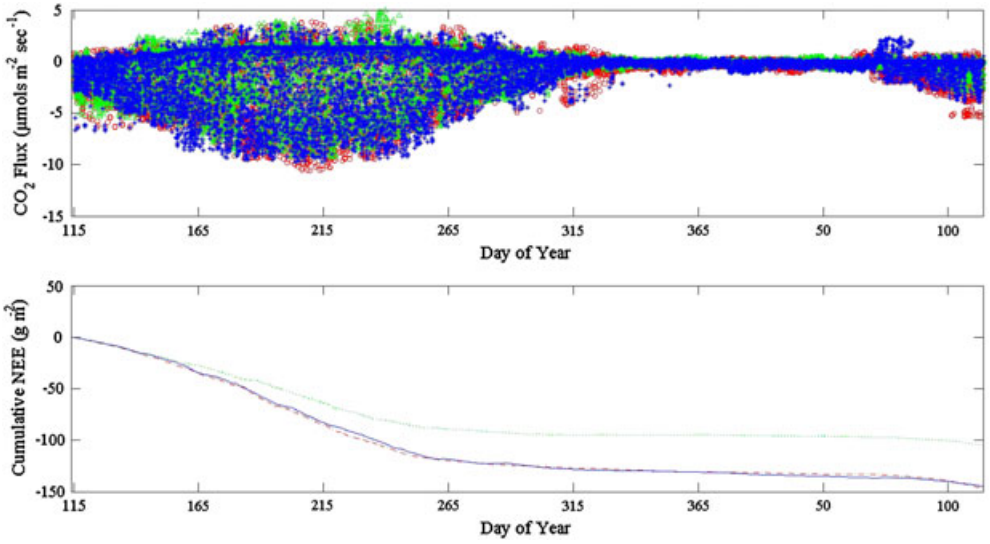

Figure 4. (top) Half-hourly gap-filled NEE and (bottom) cumulative sum for annual study periods (red circle, dash-dotted line) 2009, (green triangle, dotted line) 2010, and (blue asterisk, solid line) 2011.

in NEE ($-8.5\,\mu mol\,m^{-2}\,s^{-1}$), considerably larger than in 2009 and 2010.

[27] Of the three study years, 2009 had the largest half-hourly NEE values (i.e., net uptake) during summer ($-10.6\,mol\,m^{-2}\,s^{-1}$), while 2011 had the longest period of net uptake (98 days) compared to 2009 and 2010 (57 and 67 days, respectively). Maximum summertime R_E generally occurred at the same time as maximum CH_4 emission in all three study years. In 2010, the greatest R_E (+4 to +5 $\mu mol\,m^{-2}\,s^{-1}$) occurred for the longest duration (DOY 231–241) and coincided with a significant rainfall event (DOY 232), a positive WTD (DOY 232–239), elevated T_a (22°C–29°C), and peak CH_4 emissions (DOY 236).

[28] Wintertime R_E ranged up to +0.3 to +0.5 $\mu mol\,m^{-2}\,s^{-1}$ for 2009–2011. Wintertime fluxes contributed approximately 9%–12% of the annual CO_2 budget in 2009–2011. In 2009, an increase in both R_E and CH_4 was observed (DOY 74) immediately preceding the start of the early snow-free (DOY 74) possibly due to the melting of ice layers that had trapped gases migrating from the subsurface during wintertime [*Bubier et al*., 1998; *Dise*, 1992; *Gazovic et al*., 2010].

3.3. Environmental Controls on CH_4 Emissions

[29] Daily average CH_4 emissions were compared to a range of soil temperature depths (5–200 cm depths). The strongest relationship (exponential) occurred at T_{20} in 2009 and 2010 and at T_{50} (i.e., 50 cm belowground surface) in 2011. Both soil depths, T_{20} and T_{50}, remained below the WTD for the duration of the respective study periods. Daily average CH_4 emissions were also examined as a function of daily average WTD, but yielded weak statistical relationships. Other studies have also reported inconsistent results when examining the relationship between CH_4 emission and WTD. Some annual EC studies have demonstrated weak relationships [*Hargreaves et al*., 2001; *Rinne et al*., 2007], while a long-term mesocosm study, based on static flux chamber measurements, showed a very strong relationship, suggesting WTD to be the dominant control over methane fluxes [*White et al*., 2008].

[30] Daily average CH_4 emissions (transformed to the natural log) were examined with respect to variations in T_{20} and WTD using multiple linear regression (MLR). We examined each of the three study years using different time intervals (i.e., at weekly, monthly, spring–fall, June–August, and annual timescales). For individual study years 2009 and 2010 and the combined study years 2009–2011, a relationship between CH_4 emission, T_{20}, and WTD was evident at the annual, spring–fall, and June–August time interval that did not improve at the weekly or monthly scale (Table 1). In 2009, the strongest relationship was observed for spring, which was characterized by a strong rise in T_{20} coupled with a positive WTD. In 2010, the strongest relationship was observed for the June–August time interval when WTD had changed from a negative value in early spring to a positive value during the summer. In 2011, the MLR analyses showed very weak relationships for all time intervals. We hypothesize that this was caused by the fact that WTD was essentially positive for the entire growing season period. The combined 2009–2011 data set showed results similar to 2009 with the seasonal time interval showing the strongest relationship. Overall, the MLR analyses show that temperature was the key factor, with WTD playing a secondary role.

[31] The difficulty in identifying a strong functional relationship between CH_4 emission, temperature, and WTD may be due to the microtopographical differences at the site. Chamber-based measurements have shown strong differences in CH_4 flux between hummocks and hollows, which are likely related to the temperature, soil water content, and vegetation differences associated with such microtopography [*Bubier et al*., 1993]. For example, hollows are characterized by anaerobic conditions, conducive to CH_4 production, and vegetation type such as vascular sedges may also have a pronounced effect (e.g., due to microbial production and transmission of CH_4 directly to the atmosphere bypassing oxidation at soil water interface) [*Waddington and Roulet*, 1996; *Waddington et al*., 1996]. Additional variability in CH_4 emission associated with WTD fluctuations has been observed along site gradients (i.e., bog to rich fen) [*Bellisario et al*., 1999; *Dise*, 1993] and over a considerable range (+15 to −50 cm) [*Shannon and White*, 1994]. Laboratory studies have also shown that methane production changes with rising and falling WTD [*Moore and Knowles*, 1989; *Moore and Roulet*, 1993]. A field study conducted by *Romanowicz et al*. [1995] reported that gaseous and dissolved CH_4 confined deep in peat layers may be rapidly released when a "bubble" confining layer deteriorates by changes to WTD (e.g., drought).

[32] In this study, the ecosystem-scale EC observations integrate these microscale contributions and may act to mask some of the WTD effects that are observed in smaller scale (i.e., chamber, laboratory, mesocosm) studies. However, even chamber-based measurements have shown evidence of inconsistent relationship between WTD and methane emissions. *Treat et al*. [2007] observed elevated emissions during late summer with low water table and high soil temperatures. Furthermore, precipitation events have been shown to lead to large episodic releases of methane (i.e., an order of magnitude greater than observed in chamber measurements) [*Glaser et al*., 2004].

3.4. Link to Photosynthetic Assimilation

[33] CH_4 production is also dependent on the quality of the organic substrate and may be stimulated by recent photosynthate production and transport through roots to the anoxic zone [*Granberg et al*., 1997; *Hatala et al*., 2012; *Hendriks et al*., 2010; *Sundh et al*., 1995; *Whiting and Chanton*, 2001, 1993; Yavitt and Lang, 1988]. These studies have shown a wide range of dependency of CH_4 flux on recent photosynthate production that appears to be strongly linked to plant community composition [*Christensen*, 2003; *Joabsson et al*., 1999; *Waddington et al*., 1996]. Simultaneous 30 min measurement of CO_2 and CH_4 in a closed chamber within and across wetland types showed CH_4 response as a function of net ecosystem production [*Whiting and Chanton*, 1993]. Temperature was also shown to have a strong influence, but during summer growing conditions, the quality of the organic substrate seemed to be the controlling factor on methane production [*Rinne et al*., 2007].

[34] To investigate the potential impact of recent photosynthetic production on CH_4 emissions, we examined the functional relationships between CH_4 emissions and PAR and GEP using a lag correlation analysis. Different lag times (ranging from 0 to 240 half-hour periods or 5 days) were used to investigate the relationship between CH_4 emission versus PAR and canopy photosynthesis as derived

from NEE. Our analyses indicate that there is moderate correlation ($R^2 = 0.41$) with PAR and GEP associated with a lag factor of 6 h. This suggest that recent photosynthetic production can have an important influence on CH_4 emissions and is consistent with carbon isotope ratio analyses that have shown recently fixed carbon can be transported to the sites of root respiration within a few hours with a peak contribution ranging between 24 and 72 h in forests [*Bohn et al*., 2007; *Bowling et al*., 2002; *Högberg et al*., 2007; *Knohl et al*., 2004; *Plain et al*., 2009]. Shorter lag times are expected for the short-stature vegetation at our peatland site.

3.5. Evidence of Methane Oxidation

[35] The amount of CH_4 consumed through oxidation as it passes through the aerobic zone can significantly reduce emissions, and in some ecosystems, such as upland forests, this process can result in a significant CH_4 sink [*Butterbach-Bahl et al*., 1998; *Ojima et al*., 1993; *Sitaula et al*., 1995; *Smith et al*., 2000]. The amount of oxidation is dependent on several factors, including water table position (i.e., extent of the oxic zone), soil temperature (i.e., temperature-dependent consumption rate), and plant species composition (i.e., some vascular plants represent a direct transport pathway for CH_4 to the atmosphere). Based on chamber measurements, laboratory peat column experiments, and isotope studies, other investigators have attempted to quantify the importance of oxidation in peatlands [*Dise et al*., 1993; *Granberg et al*., 1997; *Moore and Roulet*, 1993; *Riveros-Iregui and King*, 2008; *Sundh et al*., 1995; *Waddington et al*., 1996; *Yavitt and Lang*, 1988]. Quantifying the amount of oxidation occurring at a site proves difficult because oxidation occurs simultaneously with methanogenesis and may consume 11%–100% of methane produced on a daily basis [*Riveros-Iregui and King*, 2008; *Yavitt and Lang*, 1988].

[36] In our investigation, some net CH_4 consumption was evident in each of the three study years with half-hourly net CH_4 uptake ranging up to $-0.04\ \mu mol\ m^{-2}\ s^{-1}$. We compared the annual mean WTD (0.0051, −0.0260, and 0.1073 m for 2009–2011, respectively) to daily WTD (Figure 1) and found that a net uptake mainly occurred when daily WTD was below the mean annual value (i.e., during the driest conditions). While there are similar rates in 2009–2011 ($-0.015\ \mu mol\ m^{-2}\ s^{-1}$), the most significant uptake occurred in 2011 (DOY 151–195). However, the WTD measurement is relative to an average hollow surface adjacent to Bog Lake Well [*Shurpali and Verma*, 1998], and therefore, there are many hummocks that range in height from 0.15 to 0.55 m [*Shurpali et al*., 1995] at the site, thereby creating sites where oxidation is likely. The total contribution of net CH_4 uptake is estimated to represent 9%, 5%, and 8% of the annual budget for 2009–2011, respectively.

3.6. Carbon Budget

[37] The peatland was a net sink for CO_2 each year with annual gap-filled totals of −38.6 (±15.6) g CO_2-C m^{-2} in 2009, −27.7 (±11.8) g CO_2-C m^{-2} in 2010, and −39.5 (±15.9) g CO_2-C m^{-2} in 2011 (Table 2). *Shurpali et al*.[1995] conducted a 2 year growing season study (May–October) and found Bog Lake Fen acted as a source (+71 g CO_2-C m^{-2}) in 1991 and a sink (−32 g CO_2-C m^{-2}) in 1992. Our results calculated over a similar time period (May–October) suggest that the site was a net sink of carbon each year (−29, −21, and −30 g CO_2-C m^{-2}). Other multiyear peatland studies have also found significant interannual variation in CO_2 budgets with high sensitivity to hydrometeorological conditions. For example, *Lafleur et al*. [2003] found that the carbon budget of a temperate ombrotrophic bog ranged from −10 to −76 g CO_2-C $m^{-2}\ yr^{-1}$ over a period of 4 years. *Griffis et al*. [2000] showed that a subarctic fen was very sensitive to variations in phenology and hydrometeorological conditions. In their 5 year study (growing season only), the carbon budget ranged from +21 to −64 g CO_2-C $m^{-2}\ yr^{-1}$. These previous studies, however, did not account for CH_4.

[38] The peatland was a source of CH_4 during each study year, emitting +11.8 (±3.1) g CH_4-C m^{-2} in 2009, +12.2 (±3.0) g CH_4-C m^{-2} in 2010, and +24.9 (±5.6) g CH_4-C m^{-2} in 2011 (Table 2). *Shurpali and Verma* [1998] measured CH_4 emissions at Bog Lake Fen over two growing seasons (May–October) in 1991 and 1992. Their study reported emissions of +10.4 g CH_4-C m^{-2} in 1991 and +11.5 g CH_4-C m^{-2} in 1992. Our results calculated over the same time period (May–October) were less in 2009 and 2011 (+8.8 and +9.0 g CH_4-C m^{-2}, respectively) but greater in 2011 (+18.4 g CH_4-C m^{-2}). The difference in emission may be attributed to the difference in the frequency of measurements (previous study integrated from midday values, i.e., 1000–1400 h,

Table 2. Annual Carbon Budget ($g\ m^{-2}\ yr^{-1}$) for Study Periods 2009–2011 at Bog Lake Fen Compared With Other Annual Methane Data Sets Using the Eddy Covariance Technique[a]

Grams per Square Meter per Year	CH_4	CO_2	C-CH_4	C-CO_2	Annual Budget (CH_4-C)
Bog Lake Fen 2009	+15.7(±4.1)	−141.4(±57.2)	+11.8 (±3.1)	−38.6 (±15.6)	~23%
May–October			+8.8	−29.0	
Bog Lake Fen 2010	+16.3(±4.0)	−101.4(±43.3)	+12.2 (±3.0)	−27.7(±11.8)	~30%
May–October			+9.0	−21.0	
Bog Lake Fen 2011	+33.2(±7.5)	−144.8(±58.3)	+24.9 (±5.6)	−39.5 (±15.9)	~39%
May–October			+18.4	−30.0	
Bog Lake Fen 1991[b]					
May–October			+10.4	+71.0	
Bog Lake Fen 1992[b]					
May–October			+11.5	−32.0	
Rinne et al. [2007]	+12.6	−156.0	+9.5	−42.5	~18%
Herbst et al. [2011]	+11.0	−908.0			

[a]The uncertainty estimates reported here include the random measurement error and gap filling error estimates based on a Monte Carlo approach.
[b]Bog Lake Fen: Shurpali and Verma [1998] and Shurpali *et al*. [1995].

whereas the current study is based on a continuous data set) and environmental conditions. Comparing total precipitation and average air temperature, the 1991 and 1992 growing seasons were generally wetter and cooler (452 mm and 14.9°C in 1991 and 642 mm and 13.4°C in 1992) compared to our current study years (271 mm and 13.7°C in 2009, 479 mm and 15.7°C in 2010, and 551 mm and 15.9°C in 2011). WTD was generally belowground surface in 1991 and generally aboveground surface in 1992, while in our current study, WTD varied considerably in 2009 and 2010 but remained positive throughout 2011. Other studies based on continuous annual EC data sets have measured annual CH_4 emission ranging from +9.4 g CH_4-C m^{-2} at a boreal minerotrophic fen [*Rinne et al*., 2007], +8 g CH_4-C m^{-2} at a restored wetland [*Herbst et al*., 2011], and +8.66 g CH_4-C m^{-2} at a peatland pasture [*Baldocchi et al*., 2012].

[39] Combining the gap-filled NEE and CH_4 budgets, we obtained an annual carbon budget of −26.8 (±18.7) g C m^{-2} for 2009, −15.5 (±14.8) g C m^{-2} for 2010, and −14.6 (±21.5) g C m^{-2} for 2011, with CH_4 contributing 23%–39% of the total flux. Considering the uncertainty estimates (i.e., the measurement and gap-filling uncertainty), the annual carbon budget shows almost no difference over the 3 year study. However, there is a significant difference in terms of the CH_4 budget. Although total organic carbon is measured at Bog Lake Fen (see *Methodology*), there is no visible/measureable surface water outlet at the site. Using precipitation ("*P*," i.e., input) minus evaporation ("*E*," i.e., output) as an indication of net water loss and median annual TOC measurements, a loss of 1 – 4 g C m^{-2} is estimated for study years 2009–2011. This amount of carbon loss is small (i.e., much less than the error estimates for the NEE and CH_4 budgets). Other annual EC studies have found that methane contributed approximately 22% in a fen [*Rinne et al*., 2007] and approximately 4% in a restored wetland [*Herbst et al*., 2011]. A long-term (6 year) study that assessed the complete carbon budget in a bog (i.e., NEE, CH_4, and dissolved organic carbon) found a smaller methane contribution (9%), based on chamber measurements [*Roulet et al*., 2007].

3.7. Retrospective Analysis of the CH_4 Budget

[40] Because there is considerable interest in understanding how changes in temperature, precipitation, and water table position will influence CH_4 budgets, we applied our 2009 and 2011 MLR model to a long-term (21 year) hydrometeorological data set. The 2009 and 2011 MLR model is based on the combined annual data sets for study years 2009 and 2011 (Table 1) and was independently verified against study year 2010. The 2009 and 2011 MLR predicted annual CH_4 budget of +10.8, +11.2, and +15.5 g CH_4-C m^{-2} for 2009–2011, respectively. These results are in good agreement with the measured values for study years 2009 and 2010. The very different environmental conditions in 2011 likely explain the larger discrepancy between predicted versus measured annual CH_4 values and highlight the fact that a regression modeling approach has difficulty capturing the more dynamic changes in environmental conditions such as observed in 2011.

[41] We also compared the results of our 2009 and 2011 MLR to *Shurpali and Verma* [1998] for the same time period (late May to mid-October). We calculated +10.7 and +9.7 g CH_4-C m^{-2} versus their measured values of +10.4 and +11.5 g CH_4-C m^{-2} in 1991 and 1992. Again, the predicted versus measured values are in good agreement, and the differences may be attributed to both the difference in the frequency of the measurements and the environmental conditions (discussed above).

[42] Based on the long-term hydrometeorological conditions at the site, we applied our 2009 and 2011 MLR model to estimate the potential interannual variability in the CH_4 budget (Figure 5). Seasonal trends include early spring emissions (i.e., rapid increase from 50 to 100+ mg m^{-2} d^{-1}) in mid-May (1991, 2002, 2005, and 2011), late summer peaks in August (2003 and 2009), and extended fall emissions (1991–1994, 2009, and 2010). While most years ranged between 100 and 140 mg m^{-2} d^{-1}, several years had emissions that exceeded 140 mg m^{-2} d^{-1} in (1991–1994, 2005, 2010, and 2011), while 2 years had emissions that were less than 100 mg m^{-2} d^{-1} (1998 and 2000).

[43] From these analyses, we conclude that over the past 21 years, annual methane emissions have varied from approximately +7.8 to +15.2 (±2.7) g CH_4-C m^{-2} yr^{-1} with minimum and maximum values observed in 2007 and 2011, respectively (Table 3). The uncertainty is based on the mean absolute difference observed between the measured CH_4 values (1991, 1992, and 2009–2011) and the predicted CH_4 values based on the 2009 and 2011 MLR. Over the 21 year time period, environmental conditions also varied widely for this site (annual T_{20} ±3°C, annual precipitation ±320 mm, and annual WTD ±34 cm).

[44] With the addition of the uncertainty estimates, years with the greatest CH_4 emissions (1991–1994, 1996, 1997, 1999, 2001, 2005, and 2011) measured the warmest soil conditions ($T_{20} \geq 7$°C) and near ground surface WTD. Years with the lowest CH_4 emissions (1995, 2000, 2003, and 2007–2009) were associated with colder than average conditions.

[45] ANOVA analysis was conducted for T_{20} and WTD for the past 21 years to determine which years were significantly different. Over the past 21 years, median values for T_{20} generally varied within a few degrees, except in 2005, 2010, 2012, 2013, and 2017, where median values decreased by more than 5°C ($p = 0.2667$). The 95% confidence interval between each year had values that ranged from −0.0025 to 7.7681 with the standard error for each year reported to be 0.9004. A multiple comparison analysis at the 95% confidence interval based on the ANOVA statistics reported that T_{20} did not vary significantly between any of the years. Median values for WTD over the past 21 years varied by 10 cm. However, the range of values was larger (±30 cm), resulting in a low *p*-value ($p = 0$), indicating the difference between means for each year were highly significant. The 95% confidence interval between each year had values that ranged from −0.3957 to 0.4006 with the standard error for each year reported to be 0.0117. A multiple comparison analysis at the 95% confidence interval based on the ANOVA statistics reported that WTD did vary significantly between years. Years with a significantly lower mean WTD include 1991, 1997, 1998, 1999, and 2000, while years with a significantly higher mean WTD include 1994–2002, the greatest being 1997 and 1999.

[46] While there are limitations associated with this simple functional relationship and the use of historical records (i.e., weekly temperature measurements and water table), it does provide some insight regarding the possible variability

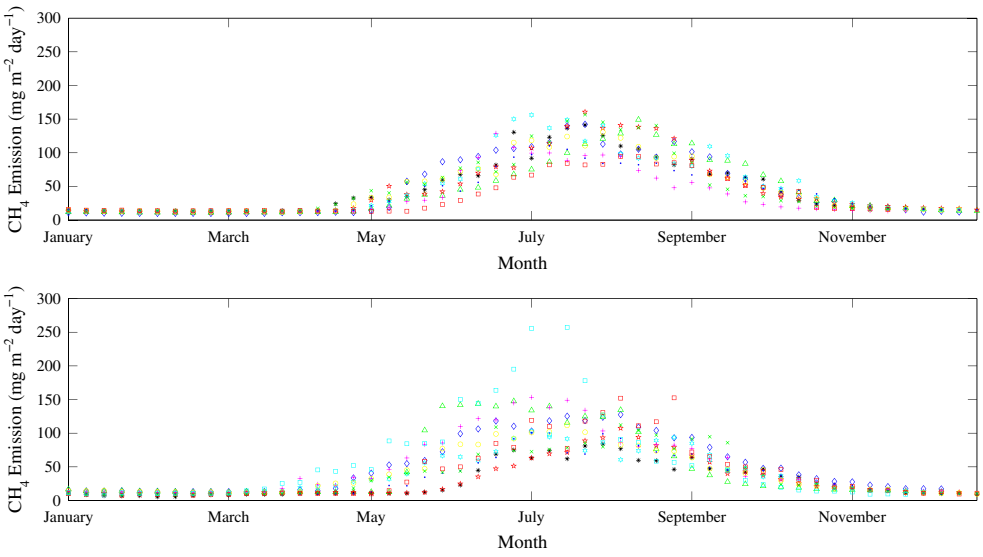

Figure 5. Predicted historical CH_4 emission at Bog Lake Fen (1991–2011) based on 2009 and 2011 MLR. The top panel displays the following years: (blue diamond) 1991, (green triangle) 1992, (red pentagram) 1993, (cyan hexagram) 1994, (magenta plus sign) 1995, (yellow circle) 1996, (black asterisk) 1997, (blue point) 1998, (green cross) 1999, and (red square) 2000. The bottom panel displays the following years: (blue diamond) 2001, (green triangle) 2002, (red pentagram) 2003, (cyan hexagram) 2004, (magenta plus sign) 2005, (yellow circle) 2006, (black asterisk) 2007, (blue point) 2008, (green cross) 2009, (red square) 2010, and (cyan square) 2011.

Table 3. Retrospective Analysis of the Annual CH_4 Budget Based on the Simple 2009 and 2011 MLR Model

Year	Predicted Annual Methane (g C-CH_4 m^{-2})	(Range of Uncertainty)	Average Soil Temperature (20 cm)	Precipitation (S3)	Average Water Table Depth (m)
1991	12.9	(10.2–15.6)	7.5	716.9	−0.10
1992	12.2	(9.5–14.9)	7.0	838.9	−0.02
1993	13.0	(10.3–15.7)	7.3	792.3	0.05
1994	13.6	(10.9–16.3)	7.4	580.0	0.12
1995	9.6	(6.9–12.3)	5.8	890.8	0.11
1996	12.6	(9.9–15.3)	7.0	835.3	0.17
1997	12.6	(9.9–15.3)	7.0	780.4	0.23
1998	11.3	(8.6–14.0)	6.7	798.3	0.16
1999	12.8	(10.1–15.5)	7.2	893.2	0.23
2000	9.1	(6.4–11.8)	5.8	732.7	0.16
2001	13.7	(11.0–16.4)	7.8	836.2	0.18
2002	12.7	(10.0–15.4)	6.4	764.6	0.18
2003	8.4	(5.7–11.1)	4.8	665.3	0.06
2004	10.5	(7.8–13.2)	6.7	819.9	0.05
2005	13.6	(10.9–16.3)	7.9	673.6	0.07
2006	11.3	(8.6–14.0)	7.0	571.8	−0.03
2007	7.8	(5.1–10.5)	4.6	718.0	−0.11
2008	9.4	(6.7–12.1)	5.6	716.7	−0.08
2009	10.4	(7.7–13.1)	6.1	694.4	−0.05
2010	11.5	(8.8–14.2)	6.3	832.0	−0.07
2011	15.2	(12.5–17.9)	8.0	685.0	0.03

The range of uncertainty represents the mean absolute difference observed between years of measured CH_4 (1991, 1992, and 2009–2011) and predicted CH_4 based on the 2009 and 2011 MLR.

of past CH_4 emissions and brings us a step closer to understanding the interannual variability associated with methane under different hydrometeorological conditions. Superimposed on changes in hydrometeorological conditions are longer-term changes in plant succession and soil organic matter development, which are known to be important at time intervals beyond 10 years [*Strack*, 2004; *Strack et al.*, 2006; *Weltzin et al.*, 2003].

[47] Historically, years with the greatest precipitation and warm soil temperature resulted in larger CH_4 emissions. The current 3 year study measured a wide range in precipitation and soil temperatures that resulted in large differences in CH_4 emissions. These results are consistent with a long-term mesocosm study whose infrared heat loading and WTD manipulations led to seasonal soil temperature response, rapid changes in soil carbon storage, and different responses

Table 4. CO_2-Equivalent Comparison Based on GWP for Annual Study Periods 2009–2011 at Bog Lake Fen Along With Other Annual Methane Data Sets Using the Eddy Covariance Technique

	Annual Budget	Carbon Balance	GWP (100 years)
2009 Carbon dioxide	-141.4 (± 57.2) g CO_2 m^{-2}	-38.6 (± 15.6) g C m^{-2}	-141.4 (± 57.2) g CO_2 m^{-2}
2009 Methane	15.7 (± 4.1) g CH_4 m^{-2}	11.8 (± 3.1) g C m^{-2}	392.8 (± 103.3) g CO_2 m^{-2}
2010 Carbon dioxide	-101.4 (± 43.3) g CO_2 m^{-2}	-27.7 (± 11.8) g C m^{-2}	-101.4 (± 43.3) g CO_2 m^{-2}
2010 Methane	16.3 (± 4.0) g CH_4 m^{-2}	12.2 (± 3.0) g C m^{-2}	407.5 (± 100.0) g CO_2 m^{-2}
2011 Carbon dioxide	-144.8 (± 58.3) g CO_2 m^{-2}	-39.5 (± 15.9) g C m^{-2}	-144.8 (± 58.3) g CO_2 m^{-2}
2011 Methane	33.2 (± 7.5) g CH_4 m^{-2}	24.9 (± 5.6) g C m^{-2}	830.0 (± 186.7) g CO_2 m^{-2}
Rinne et al. [2007]	12.6 g CH_4 m^{-2}	9.5 g C m^{-2}	264 g CO_2 m^{-2}
Herbst et al. 2011]	11 g CH_4 m^{-2}		276 g CO_2 m^{-2}

between CO_2 and CH_4 emissions influenced by community type [*Bridgham et al*., 2008; *Chen et al*., 2008; *Updegraff et al*., 2001].

3.8. Global Warming Potential

[48] *Ramaswamy et al*. [2001] defined the global warming potential (GWP) for each greenhouse gas based on the radiative forcing concept. Modeled peatland dynamics suggest that the enhanced warming effect due to CH_4 emission is generally greatest during the first few decades and later is diminished by the sequestration of CO_2 [*Frolking et al*., 2006]. Our cumulative gap-filled NEE and CH_4 budgets were compared using a 100 year time horizon, where CH_4 has a GWP of 25 (based on mass versus molecular basis). Study years 2009–2011 were found to have a positive forcing (net warming) of +69, +83, and +187 g C m^{-2}, respectively (Table 4). There is growing evidence from long-term peatland CO_2/CH_4 budget studies that they represent a positive radiative forcing on climate [*Rinne et al*., 2007]. Our 21 year retrospective analysis suggests that the CH_4 budget of this peatland and its GWP easily offsets the CO_2 sequestration.

4. Conclusions

[49] 1. Continuous EC measurements of CH_4 and CO_2 were made over a 3 year period at a transitional peatland, Bog Lake Fen. Interannual variability in hydrometeorological conditions resulted in annual carbon budget estimates of -26.8 (± 18.7), -15.5 (± 14.8), and -14.6 (± 21.5) g C m^{-2} yr^{-1} for 2009–2011. Differences among years were not significant when considering the uncertainty associated with measurement error and gap filling.

[50] 2. Annual CH_4 emissions were similar in 2009 and 2010 (+11.8 ± 3.1 and +12.2 ± 3.0 g CH_4-C m^{-2}, respectively), but significantly greater in 2011 (+24.9 ± 5.6 g CH_4-C m^{-2}), corresponding with increased temperature and precipitation.

[51] 3. Over the 3 year period, NEE decreased during 2010 in response to increased respiration (-38.6 ± 15.6, -27.7 ± 11.8, and -39.5 ± 15.9 g CO_2-C m^{-2} in 2009–2011, respectively). Although NEE was similar in 2009 and 2011, the annual carbon budget in 2011 decreased due to a substantial increase in CH_4 emissions.

[52] 4. Comparison of annual CH_4 and CO_2 budgets based on their global warming potential over a 100 year time horizon shows the peatland had a positive radiative forcing (i.e., the CH_4 budget of this peatland offsets the CO_2 sequestration).

[53] 5. Historical CH_4 emissions were predicted based on the 2009 and 2011 MLR model. Over the past 21 years (1991–2011), CH_4 emissions have likely varied considerably, with the most recent decade (2001–2011) showing greater variability and larger annual budgets compared to the previous decade (1991–2000).

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