Biogeosciences Discuss., 9, 6751–6775, 2012
www.biogeosciences-discuss.net/9/6751/2012/
doi:10.5194/bgd-9-6751-2012

Biogeosciences Discussions

Seasonal methane emission from a boreal peatland in continuous permafrost zone of Northeast China: effects of active layer depth and vegetation

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Received: 20 April 2012 – Accepted: 31 May 2012 – Published: 12 June 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Boreal peatlands are significant natural sources of methane and especially vulnerable to abrupt climate change. However, the controlling factors of CH_4 emission in boreal peatlands are still unclear. In this study, we investigated CH_4 fluxes and abiotic factors (temperature, water table depth, active layer depth, and dissolved CH_4 concentrations in pore water) during the growing seasons in 2010 and 2011 both in shrub-*sphagnum*- and sedge-dominated plant communities in continuous permafrost zone of Northeast China. The objective of our study was to examine the effects of vegetation types and abiotic factors on CH_4 fluxes from a boreal peatland. In *Eriophorum*-dominated community, mean CH_4 emissions were 1.015 and 0.801 $mg\,m^{-2}\,h^{-1}$ in 2010 and 2011, respectively. CH_4 fluxes (0.384 $mg\,m^{-2}\,h^{-1}$) released from the shrub-mosses-dominated community were lower than that from *Eriophorum*-dominated community. Moreover, in *Eriophorum*-dominated community, CH_4 fluxes showed a significant temporal pattern with a peak value in late August both in 2010 and 2011. However, no distinct seasonal variation was observed in the CH_4 flux in the shrub-mosses-dominated community. Interestingly, both in *Eriophorum*- and shrub-*sphagnum*-dominated communities, CH_4 fluxes did not show close correlation with air or soil temperature and water table depth, whereas CH_4 emissions correlated well to active layer depth and CH_4 concentration in soil pore water, especially in *Eriophorum*-dominated community. Our results suggest that CH_4 released from the thawed CH_4-rich permafrost layer may be a key factor controlling CH_4 emissions in boreal peatlands, and highlight that CH_4 fluxes vary with vegetation type in boreal peatlands.

1 Introduction

Methane (CH_4), as one of the most important greenhouse gases, is 25 times more effective in absorbing heat in the atmosphere than carbon dioxide (CO_2) on a 100-yr time horizon (IPCC, 2007). The atmospheric CH_4 abundance increased from 715 ppb

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in pre-industrial age to 1774 ppb in 2005. Increases in atmospheric CH_4 concentrations (148 %) are greater than the other two greenhouse gases (CO_2 35 % and N_2O 18 %) at the same time period. In order to reduce uncertainties in future projections of earth climate change, the current global CH_4 budget should be better known. Denman et al. (2007) estimated that more than 580 $Tg\,yr^{-1}$ of CH_4 are emitted to the atmosphere, with 33 % originating from natural ecosystem sources. However, the contribution of different CH_4 sources and sinks is still highly uncertain due to the sparseness of in situ observations.

Among all the natural ecosystem CH_4 sources, natural wetlands are regarded as the single largest methane source, accounting for 20 % of global CH_4 budget (Fung et al., 1987). While covering nearly 3 % of earth's land surface, northern peatlands store a carbon pool of 455 Pg (Gorham, 1991), approximately accounting for one-third of the global soil carbon (Rydin and Jeglum, 2006) and could potentially release carbon in the form of CH_4 to the atmosphere. The magnitude of CH_4 emission from peatland ecosystems is a comprehensive result of several processes including CH_4 production and oxidation in the peat profile and abiogenic mechanisms such as gas bubbles, diffusion, and gas transport through vascular plant aerenchyma (Whalen, 2005).

Previous studies demonstrated that wetland methane emissions depend on a large amount of abiotic and biotic factors, among the most important of which are temperature, water table depth, vegetation type, substrate quality and supply (Bellisario et al., 1999; Whalen, 2005). Temperature controls on methanogenesis and CH_4 oxidation through affecting methanogenic and methanotrophic bacteria. The wide range of Q_{10} (reaction rate increase for a 10 °C temperature increase) for methanogenesis and methane oxidation suggested highly distinct effect of temperature on CH_4 production and oxidation rates (Whalen, 2005). Substrate availability and supply originated from wetland plant litter and/or root exudates determine CH_4 production and oxidation. Otherwise, species composition of plant can affect CH_4 emissions and substrate availability for methanogens. Previous evidences showed that the vascular plants such as *Eriophorum* species (Ström et al., 2011) and *Carex* species (Ding et al., 2005) have

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a very strong effect on CH_4 emission in the northern wetlands, by supply of available substrate and/or gas transportation of aerenchyma. In addition, peatland soil aerobic or anaerobic condition resulting from a drop or increase of water table can influence on CH_4 oxidation or production and then affect CH_4 fluxes (Whalen, 2005).

Boreal regions are of closely concerning, since they are expected to undergo large changes in temperature and precipitation (Turetsky et al., 2007). Large amounts of labile soil organic matter that is currently preserved by permafrost will be vulnerable to climate change and could result in changing CH_4 emissions through changing peatland hydrology and thermal conditions. For example, permafrost degradation caused by warming will lower down water table following increased drainage in dis-continuous permafrost zone (Riordan et al., 2006) and increase thermokarst lakes area in continuous permafrost zone (Smith et al., 2005). In addition, boreal peatland soil moisture varied in different permafrost zones owing to increasing difference between potential summer evapotranspiration and precipitation that has been reported (Klein et al., 2005). Under ongoing climate changes, the uncertainties of CH_4 fluxes from boreal peatlands have increased, which might confuse the knowledge of the effects of climate change on boreal peatland carbon cycle.

Many studies about peatland CH_4 emissions were conducted in Siberia (Nilsson et al., 2001; Bohn et al., 2007) and sub-arctic or arctic region (Zona et al., 2009; Jackowicz-Korczyński et al., 2010). However, to our knowledge, there is no study reporting CH_4 emission from boreal peatlands in continuous permafrost zone in China. Understanding CH_4 emission from peatland in continuous permafrost zone can make us better understand CH_4 emission patterns and increase the accuracy of estimating peatland CH_4 budget. The goal of this study was to provide a first dataset of CH_4 fluxes from a permafrost peatland in Northeast China, and investigate the factors controlling the seasonal CH_4 fluxes from a permafrost peatland.

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2 Materials and methods

2.1 Study site and setup

The measurement was conducted in a minerotrophic peatland located in the north of Great Hing'an Mountains, Northeast China (52.94° N, 122.86° E). The study site is situated in the continuous permafrost zone. The climate of this area is cool continental, with a 30-yr (1980–2009) mean annual temperature of −3.9 °C and mean annual precipitation of 452 mm, 203 mm of which falls in rainy season (July and August). The coldest monthly mean temperature is −28.7 °C in January, and the warmest is 18.4 °C in July. The surface of the peatland site is a mosaic of microforms, which are divided into hummock, tussock and hollow. Plants usually grow from early May to late September and the dominant evergreen shrubs are *Chamaedaphne calyculata*, *Ledum palustre*. Deciduous shrubs contain *Vaccinium vitis-idaea* and *Betula fruticosa*. Hummocks were covered by *Sphagnum* mosses (*S. capillifolium*,*S. magellanicum*), *Polytrichum commune* and previously mentioned dwarf shrubs. Tussocks supported sedges (*Eriophorum vaginatum*) as dominant vascular plant species and sparse shrubs (*Vaccinium vitis-idaea*, *Ledum palustre*). A scattered of bryophytes (*Polytrichum juniperinum*) were present in hollows. The soil type in our study site is classified as peat soil, with a pH value between 4.9 and 5.0. Soil organic C (SOC) content is 40.4 % in the uppermost 20 cm, with a C/N ratio of nearly 19 (0–20 cm).

A set of twelve plots for gas sampling were selected, and eight of them were chosen so as to be representative of the dominant vegetation in the three microforms and to capture the variability for each of these situations. Four plots were established on the tussock and hollow place where dominant plant species was *Eriophorum vaginatum* (*Eriophorum*-dominated plots: EP), and four plots with hummock where dwarf shrubs and mosses as dominant species (shrub-mosses-dominated plots: SP). In order to determine the influence of peatland vascular vegetation (*Eriophorum vaginatum*) on methane emission, other four plots were established on the bare peat where

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aboveground part of dominant vascular plant (*Eriophorum vaginatum*) were carefully cut and removed before each measurement (bare peat plots: BP).

2.2 Gas flux determination

Gas fluxes were measured by the closed chamber technique (Wang and Wang, 2003). The closed chamber consisted of two parts: a square base collar and a top chamber opened at the bottom. The collar (length: 50 cm, width: 50 cm and height: 20 cm) made by stainless steel was permanently installed in each plot in May 2010. It was directly inserted to a depth of 15–20 cm for minimizing disturbance of the soils while sampling. The collars with grooves that filled with water were to create an airtight seal between the collar and the chamber during gas sampling. The top chamber shaped with 50 cm length, 50 cm width and 50 cm or 70 cm height, was made of stainless steel. Two fans were fixed on the inside symmetrical corners of each chamber to generate turbulence in the chamber closure during sampling. The chambers were wrapped with styrofoam to prevent an increase in headspace air temperature due to heating when sampling. We built boardwalks for minimizing the disturbance on plant and soil microenvironment around collars after the collars were installed.

Gas sampling started in June 2010 and continued until September 2011 at weekly interval during the two growing seasons. Gas samples were only collected in the morning (09:00–11:00 a.m.). During the flux measurements, the chambers were inserted into the water-filled groove of the collar. Head-space samples (50 mL each) were drawn from the chamber every 10 min (including zero time) over half an hour period after enclosure using 60 mL syringes and stored in Tedlar® Air Sample Bag (100 mL, Delin Ltd, Liaoning, China), which had been pre-evacuated to close to 0 Pa. A total of four samples were taken during a flux measurement.

The collected gas samples were delivered to Sanjiang Experimental Station of Wetland Ecology, Chinese Academy of Sciences, and analyzed within a week. Gas concentrations were measured by a modified gas chromatograph (Agilent 4890D, Agilent Co., Santa Clara, CA, USA). The gas chromatograph was equipped with a flame ionization

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detector (FID) for CH_4 analysis. The air bags with known standard concentration of CH_4 were delivered with the collected samples to the laboratory to evaluate the leakage of trace gases during transport and analysis. No significant changes in the concentration of the standards were found during one week of transfer. The fluxes were calculated as the change in chamber concentration over time. The fluxes were rejected unless they yielded a linear regression with coefficient $R^2 > 0.8$ for CH_4. More details of the flux calculation can be found in Song et al. (2009).

2.3 Dissolved methane concentration

Soil pore water was sampled at several depths to determine dissolved CH_4 concentration if there was enough pore-water for extracting. A set of stainless-steel tubes varied in length were installed before measuring at 10 cm intervals from peatland surface to 40 cm below the surface. Immediately after gas flux measurements, pore water samples (20 mL) were drawn from tubes using a syringe and then injected into evacuated vials (60 mL). Prior to determine CH_4 concentration in pore water, vials were shaken for a few minutes to extract dissolved CH_4. Subsequently, 40 mL of the headspace was sampled by a syringe and stored in Tedlar® Air Sample Bag. CH_4 concentration was analyzed as described above. The methods for calculating dissolved porewater CH_4 (μmol l^{-1}) have been described by Ding et al. (2003).

2.4 Abiotic variables

Air temperature, soil temperature, depth of active layer and groundwater level were measured at the same time as gas sampling. Air temperature inside the chambers was measured with a thermometer inserted into the chambers and soil temperature was measured 0, 5, 10, 15 and 20 cm below the peat surface next to the chambers using a portable digital thermometer (JM 624, Jinming Instrument CO., Ltd, Tianjin, China). Active layer depth was simultaneously measured by a steel rod. Groundwater level was monitored by digging a small well adjacent to the collar over the frost-free season. Daily precipitation data were manually recorded near the sampling site.

2.5 Data analysis

The statistic analysis was conducted by Software packages SPSS 13.0 (SPSS Inc., Chicago, IL, USA) and Origin 8.0 (Origin Lab Corporation, USA) for Windows XP. Correlation between gas fluxes and environmental factors was studied with Spearman correlation. In all analyses where $p < 0.05$, the factor tested and the relationships were considered statistically significant.

3 Results and discussion

3.1 Environment variables, CH_4 concentration in porewater and CH_4 fluxes

During the sampling period, monthly mean air temperature (MMAT) varied from 5.3 °C (September 2011) to 20.3 °C (July 2011) (Fig. 1a). There was no marked discrepancy between the MMAT and the 30-year mean value in the two measurement years ($p > 0.05$). However, we observed extreme daily temperatures in the last few days of June, and the maximum daily temperature reached 39.4 °C on 27 June 2010. Accumulative precipitations from May to September were 325.9 and 493.7 mm in 2010 and 2011, which were 11 % lower and 34.8 % greater than the 30-yr mean value during the same period, respectively (Fig. 1b). The heavy rain appeared on 23 August 2011 and the accumulative rainfall was 129.1 mm (data not shown). The seasonality of ground temperature and soil temperature were consistent with the seasonal patterns of air temperature during sampling period in 2011. The in-chamber soil temperatures observed in different vegetation plots showed that soil temperatures in the SP site were little higher than that in the EP site (Fig. 2). The presence of *Sphagnum* in the SP site preserved soil heat diffusion. The water table depth throughout the measurement period ranged from −10.7 to −24 cm (minus value means below the surface) in the

SP site and from −10.5 to −36 cm in the EP site (Fig. 3). The water table depth was consistently higher in the SP site than in the EP site during the two growing seasons (Fig. 3), and the average difference in water table between the two sites was 4 cm. The similar seasonal variation of water table depth in the SP and EP site was observed and the lowest value occurred in late June or early July due to higher temperature and less precipitation.

At the beginning of the measurement, peatland surface soil was frozen. The active layer depth continuously increased with air and soil temperatures at initial stage. In the late sampling period, the active layer depth still increased with decreasing air and soil temperatures. This might be on account of thermal in deep soil transferring slower than that in upper soil layer and atmosphere. The maximum active layer depth reached 72.4 cm and 80.7 cm by the end of the observation period in 2010 and 2011, respectively.

The details and seasonal fluctuations in pore water concentration of CH_4 measured in the peatland soil profile can be seen in Fig. 4. Pore water CH_4 concentration in 20 cm below peatland surface showed no seasonal variation and the mean CH_4 concentration in pore water was 2.09 µmol l^{-1}. However, a significant seasonal variation of CH_4 concentration in 30 and 40 cm below peat surface was observed. CH_4 concentrations at 30 and 40 cm depths increased following the development of growing season. Correlation analysis showed that average CH_4 concentration between 20 cm and 40 cm was significantly related to soil temperature at 40 cm depth ($r = 0.832$, $p = 0.005$). Figure 4 also shows that pore water CH_4 concentrations increased with depth. At the depth from 20 cm to 40 cm, the concentration of CH_4 increased sharply by 2 to 10 times of magnitude.

Generally, the peatland emitted CH_4 to the atmosphere during the two growing seasons, although CH_4 absorption might occur occasionally. In the SP site, CH_4 fluxes were in the range of −0.018 to 0.506 mg m^{-2} h^{-1}, with a mean value of 0.212 mg m^{-2} h^{-1} in the measuring period from June to September in 2010. In 2011, CH_4 fluxes ranged from 0.019 to 1.352 mg m^{-2} h^{-1} during the entire growing season in

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the SP site, and the mean seasonal flux was 0.557 mg m^{-2} h^{-1}. CH_4 fluxes measured from the EP site were significantly higher than that from the SP site, which ranged from −0.006 to 2.28 mg m^{-2} h^{-1} with a mean flux of 1.015 mg m^{-2} h^{-1} in 2010 and −0.081 to 3.511 mg m^{-2} h^{-1} with a mean flux of 0.801 mg m^{-2} h^{-1} in 2011. In present study, CH_4 fluxes obtained through static chambers during the growing seasons (∼ −0.081–3.511 mg m^{-2} h^{-1}) are greatly higher than that from Alaskan upland tundra (Bartlett et al., 1992), and they are similar in the range of those from boreal raised bog (Pelletier et al., 2007) and subarctic/arctic fen (Christensen, 1993). The CH_4 emissions are much lower than those from BOREAS peatlands (Bubier et al., 1995).

Figure 3 shows that the seasonal variations of CH_4 flux exist for both sites. The similar seasonal trend of CH_4 fluxes in disparate observation years was found in the SP and EP site. However, the variation in CH_4 emissions in the SP site is lower than that in the EP site. Except the vascular plant regulate methane emission, methane oxidation in in situ condition may play a more important role in hummocks than in tussocks. CH_4 emissions gradually increased with the development of growing season and peaked in late August in both years. Unlike other previous studies reported no seasonal variation of CH_4 fluxes from peatlands, we found that the distinct temporal variation in methane emissions was that CH_4 fluxes peaked in late summer when the active layer reached the gas-contained layer, also was consistent with peak pore water CH_4 concentration. Our results were consistent with Moore and Knowles (1990) who found CH_4 fluxes peaked in later growing season from a subarctic fen in Quebec.

3.2 Controls on CH_4 flux

Previous studies have shown that temperature (Bellisario et al., 1999; Pelletier et al., 2007; Sun et al., 2011) and water table depth (Moore et al., 2011) were primary factors that controlled peatland CH_4 emissions. The relationships between CH_4 fluxes and environment factors such as temperature, water table depth and active layer depth in independent observation year were examined. The site-specific CH_4 fluxes did not show

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any relationship with soil or air temperature and water table depth, indicating a complicated conjunct effect of variables on CH_4 flux. It was consistent with Christensen et al. (1995) who found no correlations between environment factors and CH_4 emission in Siberian mesic tundra. Ström et al. (2011) also found no correlations between seasonal mean CH_4 fluxes and water table depth and soil temperature in an arctic wetland. In the present study, the controls on seasonal variation of CH_4 flux were distinct at different stages of plant growth. In the early growing season (Period I), when moisture was adequate to support methanogenesis, temperature played a critical role in peatland CH_4 emission (Table 1). However, there was a lag time between rising temperatures and CH_4 flux in the early season because microbial communities and vegetation required time to become established. The following mechanisms might interpret temperature-dependence CH_4 fluxes during the early growing season. Firstly, temperature was an important control on methanogenesis. The widely reported Q_{10} values for methanogenesis ranged from 1 to 35 in boreal peatland soils (Whalen, 2005) suggested that temperature sensitivity of the underlying microbial processes involved in the production of CH_4 was high under appropriate substrate and moisture conditions. The lack of CH_4 production capacity under low temperature magnified the effect of temperature on CH_4 emission. Secondly, temperature controlled plant growth which could provide not only substrate for methanogenesis but also an efficient pathway for methane to liberate from peat to the atmosphere (Joabsson et al., 1999). In addition, as increased temperature, thaw depth of permafrost gradually increased, which can create appropriate soil circumstances such as saturate status and re-release of substrate previously preserved in the frozen layer for methanogens and methanogenesis (Yavitt et al., 2006). Therefore, the magnitude of CH_4 depended on soil temperature was the important limiting factor for CH_4 emission rate at the early growing season. The weak statistical relationship between methane emission and temperature at the peatland site during the growing season probably reflected the high spatial variability in emission rates at the plots, fluctuations in water table position, and seasonal changes in vegetation cover.

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In general, water table position acted as a creation of aerobic and anaerobic conditions in the peat soil profile, which determined peatland CH_4 emissions. Studies have revealed that CH_4 fluxes increased from soils under elevated water tables, or high soil moisture contents (Moore and Knowles, 1989). In this study, soil moisture was large due to low evapotranspiration in the early growing season, but CH_4 fluxes were very low. The possible reason was that CH_4 production in anaerobic condition was constrained by low soil temperature and limited substrate supply, and part of CH_4 might be consumed in aerobic layer during the process of transmitting to the atmosphere. As the growing season development (Period II), the positive correlation between CH_4 emission and water table depth was shown (Table 1). This suggests that the effects of water table depth on methane emission will be enhanced under appropriate temperature conditions. It was consistent with other studies that found similar relationship conducted in boreal peatlands (Roulet et al., 1993). A higher water table depth caused by summer precipitation and permafrost thaw might result in a larger anoxic CH_4 production zone and stimulate emissions.

This study was performed in the mountain peatland located in the southern margin of Eurasian permafrost zone where the active layer depth has been increasing in recent decades (Jin et al., 2000). Some previous studies have shown that CH_4 flux correlated well with active layer depth in peatlands underlain by permafrost (van Huissteden et al., 2005). In our study, we found a positive correlation between thaw depth and the gas fluxes of CH_4 (Table 1), which was consistent with the above mentioned studies. However, Wille et al. (2008) reported that CH_4 flux did not correlate with the thaw depth in arctic tundra. The reasons they draw were the majority of CH_4 originated from the upper soil layers, and the contribution of deep soil layers to methane emissions was small due to the temperature gradient in the thawed active layers and temperature dependence of microbial activity. However, recent studies reported that layers nearest the top of the permafrost (50–100 cm) in Alaska and Siberia contained higher CH_4 concentration, which suggest that majority of CH_4 will release from the eroding permafrost (Michaelson et al., 2011). Song et al. (2012, under review) observed high CH_4 concentration in

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the refrozen active layer and upper permafrost layer in our study region, which could partly explain high CH_4 flux in the late growing season when the active layer reached tens of centimeters. The high CH_4 content in the permafrost might be originated from modern methanogenesis by cold-adapted methanogenic archaea in permafrost soil (Wagner et al., 2007) and release of trapped-CH_4 formed in unfrozen active layer during previous winter. It is possible that CH_4 production took place in the freshly thawed permafrost due to the recovery of the bacteria from the upper permafrost (Coolen et al., 2011).

The magnitude of CH_4 concentration in soil pore water increased with depth indicated that CH_4 production was high in deep saturated soil layer. The seasonal variation in CH_4 emission was significantly correlated with mean soil pore water CH_4 (Table 1). It implied that the magnitude of soil pore water CH_4 controlled CH_4 emission rates in the peatland. Our results were in agreement with Nouchi and Mariko (1993) who reported that CH_4 emission rate was proportional to porewater CH_4 concentration. Soil pore water contained high CH_4 concentration was in correspondence with the EP site CH_4 flux rates recorded in late growing season. This suggests that plants in EP site are more effective on transporting CH_4.

We found that CH_4 emission from the EP site was significantly higher than that from the SP site. After cutting the plants, methane fluxes would decrease 77 % and 73 % from the EP sites in 2010 and 2011 (Fig. 5). In the EP site, the dominant plant was *Eriophorum vaginatum* classified as vascular plant, while the SP site was covered by *Sphagnum* species and dwarf shrubs. The vascular plants of peatland could play an important role in gas exchange between the land and the atmosphere (Joabsson et al., 1999). CH_4 transport through *Eriophorum* was the major pathway for CH_4 fluxes (Frenzel and Rudolph, 1998). However, vascular plant might act as conduit for transferring oxygen to the rhizosphere, which both inhibiting archaeal CH_4 production and enhancing methanotrophy. Yet, Frenzel and Rudolph (1998) found that oxidation of CH_4 was negligible during its passage through *E. angustifolium*. In addition, root exudates and fine root litter of *Eriophorum* could stimulate CH_4 production. Ström et al. (2011)

reported that *Eriophorum* secreted more organic acids than other highly bio-available organic matters that could be easily utilized by methanogens in arctic wetland. Mosses contributed less significantly to active gas transport since they did not develop real root system in peat (Sheppard et al., 2007). Otherwise, CH_4 oxidation was reported from mosses originated from high-latitude wetlands which decreased CH_4 emission from anoxic conditions (Larmola et al., 2010). So, different compositions of vegetation in peatland can explain the spatial variation of CH_4 fluxes.

4 Conclusions

Seasonal methane fluxes were measured from boreal peatland ecosystem in continuous permafrost zone in two consecutive years. Seasonal average CH_4 fluxes ranged from 0.212 to 1.016 $mg\,m^{-2}\,h^{-1}$, with an apparent seasonal variation. Our results showed that environmental factors such as temperature and water table level were not responsible for regulating temporal variations of methane emission. CH_4 emission rates during the growing season were strongly controlled by plant, active layer depth and CH_4 concentrations in soil pore water. It implies that permafrost peatland under warming conditions can create positive feedback to climate change due to increase CH_4 emission through altering plant composition and increasing active layer depth.

As CH_4 emission from ecosystems depended on the balance of CH_4 production and oxidation, the determination of the seasonal potential CH_4 productions and oxidations in soil layers might provide some evidences for explanation of the seasonal and spatial variations of CH_4 fluxes from boreal peatland ecosystems. In addition, future studies should focus on exploring the origination of plenty of CH_4 in lower permafrost layers and soil pore water at tens of centimeters depths in peatland, which might promote our understanding of methane emission from peatland in permafrost zone.

Acknowledgement. This work was funded by National Natural Science Foundation of China (No. 41125001, No. 40930527), Strategic Priority Research Program – Climate Change: Carbon Budget and Related Issue of the Chinese Academy of Sciences (No. XDA05050508, No.

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XDA05020502), National Basic Research Program (973) of China (No. 2009CB421103), and the Key Project of CAS (No. KZCX2-YW-JC301). We thank Yang Guisheng, Song Yanyu, Sun Xiaoxin and Wang Jiaoyue for enthusiastic laboratory assistance. We also would like to thank Sun Yue for her work at the field site.

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Table 1. Correlation coefficients between mean CH_4 fluxes and abiotic factors during sampling period of 2011.

	Temperature[a] (°C)			Water table depth (cm)			Active layer depth (cm)	Pore water CH_4 concentration ($\mu mol\,l^{-1}$)
	Period I	Period II	Entire	Period I	Period II	Entire	Entire	Entire
Mean CH_4 flux ($mg\,m^{-2}\,h^{-1}$)	0.721*	−0.491	0.033	−0.539	0.842**	−0.192	0.865**	0.664*
Pore water CH_4 concentration ($\mu mol\,l^{-1}$)			−0.112			0.58*	0.622*	1

** Correlation is significant at 0.01 levels; * correlation is significant at 0.05 levels. Period I and II were arbitrarily defined at before and after 8 July 2011.
[a] Average temperature between 5 and 10 cm below peatland surface.

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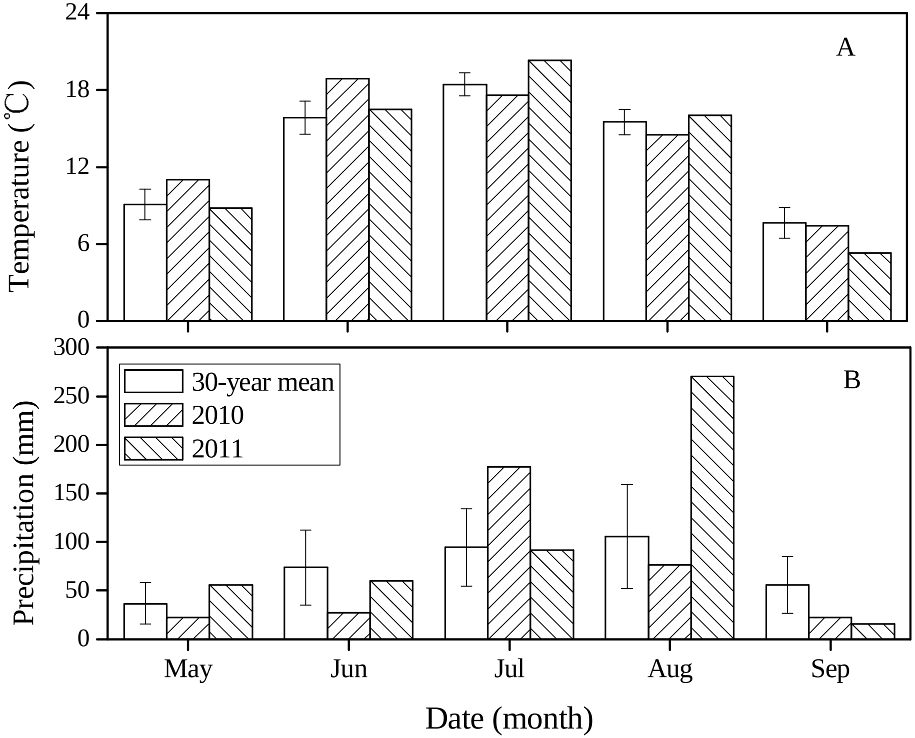

Fig. 1. Climatic characteristics of the study site during the growing season in 2010 and 2011 on the background of the long-term normal period (1980–2009; 30-yr average ± SE) recorded by China Meteorological Administration. **(A)** monthly average temperature; **(B)** Monthly accumulative precipitation.

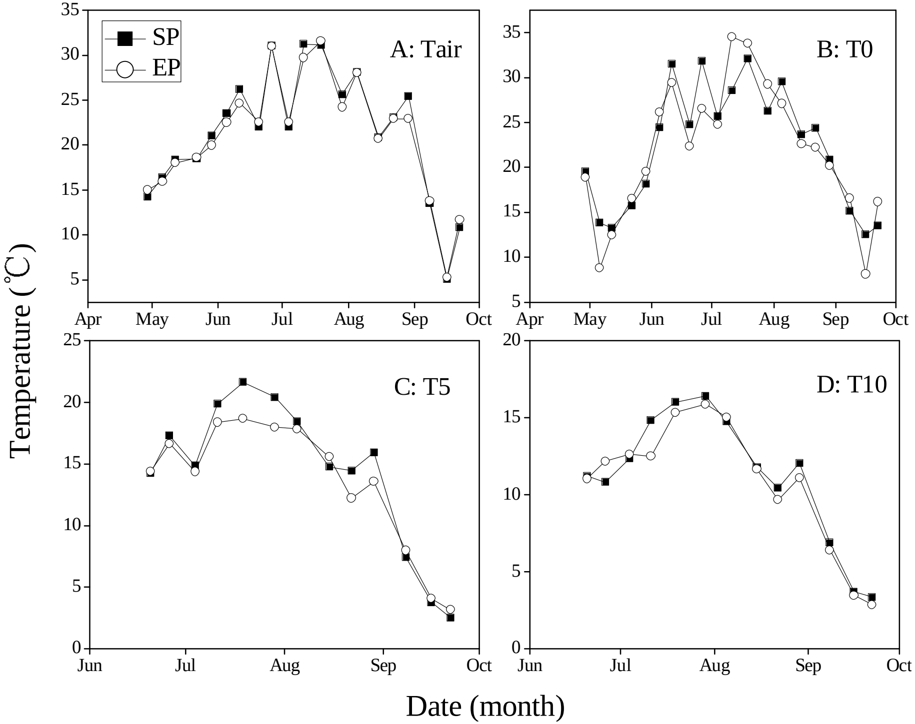

Fig. 2. Temperatures recorded by digital thermometer at SP (Shrub-mosses plots) and EP (*Eriophorum* plots) sites in the study site during sampling in 2011. **(A)** Air temperature inside the chamber; **(B)** peat surface temperature; **(C)** soil temperature at 5 cm depth; **(D)** soil temperature at 10 cm depth.

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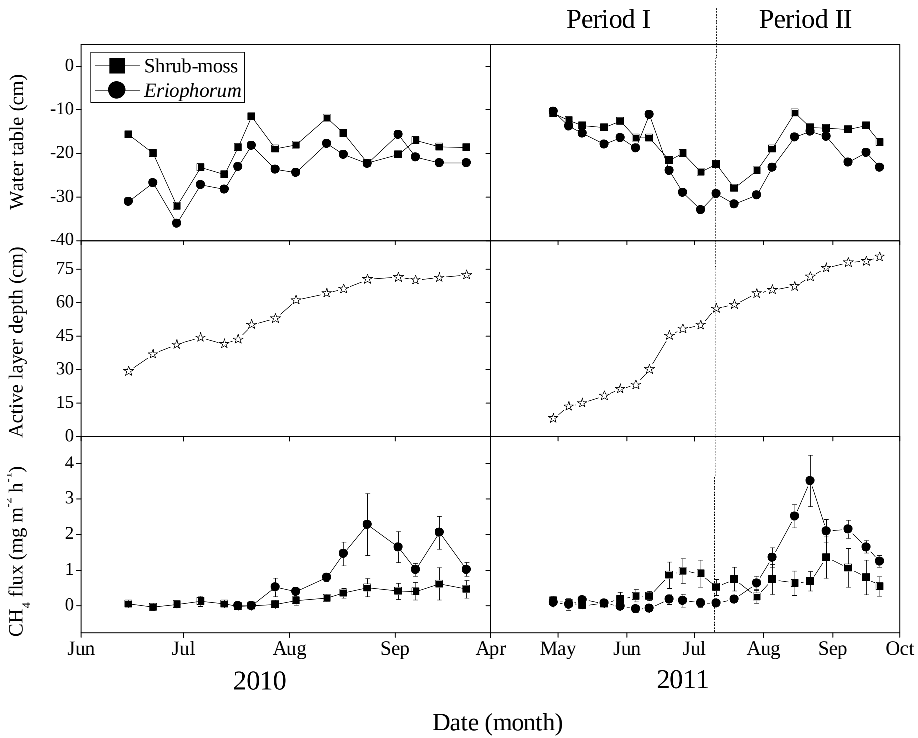

Fig. 3. The seasonal variation of net CH_4 fluxes and environmental variables (water table and active layer depth) observed at the study site in the growing season of 2010 and 2011.

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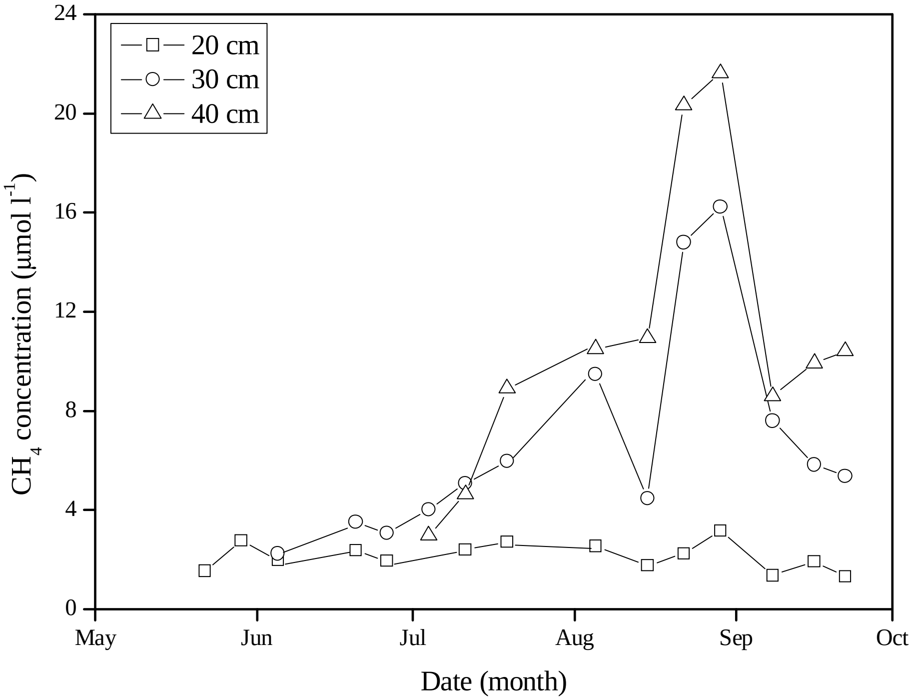

Fig. 4. Seasonal variation of dissolved pore water CH_4 concentrations in different soil depths was determined in the study site during sampling in 2011.

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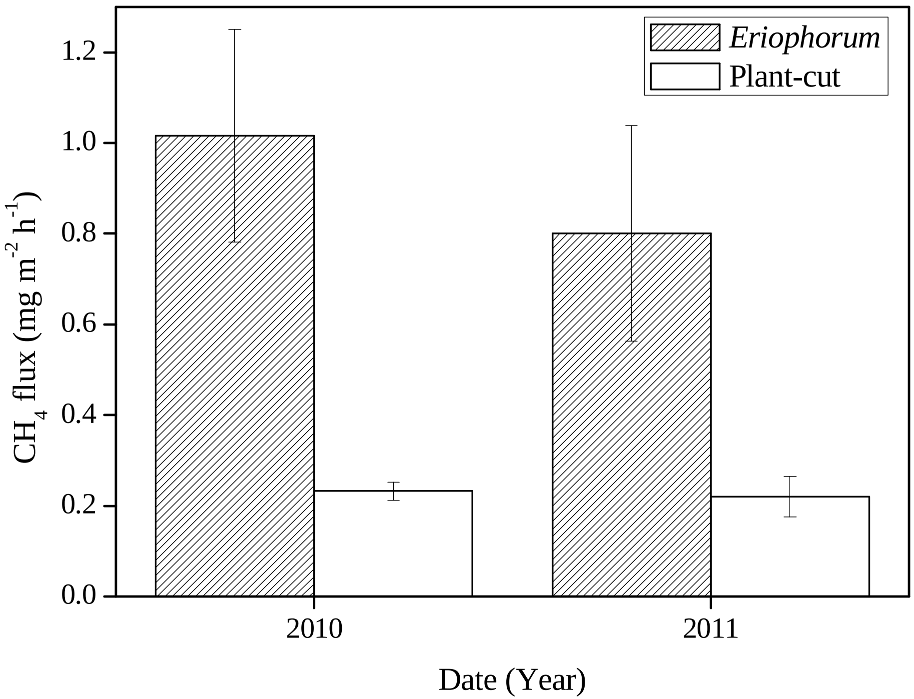

Fig. 5. Seasonal mean CH_4 flux from the EP and BP sites in both years.

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