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*Original Research*

# Spatial Variability of Greenhouse Gas Effluxes and Their Controlling Factors in the Poyang Lake in China

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## Abstract

$CO_2$, $CH_4$, and $N_2O$ (GHG) emissions are globally important in China, but few field observations have been made in freshwater lakes. In this paper, we measured the GHG effluxes from 44 sampling locations among four sub-regions in Poyang Lake in China in October 2010 using floating chambers. The mean $CO_2$, $CH_4$, and $N_2O$ effluxes were 0.23 μmol $m^{-2}·s^{-1}$, 3.0 nmol$·m^{-2}·s^{-1}$, and 0.11 nmol $m^{-2}·s^{-1}$, ranging from -0.25 to 0.54 μmol$·m^{-2}·s^{-1}$, 1.4 to 8.9 nmol $m^{-2}·s^{-1}$, and 0.012 to 0.21 nmol$·m^{-2}·s^{-1}$ for the $CO_2$, $CH_4$, and $N_2O$ efflux, respectively. We found differently related tendencies between GHG effluxes and environmental parameters for each sub-region and, totally, four sub-regions together. The 16 environmental factors explained the GHG effluxes with 55%, 70%, and 89% of the variation in $CO_2$, $CH_4$, and $N_2O$ efflux, respectively, in Poyang Lake. Our analysis revealed that sediment C/N ratio, water depth, and the difference of air-water temperature were significantly contributing variables for GHG effluxes in the lake.

**Keywords:** greenhouse gas effluxes, spatial variability, environmental factors, the Poyang Lake

## Introduction

Carbon dioxide, methane and nitrous oxide, and key radiatively active GHG, have contributed approximately 60%, 20%, and 6%, respectively, to the global greenhouse gas effect [1]. The GHG effect has played a dominate role in observed global warming in past decades [2]. Previous studies have found that freshwater bodies, such as streams, rivers, and lakes, have produced a large amount of these GHGs, most of which are through biotic processes [3-8]. It has been estimated that global lakes alone emit 71.6Tg $CH_4$ [9] and 1943 Tg $CO_2$ [10] to the atmosphere every year. So far, global $N_2O$ emissions from lakes have not been accurately estimated, due mainly to the high spatial variation of the effluxes [11, 12]. However, Yang et al. [13] revealed that Bastviken et al. [9] underestimated the global $CH_4$ emission from lakes due to lack of other regional field measurements such as Chinese lakes, which estimated the global $CH_4$ budget using 53 lakes only coming from the American or European lakes on the basis of the field measurement data. Thus, the GHG emissions from lakes in China may play an important role in global GHG budgets.

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Many previous studies have demonstrated that the GHG effluxes feature high spatial variation among lakes or even within the same lake [6, 13-15]. For example, Pavel et al. [14] reported that the $CO_2$ and $CH_4$ fluxes were only 0.7±1.0 mmol·m$^{-2}$·h$^{-1}$ and 11±9 μmol·m$^{-2}$·h$^{-1}$, respectively, in Rosulet Lake in the Romanian part of the Danube Delta, but the fluxes were about 7 times greater in Isac Lake in the same region. Bastviken et al. [6] also found that $CH_4$ fluxes varied dramatically from 3.9 to 74.2 mmol·m$^{-2}$·d$^{-1}$ in the lakes in the Pantanal region in South America during the low water season. Schrier-Uijl et al. [7] evaluated the spatial variation of $CO_2$ and $CH_4$ fluxes in different lakes in the Netherlands and found that the emission rates ranged from -6.0 to 123.9 mg·m$^{-2}$·h$^{-1}$ for $CO_2$ and from 1.4 to 18.1 mg·m$^{-2}$·h$^{-1}$ for $CH_4$. Therefore, some researchers have suggested that the lake GHG emissions should be measured on a case-by-case basis in order to estimate the global GHG budgets considering the high variations among lakes.

Examining the spatial variation of GHG effluxes and identifying their key controlling factors are critical for understanding the mechanisms of lake GHG emissions and scaling up the point-based measurements of GHG effluxes to the whole lake and even larger scales. The GHG emissions at the air-water interface in lakes are mainly determined by the GHG production in the lake sediments and production and consumption during transport in the water column. For example, plants may take up or release $CO_2$ through photosynthesis and respiration, respectively, and a large portion of the $CH_4$ produced in the sediments can be oxidized during the transport process in the water. Therefore, the GHG effluxes at the lake surface are controlled by many factors, such as water temperature, water depth, wind speed, carbon and nitrogen contents in the lake sediments and water column, pH, and electrical conductivity (EC) in the lake sediments and water bodies [7, 16]. A better understanding of the spatial patterns of the GHG effluxes and their controlling factors in key regions is crucial to accurately estimating the regional and global GHG budgets from lakes [7, 13, 17].

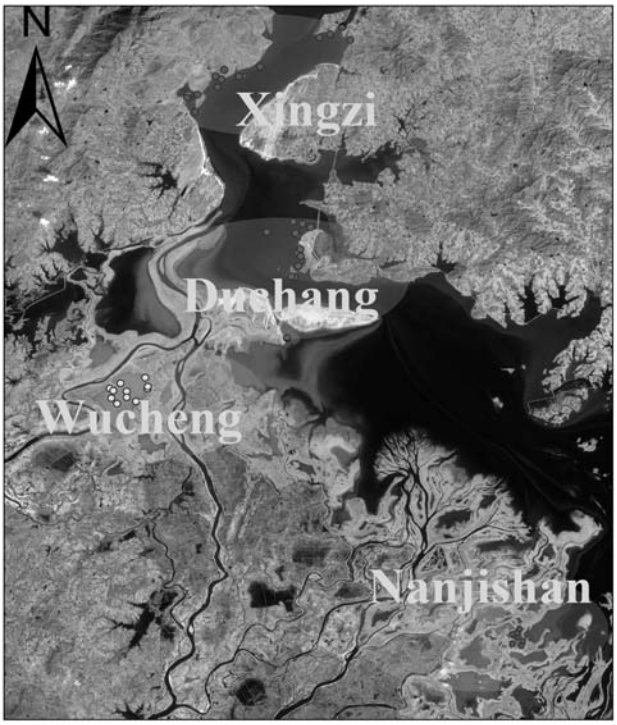

Fig. 1. Sampling locations in Poyang Lake.

Lake GHG emissions in China have rarely been measured and reported [17, 18]. China has 2,350 lakes (area >1 km$^2$) with a total area of about 1.2×10$^5$ km$^2$ [19]. Poyang Lake, the largest freshwater lake in China, is a typical subtropical lake which shares similar hydrological and ecological features with many other Chinese lakes because of the rainy season and climate. Thus, it is necessary to investigate the spatial variability of the GHG effluxes in the lake for better understanding the mechanisms of the GHG emissions. Specifically, the current study aims to:

(1) Quantify $CO_2$, $CH_4$, and $N_2O$ effluxes and elucidate their spatial patterns in Poyang Lake
(2) Identify the possible controlling factors of the effluxes by examining the correlations between the effluxes and environmental factors.

## Material and Methods

### Site Description

We conducted this study in October 2010 in Poyang Lake (E28º22′~29º45′N, 115º47′~116º45′E), which has a water area of 3,283 km$^2$ and a total catchment area of approximately 162,000 km$^2$ [20, 21]. It is located in the middle of the Yangtze River basin and in the north of Jiangxi Province in south-central China. The study site features a typically subtropical humid monsoon climate. The average annual air temperature is 17.1ºC, with a mean coldest (January) and warmest (July) monthly temperature of 5.1 and 29.5ºC, respectively. Mean annual precipitation is approximate 1,500 mm and more than two thirds of the precipitation comes with the summer monsoon. So the water level in the lake fluctuates dramatically with a high water level in the summer and low water level in the winter and early following spring, from October to the following March [21].

### Experimental Design

Considering the large area of the lake and the variation of the microclimate across the lake, we conducted a field campaign from October 16 to 18, 2010, when the climate in the entire lake was relatively similar and the water level was moderately high. The field GHG efflux measurements were taken in four sub-regions in the lake, namely the Xingzi, Wucheng, Nanjishan, and Duchang regions (hereinafter referred to as X, W, N, and D) (Fig. 1). The four regions cover a major portion of the lake and represent the geographical, hydrological, and ecological features and the typical human management activities in the lake. The W sub-region is home to migratory birds in winter, which is located in the center of Poyang Lake Nature Reserve.

Table 1. Physicochemical properties of the four sub-regions in the Poyang Lake.

| Sub-region | Properties of water | | | | | | | Properties of sediment | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WT | WD | pH | EC | DOC | $NO_3^-$-N | $NH_4^+$-N | SNC | SOC | C/N ratio | $NO_3^-$-N | $NH_4^+$-N |
| | ºC | m | | μS/cm | mg/L | mg/L | mg/L | % DW | % DW | | mg/kg | mg/kg |
| Xingzi | 20.3 | 1.9 | 6.7 | 113 | 3.8 | 0.9 | 0.19 | 0.096 | 0.75 | 7.7 | 1.01 | 16.9 |
| Wucheng | 20.6 | 1.8 | 6.8 | 82.5 | 4.0 | 0.3 | 0.12 | 0.11 | 0.7 | 6.1 | 0.55 | 23.9 |
| Nanjishan | 21.1 | 1.2 | 6.8 | 78.1 | 4.7 | 0.1 | 0.11 | 0.077 | 0.66 | 8.2 | 0.43 | 14.1 |
| Duchang | 20.4 | 1.9 | 6.5 | 75.5 | 4.1 | 0.6 | 0.22 | 0.07 | 0.7 | 10.6 | 2.58 | 13.7 |

Variables measured include water temperature (WT), water depth (WD), pH and electrical conductivity (EC) of water, water dissolved organic carbon (DOC), sediment organic carbon (SOC), sediment total nitrogen content (SNC), sediment C/N ratio, $NO_3^-$-N, and $NH_4^+$-N contents in the water and sediments. The values were spatially averaged and the DW denotes dry weight.

The N sub-region is a quasi-protected region, whereas the D and X sub-regions are subjected to human disturbances, including fishing and sand mining operations. The physicochemical properties of the four sub-regions are given in Table 1. Three transects, starting from the lake shore and extending to the middle of the lake, were randomly made in each sub-region during the field campaign. We measured the GHG effluxes on water surfaces along the transects with the sampling locations spaced >250 m apart to characterize spatial variations at different scales. Previous studies have demonstrated that no apparent autocorrelation was found for the GHG effluxes when the spatial scale was larger than 20 m from the spatial statistics of the sampling points [5]. Therefore, we chose a minimum distance of 250 m to ensure the spatial independence of our sampling. During the field campaign we surveyed the lake with 154 efflux chamber measurements. Although the samplings were not completely random across the entire lake, the mean effluxes of samples should be close to the mean effluxes of the entire lake considering the spatial distribution of the sites, the random selection of the transects and the large sample size. During the sampling period the water depth varied from 0.8 to 4.87 m, depending on the sampling locations.

## GHG Efflux Measurements

The GHG effluxes were measured using the floating chamber technique [6, 22]. Each sampling unit was made of an open-bottomed PVC chamber (20 cm in diameter and 100 cm in height) and equipped with styrofoam floats. The effective volume (the volume above water surface, 6,280 $cm^3$) of the chamber was measured on a calm day when winds and waves were absent. A pressure relieve valve was installed on the top of the chamber to balance the pressure inside and outside of the chamber. A small fan remotely controlled by a wireless sensor was installed in each chamber to mix the air inside the chamber during sampling. Four chambers were simultaneously deployed from a small boat with the chambers about 10 m away from the boat to minimize the impact of the boat. Four gas samples with 85 mL each were collected from each closed chamber using 4 air-sampling bottles, which were numbered 1 to 4 and connected in series through tubes and valves. The air was circulated between the chamber and the bottles through a pump powered by a 12VDC battery to maintain a flow rate of about 2 $L \cdot min^{-1.}$ The first sample was taken soon after the chamber was closed (ambient concentration) by temporarily powering off the pump and detaching bottle 1 from the series. The subsequent 3 samples were each taken at a 20-minute interval to finish the measurements in about an hour at each location. This sampling design avoided the pressure perturbation during the gas extraction period as with the traditional syringe sampling. The air samples were soon transported to the laboratory for analyzing the GHG concentrations with a gas chromatograph (GC 7890A, Agilent, USA). The GHG effluxes were calculated with a linear model before adjusting the system volume (including the additional volume of the gas bottles and the tubing) to the same level due to the change of the number of bottles connected and thus the sampling volume.

## Other Measurements

In addition to the GHG efflux measurements, we also measured various environmental variables in the lake sediments, the water columns and the near-surface air. We collected surface water and sediment samples (0-15 cm) immediately after the GHG efflux measurements using a plexiglass water grab and sediment sampler made of stainless steel with 3 cm in diameter. The samples were immediately transported to a laboratory for analysis. We measured water depth, wave height, and sediment active layer depth using a metal rod and a tape measure. In particular, we took 3 measurements of wave height during the efflux measurement within about one hour (at each sampling location). Then we averaged the 3 data points as the mean wave height. We also measured wind speed at about 1.5 m above the water surface using a portable anemometer (Testo410-1, Testo, Germany) and surface water (0-15 cm) temperature using a thermometer. Each sampling location was positioned using a high-precision GPS unit.

In the laboratory, the pH of the water sample was measured with a pH meter (Delta 320, Mettler-Toledo,

Switzerland) and the electrical conductivity (EC) was measured with a conductometer (DDS-307, Jingke Rex, China). We measured the dissolved organic carbon (DOC) content of all the samples using a total organic carbon analyzer (Liqui TOC II, Elementar, Germany). $NO_3^-$ and $NH_4^+$ concentrations were determined by a liquid chromatograph (AutoAnalyzer 3, BRAN+LUEBBE, Germany). Sediment total nitrogen and organic carbon contents were determined using a Vario Max CN Element Analyzer (NA Series 2, CE Instruments, Germany).

### Data Analysis

Statistical analysis was performed using SPSS software (SPSS 17.0 for windows, SPSS Inc., Chicago, IL, USA). We used standard deviation and the coefficient of variation (CV) to represent the spatial variation of the GHG effluxes among the four sub-regions. The one-way ANOVA followed by a post hoc Tukey test was used for testing the differences of GHG effluxes among the four sub-regions within the lake. We simultaneously examined the relationships between the GHG effluxes and environmental properties in the lake with regression analysis. We also conducted normality tests for the GHG effluxes and found that $CH_4$ emission rates did not follow normal frequency distribution. Thus, we log-transformed all the $CH_4$ emission data for further statistical analyses.

## Results

### GHG Effluxes and Their Spatial Variability

The mean $CO_2$ efflux in Poyang Lake was 0.23±0.15 $\mu mol \cdot m^{-2} \cdot s^{-1}$, ranging from -0.25 to 0.54 $\mu mol \cdot m^{-2} \cdot s^{-1}$ during the survey period, with a CV of 63.5%. The average $CO_2$ efflux was spatially homogenuous with no significant difference among the four sub-regions in the lake ($P>0.05$). Specifically, the mean $CO_2$ efflux in the X and N sub-region was largest, following by the D and W sub-region in decreasing order. The largest CV for $CO_2$ efflux was observed in the W sub-region, followed by the D, N, and X sub-region in a decreasing order, indicating a greater spatial variation in the northern part of the lake (Table 2).

The $CH_4$ efflux showed high spatial variation in the lake with an average $CH_4$ efflux of 3.0±1.6 $nmol \cdot m^{-2} \cdot s^{-1}$, ranging from 1.4 to 8.9 $nmol \cdot m^{-2} \cdot s^{-1}$. The CV of the $CH_4$ efflux in the entire lake was 52.2%. There were significant differences for $CH_4$ efflux between D and the other three sub-regions, whereas the differences were not statistically significant among the N, W, and X sub-region ($P>0.05$). But the mean $CH_4$ efflux in the W sub-region was smallest, following by the N, X, and D sub-region in an increasing order. The largest CV of the $CH_4$ efflux was observed in the D sub-region, followed by the N, X, and W sub-region in a decreasing order (Table 2).

We also found high spatial variation in the $N_2O$ efflux in Poyang with a CV of 53.2% during the measuring period.

Table 2. Summary of the GHG effluxes in the Poyang Lake.

| Sub-region | Number of observations | Range | Mean | CV (%) |
|---|---|---|---|---|
| $CO_2$ ($\mu mol \cdot m^{-2} \cdot s^{-1}$) | | | | |
| Xingzi | 13 | 0.21 to 0.31 | 0.27a | 12.39 |
| Wucheng | 11 | -0.25 to +0.31 | 0.17a | 122.02 |
| Nanjishan | 8 | +0.17 to +0.54 | 0.27a | 43.23 |
| Duchang | 12 | -0.20 to +0.47 | 0.23a | 76.52 |
| Whole lake | 44 | -0.25 to +0.54 | 0.23 | 63.54 |
| $CH_4$ ($nmol \cdot m^{-2} \cdot s^{-1}$) | | | | |
| Xingzi | 13 | 2.0 to 4.5 | 2.6 a | 26.71 |
| Wucheng | 11 | 1.9 to 3.6 | 2.3b | 20.94 |
| Nanjishan | 8 | 1.4 to 6.0 | 2.4b | 62.43 |
| Duchang | 12 | 1.8 to 8.9 | 4.4b | 46.3 |
| Whole lake | 44 | 1.4 to 8.9 | 3.0 | 52.2 |
| $N_2O$ ($nmol \cdot m^{-2} \cdot s^{-1}$) | | | | |
| Xingzi | 13 | 0.12 to 0.16 | 0.14b | 8.98 |
| Wucheng | 11 | 0.14 to 0.21 | 0.18a | 12.85 |
| Nanjishan | 8 | 0.032 to 0.15 | 0.088c | 40.07 |
| Duchang | 12 | 0.012 to 0.063 | 0.036d | 49.6 |
| Whole lake | 44 | 0.012 to 0.21 | 0.11 | 53.15 |

Means with different letters are significantly different as determined by multiple comparisons (one-way ANOVA, *post hoc* Tukey test, $P<0.05$).

The mean $N_2O$ efflux was 0.11±0.060 $nmol \cdot m^{-2} \cdot s^{-1}$, ranging from 0.012 to 0.21 $nmol \cdot m^{-2} \cdot s^{-1}$. It should be noted that the $N_2O$ efflux was spatially inhomogeneous with significant differences among the four sub-regions in the lake. In particular, the average $N_2O$ efflux in the W sub-region was largest, following by the X, N, and D sub-regions in decreasing order. The smallest CV of the $N_2O$ efflux was found in the X sub-region, followed by the W, N, and D sub-regions in increasing order (Table 2).

### Correlations between GHG Effluxes and Environmental Variables

The $CO_2$ efflux was strongly correlated with wave height ($r=0.39$, $p<0.01$). However, no significant correlation was found between the $CO_2$ efflux and other environmental factors. The $CH_4$ efflux was highly correlated with surface water temperature, water depth, and water $NH_4^+$-N content ($p<0.01$, $r=0.51$, 0.54, and 0.44, respectively). Significant correlation was found between $CH_4$ efflux and sediment $NO_3^-$-N sediment, total nitrogen content, sediment C/N ratio, the difference of air-water temperature, water DOC content, and water pH ($p<0.05$, $r=0.31$, 0.34, 0.38, 0.36,

Table 3. The Pearson correlation coefficient between GHG effluxes and environmental variables.

| Parameter | $N_2O$ | $CO_2$ | $CH_4$ |
|---|---|---|---|
| Wave height | 0.19 | 0.39** | 0.032 |
| Surface water temperature | 0.039 | -0.001 | 0.51** |
| Water DOC content | -0.21 | 0.053 | 0.35* |
| Surface water pH | 0.50** | -0.11 | -0.32* |
| Distance to shore | -0.34* | -0.12 | -0.19 |
| Sediment active layer depth | 0.36* | -0.075 | 0.008 |
| Water depth | -0.046 | -0.19 | 0.54** |
| Water $NO_3^-$ concentration | -0.02 | 0.047 | 0.27 |
| Water $NH_4^+$ concentration | -0.43** | 0.18 | 0.44** |
| Water electrical conductivity | 0.27 | -0.13 | 0.008 |
| Sediment C/N | -0.62** | 0.14 | 0.38* |
| Difference of air-water temperature | -0.43** | 0.14 | 0.36* |
| Sediment $NO_3^-$ concentration | -0.33* | -0.087 | 0.31* |
| Sediment organic carbon | 0.093 | 0.11 | 0.017 |
| Sediment $NH_4^+$ concentration | 0.29 | -0.12 | -0.18 |
| Sediment total nitrogen content | 0.51** | -0.074 | 0.34* |

*statistical significance ($p < 0.05$), **statistical significance ($P< 0.01$), N = 44 observations.

0.35, and -0.32, respectively). We did not find any significant relationship between the $CH_4$ efflux and other environmental variables (Table 3).

We found that the $N_2O$ efflux in the lake was significantly correlated with water $NH_4^+$-N, the difference of air-water temperature, sediment C/N ratio, water pH, sediment total nitrogen content ($p<0.01$, r=-0.43, -0.43, -0.62, 0.50, and 0.51, respectively), distance to the shore, sediment $NO_3^-$-N, and sediment active layer depth ($p<0.05$, r=-0.34, -0.33, and 0.36, respectively) (Table 3).

In addition, we made correlation analyses for each sub-region between GHG effluxes and environmental variables. But we did not observe any significant correlation between GHG effluxes and most environmental parameters. In some cases, we even found opposite tendencies when compared to the correlations analyses among four sub-regions (Table 4), indicating the spatial variability of GHG effluxes between four sub-regions.

### Contributions of Different Environmental Variables to the Observed GHG Effluxes

We found that the 16 environmental variables together explained 55%, 70%, and 89% of the variance in $CO_2$, $CH_4$, and $N_2O$ effluxes, respectively, based on our regression analysis. To quantify the contribution of each environmental variable to the GHG fluxes, we used the same method as reported by von Fischer et al. [5], where a multi-factor ANCOVA was conducted with the 16 environmental variables as predictors. Our analysis revealed that sediment C/N ratio, water depth, and the difference of air-water temperature all were significant predictors of GHG effluxes in Poyang Lake. Specifically, we found that the sediment organic carbon content contributed the most to the $CO_2$ effluxes (10.39%), followed by wave height (9.09%) (Table 5). For the $CH_4$ efflux, other significant contributing variables were sediment organic carbon content, sediment total nitrogen content, surface water temperature, distance to the shore, and water DOC content. In addition, we also found that the significant contributing variables ($p<0.05$) included sediment total nitrogen content, distance to the shore, and surface water temperature to the observed $N_2O$ efflux. The rest of the environmental variables examined were relatively minor in terms of their contribution to the lake surface GHG effluxes (Table 5).

## Discussion

### The Variability of the GHG Fluxes

The variability of the $CO_2$ flux in Poyang Lake was moderately high in comparison with other lakes in the world. The mean $CO_2$ flux found in the lake was within the typical range of -0.17 to 0.54 $\mu mol \cdot m^{-2} \cdot s^{-1}$ reported in many boreal, temperate, and subtropical lakes [11, 18, 22-27] (Table 6). It should be noted that our result was slightly higher than the average $CO_2$ flux in global lakes [30]. In addition, our study identified the wide range of the $CO_2$ flux in Poyang, from moderately high rates of $CO_2$ uptake to very high rates of emission. But the difference between maximum and minimum $CO_2$ flux in this study was slightly higher than those reported in the boreal reservoirs and lakes [7, 22, 24, 30], but lower than those found in other lake-reservoir systems [32-34] (Table 7).

The variability of the $CH_4$ efflux in Poyang was relatively low in comparison with other lakes and reservoirs in the world, especially considering the size of Poyang. The mean $CH_4$ efflux in Poyang was considerably lower than those in many temperate, subtropical lakes and the global mean $CH_4$ efflux in lakes [18, 24, 25, 28, 31] (Table 6). It should be noted that the $CH_4$ efflux observed in the current study was also lower than the efflux of 14.36 $nmol \cdot m^{-2} \cdot s^{-1}$ reported by Chen et al. [35] in the same lake, Poyang. The discrepancy may be attributed to the sand mining operations in the lake in winter, which might disturb the lake sediments as Chen et al. [35] discussed in their paper. This is the major reason why we conducted our field campaign in October, when the lake water level was relatively high to avoid the disturbances from navigation and operations in the lake in the winter. Furthermore, this study featured a low range of $CH_4$ efflux in the lake. The difference between maximum and minimum $CH_4$ flux, as opposed to $CO_2$, was lower than those reported in the boreal reservoirs and lakes (Table 7).

Table 4. Pearson correlation coefficient between GHG effluxes and environmental variables in the four sub-regions.

| | $N_2O$ | | | | $CH_4$ | | | | $CO_2$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Xingzi | Duchang | Nanjishan | Wucheng | Xingzi | Duchang | Nanjishan | Wucheng | Xingzi | Duchang | Nanjishan | Wucheng |
| WH | 0.176 | 0.694* | 0.266 | -0.366 | 0.012 | 0.346 | -0.509 | 0.511 | 0.462 | 0.400 | -0.183 | 0.495 |
| WT | 0.354 | 0.004 | 0.095 | 0.177 | -0.267 | 0.217 | -0.619 | -0.307 | 0.482 | 0.110 | 0.355 | -0.305 |
| W-DOC | -0.062 | -0.390 | 0.520 | 0.331 | -0.356 | -0.538 | -0.184 | -0.692* | -0.076 | -0.199 | 0.417 | -0.217 |
| W-pH | 0.396 | -0.151 | 0.653 | -0.003 | 0.251 | -0.437 | 0.353 | -0.088 | -0.145 | 0.168 | -0.576 | 0.144 |
| DS | -0.018 | -0.211 | -0.296 | 0.430 | 0.006 | -0.460 | -0.508 | -0.442 | -0.108 | -0.156 | -0.383 | -0.018 |
| SD | -0.527 | 0.120 | 0.238 | -0.019 | 0.383 | 0.189 | -0.072 | 0.450 | -0.435 | -0.006 | 0.560 | 0.211 |
| WD | -0.315 | -0.547 | -0.456 | -0.208 | -0.262 | 0.016 | 0.552 | -0.193 | 0.253 | -0.478 | -0.397 | -0.437 |
| WNN | -0.126 | 0.123 | -0.200 | 0.281 | -0.105 | 0.376 | -0.411 | -0.359 | -0.072 | -0.374 | 0.216 | -0.431 |
| WHN | 0.189 | -0.085 | -0.447 | 0.298 | -0.615* | 0.363 | 0.177 | 0.573 | 0.534 | -0.093 | 0.800* | 0.367 |
| EC | -0.197 | 0.061 | -0.551 | -0.012 | 0.660* | 0.320 | 0.305 | -0.371 | -0.277 | 0.139 | 0.552 | -0.730* |
| AW | -0.491 | 0.293 | -0.319 | 0.333 | -0.073 | 0.036 | 0.098 | -0.229 | -0.136 | 0.326 | -0.047 | -0.040 |
| SNN | -0.287 | 0.122 | -0.093 | -0.491 | 0.620* | 0.024 | -0.178 | -0.215 | -0.417 | -0.185 | -0.587 | 0.125 |
| SOC | -0.522 | 0.149 | 0.413 | 0.328 | 0.469 | 0.249 | -0.705 | -0.027 | -0.020 | 0.152 | 0.082 | 0.129 |
| C/N | -0.002 | 0.246 | 0.367 | 0.537 | -0.030 | 0.333 | -0.737* | 0.537 | 0.502 | -0.210 | 0.192 | 0.535 |
| SHN | -0.518 | -0.127 | -0.321 | 0.229 | -0.118 | 0.246 | -0.370 | -0.370 | 0.072 | 0.195 | 0.702 | -0.360 |
| SNC | -0.582* | 0.065 | 0.257 | 0.103 | 0.531 | 0.124 | -0.619 | -0.333 | -0.130 | 0.265 | -0.001 | -0.165 |

SOC – soil organic carbon, WH – wave height, C/N – sediment C/N ratio, WD – water depth, AW – difference of air-water temperature, SD – sediment active layer depth, EC – water electrical conductivity, WT – surface water temperature, SNC – sediment total nitrogen content, SNN – sediment $NO_3^-$ concentration, SHN – sediment $NH_4^+$ concentration, W-DOC – water DOC content, WNN – water $NO_3^-$ concentration, W-pH v the pH of water, DS – distance to the shore, WHN – water $NH_4^+$ concentration.

The number of observations for the four sub-regions was the same as that shown in Table 2. The asterisk marks the statistical significance at the 95% level, $P<0.05$.

The $N_2O$ efflux in Poyang featured a high variability compared with previous studies. In the present study, the mean $N_2O$ efflux of 0.11 nmol·m$^{-2}$·s$^{-1}$, was higher than those in boreal lakes in Finland [11, 27] (Table 6). But the mean $N_2O$ efflux in the current study was lower than that in a river in New York (0.064 nmol·m$^{-2}$·s$^{-1}$) [36]. Interestingly, our result of the $N_2O$ efflux from Poyang was also close to that of the global oceans (0.011-0.035 nmol·m$^{-2}$·s$^{-1}$) [37, 38]. Additionally, the $N_2O$ efflux widely ranged from 0.012 to 0.21 nmol·m$^{-2}$·s$^{-1}$ in Poyang. In particular, the difference between maximum and minimum $N_2O$ flux was greatly higher than those reported in the boreal reservoirs and lakes [11, 32-34] (Table 7). The high $N_2O$ efflux may be attributed to the high N content in Poyang due to the high nutrient load from the agricultural activities in the watershed. So far, few studies have reported the $N_2O$ efflux in the freshwater lakes, thus our comparisons with other studies are limited.

In addition, we also measured the GHG effluxes at 1-month intervals in the Xingzi sub-region in a year cycle using the floating chamber technique as mentioned above. It is noted that the seasonal variation of the GHG effluxes may compromise our comparisons with other studies. According to our long-term GHG efflux measurements, the GHG effluxes measured in October 2010 was slightly lower than the annual mean effluxes (Table 6), suggesting that the October measurements were close to the annual mean effluxes in Poyang Lake and thus comparable with other studies reporting the annual mean effluxes.

## Controlling Factors on the GHG Effluxes

Substrate quality (such as C and N availability) in the sediments controls GHG production because organic carbon is the main energy source for microbes and N is assimilated and metabolized as proteins in the synthesis of cellular materials during the decomposition of the organic matter in the process of GHG production [1]. Striegl et al. [39] found that the organic carbon in the sediments was the source of $CO_2$ efflux in northern temperate and boreal lakes, while other studies reported that sediment organic carbon content controlled the $CH_4$ effluxes in temperate and tropical lakes [6, 33]. In addition to sediment C and N contents, we found that the sediment C/N ratio was also critical to the GHG effluxes in the Poyang Lake with the C/N ratio being positively correlated with the $CO_2$ and $CH_4$ effluxes

Table 5. Contributions of 16 environmental variables to the observed GHG effluxes in Poyang Lake.

| | $CO_2$ | $CH_4$ | $N_2O$ |
|---|---|---|---|
| Sediment organic carbon | 10.39* | 10.96* | 3.65 |
| Wave height | 9.08* | 1.63 | 1.62 |
| Sediment C/N | 7.96* | 9.41* | 9.19* |
| Water depth | 7.05* | 6.66* | 11.17* |
| Difference of air-water temperature | 5.01* | 5.97* | 10.12* |
| Sediment active layer depth | 4.34 | 0.10 | 0.019 |
| Water electrical conductivity | 3.43 | 0.75 | 1.08 |
| Surface water temperature | 2.89 | 8.37* | 8.53* |
| Sediment total nitrogen content | 2.11 | 10.59* | 11.65* |
| Sediment $NO_3^-$ concentration | 1.41 | 0.56 | 0.22 |
| Sediment $NH_4^+$ concentration | 0.66 | 0.18 | 2.27 |
| Water DOC content | 0.26 | 6.57* | 1.37 |
| Water $NO_3^-$ concentration | 0.19 | 0.28 | 5.85 |
| Surface water pH | 0.14 | 0.82 | 4.30 |
| The distance to the shore | 0.039 | 7.02* | 9.69* |
| Water $NH_4^+$ concentration | 5.35E-05 | 0.13 | 8.31 |

The 16 variables explained 55%, 70%, and 89% of the variance of $CO_2$, $CH_4$, and $N_2O$ effluxes across the lake, respectively, and the asterisk marks the statistical significance at the 95% level. N = 44 observations, $P<0.05$. According to the multifactor ANCOVA where the contribution percentage of each variable was calculated based on the partial $R^2$ value of the variable.

and negatively correlated with the $N_2O$ efflux. Opposite of our results, Bastviken et al. [6] found no clear relationship between $CH_4$ emission and sediment C/N ratio, and Duc et al. [40] reported that methane formation was negatively correlated with sediment C/N ratio in 8 lakes in central Sweden. We believe that these discrepancies could be explained by the high N content in Poyang due to the high nutrient load from the agricultural activities in the watershed. Under high N supply, the $CO_2$ and $CH_4$ effluxes might be more limited by the C sources. Indeed, the C/N ratio in Poyang was considerably lower than that reported in Duc et al. [40]. Our results are also supported by other studies. For example, Valentine et al. [41] found a positive relationship between the C/N ratio and $CH_4$ production in the Canadian Northern Wetlands. Klemedtsson et al. [42] and Dinsmore et al. [43] also reported negative correlations between the $N_2O$ efflux and the substrate C/N ratio for peatlands in Sweden and Scotland.

In this study we found that both the $CH_4$ and $N_2O$ effluxes were also correlated with surface water temperature, and the GHG effluxes were tightly related to the difference of air-water temperature and water depth. Although the surface water temperature reflected the sediment temperature to some extent, which regulated the GHG production in the sediment, the water temperature mainly affects the transport of GHG in the water column by changing the GHG solubility. A previous study also found that the $CH_4$ efflux was positively correlated with water temperature in some lakes [11, 22]. Generally the difference of air-water temperature influenced the GHG effluxes through the enhancement of gas-transfer velocity owing to evaporation [44, 45]. Previous studies have also evidenced that destabilization of the near surface water could increase the gas-transfer velocity by 4-30% under an evaporative situation [46, 47]. In addition, water depth can influence the GHG effluxes in different ways. Firstly, frequent resuspension caused by waves and currents at the shallow depths of lakes may influence GHG emissions by a pulsed transport of reduced compounds, nutrients, and the concentration of GHG into the water column [12, 44]. Second, water depth may affect the oxidizing efficiencies of methanotrophy, as methane-oxidizing may be more efficient in deeper lakes [44]. Previous studies have shown that methane can easily escape oxidization from the sediment in the shallow lakes [6, 45, 48, 49]. Finally, water depth may impact the GHG effluxes by changing the gas diffusion coefficient in the sediment with increasing water depth. Earlier studies have demonstrated that the $N_2O$ efflux was sharply reduced by a decrease of gas diffusion coefficient because the nitrate was mostly reduced to $N_2$ due to the decrease of $O_2$ availability in deeper lakes [12, 50].

Consequently, our study revealed that the $CH_4$ efflux in Poyang was mainly contributed to sediment organic carbon, sediment total nitrogen content, and sediment C/N ratio, suggesting that $CH_4$ production processes in the lake sediments dominated the efflux at the air-water interface while $CH_4$ production and consumption during transport in the water column was relatively minor. In addition to the sediment variables, the $CO_2$ and $N_2O$ effluxes were also significantly contributed to other physical and biological variables in the water column.

## Conclusions

The variability of the $CO_2$ and $N_2O$ effluxes in Poyang Lake was high, whereas the variability for the $CH_4$ efflux was moderately low considering the size of the lake. At the same time, GHG effluxes were spatially inhomogeneous among the four sub-regions in the lake based on the correlation analysis. Furthermore, the GHG effluxes were related to both the sediment properties and water physiochemical properties, especially sediment C/N ratio, water depth, and the difference of air-water temperature, which dominated the GHG effluxes. Therefore, in order to scale-up the chamber measurements of sediment GHG effluxes to regional and global GHG budgets, it is necessary to incorporate into the model with spatial variations of GHG effluxes.

Table 6. Mean GHG fluxes from other lakes.

| Lake | Site | Climate | $CO_2$ ($\mu mol \cdot m^{-2} \cdot s^{-1}$) | $CH_4$ ($\mu mol \cdot m^{-2} \cdot s^{-1}$) | $N_2O$ ($\mu mol \cdot m^{-2} \cdot s^{-1}$) | Reference |
|---|---|---|---|---|---|---|
| Donghu | China | subtropical | 0.087 | 0.017 | | 22 |
| Vehmasjärvi | Finland | boreal | 0.54 | 0.0064 | 3.34E-05 | 11 |
| Mäkijärvi | Finland | boreal | 0.25 | 0.004 | 1.08E-05 | 11 |
| Postilampi | Finland | boreal | 0.5 | 0.11 | 4.33E-05 | 11 |
| Kevätön | Finland | boreal | 0.16 | 0.12 | | 11 |
| Örträsket | Sweden | temperate | 0.29 | | | 23 |
| Priest Pot | UK | temperate | 0.46 | 0.14 | | 24 |
| Shingobee Lake, | Minnesota, USA | temperate | 0.42 | 0.1 | | 25 |
| Williams Lake | Minnesota, USA | temperate | 0.0052 | 0.073 | | 25 |
| Sparkling Lake | Wisconsin, USA | temperate | 0.058 | 0.0021 | | 26 |
| Trout Bog | Wisconsin, USA | temperate | 0.53 | 0.02 | | 26 |
| Crystal Lake | Wisconsin, USA | temperate | 0.0046 | 0.0014 | | 26 |
| Meiliangwan | China | subtropical | 0.41 | 0.0064 | 1.89E-05 | 27 |
| Dongtaihui | China | subtropical | 0.29 | 0.0029 | 0 | 27 |
| Dongtinghu | China | subtropical | -0.041 | -0.049 | 1.26E-05 | 27 |
| Poyang | China | subtropical | 0.19 | 0.014 | 0.000133 | 27 |
| Chaohu | China | subtropical | -0.098 | 0.00038 | -1.90E-05 | 27 |
| Nansihu | China | subtropical | 0.039 | 0.00045 | 2.53E-05 | 27 |
| Hongzehu | China | subtropical | -0.17 | 0.00012 | -6.30E-05 | 27 |
| Fuxianhu | China | subtropical | 0.12 | 0.00019 | -6.30E-06 | 27 |
| Erhai | China | subtropical | -0.014 | 0.0081 | -1.30E-06 | 27 |
| Dianchi | China | subtropical | -0.12 | 0.0027 | 0 | 27 |
| Biandantang | China | subtropical | 0.28 | 0.015 | | 18 |
| 5 lakes | Netherlands | temperate | | 0.068 | | 7 |
| Wuliangsu | China | subtropical | | 0.038 | | 28 |
| Medalha | Brazil | tropical | | 0.0043 | | 29 |
| Mirante | Brazil | tropical | | 0.0051 | | 29 |
| Taihu | China | subtropical | | | 0.00014 | 17 |
| Average for natural lakes | | | 0.19 | | | 30 |
| Global mean $CH_4$ efflux in lakes | | | | 0.031 | | 31 |
| The long-term GHG effluxes in Poyang Lake | | | 0.28 | 0.0043 | 4.11E-05 | unpublished data |

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Table 7. Range of GHG fluxes from other reservoirs and lakes.

| Names | Sites | Climate | $CO_2$ ($\mu mol \cdot m^{-2} \cdot s^{-1}$) | $CH_4$ ($\mu mol \cdot m^{-2} \cdot s^{-1}$) | $N_2O$ ($\mu mol \cdot m^{-2} \cdot s^{-1}$) | References |
|---|---|---|---|---|---|---|
| Reservoirs | | | | | | |
| Three reservoirs | Canada | boreal | 0.16 to 0.3 | 0.0025 to 0.0077 | -2.63E-07 to - 9.2E-07 | 32 |
| Temperate and boreal reservoirs | | | 0.058 to 0.91 | 0.0022 to 0.039 | | 30 |
| Lokka | Finland | boreal | 0.13 to 0.85 | 0.0038 to 0.086 | -4.51E-06 to 7.06E-05 | 33 |
| Porttipahta | Finland | boreal | 0.23 to 0.60 | 0.0019 to 0.0035 | -5.79E-06 to 6.71E-05 | 33 |
| Lakes | | | | | | |
| Donghu | China | subtropical | -0.37 to 1.01 | 0.001 to 0.096 | | 22 |
| Kevätön | Finland | boreal | -0.021 to 0.29 | 0.0032 to 0.14 | -1.97E-05 to 5.09E-06 | 34 |
| Vehmasjärvi | Finland | boreal | 0.29 to 0.37 | 0.00081 to 0.0016 | 3.47E-05 to 9.84E-05 | 11 |
| Mäkijärvi | Finland | boreal | 0.097 to 0.17 | 0.001 to 0.0014 | -3.94E-05 to 0.00011 | 11 |
| Priest Pot lake | England | temperate | 0.045 to 1.18 | 0.00069 to 0.016 | | 24 |
| 5 lakes | Netherlands | temperate | -0.038 to 0.78 | 0.024 to 0.31 | | 7 |
| 15 Pantanal lakes | South America | tropical | | 0.0023 to 0.021 | | 6 |

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