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Greenhouse gas emissions from different wetlands during the snow-covered season in Northeast China

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HIGHLIGHTS

- The natural wetlands in the middle latitude are source for CO_2 and CH_4 in the snow-covered season.
- During the snow-covered season, peatland acts as N_2O sink and marshland acts as a N_2O source.
- Soil temperature is the primary factor controlling marshland greenhouse gas fluxes in the snow-covered season.

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ABSTRACT

Emission of CO_2, CH_4 and N_2O from the snowpack is an important component of annual C and N budgets in wetland ecosystems in mid- and high-latitude. However, there is little information about greenhouse gas fluxes during the snow-covered season in wetlands in Northeast China. In the present study, we investigated the trace gas fluxes from a peatland and a marsh using the methods of concentration gradient and diffusion model during the snow-covered season of 2010/2011 in this region. Estimates of CO_2 efflux from a peatland and a marsh during this period were 4.179 and 5.026 g C m^{-2} $season^{-1}$, respectively. The seasonal release of CH_4 from the peatland (0.009 g C m^{-2} $season^{-1}$) was much lower than that from the marsh (0.818 g C m^{-2} $season^{-1}$). Intriguingly, we observed that the peatland acted as sink for N_2O, and the marsh as a source for N_2O during the snow-covered season. For the peatland, snowpack such as snow density is important for CO_2 and CH_4 fluxes, while N_2O flux was controlled by soil–snow interface temperature. In the marsh, however, soil temperature was the primary parameter regulating greenhouse gas fluxes. Our results suggest that in mid- and high-latitude regions, greenhouse gas fluxes during the snow-covered season is an important part of C and N cycles in seasonally snow-covered wetland ecosystems. The difference in greenhouse gas emission from both peatland and marsh suggests that wetland types should be considered when evaluating regional gas budgets.

1. Introduction

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are three major greenhouse gases which trap outgoing heat from Earth's surface. In the last hundred years, the amount of greenhouse gas in the atmosphere has increased because of human activities, thus enhanced the natural greenhouse effect. Solomon et al. (2007) reported that atmospheric greenhouse gas increased from 280 ppm in 1750s to 379 ppm for CO_2, 715 to 1732 ppb for CH_4 and 270 to 319 ppb for N_2O in 2005, respectively. As one of the primary ecosystems in the world, wetland plays a significant role in estimating global greenhouse gas fluxes. Northern peatlands, act as carbon sink owing to its water-saturated condition which restricts organic matter decomposition, accumulate organic carbon for millennia and store nearly one thirds of soil organic carbon (Gorham, 1991; Smith et al., 2004). Meanwhile, methane can be produced via anaerobic decomposition in the form of organic matter breakdown in the absence of oxygen. According to Anderson et al. (2010), natural wetlands contribute 170 Tg CH_4 every year, which account for 37% of the total CH_4 flux into the atmosphere. Nitrous oxide is produced by two key microbial processes such as nitrification under aerobic conditions and denitrification under anoxic conditions (Firestone and Davidson, 1989). Therefore, N_2O flux from wetlands was commonly depended on soil aerobic and/or anoxic conditions.

Some previous studies suggest that greenhouse gas can be produced or consumed in soils even at temperatures below 0 °C

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(Groffman et al., 2006; Oquist et al., 2004). Greenhouse gas fluxes through snowpack are significant part of the global carbon and nitrogen budget and also to be the important component of the annual flux in mid- and high-latitude regions due to their large snow-covered land surface and long snow-covered season and possible biological production or released of gas trapped by frozen soils (Panikov and Dedysh, 2000; Schimel et al., 2006; Zhang et al., 2005; Zimov et al., 1993). It has been reported that winter emission of greenhouse gas accounted for 12–30% of CO_2 (Fahnestock et al., 1999; Kim et al., 2007), 3.5–50% of CH_4 (Heikkinen et al., 2002; Melloh and Crill, 1996; Panikov and Dedysh, 2000), 19–28% of N_2O from mid- and high-latitude ecosystems through a year (Alm et al., 1999). To understand global terrestrial biosphere–atmosphere C/N interactions and construct C and N budgets within these ecosystems, greenhouse gas emission from these snow-covered areas deserves more attention.

However, most measurements were mainly conducted in arctic and subarctic regions (Aurela et al., 2002; Fahnestock et al., 1999; Heikkinen et al., 2002; Welker et al., 2000). Little attention is given to wetlands in mid-latitude and mountain permafrost regions, where experience long cold winter covered by snowpack. In Northeast China, the area of natural wetlands which dominated by freshwater marshes and mountain permafrost peatlands is 1.017×10^{10} m^2, accounting for 26.5% of total national natural wetlands (Liu, 2005) and 0.2% of global natural wetlands (Cao et al., 1998). These wetlands are generally covered by snowpack lasting four to six months throughout a year. However, only Zhang et al. (2005) reported greenhouse gas emission from wetlands located in Sanjiang Plain in Northeast China during cold seasons. Field measurements of greenhouse gas emission are limited in this region, especially during snowpack period. So far, no investigation has ever been carried out on mountain permafrost peatlands in China. Hence, precise estimation of greenhouse gas budgets in regional and national level needs more observations in field. The aim of the present study is to evaluate greenhouse gas fluxes through snowpack in freshwater marsh and mountain permafrost peatland in Northeast China.

2. Site description and methods

2.1. Site description

The measurements were conducted in a minerotrophic peatland at Great Xing'an mountain (52.94°N, 122.86°E), and in a freshwater marsh at Sanjiang Experimental Station of Wetland Ecology (47.58°N, 133.51°E) in the Sanjiang Plain. These sites are located in mid- and high-latitude zones in Northeast China. The peatland is situated in the continuous permafrost zone, and the marsh is located in the region where underlain by seasonal frozen soil which would entirely melt during summer. The climate of the peatland is cool continental, with a 30-year (1971–2000) mean annual temperature of −4.3 °C and mean annual precipitation of 435 mm. At Sanjiang Plain, it belongs to temperature monsoon climate. The mean annual temperature and precipitation of this study area are approximately 2.52 °C and 558 mm (2002–2006) (Song et al., 2009).

The main microtopographies in the peatland surface are characterized as hummock, tussock and hollow, which are dominated by dwarf shrubs such as *Chamaedaphne calyculata*, *Leduim palustre*, *Vaccinium vitis-idaea* and *Betula fruticosa*, sedges and mosses. *Eriophorum vaginatum* comprise a sparse cover and a few previous-mentioned shrubs are present on tussocks. Hummocks and hollows are covered by *Sphagnum* mosses (*Sphagnum capillifolium*, *Sphagnum magellanicum*) and *Polytrichum commune*. At Sanjiang Plain, the marsh site with a flat topography is covered with homogeneous herbaceous vegetation dominated by *Carex lasiocarpa*. Other species in the marsh are *Carex pseudocuraica*, *Glyceria spiculosa* and *Carex meyeriama*. More data on physical-chemical characteristics of soil are given in Table 1.

2.2. Flux measurement and calculation

All measurements were carried out during the snow-covered season when lasted from October 2010 to April 2011 at the peatland and the marsh. Gas fluxes were estimated using snowpack properties and concentration gradient of CO_2, CH_4 and N_2O in the snowpack. Gases in snowpack were sampled through permanent samplers that installed before significant snow accumulation had occurred. The snowpack surrounding the samplers was not disturbed when sampling throughout the snow-covered season. The sampler was constructed of stainless steel (2 mm ID, 3 mm OD) tubings with 50 cm long fitted on a rod at heights of 0, 10, 20, 40, and 60 cm above the ground. Each of the five stainless steel tubes supported a pair of inlets, which one was connected with platinum silicone tubing (2 mm ID, 4 mm OD; 150 cm length; Shenzhen Rubber & Plastic Co., China), and the end of the tubing was attached to a three-way stopcock. The other inlet was fitted with 80 mesh gauze to prevent debris from entering the sampling line. In the peatland, we randomly installed five samplers. Gas samples collection began in late October, just after a few days of the snow and the snowpack was approximately 18 cm thick, and ended in March. In the marsh, the standard stainless steel tubings in the sampler were fitted on a rod at heights of 0, 20, 40 and 60 cm above the ground. Three samplers were established in the homogeneous terrain. We sampled snowpack gases from December to March at the marsh. The snowpack gases were collected two or three consecutive dates at both sites in each month.

Snow and atmospheric air samples for greenhouse gas analyses were taken with plastic syringes (60 mL) and the sample size was 50 mL. Approximately 10 mL were drawn and discarded to completely purge the tubing, whose internal volume was approximately 6.5 mL. Assuming a sphere volume of gas flow was sampled, the 50 mL of air withdrawn at inlet would yield an effective radius of ~2.7 cm. The sampling ports were 10 and 20 cm apart in the vertical, so there might be little influence on gas leakage from above/below layers. Samples were withdrawn from the syringes by injecting into previously evacuated Tedlar® air bags (100 mL, Delin Ltd, Liaoning, China). The sealed air bags were then transported to the laboratory and greenhouse gas concentrations were analyzed by the use of a gas chromatograph (Agilent 4890D, Agilent Co., Santa Clara, USA). The modified gas chromatograph equipped with a flame ionization detector (FID) and an electron capture detector (ECD) (Wang and Wang, 2003). N_2 was used as the carrier gas with a flow rate of 30 mL min^{-1}. CH_4 was directly measured by FID. CO_2 was firstly reduced to CH_4 and then detected by FID. N_2O was measured by ECD. To avoid the interference of CO_2 upon the N_2O signals described by Zheng et al. (2008), a buffer gas (CO_2:N_2 = 10:90) was applied to flow through the ECD cell at a rate of 1–3 mL min^{-1}. More details about gas analysis can be found in Wang and Wang (2003).

Table 1
Characteristics of wetland soils in Northeast China.

Site	SOC, g kg^{-1}	TN, g kg^{-1}	C/N	pH
Marsh	53.7 ± 0.3	4.4 ± 0.7	12.2	5.0 ± 0.04
peatland	371.7 ± 1.3	19.8 ± 0.1	18.8	4.9 ± 0.1

SOC indicates soil organic carbon; TN represents total nitrogen, the value behind plus and minus represents standard error.

The flux was calculated using Fick's first law of diffusion through porous media which assumed consistent gas concentrations at each layer in the snowpack (Sommerfeld et al., 1993; Seok et al., 2009). So, the efflux through the snowpack is calculated using the equation

$$F_g = -D_g\left(\frac{\partial C_g}{\partial z}\right), \quad (1)$$

where F_g is the diffusive flux for a gas (g) along a concentration difference (∂C_g) below z cm of snowpack. D_g is the diffusivity of gas in the snowpack airspace at the ∂z interval, and $\partial C_g/\partial z$ is the gas concentration gradient in the snowpack. In order to meet Fick's first law, we rejected the flux values if linear regressions of fitted gas profiles were lower than 0.85 for CO_2, and 0.75 for CH_4 and N_2O (Mast et al., 1994; Sommerfeld et al., 1996). The diffusivity D_g can be estimated using the equation

$$D_g = \phi\tau D\frac{P_0}{P}\left(\frac{T}{T_0}\right)^{\alpha}, \quad (2)$$

where ϕ is the snowpack porosity, τ is the tortuosity coefficient, D is the diffusion coefficient of the specific gas under consideration at standard temperature and pressure (hPa). In our study, diffusion coefficient of CO_2, CH_4 and N_2O were 0.1381×10^{-4} m^2 s^{-1}, 0.1952×10^{-4} m^2 s^{-1} and 0.1436×10^{-4} m^2 s^{-1}, respectively (Massman, 1998). T is the snowpack or air temperature (K), and the exponent $\alpha = 1.81$ is a theoretically set coefficient explained by Massman (1998). Snowpack porosity ϕ is calculated by

$$\phi = 1 - (\rho_{snow}/\rho_{ice}) \quad (3)$$

where ρ_{snow} is the mean snow density at the ∂z interval, and ρ_{ice} is 0.9168 g cm^{-3}. Tortuosity is usually described as a function of porosity with values ranging from $\phi^{1/3}$ to $\phi^{2/3}$ (Striegl, 1993). In this study, the tortuosity of the snowpack was estimated as $\tau = \phi^{1/3}$ (Hubbard et al., 2005).

Snow pits were dig for determination of snowpack properties. The snow porosity were measured from 3 volumetric snow samples taken through the snowpack from top to the bottom with a 103 mm (inner) diameter PVC tube at each gas sampling date. The snow samples were weighed in the laboratory to calculate the average snow density and porosity (Alm et al., 1999).

2.3. Abiotic factors

Air temperature, snow temperatures in the peatland (at the snow–soil interface, and at 10 cm interval in snow depths), were measured using a portable digital thermometer (JM624, Jinming Instrument CO., Tianjing, China) after the gases had been sampled. Snow depth was measured by a steel ruler at each measurement. Soil temperatures in different depths (5, 10, 15, 20, and 40 cm) and atmospheric pressure were obtained from automatic weather station in the marsh. We lost all soil temperatures due to malfunction of an automatic temperature recorder in the peatland. Atmospheric pressures on each sampling date were obtained from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/).

2.4. Statistical analysis

Statistical analyses were performed by using SPSS 13.0 (SPSS Inc., Chicago, USA). Prior to any further analysis, flux data were done by normal distribution test. A log10 or square root transformation was applied to flux data for following a normal distribution. A value of 35 was added to the N_2O flux data from the marsh before applying square root transformation to make sure that the data were positive. Correlation analysis was performed on SPSS 13.0 using *Pearson* correlation analysis.

3. Results

3.1. Snowpack and climate characteristics

During the snow-covered season in 2010/2011, snowpack began to develop in mid-October at the peatland and in mid-November at the marsh. In the peatland, the snow depth gradually increased at the early winter and kept a steady depth when it reached ca. 40 cm (Table 2). The snowpack, which reached a maximum depth of 50 cm in late December, fluctuated from 40 to 50 cm at the most of time during the snow-covered season; and snow mantled the marsh until mid-April. The snow porosity varied from 0.63 to 0.79 in the marsh and from 0.75 to 0.79 in the peatland, respectively (Table 2).

Table 2 shows air temperatures in both sites at the sampling dates. Mean daily air temperature showed large discrepancies at each month, except for November and January in the peatland and January in the marsh. The peatland experienced colder weather, and daily mean air temperature was ranged from −39.8 °C in December to −3.5 °C in March. Mean daily air temperature at the marsh was a litter higher which ranged from −22.8 °C to 0.5 °C during the measurement period. Snow temperatures were observed at the peatland showed the same pattern with air temperatures which the lowest occurred in January and the highest occurred in October. Table 2 also shows mean soil temperature from 0 to 40 cm below soil surface, which showed little variability in the extent from −1.2 °C to −0.4 °C in the marsh.

3.2. CO_2, CH_4, and N_2O concentrations in snowpack

The profiles of CO_2, CH_4 and N_2O within the snowpack at the peatland and the marsh are shown in Fig. 1. CO_2, CH_4 and N_2O

Table 2
Measured snowpack properties and environment factors in the peatland and marsh.

Site	Date	Atmospheric pressure, Pa	Snow depth, cm	Snow porosity	Air temperature, °C	Soil temperature[a], °C	Snowpack temperature[b], °C
Marsh	Dec 26–29, 2010	9.81×10^4–9.96×10^4	46–50	0.79	−13.6 to −22.6	−0.6 to −0.3	n.d.
	Jan 16–18, 2011	9.97×10^4–10^5	41–42	0.67	−16.7 to −18.6	−0.8 to −0.6	n.d.
	Feb 24–26, 2011	9.91×10^4–1.009×10^5	39–45	0.72	−5.5 to −17.7	−1.2 to −0.4	n.d.
	Mar 18–20, 2011	8.93×10^4–9.82×10^4	40–47	0.63	−8.1 to 0.5	−0.6 to −0.5	n.d.
Peatland	Oct 22–25, 2010	9.55×10^4–9.63×10^4	18–27	0.78	−14.6 to −3.5	n.d.	−4.2 to −1.5
	Nov 26–27, 2010	9.50×10^4–9.53×10^4	37	0.79	−31.8 to −29	n.d.	−26.4 to −19.4
	Jan 10–12, 2011	9.48×10^4–9.56×10^4	41–42	0.79	−39.8 to −37.2	n.d.	−31.8 to −24.6
	Feb 19–21, 2011	9.49×10^4–9.54×10^4	42–43	0.78	−22.9 to −11.6	n.d.	−21.9 to −17.5
	Mar 17–19, 2011	9.34×10^4–9.43×10^4	42–45	0.75	−11.5 to −5.5	n.d.	−12.5 to −5.4

[a] Average soil temperature between 0 and 40 cm depth below soil surface.
[b] Average snowpack temperature between 0 to actual snow depth above soil surface. n.d., not determined.

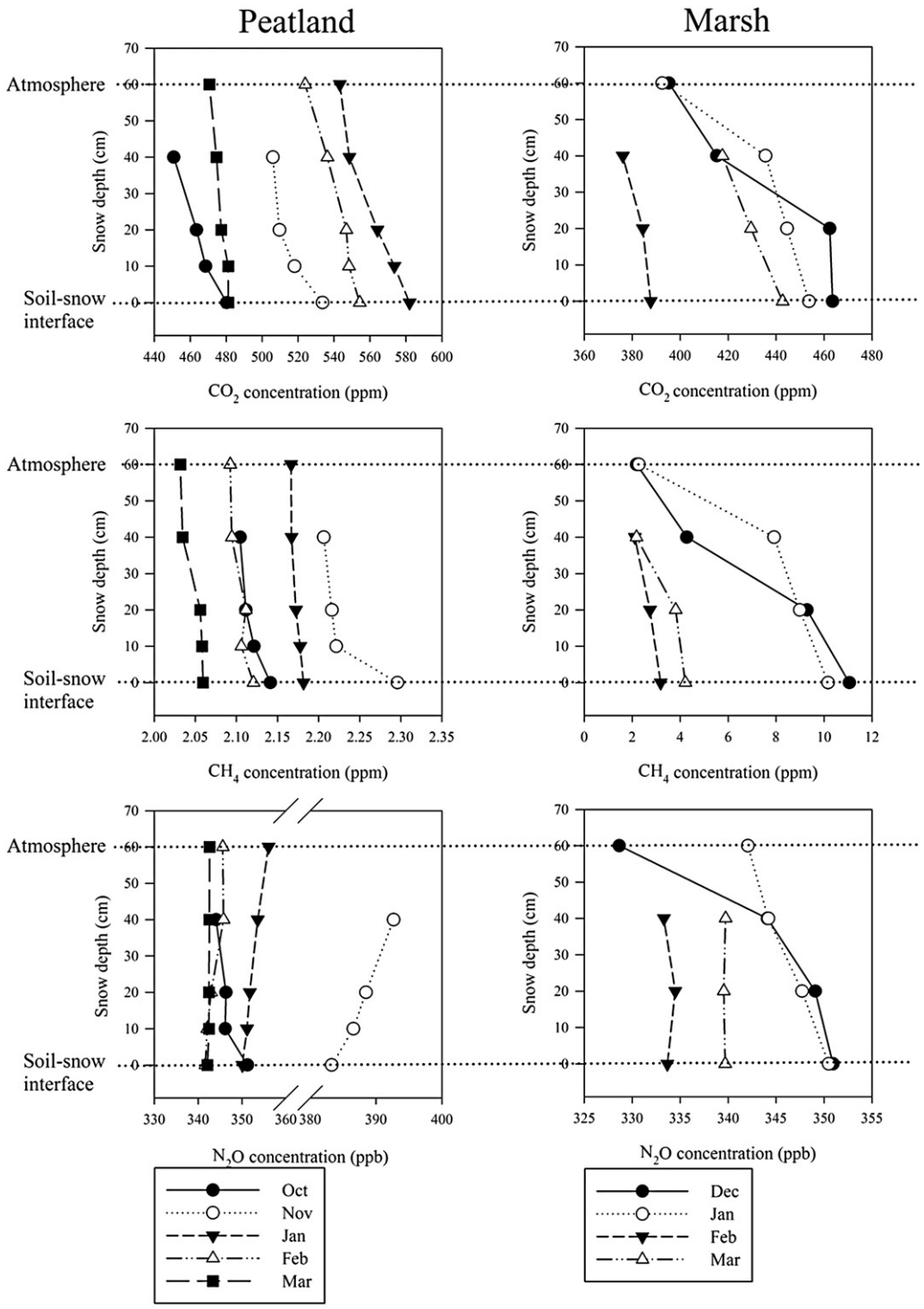

Fig. 1. Profiles of greenhouse gas concentrations in snowpack and atmosphere at the peatland and marsh sites during the snow-covered season.

concentrations in the snowpack varied temporally throughout the measurement period. Mean CO_2 concentrations in the snowpack were ranged from 463.50 to 581.99 ppm in the peatland and from 384.40 to 463.55 ppm in the marsh. The temporal of CO_2 concentrations at each layer in the peatland showed a similar pattern with the marsh. CO_2 concentrations at the base of snowpack reached maximum of 581.99 ppm for peatland and 463.55 ppm for marsh in mid-winter. In all measurements, CO_2 concentrations at the base of snowpack were much higher than that in the atmosphere.

Like the vertical distribution of snowpack CO_2 concentrations, CH_4 concentrations decreased from the soil–snow interface to the atmosphere. Temporal variations of CH_4 concentration at each specific layer showed the similar pattern in respective site. But CH_4 concentrations had a large variation at each layer in both sites. For example, CH_4 concentration at the base of snowpack varied from 3.2 to 11.1 ppm in the marsh. However, in the peatland, concentration of CH_4 ranged from 2.06 to 2.30 ppm.

The temporal variations of N_2O concentration at each layer during the snow-covered season in both sites were largely

complicated. In the peatland, N_2O concentrations at the snow–soil interface were not significantly different from the concentrations in other layers and the atmosphere. N_2O concentrations in the snowpack gradually decreased from the base to the top in the early snow-covered season, while the converse pattern occurred in mid and late snowy season. However, in the marsh, the increased N_2O concentration with increasing snow depth only occurred in late snowy season.

3.3. *Fluxes of CO_2, CH_4 and N_2O during the snow-covered season*

Fig. 2 shows greenhouse gas fluxes from the peatland and the marsh throughout the 2010/2011 snow-covered season. In the peatland, emission rates of CO_2 were on average 33.29 mg C m^{-2} d^{-1} in October, then slowly decreased to 22.24 mg C m^{-2} d^{-1} in February and last declined to 6.86 mg C m^{-2} d^{-1}. The similar trend is evident at the marsh, as early snowpack season emission rates were nearly 54.84 mg C m^{-2} d^{-1} for December while late season emissions were on average 22.58 mg C m^{-2} d^{-1} (Fig. 2). The emission rates of CO_2 from the two sites were in the same order, but CO_2 fluxes from the marsh were higher than that from the peatland. CO_2 fluxes were negatively correlated with snow density for the peatland. Meanwhile, significant relationships between marsh CO_2 fluxes and temperature were obtained for the soil temperature measured at 15–40 cm below the surface (Table 3).

Average CH_4 fluxes from the peatland ranged from 0.016 mg C m^{-2} d^{-1} to 0.112 mg C m^{-2} d^{-1}, which had an emission pattern with firstly decreased from 0.112 mg C m^{-2} d^{-1} in November to 0.016 mg C m^{-2} d^{-1} for January, then increased to 0.032 mg C m^{-2} d^{-1} in March (Fig. 2). However, in the marsh, CH_4 emission rates firstly decreased from approximately 10.313 mg C m^{-2} d^{-1} in December to 1.555 mg C m^{-2} d^{-1} in February. Then CH_4 emission rates slowly increased as 2.492 mg C m^{-2} d^{-1} in March (Fig. 2). Unlike CO_2 fluxes, CH_4 fluxes from the marsh were nearly two orders of higher than from the peatland. Soil temperature at 30 and 40 cm below surface significantly controlled CH_4 emission from the marsh (Table 3). In addition, a strong correlation between CH_4 and CO_2 fluxes was found at the marsh. While, CH_4 fluxes were negatively related with snow density in the peatland (Table 3).

During the measurement period, average N_2O fluxes varied from −30.650 μg N m^{-2} d^{-1} (minus value means consumption) to 25.344 μg N m^{-2} d^{-1} at the peatland and ranged from −0.326 μg N m^{-2} d^{-1} to 48.152 μg N m^{-2} d^{-1} at the marsh (Fig. 2). The peatland emitted N_2O at early winter, and then transferred to consume N_2O as the development of snowpack. Emission rates of N_2O from the marsh decreased to nearly zero at mid-winter and consumptions of N_2O were observed in March. Be similar with CH_4 and CO_2, marsh N_2O fluxes were dependent on soil temperatures at 20 and 40 cm below surface (Table 3). In the peatland, snow–soil interface temperature controlled on N_2O fluxes.

According to the date of first snow and disappear of snowpack, the snow-covered season was arbitrarily defined as the period from 15th October until 10th April in the peatland and from 15th November to 5th April in the marsh. The accumulative fluxes of greenhouse gas during the snow-covered period were estimated as mean monthly fluxes multiplied by the days of the month. Results of calculations are summarized in Table 4. Generally, both sites were sources of greenhouse gas during the snow-covered season except that peatland consumed N_2O. The magnitude of CO_2 emitted from the peatland was 4.179 g C m^{-2}, which was lower as compared with emissions (5.026 g C m^{-2}) from the marsh. However, CH_4 emissions from the marsh (818.15 mg C m^{-2}) were approximately 87 times higher than that from the peatland (9.409 mg C m^{-2}). Peatland soil consumed N_2O at the most of snowy season, and the cumulative absorption of N_2O was 1.639 mg N m^{-2}. In contrast, N_2O was

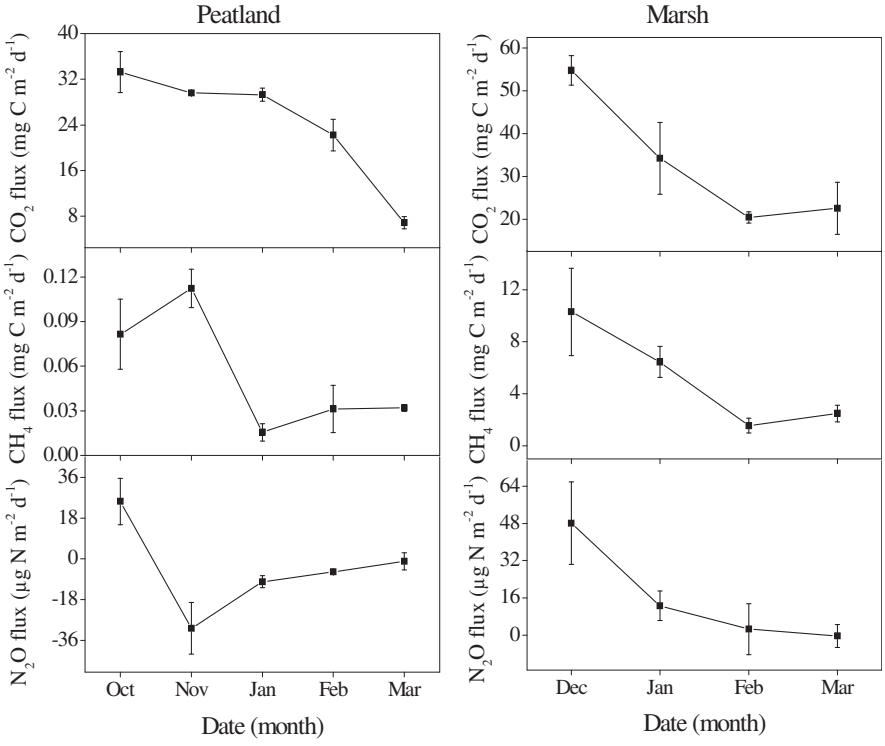

Fig. 2. Mean monthly greenhouse gas fluxes from the peatland and marsh during the snow-covered season.

Table 3
The relationships between greenhouse gases fluxes and snow properties and envrionmental factors in both sites.

	Peatland		Marsh[a]			
	Snow density, $cm^3\ cm^{-3}$	Soil-snow temperature, °C	CO_2 flux, mg $m^{-2}\ d^{-1}$	Soil temperature at 15 cm, °C	Soil temperature at 20 cm, °C	Soil temperature at 40 cm, °C
CO_2 flux, mg $m^{-2}\ d^{-1}$	−0.712**	−0.076	1	0.569*	0.77**	0.787**
CH_4 flux, mg $m^{-2}\ d^{-1}$	−0.718**	0.228	0.81**	0.446	0.717**	0.751**
N_2O flux, μg $m^{-2}\ d^{-1}$	−0.304	0.769*	0.708**	0.342	0.648*	0.659*

*Represents the significance at 0.05 level; ** Represents the significance at 0.01 level.
[a] Indicates greenhouse gases flux in the marsh were transformed in order to satisfy the normal distribution.

absorbed only in late snowy season, and the amount of 2.717 mg N m^{-2} N_2O was released to the atmosphere at the marsh.

4. Discussion

4.1. Carbon dioxide

In our study, mean snowpack season CO_2 efflux was respectively 23.88 and 35.23 mg C $m^{-2}\ d^{-1}$ for the freshwater marsh and the peatland, which was fell within some reported values in mid- and high-latitudes wetlands (Fahnestock et al., 1999; Panikov and Dedysh, 2000; Zimov et al., 1993). However, our results were greater than the mean winter respiration rate in a boreal peat bogs in West Siberia (Panikov and Dedysh, 2000), and were much lower than most of reported values in high-latitude wetland ecosystems(Alm et al., 1999). CO_2 originated from belowground respiration during the snow-covered season has been attributed to the snowpack insulating properties, which can preserve heat from soil for maintenance of the survival of microorganism (Panikov and Dedysh, 2000). In the present study, observed CO_2 concentrations at both sites increased with snow depth from the snow–soil interface, indicating that soils were CO_2 source to the atmosphere throughout the snow-covered season. However, the snow covers were thin with the maximum values of 45 and 50 cm in the peatland and marsh, respectively. The snow cover was not deep enough to effectively decouple soil temperatures from the atmosphere (Schimel et al., 2006), leading to low CO_2 emission rates. This could interpret that CO_2 efflux in our study area was much lower than that from most snowy ecosystems where existed several meters depth of snow cover (Liptzin et al., 2009).

Previous studies showed that winter CO_2 fluxes were sensitive to soil temperature and moisture availability due to microbial respiration was the most important composition of CO_2 effluxes (Liptzin et al., 2009). In the present study, we found that soil temperatures at 15–40 cm depth ranged from −0.9 °C to 3.8 °C, significantly regulating winter CO_2 flux in the marsh. It was consistent with Zimov et al. (1993) who observed the correlation between temperature and CO_2 efflux. Our results indicated that soil temperature was an important factor controlling marshland snowpack CO_2 efflux. Soil temperature was effectively decoupled from air temperature and dependent on the snowpack, which might affect soil microbial activities and communities (Schmidt and Lipson, 2004).

The absence of correlation between soil–snow interface temperature and peatland CO_2 flux indicates that temperature in surface soil is not the primary factor controlling CO_2 respiration. This may be attributed to respiratory CO_2 came from deep soil layer where temperature in it was much warmer than that in the upper soil layer (Zimov et al., 1993). The negative relationship between peatland CO_2 flux and snow density indicates snow properties are primary factors controlling CO_2 efflux from snowpack. Mast et al. (1998) found snow density was the primary factor controlling CO_2 profiles in snowpack, which determined CO_2 emission rates in snowy season.

4.2. Methane

In our study, the peatland and the marsh acted as a source for atmospheric CH_4 throughout the snow-covered season, although the magnitude of CH_4 emissions from the peatland were further lower than that from the marsh (Table 4). Our reported value of CH_4 efflux from the peatland (0.009 g CH_4–C m^{-2} $season^{-1}$) was much smaller than that from treed peatland in central Alaska (Kim et al., 2007). This can be attributed to the higher productivity of Alaskan peatland (Whiting and Chanton, 1993). CH_4 fluxes from the marsh were 0.818 g CH_4–C m^{-2} $season^{-1}$, much lower than that from temperate peatland (Melloh and Crill, 1996). The probable reason might be due to colder temperature in our study area compared to temperate peatland in New Hampshire.

Some studies reported that CH_4 emission was a synthesize result of production, oxidation and transport (Whalen, 2005). During the snow-covered season, insulating snowpack can increase soil temperature and support methanogens for CH_4 production, and

Table 4
Calculated accumulative fluxes of greenhouse gases from the peatland and marsh during the snow-covered season.

Year	Month	CO_2 g C m^{-2} $month^{-1}$		CH_4 mg C m^{-2} $month^{-1}$		N_2O mg N m^{-2} $month^{-1}$	
		Peatland	Marsh	Peatland	Marsh	Peatland	Marsh
2010	Oct[a]	0.566	n.d.	1.388	n.d.	0.431	n.d.
	Nov	0.888	0.877	3.370	165.0	−0.920	0.771
	Dec	0.913[d]	1.7	1.982[d]	319.7	−0.632[d]	1.493
2011	Jan	0.909	1.063	0.482	200.3	−0.314	0.392
	Feb	0.623	0.574	0.876	43.55	−0.162	0.073
	March	0.212	0.698	0.991	77.25	−0.032	−0.010
	April[b]	0.068	0.114	0.320	12.46	−0.010	−0.002
	Total[c]	4.179	5.026	9.409	818.15	−1.639	2.717

[a] Fluxes were calculated from 15 October when snow began to accumulate at pealtand site.
[b] Fluxes were calculated to 10 April at peatland site and 5 April at marsh site when snow disappeared.
[c] The unit in this row were g m^{-2} $season^{-1}$ for CO_2, mg m^{-2} $season^{-1}$ for CH_4 and mg m^{-2} $season^{-1}$ for N_2O, respectively.
[d] Fluxes were determined by averaging November and January emissions at peatland site due to no data in December. n.d. means no data because of no snow in October at marsh site.

thus emit CH_4 form the snowpack. We found significant positive correlation between CH_4 fluxes and soil temperature at 20–40 cm depth which indicated that microbial communities existed in soils. However, transport mechanisms of CH_4 through the snowpack to the atmosphere are still unclear. Kim et al. (2007) suggested probable CH_4 transport mechanisms from peatland in permafrost zone. They figured out soil-originated CH_4 emitted through vascular plants owing to pressured CH_4 from bottom-up and up-down freezing. In the present study, stand litter of vascular species such as *E. vaginatum* or *C. lasiocarpa* at both sites might offer transport tissue for CH_4 emission. In the peatland, we also found snow density negatively controlled CH_4 fluxes, similar to CO_2 fluxes. The effect of snow density on CH_4 efflux can be attributed to the effect of snow porosity which calculated from snow density. The porosity of snow reflects the diffusivity of gas from snowpack to the atmosphere (Mast et al., 1998). So, decreased CH_4 fluxes in the peatland can be partly explained by the declined snow porosity in the snow-covered season.

4.3. Nitrous oxide

During the snow-covered season, the peatland consumed N_2O at a rate of 14.767 μg N_2O–N m^{-2} d^{-1} and the marsh emitted 31.382 μg N_2O–N m^{-2} d^{-1} of N_2O. It is interesting that N_2O consumption occurred in the peatland, which distinguished from observations conducted in boreal ecosystems where N_2O emission occurred in the most of snowpack period (Alm et al., 1999; Oquist et al., 2007). That might be attributed to active microorganism survived in snowpack which consumed N_2O in our study area. In the peatland, the relationship between N_2O fluxes and temperature at soil–snow interface suggested temperature was an important factor controlling N_2O fluxes at some extents. However, the mechanisms of N_2O uptake from the peatland were not fully understood. More detailed soil data, as well as experimental manipulations, are needed to evaluate the relative controls of N_2O uptake in this ecosystem. In the marsh, N_2O emission decreased with development of the snowy season, and the marsh transferred to N_2O sink in late snowy season. Our results suggest that denitrifying and nitrifying microorganisms at both sites remains active throughout the snow-covered season, and whether these ecosystems acted as source or sink of N_2O depended on the balance of N_2O production and consumption.

Recent studies reported that N_2O can be produced in frozen soil originated from denitrification (Oquist et al., 2004, 2007). Oquist et al. (2004) found that net N_2O production rates at −4 °C were equivalent to those observed at 10–15 °C at appropriate moisture conditions. In the marsh, soil temperatures at 5–40 cm depth were consistently above −4 °C which favored N_2O production during the snow-covered season. The present of significant relationship between N_2O flux and CO_2 flux in the marsh suggested that microbial respiration may be of account in reducing oxygen availability to a point that favors denitrification (Table 3). However, the decrease in N_2O flux observed during the snow-covered season was consistent with the idea that substrate availability in the primary control on microbial activity within frozen soil. The decrease in labile carbon sources in late snowy season due to absence of substrate supply can result in limiting N_2O production or consumption. In addition, the increased soil frozen depth in the marsh might cause little unfrozen water which be available to denitrification.

4.4. Uncertainty analysis

The reliability of greenhouse gas fluxes determined using concentration gradients and diffusion model were evaluated (McDowell et al., 2000) and the observed fluxes were compared with the fluxes determined by chamber methods (Alm et al., 1999). In our study, however, the results obtained through concentration gradient and diffusion model were restrained by several uncertainties. Firstly, snow properties were important factors which determined the accuracy and reliability of estimating greenhouse gas fluxes. Hubbard et al. (2005) reported that the most important difficult parameter to estimate was tortuosity which can be measured directly or molded using porosity. The tortuosity in our study ranged from 0.84 to 0.92 in the marsh and from 0.91 to 0.93 in the peatland, which were within the range for those reported from 0.74 to 1 (Mast et al., 1998; Sommerfeld et al., 1993). However, porosity was another important parameter which derived indirectly from snow density (Eq. (3)), and also affected estimating gas fluxes. Seok et al. (2009) reported that errors in estimating snow density resulted in an error in the estimated CO_2 flux of 2–9% from snowy ecosystems. Therefore, a precise measurement of snow density would generate persuasively estimating gases fluxes from snowpack.

Secondly, pressure pumping caused by high wind velocity and atmospheric pressure fluctuations has been shown in significant potential error in calculating greenhouse gas fluxes by the usage of diffusion model through snowpack (Sullivan et al., 2008). The pressure pumping derived from high wind speed result in a negative bias on calculated fluxes which underestimated fluxes under high wind conditions (Seok et al., 2009). Average wind speeds during our sampling dates were 1.13 and 2.62 m s^{-1} at the peatland and the marsh, respectively. However, on one or two sampling dates, wind speeds exceeded 3.7 m s^{-1} which was the trigger causing considerable pumping effects on diffusion flux in our study sites (Hubbard et al., 2005). Otherwise, atmospheric pressure fluctuations could cause barometric pumping effect unless the fluctuations were lower than 5% during the sampling period (Jones et al., 1999). So, more work should focus on development of pressure-pumping model which apply to diffusion flux calculation for minimizing uncertainties.

Last but not the least, sampling frequency has been pointed out the significant potential bias in estimating greenhouse gas fluxes. According to previous studies, the frequency of sampling during the snow-covered season ranged from half an hour to once per entire season (Fahnestock et al., 1999; Heikkinen et al., 2002). Recently, Seok et al. (2009) suggested that the fluxes originated from a weekly sampling frequency was comparable with that of nearly 80 min sampling frequency using an automated sampling system for continuous measurements of trace gas fluxes. In our study, the measurements were conducted monthly with two to four sequential dates, which might produce uncertainties to some degree due to lack of enough samplings. Hence, a proper sampling frequency, especially the higher-frequency observation, such as the eddy covariance (Lohila et al., 2007; Merbold et al., 2011) in measuring the trace gas fluxes might be prominent in the future observations during the snowy season.

5. Conclusions

Greenhouse gas fluxes were measured from mid- and high-latitude wetlands in Northeast China during the snow-covered season. Gas concentration gradients in the snowpack varied with snow layer, and the increasing concentrations of CO_2 and CH_4 from soil–snow interface to atmosphere indicated gases emissions from the peatland and the marsh. However, contrast to CO_2 and CH_4, N_2O concentration profiles in the snowpack showed large variations. This illustrated that N_2O consumption might occur in both sites during snowy season. Our results of reported greenhouse gas fluxes confirmed that the presence of respiration and methane emission

from a wide range of northern ecosystems during the snow-covered season. Interestingly, the consumption of N_2O from the peatland was first reported in these ecosystems regardless of uncertainty from one-year measurement, which might offset partial warming potential originated from emission of CO_2 and CH_4 in the snow-covered season to some degree. In the future, continuous observation of greenhouse gas fluxes during the snow-covered season in high-latitude regions are needed to determine the accurate greenhouse gas budget. In addition, studies should concentrate on exploring the mechanisms of N_2O production and consumption in frozen soil which affected by snowpack.

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