Research Article

Understanding the Spatial Heterogeneity of CO₂ and CH₄ Fluxes from an Urban Shallow Lake: Correlations with Environmental Factors

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The spatial variability of carbon dioxide (CO₂) and methane (CH₄) fluxes across water-air interface in Xuanwu Lake was investigated in two seasons. Due to anthropogenic disturbances, the environmental factors and the fluxes of CO₂ and CH₄ in lake showed obvious spatial and seasonal variability; their average fluxes in summer are significantly higher than those in autumn. The fluxes in heavy pollution sites with high concentrations of nitrogen and phosphorus nutrient in summer were 3.9 times (142.14 : 36.07 mg·m⁻²·h⁻¹) for CO₂ and 22.3 times for CH₄ (6.46 : 0.29) higher than those in little pollution sites. In autumn, they were 12.3 times and 7.1 times higher, respectively. Anthropogenic disturbance and heavy pollution increased their fluxes, but aquatic plants reduced the emission of CO₂. Except the sampling site with flourishing lotus, most of sampling sites without aquatic plant are the emission source of CO₂ and CH₄. The correlation analysis, multiple stepwise regression, and redundancy analysis showed the key environmental factors for CO₂ including temperature (T), pH, chemical oxygen demand (COD_{Mn}) in water, organic matter (OM), total nitrogen, and ammonia nitrogen in water and sediment. As for CH₄, the key environmental factors include turbidity, oxidation-reduction potential, dissolved oxygen, COD_{Mn}, and T in water and OM and N-NH₄⁺ in sediment.

1. Introduction

Carbon dioxide (CO₂) and methane (CH₄) are two kinds of influential greenhouse gases (GHG). Their atmospheric concentrations have all increased since 1750 due to human activity. In 2011 their concentrations were 391 ppm (CO₂) and 1803 ppb (CH₄), and exceeded the preindustrial levels by about 40% and 150%, respectively [1]. Though the concentration of CH₄ is lower than CO₂, its potential contribution to the greenhouse effect is 15 to 30 times by mass higher than that of CO₂ [2]. The increased concentration of CO₂ and CH₄ can greatly enhance the contribution to total radiative forcing (up to 60% for CO₂ and 32% for CH₄) [1]. According to one statistic, the average annual growth rates in the atmospheric concentrations of CO₂ and CH₄ are 0.04% and 0.75%, respectively [3]. CH₄ in atmosphere is also susceptible to

oxidation and reacts in a series of chemical changes, resulting in certain influences on atmospheric components transformation [4]. Global warming and ecological changes caused by increased atmospheric concentrations of greenhouse gases have become a worldwide concern [5–8]. Due to the very large size of global wetland areas, about 8.56 × 10⁸ hm² [9], wetland has been considered one of the important sources of greenhouse gas emissions [10–12].

Considerable efforts have been invested to quantify the CO₂ and CH₄ fluxes from different lake wetlands in different regions of the world [11, 13–20]. Some studies suggested that CH₄ emission rates were significantly higher in tropical and subtropical wetlands than in boreal wetlands due to high temperature, and summer is also conducive to the emission of CH₄. Moreover both the emission of CH₄ and the ratio of CH₄ to CO₂ emissions increase markedly with seasonal

increases in temperature [2, 16, 21]. Moreover, higher ebullition and diffusion of CH_4 are observed in eutrophic than oligomesotrophic lakes [22]. Riera et al. [23] also reported that bog lakes with high dissolved organic carbon (DOC) waters have higher fluxes of CO_2 and CH_4 than clear-water lakes with low DOC. The macrophyte (e.g., *water chestnut*, *water hyacinth*) also plays an important role in reducing CO_2 flux [24] and in increasing CH_4 emission from lake [25], but Kosten et al. [26] reported that up to 70% of the CH_4 produced may become oxidized as a result of a strong decrease in gas exchange velocity (up to 90%) combined with high CH_4 oxidizing bacteria activity of the rhizosphere microbiome in a shallow (1 m) system. Hydrodynamics and allochthonous organic material are also important factors affecting CH_4 emission; McGinnis et al. [27, 28] found that higher fluxes occurred in river deltas ($10^3 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) compared to nonriver bays ($<100 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) in Lake Kariba. Harrison et al. [29] showed that water-level draw-downs (as small as 0.5 m) can greatly increase per-area reservoir CH_4 fluxes (accounting for more than 90% of annual reservoir CH_4 flux) to the atmosphere. Reservoirs with higher epilimnetic [chlorophyll a] experienced larger increases in CH_4 emission in response to drawdown ($R^2 = 0.84$, $p < 0.01$), suggesting that eutrophication magnifies the effect of drawdown on CH_4 emission.

However, few studies have focused on the emission characteristics of urban lakes and the environmental factors. Urban shallow lakes, which are a kind of typical wetland, play an irreplaceable role in multiple ecological service functions in landscape, entertainment, water diversion, and many other ways. The acceleration of urbanization and dangerous human activities speeds up the export of carbon, nitrogen, and other nutrients from terrestrial ecosystems into the aquatic ecosystems, causing a significant increase in emissions of greenhouse gases from aquatic ecosystems [30–32]. It is unclear whether the dominant factors in natural lakes would also control C exchange across air-water interface of urban lakes. Therefore, the impact of anthropogenic disturbance to lake aquatic ecosystems and global greenhouse gases requires urgent attention [33, 34].

Xuanwu Lake is the largest shallow lake of Nanjing (3.7 km^2), which has been subjected to a series of human disturbances, such as the inflow of domestic sewage from site 6# (Figure 1), surface rain runoff from the surrounding residents and mountain through Tangjiashangou river and Zijinshangou river, water diversion from Shangyuanmen ($1.0 \times 10^5 \text{ t/d}$) and Daqiao drink water treatment plant ($8 \times 10^4 \text{ t/d}$) into lake ($1.8 \times 10^5 \text{ t/d}$), tourist entertainment and rubbish in lake park, and water treatment project with higher aquatic plants at sites 6# and 8#. Therefore, Xuanwu Lake is a typical representative of urban shallow lakes. The objective of this study is to investigate the spatial variation among near-shore areas of CO_2 and CH_4 emission across the water-air interface using static floating chamber and to identify the influence of anthropogenic disturbance and lake's environmental factors on the greenhouse gases emission in summer and autumn. This study will provide the theoretical reference for the control of greenhouse gases emission at the water-air interface.

2. Materials and Methods

2.1. Sampling Sites. The water surface area of Xuanwu Lake is 3.7 km^2 with an average depth of 1.2 m–1.3 m (water depth range: 1.1 m–2.31 m). Its hydrological functions include landscape, supply water for Inner Qinhuai river, impoundment and flood protection, and ecological function. The arrows in Figure 1 show the direction of lake's inlet and outlet. Figure 1 shows the distribution of 10 sampling sites in Xuanwu Lake and its surrounding rivers' flow direction. The sampling sites of 1#, 2#, and 9# are located in surrounding rivers of the lake, and other sampling sites are located inside the lake's area. Each sampling site was positioned by using GPS to ensure the consistency of sampling location. The distribution and environmental characteristics of sampling sites are shown in Figure 1 and Table 1.

2.2. Sample Collection and Factors Determination

2.2.1. Collection and Determination of Gas Samples [15]. Detailed measurements of CH_4 and CO_2 fluxes across water-air interface were performed with floating chambers on June and October, 2014. Gas samples were taken from the headspace of each closed cylindrical dark chamber (30 cm height, 40 cm diameter). Each chamber was fixed on the lifebuoy and placed onto water surface, ventilation tube was used to balance the pressure inside and outside the chamber, and a small fan was installed in the chamber to homogenize the inside air. Gas samples were taken with a syringe (equipped with a three-way valve) every 15 minutes during a 75 min period (to get 5 gas samples per site). The slope dC/dt of the gas concentration curve at time $t = 0$ was estimated using linear regression [37]. For one of the sampling sites, the gas samples were collected twice in morning and afternoon, respectively, and the average of these samples represents the flux of the day time.

CO_2 and CH_4 concentrations of gas samples were determined by Agilent 7890 gas chromatography (Agilent, USA). After CO_2 was converted into CH_4 by Nickel catalyst at 375°C , the concentrations of CH_4 and CO_2 in the gas samples were determined with a FID detector equipped with HP-5 column. The flow rate of carrier gas (nitrogen) was $30 \text{ ml}\cdot\text{min}^{-1}$, the flow rate of fuel gas (hydrogen) was $47 \text{ ml}\cdot\text{min}^{-1}$, and the flow rate of combustion-supporting gas (air) was $400 \text{ ml}\cdot\text{min}^{-1}$. The detector temperature was 200°C , and the column temperature was 45°C .

2.2.2. Collection and Determination of Water Samples. Near the collection point of gas samples, 500 ml water was collected in sampling bottles that have been flushed before, 5 drops of concentrated sulfuric acid were added to kill microorganisms, and $\text{pH} < 2$ was adjusted. The water samples were brought to laboratory and stored at 4°C , completing the determination of physical and chemical factors within 24 h.

Wind speed and temperature (T) were measured at 1.5 m height from water surface by portable meteorological instrument (Kestrel-3500, USA). Water flow rate (Wf) was measured by LSH10-1A portable ultrasonic Doppler flowmeter (Boyida instrument Co., Ltd., Xiamen, China). Dissolved

FIGURE 1: The schematic diagram of sampling sites.

oxygen (DO), pH, oxidation-reduction potential (ORP), water temperature (Tw), and electrical conductivity (COND) were measured in situ using SX751-series portable electrochemical meters (San-Xin Instrumentation Inc., Shanghai, China). Turbidity (Tur) was measured with a 2100Q portable Turbidimeter (Hach, Loveland, Co., USA). Total nitrogen (TN), ammonia nitrogen (N-NH_4^+), and nitrate nitrogen (N-NO_3^-) were measured in laboratory within 24 h; TN was measured by potassium persulfate oxidation-ultraviolet spectrophotometry and N-NH_4^+ was measured by Nessler's reagent spectrophotometry [43]. Chemical oxygen demand (COD_{Mn}) was measured by titration analysis with KMnO_4 . N-NO_3^- was determined by thymol spectrophotometry [44] (UV-1201, Beifen-Ruili analytical instruments Co., Ltd., Beijing). Nitrite nitrogen (N-NO_2^-) was determined by N-(1-radical)-ethidene diamine spectrophotometry [43]. The indexes of T, pH, DO, ORP, COND, wind speed, and Wf were measured twice in morning and afternoon, respectively, while other water and sediment indexes were measured only once a day.

2.2.3. Collection and Determination of Sediment. Surface sediment samples were collected by grab sampler. Each sample consisted of central parts of 5 subsamples randomly collected at 5 points within the sampling area. After collection, samples were put into sampling bottle, sealed, and stored in refrigerator at -20°C . After sediments were lyophilized and debris was removed, the sediments were ground and passed through

a 100-mesh sieve (0.147 mm). The OM was determined by low temperature external heating-potassium dichromate oxidation-colorimetry. Total nitrogen in sediment (TN_s) was analyzed by potassium dichromate-sulfuric acid digestion method. Ammonium nitrogen in sediment (N-NH_4^+) was determined by KCl extraction-colorimetry.

2.3. Data Analysis

2.3.1. Calculation for Fluxes of CH_4 and CO_2 across Water-Air Interface. According to the change rate of gas concentration, the flux of greenhouse gas was calculated by the formula

$$F = \frac{F_1 \times F_2 \times V \times \Delta C}{F_3 \times A \times \Delta t}, \quad (1)$$

where F represents the fluxes of greenhouse gas across the water-air interface ($\text{mg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$). F_1 is the unit conversion factor between ppm and $\mu\text{g} \cdot \text{m}^{-3}$ (CO_2 : 1798.45; CH_4 : 655.47). F_2 is the conversion factor between min and h (=60). F_3 is the unit conversion factor between μg and mg (=1000). V represents air volume in chamber (m^3); A is the cross-sectional area of sampling chamber (m^2); $\Delta c/\Delta t$ represents the line's slope of concentration change of greenhouse gas in chamber ($10^{-6} \cdot \text{min}^{-1}$).

2.3.2. Redundancy Analysis. According to the data characteristic analysis, the redundancy analysis (RDA) between

TABLE 1: The code of sampling sites and their surrounding environmental characteristics.

Number	Sites	Water depth/m	Water vegetation	Surroundings environmental characteristics
1#	Zijinshangou river	0.5	/	The river, which enters lake, carries domestic sewage and rainwater from surrounding residents in flood season.
2#	Zhenzhu Bridge	1.7	/	Located in the lake outlet of Wumiao Gole, with fast flow rate and concrete vertical slope, receiving domestic sewage and construction waste water from surrounding residents and construction sites.
3#	Railway station	1.6	/	Located near the square of railway station, and near the main transportation road and commercial buildings.
4#	Inflow mouth of clean water	1.4	/	Located at the inflow mouth of clean water from Daqiao drink water treatment plant with relatively fast water flow rate and significant disturbance on water body.
5#	Lake outlet at Dashugen Gole	1.6	/	Located in lake outlet at Dashugen Gole with fast water flow rate.
6#	Southwest lake	1.3	<i>Potamogeton crispus</i> (20%–30%) ^a	Located in southwest of the lake with an influx of domestic sewage near the lake shore, near an ongoing ecological restoration project.
7#	Lingzhou island	1.5	<i>Potamogeton crispus</i> (30%–40%)	Located in the north of the southeast lake and near Lingzhou island with less anthropogenic interference.
8#	Yingzhou island	1.1	<i>Lush lotus</i> (100%)	Located in the northeast of Yingzhou island with lush lotus.
9#	Moat	1.2	/	Located in the moat, an inflow river into the lake with concrete slope and residential area on the bank.
10#	Liangzhou island	1.8	/	Located in the northwest of Liangzhou island with many cruise ships in the lake and greater anthropogenic interference.

^aThe coverage of aquatic plant.

environmental factors and greenhouse gas flux was carried out using CANOCO 5.0. The fluxes data was used as species data and various environmental factors as environmental data [45]. In Figure 8, solid arrows represent the fluxes of greenhouse gases, while hollow arrows indicate various environmental factors. The arrow length represents the importance degree of the environment factors, while the cosine value between two arrows represents the correlation between species and environmental variables [46].

2.3.3. Identification of Environmental Factors Affecting GHG Fluxes. In order to identify the key environmental factors affecting CO₂ and CH₄ fluxes, the order of environmental factors was sorted according to R^2 value and significant level p value from Pearson and Spearman correlation analysis, the standardized coefficients (β) in Multiple Stepwise Regression Analysis (MSRA) equation, the correlation coefficients among environmental factors, flux, and RDA ordination axes. At last, the order of environmental factors was expressed as C_n , $C_n = 1, 2, 3 \dots$ and 17. The importance of environmental factors in affecting the fluxes of CO₂ and CH₄ (In , n represents different environmental factors) was calculated by the equation: $In = (17 - C_n + 1)/17$; the value of In ranged from 0 to 1. The bigger the value is, the more important it is.

The figures were plotted using GraphPad prism 5.0. The correlation analysis and Multiple Stepwise Regression Analysis were calculated by Statistics 10 and SPSS 22 software.

3. Results and Analysis

3.1. Variability of Environmental Factors. Table 2 shows the variation characteristics of meteorological factors, water environmental factors, and environmental quality factors of water and sediment in summer and autumn. The water body was slightly alkaline. The average temperatures of air and water in summer were higher than those in autumn by about 4°C. The DO, ORP, pH, and COND in autumn were all higher than those in summer, and only the turbidity in summer was higher than that in autumn. Except that N-NH₄⁺ of water in summer was more than that in autumn, N-NO₃⁻ and N-NO₂⁻ were characterized by autumn > summer. Moreover, the values of COD_{Mn} in water and OM, TN, and N-NH₄⁺ in sediment in summer were all more than those in autumn. In consequence, the water quality in autumn was better than that in summer, and most of sampling sites belong to IV-Inferior class V due to excessive nitrogen (the surface water environmental quality standard of China, GB3838-2002). Regarding the spatial characteristics, the environmental factors of wind

TABLE 2: The characteristics of environmental factors in water, air, and sediment.

Environmental factors	Heavily polluted sites 1#, 2#, 4#, 5#, 6#, 8#				Lightly polluted sites 3#, 7#, 9#, 10#			
	Max	Min	Average	SD	Max	Min	Average	SD
Wind1 ⁽¹⁾	1.32	0.13	0.99 ⁽³⁾	0.44	1.38	0.21	0.88	0.54
Wind2 ⁽²⁾	0.53	0.01	0.16	0.19	1.25	0.10	0.60	0.53
Wf1	0.32	0.01	0.14	0.14	0.06	0.01	0.02	0.03
Wf 2	0.28	0.01	0.12	0.13	0.04	0.01	0.02	0.02
DO1 ⁽⁴⁾	5.36	3.47	4.25	0.75	5.72	3.46	4.86	0.99
DO2	7.28	3.54	5.35	1.42	7.22	5.38	6.33	0.75
pH1	8.11	7.25	7.83	0.34	8.41	7.71	8.08	0.29
pH2	8.61	7.87	8.21	0.30	8.94	8.21	8.52	0.30
Tur1	38.20	10.40	25.81	10.81	25.60	13.73	20.98	5.29
Tur2	24.80	12.25	18.53	4.72	22.25	16.95	19.16	2.61
T1	30.40	28.90	29.68	0.53	29.60	28.50	29.08	0.46
T2	25.40	24.90	25.17	0.16	25.15	24.75	24.95	0.17
Tw1	28.90	27.60	28.43	0.52	28.40	27.40	27.95	0.42
Tw2	25.00	23.55	24.23	0.53	25.00	23.30	24.39	0.75
COND1	306.00	279.00	293.83	10.65	303.00	283.00	290.50	8.70
COND2	363.50	298.00	332.42	29.73	359.50	291.50	314.00	31.04
ORP1	117.00	68.00	91.50	17.78	132.00	87.00	114.50	19.60
ORP2	141.00	95.50	114.92	17.63	132.00	95.00	112.38	15.23
TN1	3.76	1.52	2.92	0.87	2.29	1.35	1.74	0.40
TN2	3.62	2.41	2.84	0.43	2.36	1.40	1.90	0.48
N-NH ₄ ⁺ 1	2.31	0.98	1.76	0.61	1.35	0.81	1.15	0.24
N-NH ₄ ⁺ 2	2.43	0.92	1.59	0.61	1.16	0.36	0.72	0.33
N-NO ₃ ⁻ 1	0.53	0.07	0.35	0.16	0.37	0.14	0.25	0.10
N-NO ₃ ⁻ 2	0.70	0.45	0.59	0.10	0.53	0.22	0.36	0.15
N-NO ₂ ⁻ 1	0.07	0.02	0.04	0.02	0.04	0.01	0.03	0.01
N-NO ₂ ⁻ 2	0.06	0.03	0.05	0.01	0.05	0.02	0.04	0.01
COD1	9.27	5.78	7.56	1.22	5.87	4.71	5.26	0.48
COD2	8.65	4.94	6.40	1.59	5.25	4.37	4.70	0.39
OM1	4.97	3.95	4.70	0.38	3.76	3.39	3.53	0.17
OM2	4.61	4.06	4.32	0.24	3.85	3.15	3.57	0.30
TNs1	4392.89	2671.02	3522.90	613.50	3689.53	2577.65	3135.61	477.05
TNs2	4286.14	2944.51	3554.32	525.95	3082.49	2562.86	2791.87	215.86
N-NH ₄ ⁺ s1	2106.92	1305.64	1750.79	298.74	1835.45	1256.15	1558.62	244.49
N-NH ₄ ⁺ s2	2068.79	1425.03	1706.08	270.66	1590.89	1014.23	1309.27	239.53

Note. ⁽¹⁾1 refers to the data in summer; ⁽²⁾2 refers to the data in autumn; ⁽³⁾the bold number is larger value in two kinds of sampling sites (heavily polluted sites or lightly polluted sites). ⁽⁴⁾The units of wind rate and Wf (water flow rate) are all m/s; the unit of Tur is NTU; the unit of T and Tw is °C; The unit of COND is $\mu\text{s/cm}$; the unit of ORP is mv; the units of DO, TN, N-NH₄⁺, N-NO₃⁻, N-NO₂⁻, and COD are all mg/L; the unit of OM is %; the units of TNs and N-NH₄⁺s are mg/kg.

speed, water flow rate, turbidity, COND, TN, N-NH₄⁺, N-NO₃⁻, N-NO₂⁻, and COD_{Mn} in water and OM, TNs, and N-NH₄⁺s in sediment at heavily polluted sites (1#, 2#, 4#, 5#, 6#, and 8#) were all higher than that at lightly polluted sites (3#, 7#, 9#, and 10#). In contrast the pH and DO showed the opposite situation. Although the concentration of nitrogen compounds was not high at 8#, it still belongs to the heavily polluted site due to the high concentration of OM in sediment. Even if the water at 4# comes from the Daqiao water treatment plant, the 4# site is still a heavily polluted site

because of its high concentration of nitrogen compounds in water (TN: 2.56–3.63 mg/L, N-NH₄⁺: 1.85–2.28 mg/L).

3.2. Variability of CO₂ and CH₄ Fluxes. Figure 2 shows the average fluxes of CO₂ and CH₄ across water-air interface in summer and autumn in different sampling sites. During the observation period, the emission characteristics of CO₂ in two seasons showed a consistent rule: 8# site had a negative value, while the others had positive values. The average flux of CO₂ in summer (72.93 mg·m⁻²·h⁻¹, from -19.56 to

FIGURE 2: The flux of CO₂ and CH₄ in summer and autumn in various sites.

229.09 mg·m⁻²·h⁻¹) is 4.54 times higher than that in autumn (16.06 mg·m⁻²·h⁻¹, from -10.49 to 70.70 mg·m⁻²·h⁻¹). The higher values appeared at 1#, 2#, 4#, and 6# site with the average of 142.14 mg·m⁻²·h⁻¹ in summer and 38.82 mg·m⁻²·h⁻¹ in autumn, respectively. The 4# site, located at the inflow mouth of the pretreatment water from Daqiao drink water treatment plant, is characterized by its relatively fast water flow rate and by high concentrations of TN and COD_{Mn}, and the high flux values of 1#, 2#, and 6# sites are all related to the inflow of domestic sewage with higher concentrations of TN and COD_{Mn}. The negative flux of CO₂ (summer: -19.56 mg·m⁻²·h⁻¹ and autumn: -10.49 mg·m⁻²·h⁻¹) in 8# site is related to the photosynthesis of lush *lotus* [47]. The 3#, 5#, 9#, and 10# sites with slight pollution and without the intensive disturbance of anthropological activities have lower average flux of CO₂ (summer: 36.07 and autumn: 3.16 mg·m⁻²·h⁻¹). The average fluxes of CO₂ in heavily polluted sites were 3.9 times in summer and 12.3 times higher in autumn than those in less polluted sites, respectively.

The positive flux of CH₄ implied Xuanwu Lake was an emission source of CH₄ in two seasons. The average flux of CH₄ in summer (2.76 mg·m⁻²·h⁻¹, from 0.07 to 12.54 mg·m⁻²·h⁻¹) is 7.26 times higher than that in autumn (0.38 mg·m⁻²·h⁻¹, from 0.02 to 1.72 mg·m⁻²·h⁻¹). The locations with high flux values were the 1#, 2#, 5#, and 8# sites with the average of 6.46 mg·m⁻²·h⁻¹ in summer and 0.78 mg·m⁻²·h⁻¹ in autumn, which is related to the heavy pollution characteristics, especially the lower ORP and DO and higher OM in sediment in these sites. Low flux values were observed at 3#, 4#, 6#, 7#, 9#, and 10# sites with 0.29 mg·m⁻²·h⁻¹ in summer and 0.11 mg·m⁻²·h⁻¹ in autumn, which is attributable to low pollution and the lower ORP and DO in these sites compared to other sites. The average of CH₄ in heavily polluted sites was 22.3 times higher in summer and 7.1 times higher in autumn than those in slight pollution sites, respectively.

In addition, a very interesting phenomenon can be observed in Figure 2: the fluxes of CO₂ and CH₄ in the same

sampling site appeared complementary; that is, the sampling site with low flux of CO₂ had high flux of CH₄, and vice versa. This suggests the two kinds of greenhouse gases appeared as mutually transformed, so the environmental conditions in sampling site are the key factors affecting the residues and flux [37].

3.3. Correlation Analysis between Fluxes and Environmental Factors

3.3.1. Correlation Analysis of Pearson and Spearman. The emission of greenhouse gases across the water-air interface relies primarily on diffusion, ebullition, and internal transmission in aquatic plants aerenchyma [48]. According to field survey, there are no aquatic macrophytes in all sampling sites except for 6#–8# site. Therefore, the emission of greenhouse gases in studied area relies mainly on diffusion and ebullition. The Pearson and Spearman correlation between greenhouse gases fluxes (CO₂ and CH₄) and various environmental factors are shown in Table 3.

The results showed a significant positive correlation ($p < 0.01$ and < 0.05) between CO₂ flux and the T of air and water and significant negative correlation with pH (spearman correlation, $p < 0.01$); this suggests the effect of T on the flux of CO₂ is clear. A significant positive correlation ($p < 0.05$) between CO₂ flux and environmental factors (including TN, N-NH₄⁺, and COD_{Mn} in water and OM in sediment) was also observed. Spearman correlation, in addition to the significant correlation mentioned above, also showed significant positive correlation with TNs and N-NH₄⁺s in sediment ($p < 0.05$).

As to the flux of CH₄, both Pearson and Spearman correlation analyses showed positive correlations with meteorological factors (T and wind speed), but the correlation was not significant. CH₄ emission was significantly positively correlated with turbidity ($p < 0.01$), significantly negatively correlated with DO and ORP ($p < 0.05$), and significantly positively correlated with OM in sediment ($p < 0.05$).

3.3.2. Multivariate Stepwise Regression Analysis (MSRA). The applicable conditions of MSRA include a linear trend between independent variables and dependent variables and the independence, normality, and homoscedasticity of different residuals. The negative datum of CO₂ at site 8# was removed, and the data of CO₂ and CH₄ were treated with logarithmic transformation. After this treatment, the distribution of CO₂ (with mean 1.349 and standard deviation 0.68) and CH₄ (with mean -0.560 and standard deviation 0.75) was normal distribution tested with one-sample Kolmogorov-Smirnov test (Figure 3).

Linear Trend between Independent Variables and Dependent Variables. The 17 environmental factors including T (X_1), water temperature (X_2), wind speed (X_3), flow rate (X_4), pH (X_5), DO (X_6), ORP (X_7), COND (X_8), Tur (X_9), TN (X_{10}), N-NH₄⁺ (X_{11}), N-NO₃⁻ (X_{12}), N-NO₂⁻ (X_{13}), COD_{Mn} (X_{14}), OM (X_{15}), TNs in sediment (X_{16}), and N-NH₄⁺s in sediment (X_{17}) were discussed with the fluxes of CO₂ and CH₄. Figure 4 showed that the lgCO₂ has good linear correlation with T ($r = 0.7419$, $p < 0.0004$), Tw

TABLE 3: Pearson and Spearman analysis between flux and environmental factors ($n = 18$).

Correlation	T	Tw	Wind	Wf	pH	DO	ORP	COND	Tur	TN	N-NH ₄ ⁺	N-NO ₃ ⁻	N-NO ₂ ⁻	COD _{Mn}	OM	TNs	N-NH ₄ ⁺ s
CO ₂ Pearson	0.573**	0.504*	0.352	0.413	-0.354	-0.262	-0.168	-0.152	0.093	0.536*	0.469*	0.136	0.371	0.545*	0.494*	0.204	0.287
CO ₂ Spearman	0.652**	0.431	0.319	0.320	-0.460**	-0.436	-0.032	-0.081	0.191	0.517*	0.540*	0.116	0.223	0.546*	0.405*	0.508*	0.489*
CH ₄ Pearson	0.363	0.362	0.206	-0.081	-0.264	-0.517*	-0.656*	-0.172	0.696**	0.306	0.354	-0.158	0.027	0.424	0.524*	0.217	0.280
CH ₄ Spearman	0.364	0.402	0.113	-0.167	-0.386	-0.618**	-0.329	-0.236	0.653**	0.196	0.277	-0.069	-0.040	0.391	0.489*	0.320	0.384

Note. **Indicating a significant correlation at the 0.01 level; * indicating a significant correlation at the 0.05 level; T: atmospheric temperature; Tw: water temperature; wind: wind velocity; Wf: water flow rate; DO: dissolved oxygen; ORP: oxidation-reduction potential; COND: conductance; Tur: turbidity.

FIGURE 3: The normal distribution test of lg CO₂ and lg CH₄. FIGURE 4: The linear trend between independent variables and lg CO₂.

(water temperature, $r = 0.6630, p < 0.0027$), DO ($r = -0.5778, p < 0.0120$), pH ($r = -0.7255, p < 0.0007$), COD ($r = 0.5964, p < 0.0090$), and OM ($r = 0.6392, p < 0.0043$), but significant correlation was also observed between T and Tw ($r = 0.9719, p < 0.0000$), DO and pH ($r = 0.7463, p < 0.0004$), COD and OM ($r = 0.8271, p < 0.00002$), and COD and DO ($r = -0.6430, p < 0.004$). At the same time, the lg CH₄ also has good linear correlation

with DO ($r = -0.6808, p < 0.0019$), Tur ($r = 0.7758, p < 0.0002$), ORP ($r = -0.4382, p < 0.0689$), N-NH₄⁺ ($r = 0.5261, p < 0.0249$), and OM ($r = 0.4614, p < 0.0539$); however significant correlation was also observed between DO and Tur ($r = -0.5400, p < 0.0207$) and N-NH₄⁺ and OM ($r = 0.6979, p < 0.0013$, Figure 5). This implies that there are collinearity phenomena of independent variables in the model obtained with forward stepwise regression method

FIGURE 5: The linear trend between independent variables and lg CH₄.

$[Y_{CO_2} = -466.69 + 33.23X_1 + 43.01X_{15} - 3.10X_9 + 25.29X_3 - 0.03X_{16} + 57.04X_{10} - 34.71X_{11} - 18.84X_2$ ($F = 17.22, R^2 = 0.9387, \rho < 0.0001$). In the case of CH₄ one gets $Y_{CH_4} = -18.99 + 0.27X_9 - 0.15X_7 - 0.59X_6 - 1.60X_{14} + 1.37X_{15} - 0.86X_2 + 0.006X_{16} - 0.01X_{17} + 0.07X_8 + 1.32X_1$ ($F = 32.05, R^2 = 0.9727, \rho < 0.0001$)]. This issue also explained why some variables (e.g., water temperature) show positive influence on the CO₂ and CH₄ flux for simple regression, but in the case of the multiple regression their impact is negative.

In Order to Overcome the Collinearity Phenomenon of Independent Variables in Model, Standard Stepwise Regression Method Was Adopted. The MSRA was carried out with the software of SPSS 22.0, with probabilities of F for entry and removal of 0.05 and 0.1, respectively. There are two optimal models that have higher R^2 and smaller standard error (SE) of the estimate values than other models (Table 4), which meet the conditions that the significance of T test for regression coefficients should be less than 0.05 and the variance inflation factor (VIF) should be less than 10 (or tolerance > 0.1) (Table 5). The stepwise regression equation of CO₂ is $\lg Y_{CO_2} = 0.499 + 0.147X_1 + 0.469X_{15} - 0.624X_5$, where “lg” is a decimal logarithm ($F = 23.915, R^2 = 0.837, \rho < 0.0001$, and $SE = 0.3015$). In the case of CH₄ it is $\lg Y_{CH_4} = -2.625 + 0.068X_9 + 0.422X_{11}$ ($F = 19.717, R^2 = 0.724, \rho < 0.0001$, and $SE = 0.4164$).

Test of the Model Rationality

(1) *Identification of Normality of Residuals.* Figure 6 shows the frequency distribution histogram of regression standardized residuals of lg CO₂ and lg CH₄, which showed that they belonged to normal distribution.

(2) *Identification of the Independence of Residuals.* In Table 4, the Durbin-Watson test values (DW) are 1.659 and 2.859 for the regression model of lg CO₂ and lg CH₄, respectively. The lower (DL) and upper bounds (DU) of critical values for the Durbin-Watson test of lg CO₂ and lg CH₄ regression model are “1.046 and 1.535” and “1.046 and 1.535,” respectively. Because both of the DWs are all higher than their upper bounds (DU), their relations among the residuals are independent and there is no autocorrelation.

(3) *Identification of Homogeneity of Variance.* Figure 7 showed the scatterplot of regression standardized residual versus predicted value of lg CO₂ and lg CH₄. The fluctuation range of standard residuals is basically stable with the change of standard predicted values. It suggested the homogeneity of variance.

(4) *Collinearity Diagnosis.* Tables 5 and 6 showed the diagnosis results, and we can find that the tolerances of the independent variables in the regression model are all more

TABLE 4: Model summary.

Dependent variable	Model	R	R square	Adjusted R square	Std. error of the estimate	R square change	Change statistics F change	df1	df2	Sig. F change	Durbin-Watson
lg CO ₂	1	0.742 ^a	0.550	0.522	0.4679	0.550	19.592	1	16	0.000	
	2	0.885 ^b	0.783	0.754	0.3358	0.232	16.067	1	15	0.001	
	3	0.915^c	0.837^f	0.802	0.3015	0.054	4.611	1	14	0.050	1.659
lg CH ₄	1	0.776 ^d	0.602	0.577	0.4847	0.602	24.187	1	16	0.000	
	2	0.851^e	0.724	0.688	0.4164	0.123	6.672	1	15	0.021	2.859

^aPredictors: (constant) T; ^bPredictors: (constant) T, OM; ^cPredictors: (constant) T, OM, pH; ^dPredictors: (constant) Tur, N-NH₄⁺; ^ePredictors: (constant) Tur, N-NH₄⁺; ^fthe bold numerical values are the optimal solution.

TABLE 5: Coefficients.

Dependent variable	Model	Unstandardized coefficients		Standardized coefficients		t	Sig.	Collinearity statistics	
		B	Std. error	Beta				Tolerance	VIF
lg CO ₂	1	(Constant)	-4.670	1.364		-3.423	0.003		
		T	0.221	0.050	0.742	4.426	0.000	1.000	1.000
	2	(Constant)	-6.119	1.044		-5.863	0.000		
		T	0.187	0.037	0.629	5.086	0.000	0.948	1.055
	3	OM	0.580	0.145	0.495	4.008	0.001	0.948	1.055
		(Constant)	0.499	3.221		0.155	0.879^a		
		T	0.147	0.038	0.495	3.896	0.002	0.722	1.386
		OM	0.469	0.140	0.401	3.359	0.005	0.819	1.221
		pH	-0.624	0.290	-0.294	-2.147	0.050	0.624	1.603
lg CH ₄	1	(Constant)	-2.206	0.354		-6.239	0.000		
		Tur	0.077	0.016	0.776	4.918	0.000	1.000	1.000
	2	(Constant)	-2.625	0.344		-7.622	0.000		
		Tur	0.068	0.014	0.689	4.936	0.000	0.942	1.061
		NH ₄	0.422	0.163	0.361	2.583	0.021	0.942	1.061

^aThe bold numerical values are the optimal solution.

FIGURE 6: The normal distribution histogram of regression standardized residual of lg CO₂ and lg CH₄.

FIGURE 7: The scatterplot of regression standardized residual versus predicted value of lg CO₂ and lg CH₄.

than 0.1, and the VIF are also lower than 10; thus the effect of collinearity on the regression model is no problem. Therefore, the regression model is rational.

Results showed CO₂ flux can be fitted to the optimal regression linear equation with 3 factors of T (X_1), OM (X_{15}), and pH (X_5). The flux of CH₄ can be used to obtain the optimal regression linear equation with the 2 factors of Tur (X_9) and N-NH₄⁺ (X_{11}). Their significance of p is all lower than 0.0001 (CO₂: $R^2 = 0.837$, CH₄: $R^2 = 0.724$).

3.3.3. Redundancy Analysis of Flux and Environmental Factors. The main environmental factors affecting the fluxes are discussed with RDA. The statistical results are shown in Tables 7 and 8. As Table 7 shows, the eigenvalues of the first two species axes were 0.9463 and 0.0025, respectively, the total eigenvalue was 0.9488, and the first two ordination axes can account for 94.9% of the total amount of information. The tables also show that the correlation coefficients between the first two species axes and the first two environmental

axes are 0.974 and 0.998, respectively, indicating that these axes are well correlated. In contrast, the correlation coefficient between the two species axes was -0.007 , showing these axes were poorly correlated. The correlation coefficient of the two environmental axes was 0.000, indicating they were perpendicular. This demonstrates that the ordination results can reflect the relationships between the greenhouse gases fluxes and environmental factors.

The first ordination axis represents the flux of CO₂, and the second ordination axis primarily represents the flux of CH₄ (Table 8 and Figure 8). Most environmental factors, such as T, wind speed, COD_{Mn}, TN, and N-NH₄⁺ in water and OM in sediment, are positively correlated with the two gas ordination axes. The correlation of environmental factors with CO₂ is higher compared with CH₄. In addition, water flow rate was positively correlated with CO₂ flux ($r = 0.4124$), indicating that a faster water flow rate contributes to CO₂ emission. Nitrate nitrogen and nitrite nitrogen also have a higher correlation with CO₂ flux, suggesting these

TABLE 6: Collinearity diagnostics.

Model		Eigenvalue	Condition index	Variance proportions			
				(Constant)	T	OM	pH
lg CO ₂	1	3.979	1.000	0.00	0.00	0.00	0.00
	2	0.015	16.511	0.00	0.01	0.75	0.01
	3	0.006	26.421	0.00	0.58	0.07	0.04
	4	0.000	112.854	0.99	0.41	0.18	0.95
Model		Eigenvalue	Condition index	Variance proportions			
				(Constant)	Tur	N-NH ₄ ⁺	
lg CH ₄	1	2.842	1.000	0.01	0.01	0.02	
	2	0.106	5.168	0.05	0.27	0.91	
	3	0.051	7.432	0.94	0.72	0.08	

TABLE 7: Eigenvalues for RDA axis and the correlation of species-environment factors.

Axes	1	2	3	4	Total variance
Eigenvalues	0.9463	0.0025	0.0512	0	1.00
Explained variation (cumulative)	94.63	94.88	100	100	
Pseudo-canonical correlation	0.974	0.998	0	0	
Explained fitted variation (cumulative)	99.74	100			

TABLE 8: Correlation coefficients among environmental factors, flux, and RDA ordination axes.

Environment factors	Resp Ax1	Resp Ax2
CO ₂	0.9740^a	-0.0003
CH ₄	0.1018	0.9933
T	0.5731	0.3045
Tw	0.5044	0.3105
Wind rate	0.3524	0.1697
Flow rate	0.4124	-0.1248
pH	-0.3537	-0.2276
DO	-0.2626	-0.4917
ORP	-0.1679	-0.6412
COND	-0.1521	-0.1569
Tur	0.0927	0.6894
TN	0.5365	0.2512
N-NH ₄ ⁺	0.4695	0.3059
N-NO ₃ ⁻	0.1364	-0.1730
N-NO ₂ ⁻	0.3705	-0.0120
COD _{Mn}	0.5450	0.3683
OM	0.4938	0.4747
TNs	0.2038	0.1964
N-NH ₄ ⁺ s	0.2875	0.2514

^aThe bold numerical values suggest that the absolute values of the correlation coefficient (*R*) between environmental factors and corresponding RDA ordination axis 1 or axis 2 are more than 0.25.

compounds are conducive to the formation and emission of CO₂. DO showed high negative correlation with the CH₄ emission ($r = -0.4917$), as also does the ORP ($r = -0.6412$), suggesting the conditions of reduction and low dissolved oxygen help the generation and emission of CH₄, but turbidity was highly positively correlated with the CH₄

FIGURE 8: RDA ordination among greenhouse gas fluxes, sampling sites, and environmental factors.

emission ($r = 0.6894$), implying the high turbidity and dark conditions encourage CH₄ formation and emission.

4. Discussion

4.1. Comparison of GHG Fluxes between This Study and Other Studies. Table 9 shows the GHG fluxes from this

TABLE 9: CO₂ and CH₄ fluxes from this study and literature.

Location	Vegetations	CO ₂ (mg m ⁻² h ⁻¹)	CH ₄ (mg m ⁻² h ⁻¹)	Observation period	References
Xuanwu lake	<i>Lotus</i>	Jun.: -19.56, Oct.: -10.59	Jun.: 5.59, Oct.: 1.72	Jun. and Oct., 2014	This study
	Heavy pollution	Jun.: 142.14, Oct.: 38.82	Jun.: 6.46, Oct.: 0.78		
	slight pollution	Jun.: 36.07, Oct.: 3.16	Jun.: 0.29, Oct.: 0.11		
Yellow River estuary, China	<i>T. chinensis</i> , <i>S. salsa</i> , <i>S. alterniflora</i>	111.03–241.97	-0.02–0.20	Jun.–Dec., 2013	[18]
	Aquaculture pond	-39.49	0.0034		
Poyang Lake, China	Heavy pollution	-39.60–212.30	0.08–1.12	Oct., 2010	[35]
Polegar Lake, Brazil	Oligomesotrophic	ND	Win.: 0.01–0.22 Sum.: 0.55–2.91	Win., 2006 Sum., 2007	[22]
Biguás Lake, Brazil	Eutrophic	ND	Win.: 0.06–0.83 Sum.: 0.68–40.16	Win., 2006 Sum., 2007	[22]
Crystal Bog	Dystrophic	30.46	1.24	Apr.–Nov., 1998	[23]
Trout Bog	Dystrophic	45.70	1.71		
Crystal Lake	Oligotrophic	0.40	0.12		
Sparkling Lake, USA	Mesotrophic	5.00	0.18		
Oxbow Lake, Italy	Stagnant, <i>water chestnut</i>	269.68 ± 19.80– 822.25 ± 19.43	44.00 ± 4.27– 77.53 ± 5.33	Jul., 2005	[25]
Yangtze River estuary	<i>S. alterniflora</i>	ND	0.64 (0.16–1.12)	Apr.–Oct., 2004	[36]
5 lakes, Netherlands	Mesotrophic-eutrophic	-6.00–123.90	1.40–18.10	Jun.–Jul., 2009	[37]
Bay of Fundy, Germany	<i>S. alterniflora</i> , etc.	104.17	6.67	Jul.–Sep., 1996	[38]
Min River estuary, China	Shrimp pond	-48.79	1.00	Oct., 2011	[39]
	Polyculture pond of fish and shrimp	-105.25	5.74		
Québec's reservoirs, Canadian	Reservoirs	62.83	0.37	1993–2003	[40]
30 Boreal lakes, Finland	Eutrophic	ND	Median of 0.137	1998–1999	[41]
11 lakes, North America	Lakes	ND	0.15–3.2	Jun. to Aug., 2001	[11]
Switzerland	Reservoirs	40.42	0.01	Sep., 2003–Aug., 2006	[42]

Note. ND: no data. Win.: winter. Sum.: summer.

study and other studies. Compared with CO₂ and CH₄ fluxes from natural wetlands, which are affected minimally by human activities, we observed that CO₂ fluxes recorded from heavily polluted sites (1#, 2#, 4#, and 6# sites) with higher concentration of TN and COD_{Mn} in our study were greater [23], while CO₂ fluxes from less polluted sites were close to the reported values in dystrophic lakes [23], 5 mesotrophic-eutrophic Netherlands lakes [37], and reservoirs [40, 42]. The CO₂ fluxes with lush *lotus* in this study were close to the aquaculture pond [18, 39], and lower than those from the wetlands with vegetation (e.g., *T. chinensis*, *Suaeda salsa*, and *S. alterniflora* in Yellow River estuary [18]; *water chestnut* in oxbow Lake, Italy [25]; *Spartina alterniflora* in Bay of Fundy, Canada [38]); the differences in vegetation may be the main reason.

CH₄ fluxes from heavy pollution sites (1#, 2#, 5#, and 8# sites) in our study were close to the Poyang Lake [35], Yangtze River estuary [36], 5 Netherlands lakes [37], the Bay of Fundy [38], and the Shrimp pond of Min River estuary

[39] and were greater than those from natural wetlands and less polluted lakes, such as 11 North America lakes [11], Polegar Lake [22], Yellow River estuary wetlands [18], Sparkling Lake [23], 30 boreal lakes [41], reservoirs [40, 42], and less polluted sites (3#, 4#–6#, 7#, 9#, and 10# site) in this study. The heavily polluted sites in our study are significantly influenced by human activities (such as the introduction of domestic sewage and surface rain runoff, water diversion from Shangyuanmen (1.0 × 10⁵ t/d) and Daqiao drink water treatment plant (8 × 10⁴ t/d) into lake, tourist entertainment and rubbish in lake park, and water treatment project with higher aquatic plants); therefore nutrient substance content and physicochemical property of these sites will be different from natural water bodies (field lakes, reservoirs), which can lead to differences in GHG emissions [49]. However, our results from heavily polluted sites were still smaller than the eutrophic and stagnant lakes [22, 25], which is related to the eutrophic status and adverse environmental conditions, such as lower ORP and DO and higher OM in sediment.

FIGURE 9: The schematic diagram of identification of environmental factors affecting the fluxes of CO_2 and CH_4 . Pearson and Spearman: the correlation analysis of Pearson and Spearman; MSRA: multiple stepwise regression analysis; RDA: redundancy analysis; T: atmospheric temperature; Tw: water temperature; wind: wind velocity; Wf: water flow rate; DO: dissolved oxygen; ORP: oxidation-reduction potential; COND: conductance; Tur: turbidity. The color change from green to red shows the increase of importance on the effect of CO_2 and CH_4 fluxes. For the calculation method see Section 2.3.3.

4.2. Identification of Environmental Factors Affecting the Fluxes of CO_2 and CH_4 . The relative role of different environmental factors in affecting the fluxes of CO_2 and CH_4 (In values) based on the calculation of Pearson and Spearman correlation analysis, MSRA, and RDA is shown in Figure 9. It can be found that the T, wind speed, water flow rate, pH, TN, N-NH_4^+ , and COD_{Mn} in water body and N-NH_4^+ s, TNs, and OM in sediment have important effects on the flux of CO_2 . As for CH_4 , its main controlling factors include Tur, ORP, DO, T, and COD_{Mn} of water body and OM and N-NH_4^+ s of sediments. The results of Liu et al. [50] also showed that environmental factors, such as sediment temperature, sediment total nitrogen content, dissolved oxygen, and total phosphorus content in the water of Poyang Lake, mainly regulated the CH_4 efflux on a seasonal scale. Gonzalez-Valencia et al. [31] also indicated that trophic state and water quality indexes were most strongly correlated with CH_4 fluxes from Mexican freshwater bodies.

4.3. Impacts of Environmental Factors on the Flux of CO_2 . The effect of temperature (T) on CO_2 flux is multifaceted. On the

one hand, high T is conducive to photosynthesis of aquatic plants and the depletion of CO_2 , which will help CO_2 dissolve into water from atmosphere; on the other hand, high T will promote microbial respiration and decomposition of organic matter in sediments and accelerate CO_2 emission from water. In addition, high T will also reduce the solubility of CO_2 in water, which is conducive to CO_2 emission from water [51]. Baggs and Blum [52] noted the effect of T on CO_2 emission is the result of joint action. Marotta et al. [53] found a general positive relationship between pCO_2 and water temperature across lakes (119 Brazilian lakes) involving an average increase ($\pm \text{SE}$) in $6.7 \pm 0.8\%$ per $^\circ\text{C}$. However, Sobek et al. [54] reported that T is not an important regulator of pCO_2 in lakes (4902 lakes); instead, the concentration of dissolved organic carbon (DOC), a substrate for microbial respiration, explains significant variation in lake pCO_2 . The effects of climate change on the carbon balance of lakes may not be due to rising temperature per se, but rather to climatically induced changes in the export of DOC from terrestrial soils to aquatic habitats. In this study, CO_2 flux was significantly positively correlated with T (Table 3). Therefore, except the 8# site, the impact of photosynthesis of aquatic plants on CO_2 emissions is weak in Xuanwu Lake due to the scarcity of aquatic plants for most of sampling sites in Xuanwu lake (Table 2); thus the effects mainly come from microbial activity and decomposition of OM in sediment, which is affected by T.

Wind speed is also an important factor affecting CO_2 emission (Table 3). The main reasons are summarized in the following 3 aspects: ① the shear stress of wind makes water surface broken; water-vapor contact area increases, thus contributing to the emission of CO_2 ; ② Xuanwu Lake is a shallow lake, and strong winds will cause sediment resuspension and lead the sediment carbonate into water, which leads to pH increase, thereby promoting CO_2 emissions to atmosphere; ③ because wind wave can cause algae to float in the water, the photosynthesis or respiration of algae makes the partial pressure of CO_2 decrease or increase and changes the fluxes of CO_2 . Previous studies have consistent results [55].

The pH value of water can control microbial activity, change the balance of carbonate in water, and affect the migration and conversion process of substances. Higher pH value causes CO_2 to easily dissolve in water to form carbonate, reduces the partial pressure of CO_2 in surface water [56], and decreases the CO_2 flux; on the contrary, low pH value can promote the emission of CO_2 into atmosphere from the water. In this study, the flux of CO_2 showed a significant negative correlation with pH values ($r = -0.46$, $p < 0.01$, Table 3). Li et al. [57] have pointed out the changing trend of CO_2 flux is opposite to the trend of pH. Tremblay et al. [56] also found that the large amounts of CO_2 from atmosphere were absorbed by the observed water body when the pH value of water was higher than 8.

Nitrogen is an essential nutrient, providing material support for the life of aquatic organisms. In this study, TN in water showed a significant positive correlation relationship with the flux of CO_2 ($r = 0.536$, $p < 0.05$, Table 3). The water quality of Xuanwu Lake is characterized by TN exceeding the standard; coupled with the slow flow rate and eutrophication, it may promote the increase of heterotrophic

aquatic organisms and depletion of DO. The large number of dead rotting aquatic plants can produce OM, providing favorable material conditions for CO_2 and CH_4 formation in sediment.

Organic matter (OM) is a major carbon source for microorganism respiration, providing matrix for CO_2 generation. The higher the content of OM in sediment, the greater the corresponding release capacity of CO_2 [58, 59]. Moreover, microorganisms easily absorb and utilize dissolved OM to produce CO_2 gas. Striegl et al. [60] found the content of OM in lake sediment is an important factor for the production of CO_2 . Our study is consistent with this result and found that CO_2 flux was significantly positively correlated with the OM in sediment ($r = 0.494$, $p < 0.05$, Table 3).

Dissolved organic carbon (DOC) also affected the flux of CO_2 . Riera et al. [23] reported that clear-water lakes with low dissolved organic carbon (DOC) quickly became undersaturated following ice-out and remained undersaturated until fall turnover. Bog lakes with high DOC waters were supersaturated in CO_2 throughout the ice-free season. Differences in seasonal patterns of CO_2 were attributed to morphometry and the timing and intensity of mixing events. Ice-free season fluxes of CO_2 were 6.7 and $10.0 \text{ mol} \cdot \text{m}^{-2}$ in the bog lakes and 1.2 and $0.09 \text{ mol} \cdot \text{m}^{-2}$ in the clear-water lakes. Fluxes of CH_4 were significant only immediately after ice-out and during autumn turnover, and were $<0.4 \text{ mol} \cdot \text{m}^{-2}$ in the bog lakes and $<0.05 \text{ mol} \cdot \text{m}^{-2}$ in the clear-water lakes. Compared with changes in carbon pools in the lakes, these results indicate rapid carbon turnover rates in bog lakes, as opposed to clear-water lakes, and suggest that allochthonous inputs of CO_2 may be responsible for this rapid turnover.

The macrophyte (e.g., *water chestnut*, *water hyacinth*) also plays an important role in reducing CO_2 flux [24, 25]. Bolpagni et al. [25] reported that the CO_2 emission flux across the plant-free water surface (*Trapa natans* L.) ($448.5 \pm 10.6 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) is about three times higher compared to a surface covered with water chestnut ($147.1 \pm 10.8 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), thus the covering of water chestnut significantly reduced the CO_2 flux. The role of extensive stands of floating macrophytes colonizing floodplains areas on the net ecosystem exchange of CO_2 (NEE) is assessed by Peixoto et al. [24] in two tropical floodplain lakes in Pantanal, Brazil, during different hydrological seasons. In both lakes, areas colonized by floating macrophytes (*water hyacinth*; *Eichornia* sp.) were a net CO_2 sink during all seasons. In contrast, open waters emitted CO_2 , with higher emissions during the rising and high water periods. Their results indicate that the lake NEE can be substantially overestimated (fivefold or more in the studied lakes) if the carbon fixation by macrophytes is not considered. The contribution of these plants can lead to neutral or negative NEE (i.e., net uptake of CO_2) on a yearly basis. This highlights the importance of floating aquatic macrophytes for the C balance in shallow lakes and extensive floodplain areas.

4.4. Environmental Factors Effecting Flux of CH_4 . Water temperature (T) can affect the whole process of CH_4 production, oxidation, and transmit. Previous research indicated

that T can control the decomposition of sediment OM by affecting the quantity and activity of methanogenic bacteria and CH_4 -oxidizing bacteria [37]. Related studies showed that the optimum T range for methanogenic bacteria is $35\text{--}37^\circ\text{C}$: within a certain T range, bacteria activity and the generation amount of CH_4 will increase with the T increase [61]. Hosono and Nouchi [62] reported that when the T increased from 10°C to 23°C , the emission amount of CH_4 increased by 6.6 times. Yvon-Durocher et al. [2] also reported that both the emission of CH_4 and the ratio of CH_4 to CO_2 emissions increase markedly with seasonal increases in temperature. Wilkinson et al. [63] showed that sediment CH_4 formation of Saar River was dominated by the upper sediment (depths of 0.14 to 0.2 m) and the key driver of the seasonal CH_4 ebullition dynamics was temperature. In addition, saturation solubility of CH_4 at 20°C is $1.6 \text{ mol} \cdot \text{m}^{-3}$; its solubility will decrease with increasing T and promote the emission of CH_4 from water into atmosphere. Table 2 shows both air and water T significantly positively correlated with CH_4 fluxes. Xuanwu Lake is a shallow lake, and the effect of water T on the CH_4 flux may be realized mostly by influencing the sediment surface T and CH_4 solubility.

ORP and DO are two important factors affecting the release of CH_4 from sediment. CH_4 is generated only under anaerobic conditions and is also easily oxidized and consumed by microorganisms after its release [64, 65]. Kuangfei et al. [66] reported that the soil OM gradually began anaerobic decomposition after the paddy field was flooded, and the decrease of DO and ORP promoted the release of CH_4 . In addition, ORP will not only impact the generation of CH_4 but also affect the gas transmission of plants, and low ORP makes plant ventilation tissues more developed, which will help CH_4 transmission [67]. This study also found the flux of CH_4 was significantly negatively correlated with DO and ORP ($p < 0.05$, Table 3), indicating lower ORP and DO values can promote the generation and emission of CH_4 . For example, the biggest values of CH_4 appeared at sites 1#, 2#, and 8# due to the lower ORP (68–89 mV).

CH_4 generation is the joint action of methanogenic bacteria and CH_4 -oxidizing bacteria [68], which can only use N-NH_4^+ as a direct energy source, rather than take advantage of N-NO_3^- , N-NO_2^- , and other forms of nitrogen nutrient [69, 70]. The promotion effects of N-NH_4^+ content in water on the CH_4 flux can be explained by the following two aspects: (1) CH_4 -oxidizing bacteria are capable of oxidizing both CH_4 and N-NH_4^+ ; N-NH_4^+ in water can compete with CH_4 , so that the oxidation of CH_4 is restrained, and the flux of CH_4 is increased [71]. (2) The increase of N-NH_4^+ in water can stimulate the growth and activity of methanogenic bacteria, increasing the emission of CH_4 [72]. Huttunen et al. [73] have indicated that nutrient loading increases autochthonous primary production in lakes, promoting oxygen consumption and anaerobic decomposition in sediments, and this can lead to increased CH_4 release from lakes to atmosphere. Our results found the flux of CH_4 increases significantly with the increase of N-NH_4^+ content in water, which proved the hypothesis.

The content of sediment OM can determine the production rate of CH_4 . Kelly and Chynoweth [74] found that

continuous addition of fresh organic matter to sediments may promote microbial oxygen-consumption respiration, providing an anaerobic environment, which is conducive to microbial anaerobic decomposition of OM and the generation of CH_4 . Researchers found that CH_4 emission was positively correlated with BOD and COD content in water [75]. In this study, the significant positive correlation among CH_4 flux, the OM content in sediment, and COD_{Mn} in water ($p < 0.05$) confirmed the important influence of carbon source on CH_4 emission.

This study also found that the CH_4 flux in Xuanwu Lake is significantly positively correlated with turbidity of water ($p < 0.01$), which may be related to the resuspension of sediment or the mass growth of algae, but the relevant research is very scarce. Upstill-Goddard et al. [76] reported under both high and low salinity situations that the existence of a large in situ CH_4 supply was associated with high turbidity. Abril et al. [77], however, found that suspended clays (high turbidity) in the estuarine turbidity maximum (ETM) area enhanced CH_4 oxidation and strongly reduced CH_4 fluxes to the atmosphere. Linto et al. [78] reported that fourfold higher turbidity during the wet season is consistent with elevated net benthic and/or water column heterotrophy via enhanced organic matter inputs from adjacent mangrove forest and/or the flushing of CO_2 -enriched soil waters, which may explain these high emission data of CO_2 . A possible mechanism is that the increase of turbidity reduced the photosynthesis of aquatic plants and the reoxygenation capacity of water, thereby establishing an anaerobic reducing environment at the water-sediment interface, which is conducive to the generation and emission of CH_4 .

The large aquatic plants play an important role in gas exchange in water environment, and the diurnal emission flux of CH_4 across the water surface covered by water chestnut is $116.3 \pm 8.0 \text{ mmol m}^{-2} \text{ d}^{-1}$, while that across the plant-free water surface is $66.0 \pm 6.4 \text{ mmol m}^{-2} \text{ d}^{-1}$. Therefore, the water chestnut (*Trapa natans* L.) enhanced methane delivery to the atmosphere [25].

5. Conclusion

Anthropogenic disturbance and pollution status of water body have an important role in affecting the fluxes of CO_2 and CH_4 from the water surface. In the sampling site with aquatic plants, the reduction of CO_2 emission due to the occurrence of aquatic plants was also observed. In the sampling site without aquatic plants, the main controlling factors for the flux of CO_2 include T, wind speed, water flow rate, pH, TN, N-NH_4^+ , and COD_{Mn} in water and OM, TN, and N-NH_4^+ in sediment. The significant influencing factors for CH_4 include Tur, ORP, DO, COD_{Mn} , and T in water and OM, TN, and N-NH_4^+ in sediment.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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