Carbon exchange in a freshwater marsh in the Sanjiang Plain, northeastern China

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A R T I C L E   I N F O

Article history:
Received 11 November 2010
Received in revised form 26 March 2011
Accepted 4 April 2011

Key words:
Net ecosystem CO2 exchange
Methane
Environmental control
Eddy covariance
Static chamber
Marsh

A B S T R A C T

Northern wetlands are critically important to global change because of their role in modulating atmospheric concentrations of greenhouse gases, especially CO2 and CH4. At present, continuous observations for CO2 and CH4 fluxes from northern wetlands in Asia are still very limited. In this paper, two growing season measurements for CO2 flux by eddy covariance technique and CH4 flux by static chamber technique were conducted in 2004 and 2005, at a permanently inundated marsh in the Sanjiang Plain, northeastern China. The seasonal variations of CO2 exchange and CH4 flux and the environmental controls on them were investigated. During the growing seasons, large variations in net ecosystem CO2 exchange (NEE) and gross ecosystem productivity (GEP) were observed with the range of −4.0 to 2.2 (where negative exchange is a gain of carbon from the atmosphere) and 0–7.6 g C m−2 d−1, respectively. Ecosystem respiration (RE) displayed relatively smooth seasonal pattern with the range of 0.8–4.2 g C m−2 d−1. More than 70% of the total GEP was consumed by respiration, which resulted in a net CO2 uptake of 143 ± 9.8 and 100 ± 9.2 g C m−2 for the marsh over the growing seasons of 2004 and 2005, respectively. A significant portion of the accumulated NEE-C was lost by CH4 emission during the growing seasons, indicating the great potential of CH4 emission from the inundated marsh. Air temperature and leaf area index jointly affected the seasonal variation of GEP and the seasonal dynamic of RE was mainly controlled by soil temperature and leaf area index. Soil temperature also exerted the dominant influence over variation of CH4 flux while no significant relationship was found between CH4 emission and water table level. The close relationships between carbon fluxes and temperature can provide insights into the response of marsh carbon exchange to a changing climate. Future long term flux measurements over the freshwater marsh ecosystems are undoubtedly necessary.

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1. Introduction

Natural wetlands in mid-high latitudes are significant contributors to the global carbon (C) cycle through the exchange of greenhouse gases, especially CO2 and CH4, because their soils store large amount of carbon (Post et al., 1982; Chapin et al., 2002) and because of the high temperature sensitivity of the biogeochemical processes associated with cool local environments (Davidson and Janssens, 2006; Zimov et al., 2006; Koch et al., 2007).

Compared to upland ecosystems, such as forests and grasslands, northern wetlands tend to have relatively small CO2 exchange rates (Schimel, 1995; Frolking et al., 1998), however, the fate of the large C store in northern wetlands is of concern given the spatial pattern and magnitude of current and anticipated changes in climate (Schlesinger, 1997; IPCC, 2007). Wetlands are among the primary sources of atmospheric CH4, as they release about 20–39% of the annual global CH4 budget (IPCC, 2007). Neglecting CH4 in the estimation of wetland C balance prohibits determining whether the balance is significantly different from zero (Roulet et al., 2007).

Although many studies have been conducted on greenhouse gas emissions from natural freshwater wetlands around the world (Aselmann and Crutzen, 1989; Martikainen et al., 1993; Melloh and Crill, 1996; Alm et al., 1999; Arnold et al., 2005; Bonneville et al., 2008), few measurements have been carried out for the wetlands in Asia, especially in China (Ding and Cai, 2007). While several observations have been reported in the past decades on natural wetlands in China, using the chamber method (e.g. Ding et al., 2004a,b; Wang et al., 2006; Yang et al., 2006), long-term continuous observations of CO2 and CH4 fluxes are still lacking.

The eddy covariance (EC) technique allows near continuous measurements of net ecosystem CO2 exchange (NEE) to be made during diurnal, seasonal and annual variation in weather (Aubinet et al., 2000; Baldocchi, 2003). NEE measured by EC technique can
be erroneous under stable atmospheric conditions (especially during the nighttime) or when the precipitation events occur (as far as the open path gas analyzers are concerned). Thus the data measured must be carefully quality controlled and gap filled to obtain acceptable time series. In spite of the limitations of EC technique, analysis of the NEE data can provide important information for the assessment and improvement of mechanistic ecosystem models and also for providing empirical information about the potential responses of ecosystems to future environmental changes (Aubinet et al., 2000; Baldocchi, 2003).

In this paper, we report EC measurements of $CO_2$ flux and the static chamber/gas chromatography measurements of $CH_4$ flux for the growing seasons of 2004 and 2005 in a freshwater marsh in the Sanjiang Plain in northeastern China. The objectives of this study are: (1) to determine the magnitude and seasonal pattern of gross ecosystem productivity (GEP), ecosystem respiration (RE) and NEE; (2) to investigate the magnitude and seasonal variation of $CH_4$ emission from the marsh and (3) to explore the major environmental controls on these carbon exchange terms.

2. Materials and methods

2.1. Site description

The study site is located at Sanjiang Experimental Station of Wetland Ecology, Chinese Academy of Sciences (47°35'N, 133°31'E) at an altitude representative of the natural freshwater wetland in the Sanjiang Plain (56 m a.s.l.), northeastern China. The Sanjiang Plain inhabits the largest freshwater wetland area in China, approximately 10,400 km² (Zhao, 1999). Covered continuously by a clay layer, the Sanjiang Plain has a slope of about 1:5000–1:10,000, which is favorable for wetland formation. Wetland initiation in the Sanjiang Plain started during late-Pleistocene epoch due to convergence of the water from Helongjiang River, Songhuajiang River and Wusuliang River and blockage of water seepage by the clayey soil. Generally, the long term accumulation and decomposition rates of plant residues are approximate and there is little peat accumulation for most of the wetlands in the Sanjiang Plain (Zhao, 1999). The three types of wetland present are: permanently inundated wetlands, seasonally inundated wetland, and shrub swamp, amount 56.9%, 22.6% and 20.5%, respectively, for the wetland area in the Sanjiang Plain (Zhao, 1999; Liu, 2005). Freshwater sedge marshes are the major form of wetland in this area.

In this research, the EC flux tower was set at a permanently inundated and eutrophic freshwater marsh. The vertical profile of the marsh is composed of standing water (0–50 cm), live and dead root layer saturated with water (20–40 cm), humus layer (5–10 cm) and gley soil layer whose soil parent material is impermeable clay and sub-clay. The topography of the marsh is flat with homogenous herbaceous vegetation dominated by Carex lasiocarpa, Glyceria spiculosa and Carex meyeriana. Other plants in the marsh include Carex pseudocuraica, Glyceria spiculosa and Carex meyeriana.

The climate is a temperate continental monsoon type with annual mean temperature 2.5 °C. The mean temperature in July and January is 22 and −21 °C, respectively. The annual mean precipitation is approximately 552 mm with approximately 80% occurring during the growing season from May to September. Precipitation is the main water source in freshwater marshes in normal years. Water and soil in marshes are completely frozen from late October to next April and begin to melt from late April till July.

2.2. Eddy covariance and meteorological measurements

$CO_2$ flux was measured with EC system from June to September 2004 and during the growing season (May to September) of 2005. The EC system includes a three-dimensional ultrasonic anemometer (CSAT-3, Campbell, Scientific, USA), used to measure wind velocity and direction, as well as sonic temperature fluctuation, and a fast response open-path infrared gas analyzer (IRGA, Li-7500, Li-Cor Inc., USA), used to simultaneously measure changes in $CO_2$ and $H_2O$ molar densities. The spatial separation distance between the mid-points of these two neighboring sensors was about 15 cm to minimize underestimation of fluxes (Lee and Black, 1994). All signals for the sensors were sampled at 10 Hz by a datalogger (CR5000, Campbell Scientific, USA) and then block-averaged over 30-min intervals for analyses and archiving. $CO_2$ flux data were corrected for the variation of air density caused by the transfer of heat and water vapor (Webb et al., 1980). Instruments were mounted on the tower approximately 2.5 m above the ground and 2 m above the fully grown vegetation.

Parallel to the flux measurements, meteorological data such as net radiation ($R_n$) and photosynthetically active radiation (PAR) at a height of 2 m, air temperature and relative humidity at 2 and 3 m, wind speed and direction at 0.5, 1, 2, and 3 m, soil temperature at 5, 10, 15, 20, 30, 40 and 70 cm depth below the surface and precipitation were obtained from a long-term automatic weather station about 200 m away from the EC system in the marsh. Vapor pressure deficit (VPD) was calculated as the difference between the saturation and actual vapor pressures at the given temperature based on the measured relative humidity and air temperature.

Site visits every 6–10 days were conducted for maintenance and collection of the most recent data. Water level above the marsh surface was recorded manually at each site visit. Phenology observation and measurements of leaf area index (LAI) were done every ten days for the two growing seasons. By destructive sampling three 0.25 m² quadrates within a radius of 200 m around the EC system, the total leaf area in each quadrat was measured using the area meter (CI 203, CID Inc., USA). LAI was calculated as the mean value of the measured data in each measurement. Linear interpolation was applied between measurements.

2.3. Chamber measurement

A site with three replicated measurement plots was set up for chamber measurements at locations about 150 m south-east (prevailing wind direction) of the EC tower. Boardwalks were constructed around the sample plots to minimize disturbance. $CH_4$ emissions were measured at weekly to biweekly intervals using opaque static chambers (stainless steel made, 50 cm × 50 cm × 50 cm) during the growing seasons of 2004 and 2005 (Song et al., 2008). There was only one sample site with three replicates for $CH_4$ measurements in the current study because of the limitation in manpower to carry out the labor intensive chamber measurements. However, the spatial variability of $CH_4$ emissions can be generally considered small since the microrelief of the marsh is flat with evenly distributed vegetation. During each observation, the chambers were placed into the collars (also stainless steel made) with water to prevent leakage, and the vegetation was included within the chambers. Inside each chamber, a small fan that was used to stir the air, and a thermometer sensor and a trinal-venthole were installed. Gas sampling lasted half an hour and four gas samples were taken in 10-min intervals. Measurements were usually carried out around 9:00 AM at local time.

The gas samples were stored in syringes less than 12 h before being measured. Gas chromatography (Agilent 4890D, Agilent Co., Santa Clara, CA, USA) was used to measure the gas concentrations; then the gradient of gas concentration during sampling was used to calculate the $CH_4$ flux. Sample sets were rejected unless they yielded a linear regression of $R^2$ greater than 0.9. Average $CH_4$ flux and standard error were calculated from the three replicates for each observation.
At the same time the chamber measurements were conducted, the air temperature inside and outside the chambers and the soil temperature at 0, 5, and 10 cm depth at the sample plots were measured.

2.4. Data quality control

On average, 33% of the half-hour CO₂ flux measurements by EC system were removed from each year’s data set due to instrument malfunction or quality control procedures described by Lafleur et al. (2003). Of the removed data, 24% were due to calm conditions when friction velocity (u*) fell below the threshold of 0.1 m s⁻¹ at night; 73% were due to concerns over data quality and instrument malfunction, and 3% were due to a C uptake at night.

The variation of CO₂ storage in the air column beneath the EC instrumentation in our case was neglected since the height of the micrometeorological sensors at 2.5 m above ground corresponded to the low (<0.5 m) and sparse (LAI < 2.0) vegetation and flat microtopography of the footprint. Further, the long-term sum of the storage flux was assumed to be zero (Baldocchi et al., 2000).

The footprint routine used in this study is the flux source area model FSAM by Schmid (1994, 1997). According to the calculation of FSAM, the footprint was estimated between 40 and 180 m from the EC tower (representing 90% of the total flux), depending on the atmospheric conditions during the time the footprint prediction was calculated. The footprint analysis indicated that most EC fluxes originated from within the marsh over the two growing seasons.

Since soil and water heat fluxes were not measured in this study, the energy balance was calculated on a daily basis to minimize the influence of these fluxes. The energy balance closure was estimated by regressing the daily mean of the convective heat fluxes (latent heat flux LE plus sensible heat flux H) against net radiation \( R_n \) over the two growing seasons, giving the linear equations

\[
\begin{align*}
H + LE &= 0.71 \\
H + LE &= 0.66
\end{align*}
\]

The second term describes the rectangular hyperbolic relationship between GEP and PAR (Eq. (3)), \( T_{ref} \) is the reference temperature set to 283.15 K and \( T_0 \) is kept constant at 227.13 K as in Lloyd and Taylor (1994). \( R_{ref} \) and \( E_0 \) are the free estimated parameters representing the ecosystem respiration rate at reference temperature and the activation energy that represents the response of respiration to a temperature variation. \( A_m \) is the maximum gross productivity (mg CO₂ m⁻² s⁻¹), and \( \alpha \) is the initial slope of the GEP–PAR relationship (quantum yield, mg CO₂ μmol⁻¹ quantum).

The first step in gap filling was to determine the relationship between nighttime (\( R_n > 10 \) W m⁻²) NEE with \( u^* > 0.1 \) m s⁻¹ and temperature. Since there is greater variability for the observed nighttime NEE at higher temperature because of intermittent turbulence (Morgenstern et al., 2004), a logarithmic transformation was used to reduce the variation of the original nighttime data and stabilize the variance of errors (Chatterjee and Hadi, 2006). Then linear ordinary least square regression was used to find the best fit and estimate the parameter of \( E_0 \). After \( E_0 \) was fixed for the whole growing season, the parameters \( R_{ref}, \alpha \) and \( A_m \) were derived from daytime (\( R_n > 10 \) W m⁻²) data. As the GEP–PAR relationship varies in time, due to seasonal changes in plant biomass and microbial activity (Lafleur et al., 2003), separate relationships in Eq. (1) were derived for every 15 days during the growing seasons. Parameters \( R_{ref}, \alpha \) and \( A_m \) were estimated using the nonlinear regression of SPSS 13.0.

Of the temperature monitored in this study, soil temperature at a depth of 10 cm (\( T_{s10} \)) demonstrated the best correlation with nighttime respiration, thus hourly RE was calculated using Eq. (2) and known \( T_{s10} \). Similarly, Eq. (3) and PAR were used to estimate hourly GEP. Daily and monthly GEP and RE were obtained by summing all the half-hourly values.

Continuous EC measurements at the study site for the growing seasons of 2005–2007 have proved that the monthly NEE is almost equal to the monthly RE in May due to the low photosynthesis of the sedges during this period. In this study, since the EC measurement began in June 2004 and the monthly NEE in May was absent, we used the monthly RE in May 2004 as a substitute.

For EC measurements, a random error corresponding to a SD of 20% was applied on 30 min fluxes (Morgenstern et al., 2004; Humphreys et al., 2006; Nilsson et al., 2008), both on measured and gap-filled 30 min values. The total seasonal uncertainty (SD) was then calculated as the square root of the sum of the respective variances. As to the CH₄ measurements, standard error was calculated from the three replicates from each observation.

3. Results and discussion

3.1. Climate variation

The study site is characterized by strong variation in air temperature, with the highest average (±SD) temperature of 21.6 ± 0.9 °C occurring in July and the lowest average temperature of −20.8 ± 2.1 °C observed in January (Fig. 1a). The annual mean temperatures in 2004 and 2005 were 2.14 and 2.25 °C, respectively, close to the long-term average of 2.52 ± 0.9 °C.

Monthly average precipitation also showed large seasonal variation, with nearly half of the annual precipitation occurring in July and August (Fig. 1b). The precipitation was lower in 2004 (449 mm), compared with the long-term average of 552 ± 94 mm, mainly due to decrease during August; 31 mm falling in August 2004, compared with the long-term average of 136 ± 57 mm during this month. The precipitation was near normal in 2005 (544 mm).

The water table level (WTL), which was always above the marsh surface during the growing seasons generally increased with rainfall and decreased with evapotranspiration. The growing season
WTL was generally higher in 2004 than 2005 (Fig. 1c), with an average of 19 cm and 7 cm, respectively, although the growing season precipitation was lower in 2004 (315 mm) than that of 2005 (399 mm). We did not find significant difference between the precipitation amount during October 2003 to April 2004 and that during October 2004 to April 2005. Therefore, the relatively higher WTL in the growing season of 2004 could be attributed to the especially high rainfall in May 2004 (131.4 mm) compared to 65 mm in May 2005 and the long-term average of 57.7 ± 38.8 mm during this month.

The vegetation in the marsh began to leaf-out in May and reached the maximum LAI around 2 in late July and early August (Fig. 1d). The plants showed visible signs of senescence in late August. Senescence accelerated in September and there was almost no green leaves remaining by late September.

3.2. Daily and seasonal variation of ecosystem CO2 exchange

Daily RE displayed relatively smooth seasonal pattern with the range 1.1–3.6 and 0.8–4.2 g C m⁻² d⁻¹ during the growing seasons of 2004 and 2005, respectively, while daily NEE and GEP showed a similar overall pattern with noticeable variations with season (Fig. 3). Daily NEE gradually switched from positive values in May to a maximum daily net uptake rate of 3.8–4.0 g C m⁻² d⁻¹ in July (24 July in 2004 and 18 July in 2005) when the marsh canopy fully developed and the monthly average temperature reached its peak in 2004 or approached its peak in 2005. Daily NEE gradually declined after August and net CO₂ release was observed on 16 September 2004 and 9 September 2005, respectively. Similar to NEE, maximum daily GEP also occurred in July 2004 and 2005 with the rate of 7.6 and 6.2 g C m⁻² d⁻¹, respectively.

Although net uptake of CO₂ occurred for most days during the growing seasons, there were some close to zero or minor positive NEE peaks (low GEP peaks) in July and August (Fig. 2). For example, the PAR during the rainy or heavily overcast days of 19 July and
8 August 2004 deceased by about 75% compared with that of the adjacent sunny days, while GEP decreased by about 45% and 68%, respectively, and the NEE for these two days was positive or close to zero, accordingly. Similar patterns could also be found in the measurement period of 2005. This pattern suggests that low photosynthetic activity is responsible for the observed low net absorption rates during the vigorous growing period. The large variation in daily NEE and GEP indicates that the marsh at the study site has the potential to respond to a changing climate, within certain limits.

During the measurement periods, both monthly GEP and NEE reached maximum value in July while monthly RE was highest in July or August (Fig. 3). The cumulative CO₂ uptake (GEP) was 472 g C m⁻², 71% of which was lost through ecosystem respiration, which resulted in a net CO₂ uptake of 143 ± 9.8 g C m⁻² for the marsh during growing season of 2004. The cumulative CO₂ uptake was 416 g C m⁻², 76% of which was lost by ecosystem respiration, which resulted in a net CO₂ uptake of 100 ± 9.2 g C m⁻² during the growing season of 2005.

Although many studies have examined the growing season CO₂ fluxes in northern wetlands based on eddy covariance measurements, large variability exists in the findings due to the diverse vegetation and climate types or the different definition of the growing season length. Here, we selected the very limited studies that have similar vegetation and climate types or growing season length with our site for comparison.

In this research, the cumulative growing season NEE was −143 ± 9.8 and −100 ± 9.2 g C m⁻² in 2004 and 2005, respectively. In the study of Glenn et al. (2006), the net CO₂ uptake at an extreme rich fen dominated by C. lasiocarpa in northern Alberta Canada was about −43 g C m⁻² for the period of May to September 2004. Roulet et al. (2007) reported the cumulative growing season (mid-April to mid-October) NEE-C ranged from −164.8 to −76 g C m⁻² with an average of −97.1 ± 38.7 g C m⁻² from a northern ombrotrophic bog of Mer Bleue during 6 years of continuous observation. Nilsson et al. (2008) reported the accumulative net CO₂ uptake in the Deger Stormyr mire was 92 and 86 g C m⁻² during the net uptake season (157 ± 7 days) of 2004 and 2005, respectively. Suyker et al. (1997) estimated that a boreal minerotrophic fen in Central Saskatchewan was a net sink of approximately 88 g C m⁻², during mid May to early October. Our results of the growing season NEE were similar to or higher than the above mentioned results but lower than the cumulative NEE of about −355 g C m⁻² from May to September 2004 at a cattail marsh east of Ottawa, Ontario, Canada (Bonneville et al., 2008), mainly because the cattail marsh has much higher plant productivity.

According to Eq. (1), the seasonal average of R_{ref} (ecosystem respiration rate at 10°C) was 0.07 mg CO₂ m⁻² s⁻¹ in 2004 and 0.06 mg CO₂ m⁻² s⁻¹ in 2005, which was within the range 0.04–0.10 mg CO₂ m⁻² s⁻¹ of R₁₀ (ecosystem respiration rate at 10°C) for the sedge-dominated peatland in northcentral Alberta, Canada (Glenn et al., 2006), and the R₁₀ value 0.02–0.11 mg CO₂ m⁻² s⁻¹ determined for three grassland ecosystems in China (Fu et al., 2009). Compared with R₁₀ (0.16–0.18 mg CO₂ m⁻² s⁻¹) from the temperate forest in eastern China (Yu et al., 2008), the R₁₀ values determined in the current study were low. This difference was likely due to lower live biomass and decomposition rates under water saturated conditions of the marsh substrate.

3.3. Environmental controls over gross ecosystem productivity and ecosystem respiration

Since NEE is the difference between RE and GEP, environmental variables affect NEE indirectly through their controls on RE and GEP. On a daily timescale, a simple regression (Pearson correlation, 2-tailed test for significance) showed that of all the environmental and biological variables measured or calculated in this research, variables that correlated significantly with GEP included T_a, LAI, PAR, and VPD (P < 0.01), whereas those that correlated significantly with RE included T₁₁₀, LAI and GEP (P < 0.01).

We performed a multiple regression analysis to differentiate variables of particular importance for GEP and RE. These analyses were performed between GEP or RE and the variables that significantly correlated with them in simple regressions. The analyses performed were step-wise regression where a condition index (CI) greater than 15 was used to indicate potential multicolinearity problems (Chatterjee and Hadi, 2006).

Results showed that the multiple variable model of daily GEP included air temperature and leaf area index (Table 1). Variable of PAR or VPD had to be removed from the multivariable model due to CI > 15 which indicated a colinearity problem.

Daily GEP increased exponentially with air temperature and leaf area index during the two growing seasons (Fig. 4, Table 2). To use the multiple stepwise regressions, the relationships between the explained variable and the explanatory variables are assumed to be linear while actually more appropriate relationships may be nonlinear. The exponential models shown in Table 2 reduced the specification bias efficiently and thus R² increased. Air temperature and leaf area index expressed about 80–84% of the variations of GEP during the growing seasons. Although most variation of GEP can be explained by temperature, GEP did not increase obviously when daily mean air temperature increased from 0 to 10 °C (Fig. 4), which mainly happened in May. This was because it took a long time for C. lasiocarpa to develop leaf tissue in spring (May) that their photosynthetic capacity was correspondingly low. After daily mean air temperature exceeded 15 °C, GEP increased rapidly with
the increase of temperature and the vigorous growth of Carex in the marsh.

As shown in Table 1, soil temperature at 10 cm depth and leaf area index explained about 76–89% of the variability in daily RE. Although there existed close relationship between RE and GEP in bivariate correlation analysis ($R^2$ 0.80 in 2004 and 0.65 in 2005, $P<0.001$), GEP had to be removed from the multivariable model because of the causation of GEP as RE minus NEE in this study (Vickers et al., 2009; Lasslop et al., 2010a,b).

Although water table position may be an important controlling factor over wetland ecosystem respiration (Bubier et al., 1998; Syed et al., 2006), we found no significant relationship between respiration rates and water table levels in this study. We consider this lack of influence of water table level on respiration may be due to the fact that the marsh soil and vegetation roots layer are permanently inundated during the growing seasons, thus the fluctuations of water level above marsh surface have minor effects on soil respiration and decomposition processes which largely depend on oxygen availability and microbial activity. Similar result can also be seen in the research of Bonneville et al. (2008).

### 3.4. Seasonal dynamic and environmental controls on CH$_4$ flux

The seasonal dynamics of CH$_4$ emission over the marsh ecosystem during the two growing seasons are shown in Fig. 5. Increasing emissions were noticeable from the beginning of May, and maximum CH$_4$ flux was observed on 24 July ($30.5 \pm 23.5$ mg C m$^{-2}$ h$^{-1}$) and 5 August ($28.3 \pm 16.4$ mg C m$^{-2}$ h$^{-1}$) in 2004 and 2005, respectively. CH$_4$ emission decreased gradually since mid August, however, by the end of September, CH$_4$ flux kept relatively high ($5–13$ mg C m$^{-2}$ h$^{-1}$) compared with the beginning of the growing season ($0.1–0.2$ mg C m$^{-2}$ h$^{-1}$).

By bivariate correlation analyses between measured CH$_4$ flux and variables including $T_a$, soil temperature at 5 cm depth ($T_{s5}$), $T_{s10}$ and WTL, we found that the seasonal variation of CH$_4$ fluxes was significantly correlated with temperature ($P<0.01$) but barely correlated with water table level ($P>0.1$). Of the temperature mentioned above, $T_{s5}$ demonstrated better correlation with CH$_4$ flux compared with $T_a$ and $T_{s10}$. CH$_4$ emission increased exponentially with the increase of $T_{s5}$ which could explain about 74–77% of the seasonal variation of CH$_4$ fluxes during the measurement periods (Fig. 6).

Since methanogenesis occurs across a range of soil depths which have different soil temperatures and diurnal temperature lags, determining the relationship between short-term soil temperature patterns and CH$_4$ flux may not be straightforward (Zona et al., 2009). The close relationship between CH$_4$ emission and $T_{s5}$ in this research could be ascribed to that soil temperature around 5 cm depth represented the average temperature condition conducive to methanogenesis.

Water table level is generally considered to be a physical parameter of major importance for CH$_4$ emissions from wetlands (Kettunen et al., 1999; Frenzel and Karfeld, 2000; Updegraff et al., 2001; Treat et al., 2007). In this study, the bivariate correlation analysis showed that WTL was not significant in predicting CH$_4$ fluxes. This relationship is probably due to the fact that the water table was always above the marsh surface (Fig. 1c) and thus the anaerobic environment for methanogenesis was kept relatively stable during the growing seasons.

CH$_4$ transport through vascular plants is frequently mentioned as one of the major pathways for CH$_4$ emissions from wetlands (Kelker and Chanton, 1997; Greenup et al., 2000; Kutzbach et al., 2004). At the study site, more than 3/4 of the biomass of Carex lasiocarpa was belowground and root biomass was therefore correspondingly
the growing seasons of 2004 and 2005.

beginning of the growing season (Fig. 5).

high within the marsh (Yang et al., 2002). The root aerenchyma of Carex could serve as conduits for CH4 transport to the atmosphere and the effect of plant-mediated CH4 transport could be maximized by the high water level and the bulk of the roots growing in anoxic soil horizons (Waddington et al., 1996). In contrast to the slow by the high water level and the bulk of the roots growing in anoxic soil horizons (Waddington et al., 1996). In contrast to the slow

The main period for CH4 emission was from July to the estimated CH4 emissions were to some extent representative of distributed sedge-dominated plant community, we assumed that

Carex

CH4 flux (mg C m⁻² h⁻¹)

CH4 flux (mg C m⁻² h⁻¹)

Fig. 6. Relationship between CH4 flux and 5 cm depth soil temperature (T_soil) during the growing seasons of 2004 and 2005.

4. Conclusions

end of the growing season, which indicated the great potential of CH4 emission from the inundated marsh. The seasonal variations of GEP and RE were jointly affected by temperature and LAI, of which, temperature acted as the primary controlling factor. Soil temperature exerted the dominated influence over the seasonal variation of CH4 flux.

As the chamber measurement for CH4 flux was made at plot scale (<1 m²), to determine CH4 emission from the marsh ecosystem, more sample sites within the marsh should be included and more attention should be paid on the upsampling of the plot-scale chamber measurements. To estimate the carbon budget of the marsh ecosystem, measurements of fluxes of dissolved organic and inorganic carbon are also necessary. Future work should focus on the long-term and complete observations of all terms of carbon fluxes and the associated environmental factors to determine the carbon balance of the marsh ecosystem and its response to a changing climate.

Acknowledgements

This work has been jointly supported by the National Basic Research Program of China (2009CB421103), the National Nature Science Foundation of China (40930527, 41001051), the Key Project of CAS (KZCX2-YW-JC01) and the Young Scientist Foundation of Northeast Institute of Geography and Agroecology (08H2081). We acknowledge two anonymous reviewers for their constructive comments on an earlier version of this paper.

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