



Seasonal and diurnal variations in methane emissions from Wuliangsu Lake in arid regions of China

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Abstract

CH₄ emissions have been widely studied in various wetlands, such as boreal peatlands, rice paddies, and tropical swamps. However, little investigation has been carried out for CH₄ emissions from lakes or wetlands in arid regions where these freshwaters play a vital role in providing ecosystem services for local people. To quantify the spatial and temporal variations of CH₄ flux and understand its key controlling factors in shallow lakes in arid regions of Western China, CH₄ fluxes from Wuliangsu Lake were measured at different vegetation zones and water depths with a static chamber technique during a growing season from April to October in 2003. Results showed that the average emission flux of CH₄ from submerged plant (*Potamogeton pectinatus*) growing zones was 2.16 mg CH₄ m⁻² h⁻¹, which was 85.8% lower than that from emergent macrophyte (*Phragmites australis*) growing zones. CH₄ emissions increased with increasing water depth in *Phragmites* Community. Significant seasonal and diurnal variations of CH₄ emission were observed for *P. australis* during the plant growth stage, for *P. pectinatus* growing zones, however, the variations were minor. In addition to vegetation cover and water depth, bottom silt temperature and light intensity were also important factors influencing seasonal and diurnal variations of CH₄ flux from *Phragmites* growing zone.

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1. Introduction

Methane (CH₄), a radiative gas, plays an important role in the greenhouse effect and in the chemistry of ozone destruction (Etiopie and Klusman, 2002). Methane emissions have been widely studied in various wetlands, such as peat soils, paddy fields, and tropical swamps, where freshwater ecosystems have been estimated to contribute over 70% of the natural source of CH₄ (Khalil, 2000) and over 20% of the total CH₄ source to the atmosphere (IPCC, 2001). In China, great

efforts have recently been undertaken to quantify methane emissions from rice paddies and natural wetlands (Cui, 1997; Ye et al., 2000; Jin et al., 1999; Huang et al., 2001; Ding et al., 2004; Hirota et al., 2004). Most of the CH₄ emissions from the natural wetlands in China are suggested to be released from the northern freshwater marshes (Ding et al., 2004). However, there is still no investigation for CH₄ emissions from lakes and wetlands in arid regions of China, where these aquatic ecosystems play a vital role in providing ecosystem services for local people.

The arid regions in northwestern China with the annual precipitation below 400 mm include Gansu, Qinghai, Ningxia, Xizhang and Xinjiang Provinces

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and western Inner Mongolia (Fig. 1). Lakes and wetlands in these regions mainly locate in the middle and lower reaches of large rivers such as Yellow River and Tarim River. They are formed by groundwater or irrigation water discharged from nearby farms. In Mongolian–Xinjiang Plateau, there are 724 lakes with an area more than 1 km^2 and with a total area of $1.95 \times 10^9\text{ km}^2$, i.e. 21.5% of the total lake area in China. To estimate the contribution of CH_4 emission from these lakes to global CH_4 budget, CH_4 emission factors are need.

Most of the lakes in arid regions are dominated by macrophytic vegetations, which are recently considered to control CH_4 emissions from the lakes and wetlands (Joabsson et al., 1999; Joabsson and Christensen, 2001). Aquatic plants affect all CH_4 processes including production, oxidation and transport by supplying decomposable carbon (C) to the soil/sediment through root exudation and plant litter for CH_4 -producing bacteria (*methanogens*) (Whiting and Chanton, 1993; Minoda and Kimura, 1994; Dannenberg and Conrad, 1999), transporting atmospheric O_2 to the rhizosphere for CH_4 -oxidizing bacteria (*methantrophs*) (Epp and Chanton, 1993; King, 1994) and providing a gas conduit accelerating CH_4 emission to the atmosphere (Chanton and Dacey, 1991; Shannon et al., 1996). Therefore, the characteristics of the plant community such as biomass, growing stage, species diversity, and root-rhizome architecture may then explain the temporal and spatial variations of CH_4 emissions.

In this study, we measured CH_4 emissions from Wuliangsu Lake in an arid region in China with an emphasis on seasonal and diurnal variations for methane fluxes from different vegetation zones. Several

environmental factors were also monitored in order to explain the controls on the CH_4 dynamics in the lake.

2. Materials and methods

2.1. Site description

This study was carried out at Wuliangsu Lake ($40^\circ 47' - 41^\circ 03' \text{N}$, $108^\circ 43' - 108^\circ 57' \text{E}$) in Inner Mongolia, China. It is the largest lake system in the valley of Yellow River and has an area of 29,300 ha, with mean and maximum depths of 0.7 and 4.0 m, respectively, and water depth in most of the lake are between 0.5–1.0 m (Li, 2002). Wuliangsu Lake has been increasingly eutrophicated as a result of non-point pollution from Hetao Irrigation District, where the total nitrogen and phosphorus concentrations have been 3.47 and 0.14 mg l^{-1} , respectively. Almost half of the lake is covered by emergent vegetation, mainly common reed (*Phragmites australis* (Cav.) Trin. ex Steud.). Among the reed community there are also scattered *Typha latifolia* L. and *Scirpus acutus*. In the open-water area, *Potamogeton pectinatus* L. is the most common submerged macrophyte. There is approximately 0.2–0.4 m of recent plant litter in the bottom which rested on sediment layers consisting primarily of organic matter.

2.2. CH_4 flux measurements

Four kinds of plots were chosen according to water table and the dominant plant communities—reed (*Phragmites*) and pondweed (*Potamogeton*): Reed-H,

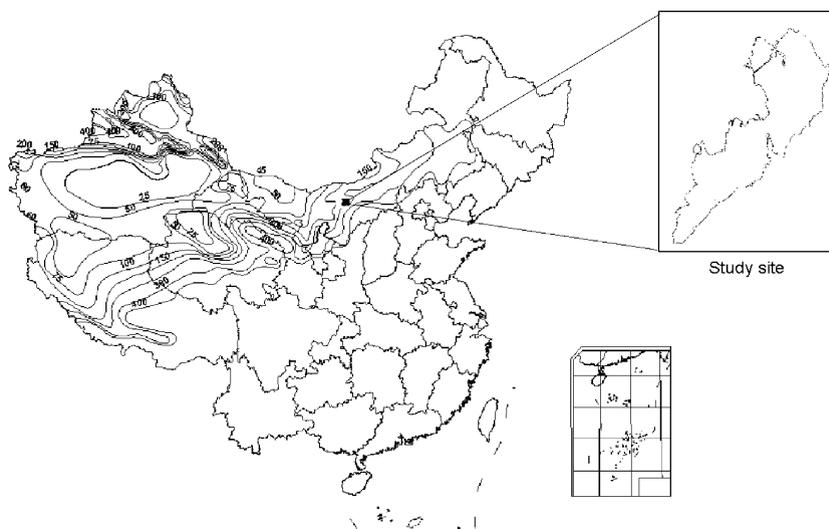


Fig. 1. Arid regions in northwestern China and location of study site.

Reed-L, Pondweed-H, and Pondweed-L (H and L represent high water depth and low water depth respectively, Table 1). The measurements were carried out along a boardwalk in order to minimize disturbance of the plots during gas sampling. Methane fluxes were measured with static chamber technique. In Pondweed-H and Pondweed-L plots, CH₄ emission was measured with floating static chambers (Huttunen et al., 2002). The floating chambers (50 cm × 50 cm × 50 cm) were constructed of Plexiglass and equipped with floating pontoons. In Reed-H and Reed-L plots, static chambers (50 × 50 × 50 cm, or 50 × 50 × 100 cm) stood on adjustable legs keeping the lower edges of the chambers beneath the water surface (Hyvönen et al., 1998). The legs were inserted into the sediment one day prior to measurements. When the reed stand was taller than the chambers, the shoots were gently folded.

Samples for seasonal changes were taken biweekly from April to October and the diurnal samples were taken once a month from April to October, except June and July.

To compare CH₄ emissions from different plant communities, another four adjacent plots were established. These were dominated by *P. australis*, *P. pectinatus*, *T. latifolia* and *S. acutus*. Measurements at these plots were conducted on 29 July and 2 September at 10:00 and 14:00 (GMT + 8 h).

Four gas samples were collected from each chamber into an air-sampling bag (volume 1 L) using a battery-operated pulse pump (Sibate, flow 1 L min⁻¹) at 0, 10, 20 and 30 min after the chamber was deployed. Methane concentration in the gas samples was determined using a gas chromatograph (GA 112A) equipped with a flame ionization detector (FID) and separated with a Teflon column (2 m × 3 mm) packed with TDX-01 (60–80 mesh). The oven, injector, and detector temperatures were 80, 100 and 180 °C, respectively. The carrier gas (N₂) flow rate was 30 ml min⁻¹, flame gases (H₂ and compressed air) were set at 20 and 30 ml min⁻¹, respectively. The CH₄ fluxes were calculated from the linear changes ($R^2 > 0.90$) in the chamber CH₄ concentration as a function of time.

2.3. Environmental variables

Temperature and relative humidity of air were measured with psychrometers equipped with platinum resistance thermometers and capacitive relative humidity sensors (Vaisala, model HMP35A). Photosynthetically active radiation (PAR) was measured with a quantum sensor (LI-COR, model QZ190). Water and sediment temperatures were measured with T-type thermocouples at the water surface and at depths of 0.05, 0.15 and 0.50 m below the sediment surface. These data were recorded by a datalogger (Campbell

Table 1
The characteristics of sampling plots in Wuliangsu Lake

Plot	Vegetation type	Mean water level (m)	Density (stem m ⁻²)	Mean height (cm)	Mean over-ground biomass (dry weight, kg m ⁻²)
Reed-L	<i>Phragmites australis</i>	0.46 ± 0.09 (n = 32)	131 ± 23 (n = 3)	223 ± 21 (n = 3)	1.86 ± 0.41 (n = 3)
Reed-H	<i>Phragmites australis</i>	0.83 ± 0.12 (n = 32)	108 ± 17 (n = 3)	301 ± 35 (n = 3)	2.52 ± 0.53 (n = 3)
Pondweed-L	<i>Potamogeton pectinatus</i>	0.51 ± 0.11 (n = 32)			1.65 ± 0.25 (n = 3)
Pondweed-H	<i>Potamogeton pectinatus</i>	0.78 ± 0.14 (n = 32)			1.85 ± 0.62 (n = 3)

Scientific, model CR10X) with a recording interval of 10 min. The sediment pH and redox potential were measured with a pH/Eh meter (HANNA, model HI8414) in situ.

3. Results

3.1. Seasonal variation in CH₄ flux

Apparent and similar seasonal variations in CH₄ flux from both Reed-H and Reed-L were observed. The CH₄ flux increased from early April when the shoots did not yet emerge from the water, and reached its maximum in mid-summer (Reed-H) or late-summer (Reed-L), and then declined. In contrast, there was only a small seasonal variation in CH₄ release from the Pondweed-H and Pondweed-L plots and the highest emission rate (6.94 mg m⁻² h⁻¹) was observed for the Pondweed-L plot in August (Fig. 2).

The average CH₄ flux from Reed-H was 17.93 ± 8.77 mg m⁻² h⁻¹ during the overall measuring period, which was higher than that from Reed-L (12.67 ± 6.18 mg m⁻² h⁻¹). However, both reed plots showed higher CH₄ emissions than the pondweed plots (Table 2). In addition, there was no significant difference in CH₄ release between the Pondweed-H and Pondweed-L plots ($p > 0.05$), where the average emissions fluxes were 2.09 ± 0.78 and 2.32 ± 0.91 mg m⁻² h⁻¹, respectively.

Methane flux and soil temperature were positively correlated in Reed-H and Reed-L with an exponential correlation (Fig. 3). Other environmental factors, such as relative humidity (RH) and electro-harmonix (Eh) had no significant correlation with the fluxes from any zone during the growing season.

3.2. Diurnal variation in CH₄ flux

Different trends were observed on different sampling days in reed-dominated plots (Fig. 4). In early April, diurnal variations in the flux were minor and the ratio of nighttime to daytime was 0.72 and 0.70 for Reed-H and Reed-L, respectively. In July and August, there was a significant difference for CH₄ emissions between day and night (the average daytime and nighttime emission rates were 37.05 and 15.12 mg m⁻² h⁻¹ from Reed-H and 18.18 and 10.04 mg m⁻² h⁻¹ from Reed-L, respectively). The emissions in nighttime were almost constant. The maximum CH₄ flux was 24.89 mg m⁻² h⁻¹ at 10:00 (LT) in September for Reed-H plot, whereas no peaks were observed in October. The trends were flat for Reed-L plot. From September to October, the ratio between nighttime to daytime methane flux increased from 0.57 to 0.72, 0.43 to 0.64 for Reed-H and Reed-L plots, respectively.

In Reed-H and Reed-L, diurnal variations for methane emission could be related to irradiation during growing stage. It was a clear day on 8 August and sunny light resulted in an increment of methane emission for Reed-H and Reed-L plots (Fig. 5). However, the relationship between sunlight and CH₄ emission was not

Table 2
CH₄ flux from Wuliangsu Lake ($n = 32$)

Plot	Mean CH ₄ emission (mg CH ₄ m ⁻² h ⁻¹)
Reed-L	12.67 ± 6.18
Reed-H	17.93 ± 8.77
Pondweed-L	2.32 ± 0.91
Pondweed-H	2.09 ± 0.78

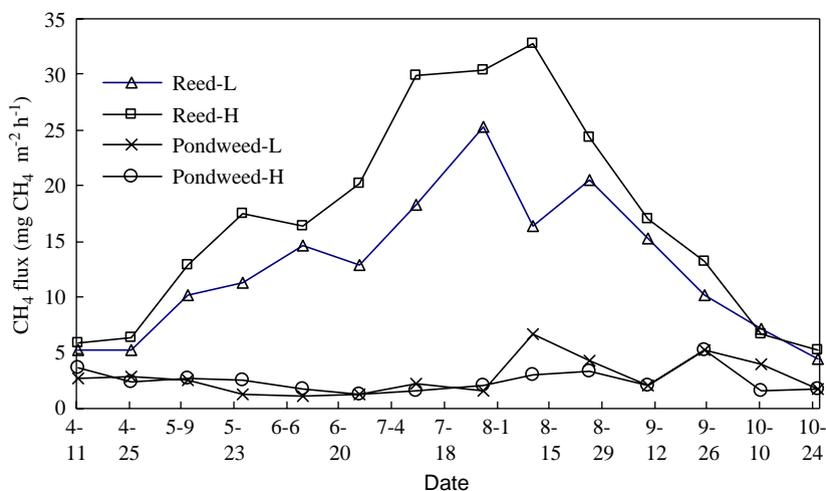


Fig. 2. Seasonal variation of CH₄ emissions from reed and pondweed plots in Wuliangsu Lake.

significant ($p > 0.05$) before emergence of the plants and after their senescence.

The diurnal pattern of CH_4 emissions from Pondweed-H and Pondweed-L did not differ significantly ($p > 0.05$) with season. CH_4 emissions were low in nighttime, increased in the morning and reached its

maximum primarily between 14:00 and 18:00 when the sediment temperature was highest.

3.3. Variations in methane flux from different vegetations

In the four adjacent plots as described above, the averages of CH_4 flux were 30.58 ± 5.23 and $10.65 \pm 3.32 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ for *Phragmites* stand on 29 July and 2 September, respectively. These emission rates were higher than those from *T. latifolia* and *Scirpus lacustris* plots. In the whole, CH_4 emission rates were higher for all plots with emergent plants than those for the *Potamogeton*-dominated plots (Fig. 6).

4. Discussion

4.1. Abiotic factors influencing CH_4 fluxes

CH_4 fluxes in this study varied among plots, and a relatively high mean CH_4 emission rate was found in Reed-H with the deepest standing water depth. However, no significant relationship between CH_4 fluxes and water table in specific plots ($p > 0.05$) was observed, this was probably due to relatively high and constant

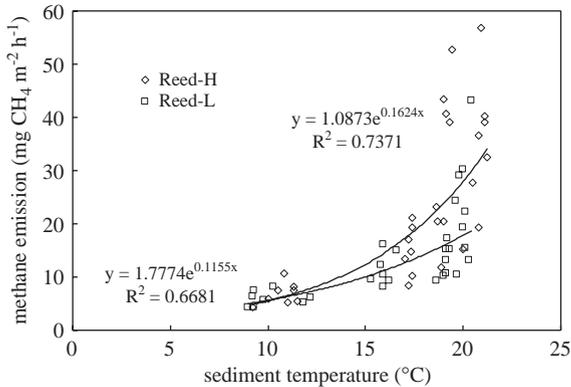


Fig. 3. Relationship between methane emission and sediment temperature in Reed-H and Reed-L plots in Wuliangsu Lake.

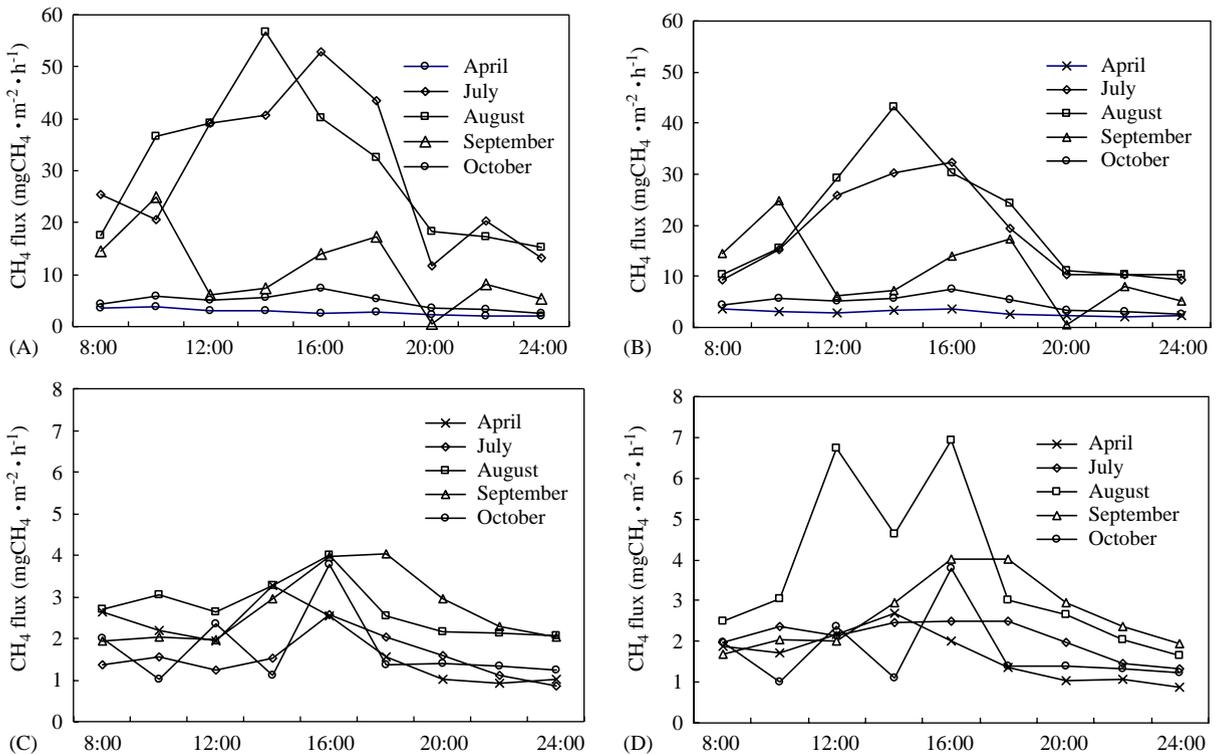


Fig. 4. Diel variation of methane emissions from (A) Reed-L, (B) Reed-H, (C) Reed-L and (D) Reed-H plots in Wuliangsu Lake. L = low water table, H = high water table.

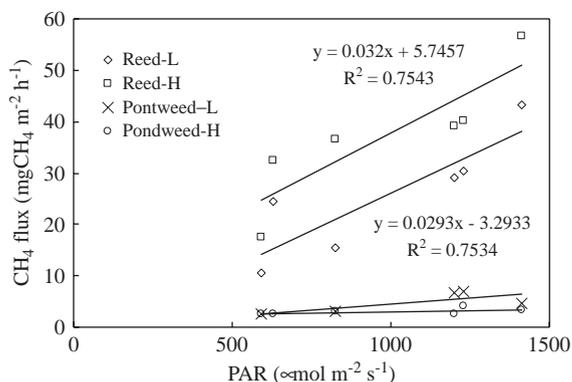


Fig. 5. The relationships between CH₄ flux and PAR in daytime (on 10 August 2003) in sampling plots.

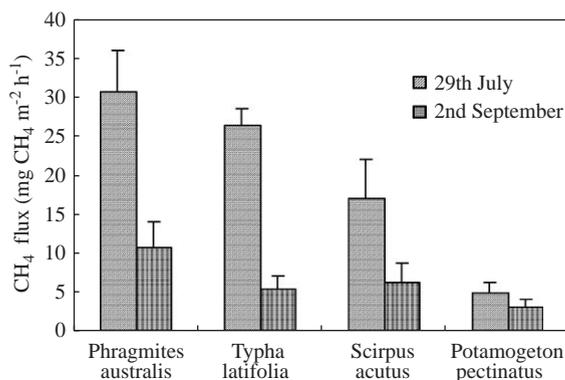


Fig. 6. The average CH₄ emissions from the stands of four different aquatic plants in Wuliangsu Lake. Methane flux measurement were carried out at 10:00 and 14:00 on (a) 29 July and (b) 2 September 2003. Error bars represent S.E. of the mean ($n = 2$).

water table during the study period. Since different CH₄ emissions were observed among different vegetation zones, water table might influence CH₄ emission indirectly by determining distribution of emergent macrophytes. *S. acutus* and *T. latifolia* existed in the shallowest zone of Wuliangsu Lake. *P. australis* appeared in the zones where the water depth was under about 2.0 m, whereas *P. pectinatus* could be found at any water depth.

In addition, the biomass of Reed-H was larger than that of Reed-L (Table 1) and a positive relationship between reed biomass and water depth was determined at the same lake in a previous study (Duan et al., 2004), which indicated that reed stands at different water depth differ in their activities of carbon fixation. However, no difference was observed for CH₄ emission

and biomass between the Pondweed-H and Pondweed-L plots.

PAR was another important factor affecting the diurnal variation of CH₄ emission for the reed-growing zone. The incident light probably drove the pressure difference associated with thermally induced convection (Van der Nat and Middelburg, 1998). So, during the convective flow-dominated period of the summer, PAR had more significant effect on the diurnal changes for CH₄ fluxes than during the ebullition- and diffusive-dominated periods in early spring and autumn, respectively. No relationship existed between CH₄ flux and PAR in Pondweed-H and Pondweed-L, probably because the diffusive gas transport mechanism was dominant in the submerged plant-growing zone.

The correlations between CH₄ emission and environmental factors indicated that mean seasonal soil temperature acted as a strong predictor for methane fluxes. Previous studies indicated that CH₄ fluxes exhibited variable relationships with soil/sediment temperatures (Crill et al., 1988; Moore and Knowles, 1990; Roulet et al., 1992; Rask et al., 2002), because CH₄ release can also be affected by other environmental factors such as composition of species and substrate supply. For the *P. australis* zone, the multiple regression analyses showed that the influence of sediment temperature at the depth of 5 cm was more important than that of other measured variables ($F = 22.80$; $p < 0.01$).

In diurnal cycle, no significant relationship between CH₄ fluxes and sediment temperature existed in any plots. This was in accordance with the results of Van der Nat et al. (1998) who found that the contribution of temperature to CH₄ emissions during diurnal variation from aquatic vegetation was no more than 35%.

However, there were no significant relationships between the CH₄ emissions and the environmental factors ($p > 0.05$) in the submerged plant-growing zone. The possible reasons can be explained by as follows: on one hand, the growth of *P. pectinatus* was suppressed by cyanobacteria and the water became turbid due to eutrophication of the lake in June and July, which might have influence on CH₄ seasonal exchange in the *Potamogeton*-dominated zone. On the other hand, presence of methanotrophic bacteria (Van der Nat and Middelburg, 1998) and their increased activity influence the CH₄ dynamics of submerged aquatic macrophytes (Sorrell et al., 2002).

4.2. The role of vegetation in the control of CH₄ emissions

The CH₄ emissions were higher from the emergent macrophytes than from the submerged macrophytes,

the emergent plants can transport CH₄ to the atmosphere directly, whereas CH₄ emission from the submerged plants only distributed to the water column and its flux was controlled by ebullition and diffusion from plants and sediment surface (Sorrell and Dromgool, 1987). On the basis of the point-measured CH₄ flux and the area occupied by each zone, the CH₄ emission from Wuliangsu Lake was roughly estimated to be 1207.44 t CH₄ from April to November and 84.86% of the emissions were from *P. australis* community. Compared with the results from reed community at other sites, the flux obtained by this study was higher than that from a boreal meso-eutrophic lake (Ojala et al., 2000), similar to that from a middle-latitude marsh in North America (Kim et al., 1998).

Two different gas transport mechanisms, molecular diffusion and convective throughflow, are used in different kinds of emergent plants. In this study, CH₄ flux from *Phragmites* and *Typha*, which were suggested to be based mostly on convective gas transport (Ojala et al., 2000), was higher than the emissions from *S. lacustris* based on molecular diffusion (Van der Nat et al., 1998). In general, CH₄ emission rates based on transport mechanism were higher comparable to when CH₄ transport is based on molecular diffusion (Chanton et al., 1993; Sorrell and Boon, 1994; Whiting and Chanton, 1996). Therefore, the spatial variation in CH₄ fluxes from wetlands can be attributed to the coverage of aquatic plants with the different gas-transport mechanisms (Whiting and Chanton, 1996; Van der Nat and Middleberg, 2000). According to the distribution of plants, CH₄ flux increased from the edge to the center of the lake.

The variations of methane fluxes from reed plots can also be attributed to the change of transport mechanisms. *P. australis* based on the diffusive transport in the dark, and additional convective transport under light condition, led to relatively large diurnal variation (Van der Nat et al., 1998; Käki et al., 2001). The capacity of convective transport differ during different growth stages. After tillering, the convective throughflow is the prevailing transport mechanism, and less important as the plants became old (Kim et al., 1998). The changes of transport coincided with seasonal variations in methane emissions.

It became evident from our study that the processes controlling CH₄ emissions from vegetated zones of the lake are so complex, that no single environmental variable can fully explain CH₄ release. However, vegetation characteristics can be good predictors of the CH₄ emissions since it can explain temporal and spatial variations. On a smaller scale, occurrences of certain vascular plant species have been found to be indicators of CH₄ fluxes in wetlands (Bubier et al., 1995) and species distribution and biomass density are

the most important factors when vegetations is used to predict CH₄ emissions (Van den Pol-van Dasselaar et al., 1999).

On a larger scale, vegetation succession is a common phenomenon in wetlands and shallow lakes as a result of changes in environmental factors. In the past, the dominant species was *Chaca* spp. in Wuliangsu Lake. This is a submerged plant that was displaced by reed, because of eutrophication and the decrease in the water depth of the lake. The area of emergent plants has increased 50-fold from the 1950s in the study site. Correspondingly, methane emission should increase, similarly to what was predicted in Qinghai–Tibetan Plateau wetland (Hirota et al., 2004). Lakes in arid regions of northwestern China receive nutrients (mainly nitrogen and phosphorus) from upstream of rivers and stimulate the growth of aquatic plants. Bosten Lake, Wulungu Lake and Aibi Lake in arid regions have 300, 42.3, and 26 km² of *Phragmites* communities, respectively. Perhaps these lakes have high CH₄ emission. However, water shortage is the major problem for lakes and wetland in arid regions of northerwestern China, leading to the decrease in water depth and cover area in recent years. As a result, emergent macrophytes may have a trend to decline or to be displaced by salted plants such as *Kalidium cuspidatum*, *Nitrari schoberi*, therefore methane fluxes are likely to change accordingly.

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