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Invasive Water Hyacinth (*Eichhornia crassipes*) Increases Methane Emissions from a Subtropical Lake in the Yangtze River in China

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Abstract: Lakes represent an important source of atmospheric methane (CH_4); however, there are few studies on which lake-dwelling invasive aquatic plants generate CH_4. Therefore, in this study, CH_4 emissions were measured using a floating chamber and gas chromatography in a subtropical lake in China. We considered four community zones of invasive plants (*Eichhornia crassipes*), emergent vegetation (*Zizania latifolia*), floating-plant (*Trapa natans*) and open-water zones. The results indicate that the flux of CH_4 emissions varied between −5.38 and 102.68 mg m^{-2} h^{-1}. The higher emission values were attributed to lake eutrophication. Moreover, the flux of CH_4 emissions in the invasive plant zone was 140–220% higher than that in the open-water and the floating-plant zones. However, there was no significant difference in CH_4 emissions between the invasive plant and the emergent vegetation zones. This may be due to a higher production of plants, as well as the rapid reproductive rate of the invasive plants. Finally, CH_4 emissions were positively associated with the air and water temperature; however, the emissions were also negatively associated with water depth. Our results suggest that invasive plants enhance freshwater CH_4 emissions, thus contributing to global warming.

Keywords: methane emission; lakes; water hyacinth; climate change; greenhouse gases

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1. Introduction

Despite the fact that lake ecosystems cover approximately 3.7% of the Earth's continental land area [1,2], they are believed to be a major source of the greenhouse gas (GHG) methane (CH_4) [3,4]. The greenhouse effect of CH_4 is approximately 28-fold higher than that of CO_2 for the century-long time scale, accounting for approximately 20% of total global warming [3,5]. The CH_4 concentration in the atmosphere, which is mainly caused by human activity, has increased by 150% since pre-industrial times and continues to increase. This may further enhance global warming to a greater extent [5,6].

Top-down and bottom-up estimates for global CH_4 emissions are 576 and 727 Tg yr^{-1}, respectively, of which CH_4 emissions from freshwater wetlands (including lakes and rivers) account for 308 Tg yr^{-1} [5]. CH_4 emissions between and within lakes exhibit high spatiotemporal variability [7,8], and it is estimated that CH_4 emissions from lakes account for 8–48 Tg yr^{-1}, with approximately 50% of the flux being attributed to tropical/subtropical regions [3,9]. Although several studies have determined the CH_4 emissions from these lakes are largely the result of a warming climate, invasive alien plants, pollution and enclosure aquaculture [10–13], there are few studies on the contribution of human activity (e.g., introduction of alien plants) to CH_4 emissions from lakes. In addition, these studies suggest that current and future increases in CH_4 emissions will intensify climate change [12–14]; therefore, it is necessary to further explore CH_4 emissions from lakes.

The free-floating water hyacinth (*Eichhornia crassipes*) is one of the world's most invasive aquatic plants. It causes significant ecological and socio-economic effects [15]. As an ornamental plant originating from tropical South America, this invasive water hyacinth weed was introduced into China in the 1900s [16], and it has subsequently been extensively cultivated as animal feed since the 1950s. It is distributed widely in the aquatic ecosystems of the Yangtze River in China [16]. The water hyacinth commonly forms dense, interlocking mat-forming floating aquatic plants on the water surface. This results from a rapid reproductive rate, complex root structure and a doubling of its biomass within five days [10,15,17,18]. The water hyacinth mats prevent the transfer of oxygen from the air to the water's surface and block the light required for photosynthesis by phytoplankton and submersed vegetation [15,18]. The water hyacinths on the water surface can prevent light penetration into the water column below [18], which decreases the temperature (water and sediment) [19,20]. Finally, changes in these factors affect the spatiotemporal variability of CH_4 production and emissions from the lake and impact whole-lake emission estimates on an annual basis [3,7,10]. Therefore, it is important to study the influence of the invasive water hyacinth weed on CH_4 emissions in these lakes.

Hong Lake is the seventh largest shallow lake in China and the largest natural lake in Hubei Province, which is located within the middle reaches of the Yangtze River [21]. Because of the abundant natural resources in Hong Lake, rapid socio-economic development has caused the lake to undergo a variety of environmental changes over the past few decades, including a shrinking water area, deterioration of water quality and a decline in biodiversity [21–23]. Several studies have confirmed that CH_4 emissions from the invasive *Spartina altrniflora* weed have significantly increased compared with the CH_4 emissions from the native plant community [24–26]. Banik et al. [27] also reported that the invasive water hyacinth has clearly increased CH_4 emissions from the freshwater ecosystems in India, which were estimated to reach 1.2 Tg yr^{-1}. Conversely, Attermeyer et al. [10] reported that CH_4 emissions from invasive water hyacinth zones were reduced compared with those from open-water zones. This was caused by the oxidation of CH_4 catalysed by methanotrophic bacteria. Therefore, the influence of invasive aquatic plants on CH_4 emission rates in freshwater ecosystems requires further examination.

In the present study, we focused on the effects of the invasive water hyacinth on CH_4 emissions in a shallow lake in subtropical China. CH_4 emissions in the shallow lake were measured with floating chambers and a gas chromatography method. In addition, to reveal the scope of its influence, we analysed the relationship between ecological factors (water depth, temperature and dissolved oxygen from water) and CH_4 emissions.

2. Materials and Methods

2.1. Study area Description

The study was conducted at the Hong Lake Natural Reserve (113°12′–113°26′ N, 29°40′–29°58′ E) towards the middle reaches of the Yangtze River. Hong Lake has a surface area of 344 km^2 with an open-water area of 308 km^2, a littoral area of 36 km^2 and a mean water depth of 1.5 m [21,28]. Hong Lake was listed as an internationally important wetland in the Ramsar convention in 2008 and was entered into the China Wetland Ecosystem Research Network in 2014. The region is characterised by a north subtropical humid monsoon climate, with a mean annual temperature of 15.9 °C–16.6 °C. The minimum and maximum mean monthly temperatures were 3.8 °C in January and 28.9 °C in July and/or August, respectively. The annual average evaporation is 1000–1300 mm and the mean annual precipitation is 1174 mm, 74% of which occurs between April and October [21].

According to the change in water depth and the vegetation type from the littoral zone to the open water, four zones in the study region were selected to monitor CH_4 emission flux between April and October of 2021 (Figure 1). The first site (OPs) was the open water of the lake in which no vegetation grew. The second site (ECs) was an area invaded by an alien species of water hyacinth (*E. crassipes*), which covered 100% of the area. The third site (TNs) was covered by the floating plant *Trapa natans* (*T. natans*), with a total vegetation coverage of 95%. The fourth site (ZLs) consisted of the emergent aquatic plant *Zizania latifolia* (*Z. Latifolia*), with a total vegetation coverage of 90% and sparse areas containing *Nelumbo nucifera* and *T. natans*.

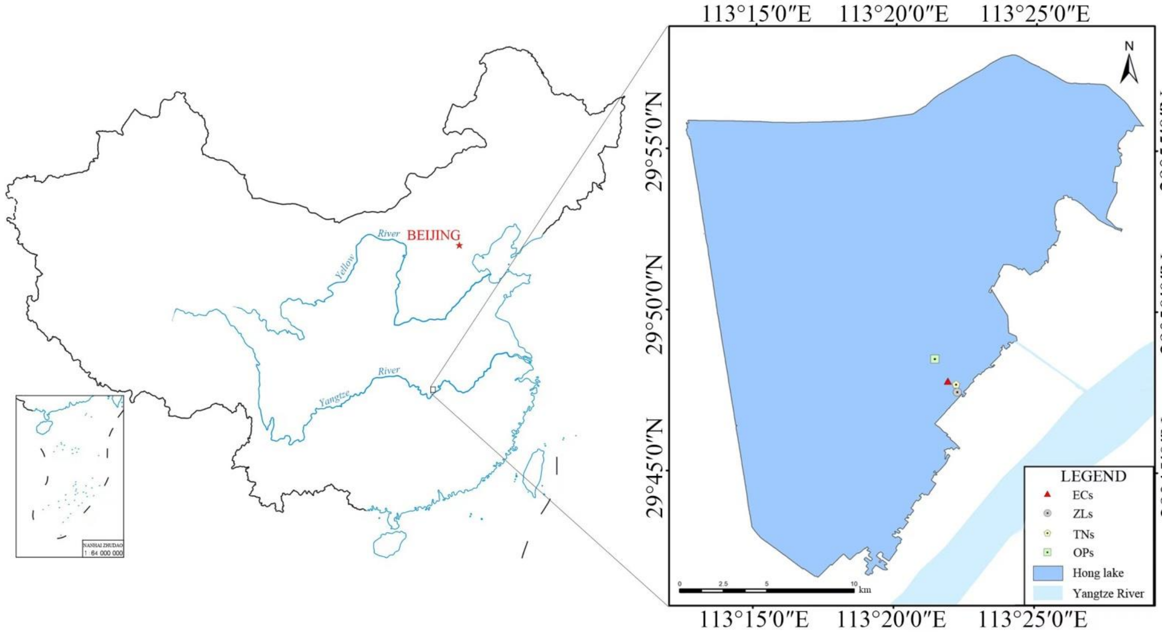


Figure 1. The study was conducted at Hong Lake in the middle reaches of the Yangtze River.

2.2. CH_4 Measurements

CH_4 flux measurements were taken at four sites in Hong Lake from April to December 2021. The measurements were carried out using floating chambers [29], which included three plastic opaque chambers (height above the water level 30 cm, volume 28.8 L) made of acrylic organic glass. The outside of the chamber contained a rubber plastic film to prevent an increase in the inner temperature of the chamber (Figure 2). In addition, the open-end of the chamber was fitted with a cystosepiment and tyre as floating equipment. The headspace of the chamber was equipped with a fan to mix the air and one sampling port and a temperature sensor. Before sampling, three chambers were placed upside down 50 to 100 cm apart on the water surface. Gas samples were drawn from each chamber every 5 min for 15 min with 60 mL polypropylene syringes equipped with three-way stopcocks and then transferred to a gas bag.

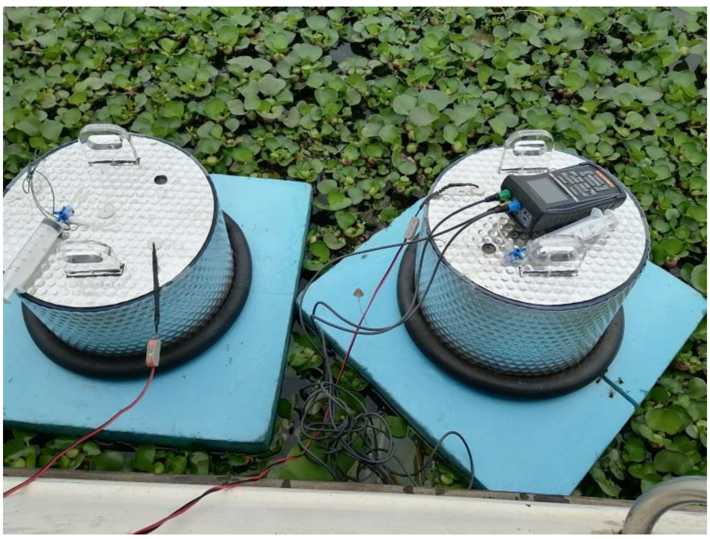


Figure 2. The measuring chambers at the invasive water hyacinth site (ECs) of Hong Lake.

Within one week, the CH_4 concentration of all samples was determined by a gas chromatography instrument (Agilent, 7890A, GC system, Agilent Co., Wilmington, DE, USA) equipped with a flame ionisation CH_4 detector from the Institute of Hydrobiology, Chinese Academy of Sciences. The fluxes were calculated using linear regression based on the concentration change as a function of time. 91% of all fluxes had a r-squared value of 0.70 or above (of which, 53% had a r-squared value of 0.9 or above). CH_4 flux at each site was calculated using the following equation:

$$F = \frac{d_c}{d_t} \times \frac{M}{V_0} \times \frac{T_0}{T} \times \frac{V}{A} \times 60 \quad (1)$$

F, flux at the time of chamber closure (mg m^{-2} h^{-1});
d_c/d_t, time derivative (slope) CH_4 concentration change over time (ppm min^{-1});
M, molecular mass of CH_4 (g mol^{-1});
V_0, ideal gas mole volume (0.0224 m^3 mol^{-1});
T_0, absolute temperature (273.15 K);
T, absolute temperature inside of chamber at sampling (K);
V, chamber volume (m^3) above the water surface;
A, chamber area (m^2).

2.3. Measurement of Environmental Factors

The water depth at each site was measured with a ruler and bamboo during sampling. The air temperature was measured using a digital thermometer (TM-902C, Factory of Lihuajin Instrument, Guangzhou, China). Conductivity, water temperature, pH and DO concentration at a water depth of 10 cm were measured using a portable multi-parameter water quality meter (Multi 3630 IDS, WTW Co., Munich, Germany).

At each site, the plants were sampled in September 2021 to measure biomass. Three 50 cm × 50 cm plots were randomly selected for these measurements. The plant samples were oven-dried at 70 °C for 48 h, and then weighed. In addition, three soil samples at each site were collected at a depth of 10 cm, and all soil samples were transferred to the laboratory, air-dried indoors and then dried at 70 °C for 48 h. The samples were milled and passed through a 0.125 mm sieve to determine the organic carbon concentration (SOC, g kg^{-1}) using the wet oxidation method with K_2CrO_7, and the soil pH was measured using the potentiometric method. In addition, total nitrogen (TN) concentration (g kg^{-1}) was measured using the Kjeldahl method with H_2SO_4 digestion. The total phosphorus (TP) concentration of the soil was determined by colorimetry by alkali fusion with NaOH.

2.4. Statistical Analysis

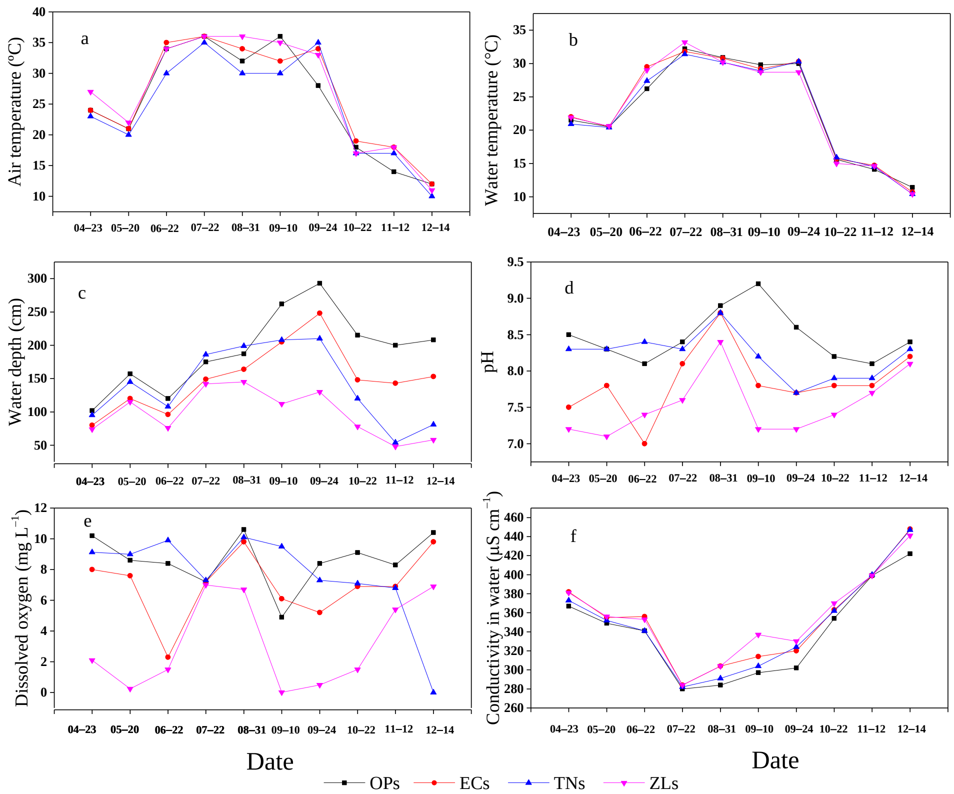
The significant differences in CH_4 fluxes at the four sites were analysed using SPSS software (18.0 version) based on Bonferroni's test as obtained by one-way analysis of variance. The relationship between CH_4 fluxes and environmental variables was determined using Pearson's rank correlation. $p < 0.05$ was considered statistically significant.

3. Results

3.1. Environmental Factors

The mean air temperature at the ECs, OPs and ZLs sites from April to December was not significantly different ($p > 0.05$), with mean values of 26.5 °C, 25.5 °C and 26.9 °C, respectively, whereas the mean air temperature at the ECs and ZLs sites was significantly higher ($p < 0.05$) than that of the TNs site (mean value of 24.7 °C, $p < 0.05$) (Figure 3a). The mean water temperature at the ECs, OPs and ZLs sites was not significantly different ($p > 0.05$), with mean values of 23.5 °C, 23.2 °C and 23.2 °C, respectively, but it was higher ($p < 0.05$) than that at the TNs site (23.0 °C) (Figure 3b). The mean water depth at the ECs, OPs, TNs and ZLs sites was 151, 192, 141 and 97.8 cm, respectively, and significant differences were observed ($p < 0.05$); however, there were no significant differences ($p > 0.05$) between the ECs and TNs sites (Figure 3c). The mean pH of the water at the ECs site

(7.9) was significantly lower ($p < 0.05$) than that at the OPs and TNs sites (8.5 and 8.2, respectively), and higher ($p < 0.05$) compared with that at the ZLs site (7.5) (Figure 3d). The mean DO at the ECs site (7.0 mg L^{-1}) was significantly lower ($p < 0.05$) than that at the Ops site (8.6 mg L^{-1}), but significantly higher ($p < 0.05$) than that of the ZLs site (3.2 mg·L^{-1}). There were no significant differences ($p > 0.05$) between the ECs and TNs sites (mean value of 7.6 mg L^{-1}) (Figure 3e). The mean conductivity of water at the ECs site (352.5 μS cm^{-1}) was significantly higher ($p < 0.05$) than that at the OPs (339.5 μS cm^{-1}) and TNs sites (347.6 μS cm^{-1}); however, there were no significant differences ($p > 0.05$) between the ECs and ZLs sites (355.5 μS cm^{-1}) (Figure 3f).



ECs, Invasive plant; OPs, Open water; TNs, Floating plant; ZLs, Emergent aquatic plant.

Figure 3. The spatial dynamics of environmental factors, including (**a**) air temperature, (**b**) water temperature, (**c**) water depth, (**d**) pH, (**e**) dissolved oxygen concentration and (**f**) water conductivity in the four community study zones.

The vegetation biomass at the ECs site was significantly higher ($p < 0.05$) than that at the Ops site, but lower than that at the ZLs site, and higher than that at the TNs site, whereas there were no significant differences among the ECs, TNs and ZLs sites ($p > 0.05$) (Table 1). The soil pH in the ZLs site was significantly lower than that of the Ops site ($p < 0.05$), and no significant differences were observed for the others ($p > 0.05$). The SOC and TP concentration in the top 10 cm of the soil at the ZLs were significantly higher than those at the OPs and ECs ($p < 0.05$); however, there were no significant differences between the ZLs and TNs sites ($p > 0.05$). Finally, the carbon-to-nitrogen ratio and the TP concentration were not significantly different between the sites ($p > 0.05$) (Table 1).

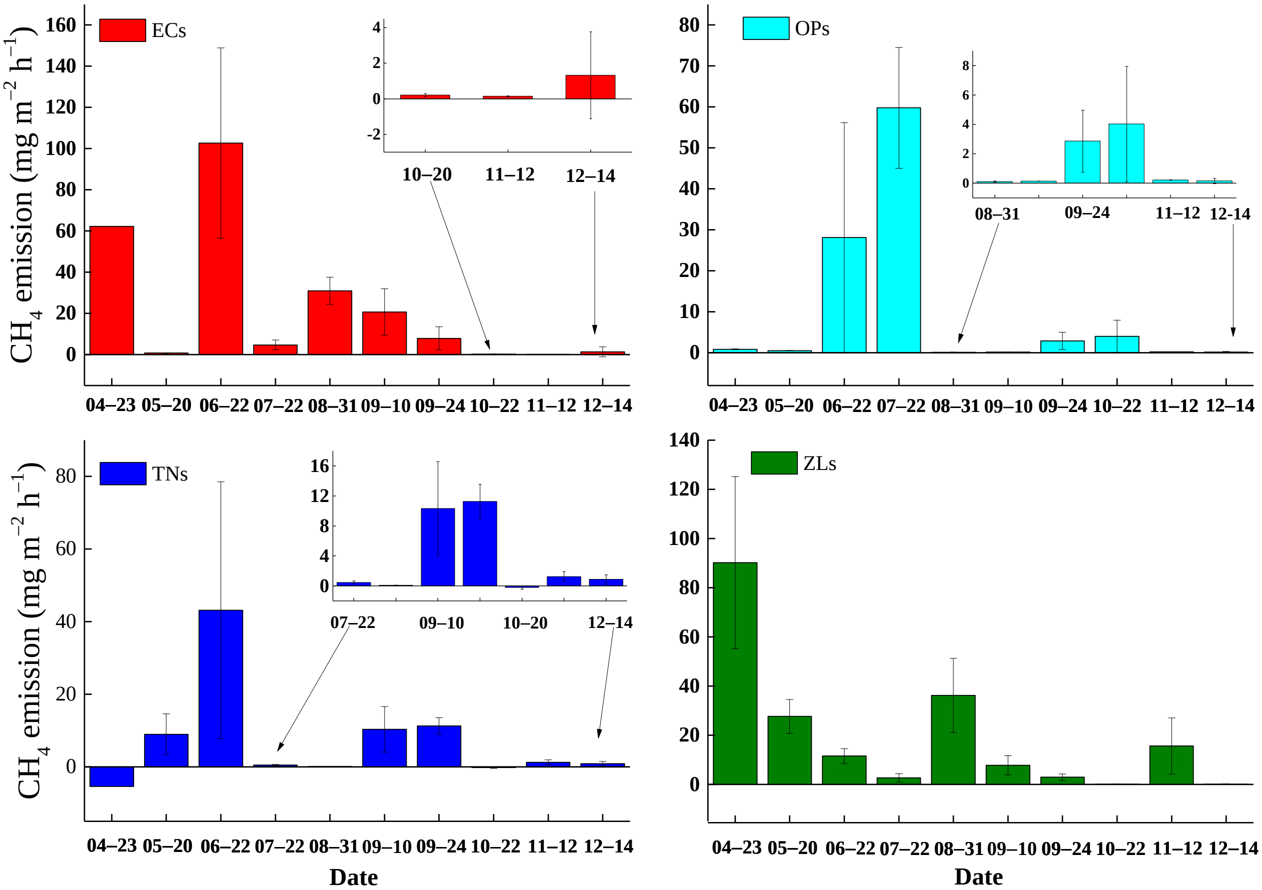
3.2. CH_4 Emission Fluxes

Temporal variations in CH_4 emission fluxes were recorded at the four sites, and the peak values occurred in the spring and/or summer, whereas the lowest values occurred in winter. The CH_4 emission fluxes at the ECs, OPs, TNs and ZLs sites ranged from 0.15 to 102.68, 0.12 to 59.75, −5.38 to 43.14 and 0.06 to 90.19 mg m^{-2} h^{-1}, respectively (Figure 4).

Table 1. The physicochemical characteristics at the four sites.

Sites	Vegetation		Soil				
	Types	Biomass (g m^{-2})	pH	SOC/g kg^{-1}	TN/g kg^{-1}	C:N Ratio	TP/g kg^{-1}
Open water (OPs)	—	No grown vegetations	8.12 ± 0.05 a	16.63 ± 1.54 a	1.33 ± 0.14 a	12.54 ± 0.21 a	0.64 ± 0.01 a
Invasive plant (ECs)	*E. crassipes*	270.02 ± 20.64 a	7.96 ± 0.04 ab	29.10 ± 1.71 a	2.42 ± 0.05 a	12.01 ± 0.65 a	0.63 ± 0.01 a
Floating plant (TNs)	*T. natans*	211.08 ± 17.63 a	7.57 ± 0.29 ab	46.47 ± 11.31 ab	3.44 ± 0.78 ab	13.37 ± 0.49 a	0.61 ± 0.01 a
Emergent aquatic plant (ZLs)	*Z. latifolia*, *N. nucifera*, *T. natans*	618.30 ± 187.50 a	7.03 ± 0.07 b	56.63 ± 2.84 b	4.49 ± 0.30 b	12.61 ± 0.17 a	0.67 ± 0.01 a

Note: different lowercase letters indicate a significant difference exists among the three sites. Significance level: 0.05.



ECs, Invasive plant; OPs, Open water; TNs, Floating plant; ZLs, Emergent aquatic plant.

Figure 4. Seasonal variations in CH_4 emission fluxes at the four sites.

Mean CH_4 emissions at the ECs, OPs, TNs and ZLs sites from April to December were 23.16, 9.68, 7.08 and 19.48 mg m^{-2} h^{-1}, respectively (Figure 5). The highest CH_4 emissions were observed at the ECs site. These differences indicate that the invasive plant, *E. crassipes*, exerts an enormous influence on CH_4 emissions at Hong Lake. A one-way analysis of variance showed that there was a significant difference in CH_4 emissions between the ECs and TNs sites ($P = 0.03$), slight differences between the ECs and OPs sites ($p < 0.1$) and no significant differences between the ECs and ZLs sites ($p > 0.10$).

3.3. Dependence of CH_4 Fluxes on Environmental Factors

CH_4 emission fluxes at all four sites were significantly positively correlated with air and water temperature (Figure 6a, $p < 0.01$), and significantly negatively correlated with water depth (Figure 6b, $p < 0.01$). The CH_4 emission fluxes had no significant correlation with the DO concentration in the water (Figure 7, $p > 0.05$).

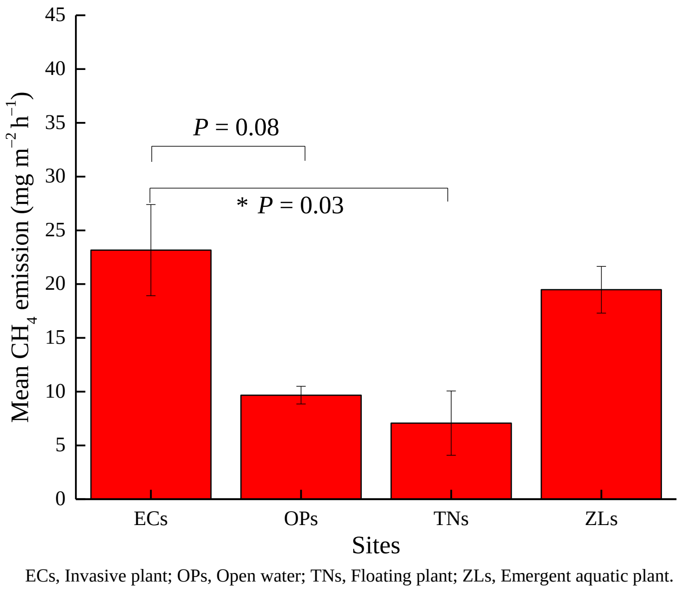


Figure 5. Mean CH_4 emission fluxes at the four sites (* indicated the significant levels at 0.05).

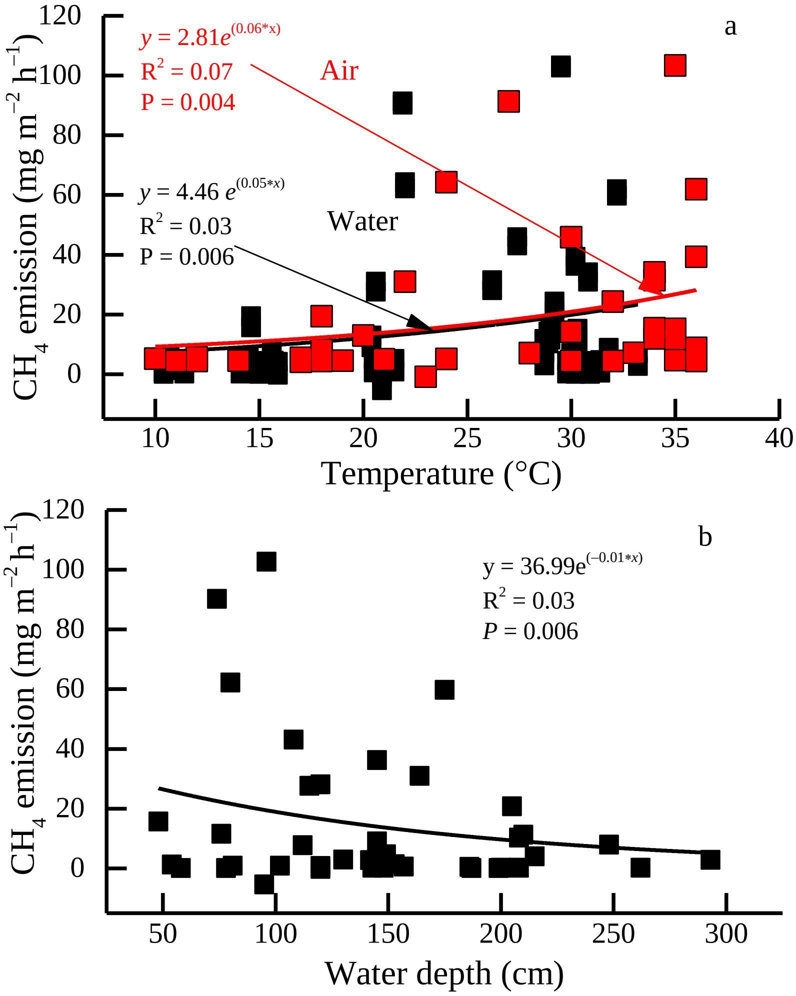


Figure 6. The correlation between CH_4 emissions, temperature (air and water) and water depth.

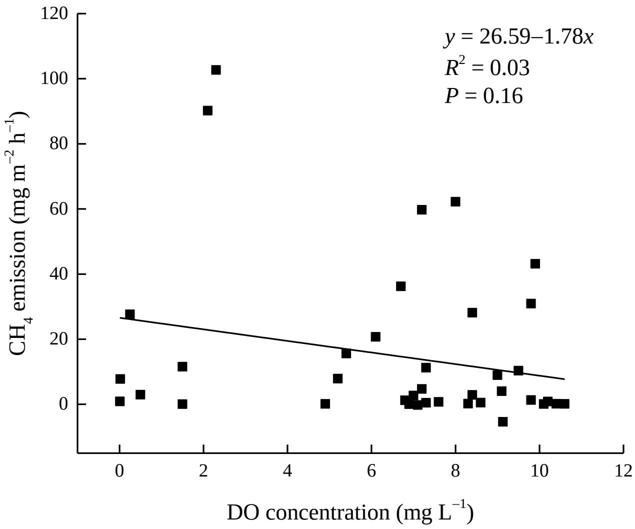


Figure 7. The correlation between CH_4 emissions and dissolved oxygen concentration.

4. Discussion

In this study, CH_4 emission fluxes at Hong Lake ranged from −5.38 to 102.68 mg m^{-2} h^{-1} (Figure 4). The results indicate that this shallow lake releases a large amount of CH_4 into the atmosphere, but the flux values matched the ranges recorded in other lakes in tropical and subtropical regions (ranging from −1.7 to 326 mg m^{-2} h^{-1}) [27,30]. Moreover, Gondwe and Masamba [31] reported that the maximum diffusive CH_4 emission rates in tropical wetlands varied between 0.24 and 293 mg m^{-2} h^{-1}, with a mean of 23.2 mg m^{-2} h^{-1}. The CH_4 flux at Hong Lake was one to two orders of magnitude higher than that at Dong Lake in the Yangtze River in China (ranging from 0.06 to 5.53 mg m^{-2} h^{-1}) [32], and higher than that at lakes in North America (ranging from 0.002 to 0.826 mg m^{-2} h^{-1}) [29,33] and a reservoir in the boreal region (ranging from 18 to 36 mg m^{-2} h^{-1}) [34]. A hydro-electric reservoir in French Guyana released CH_4 at flux intensities ranging from 8 to 35 mg m^{-2} h^{-1} [35].

Over the last five decades, Hong Lake has been extensively altered by flood regulation, irrigation, fish aquaculture and water supply demands [23]. This has resulted in a deterioration of water quality and caused the TP and TN to exceed their protective targets (TP $\leq$ 0.05 mg L^{-1} and TN $\leq$ 1.0 mg L^{-1}) [21]. According to a report in 2004, approximately 80% (250 km^2) of the lake has been used for large-scale aquaculture since the 1990s [36]. In 2017, the area used for aquaculture decreased to 40% of the lake area as a consequence of wetland protection and a restoration project at Hong Lake beginning in 2004 [21,23]. Based on our measurements, the TP at the lake was 0.088 mg L^{-1} in August and 0.239 mg L^{-1} in November 2021, which could have altered the CH_4 emissions of the lake [3]. Many studies have found that eutrophic lakes release more CH_4 emissions into the atmosphere [14,37,38]. Zhou et al. [37] reported that emission values ranged from 0.1 to 351.9 mg h^{-2} h^{-1} for shallow lakes in the Yangtze River Basin and were related to more enriched waters. Pickard et al. [12] also reported that severe pollution in urban lakes resulted in higher CH_4 emissions, including a large amount of untreated sewage input, with the highest flux recorded at 335 mg m^{-2} h^{-1}.

We consulted internal data from the Administration of the Hong Lake National Nature Reserve, beginning with the water hyacinth weed invasion in the 1990s. The coverage of the invading hyacinth increased from approximately 1300 ha in 2009 to 6000 ha in 2014, but decreased to 1200 ha in 2017 because of a project to remove water hyacinth from the lake. To date, it covers approximately 300 ha of the lake (Figure 8). The invasive water hyacinth weed exhibited high growth rates and a mean net CO_2 exchange (−3.4 to −5.4 g C-CO_2 m^{-2} d^{-1}, negative values indicate ecosystem CO_2 uptake) compared with open water (2.3 to 5.1 g C-CO_2 m^{-2} d^{-1}, positive values indicate ecosystem efflux) [39]. However, the extensive water hyacinth coverage of the lake surface resulted in the eutrophication of the lake [40]. Furthermore, the large water hyacinth mats prevented the transfer of oxygen from the atmosphere to the water and decreased oxygen production by other plants and algae [10,15]. This changes other ecological factors, such as the DO concentration in water and sediment temperature of the lake [19,20], which may be linked to CH_4 production and emissions from the lake [10]. In the present study, CH_4 emission fluxes at the ECs site were 139–227% higher on average than those at the OPs and TNs sites, and were approximately 20% higher than that at the ZLs site, although there was no significant difference between the ECs and ZLs sites (Figure 5). Our results are consistent with those of previous studies [27]. For the ECs site, higher CH_4 release rates during sampling may be explained by higher biomass. Wang et al. [30] found that the vegetation in the inundated area played an important role in CH_4 production and represented "hotspots" of CH_4 fluxes in water systems. Table 1 shows that the plant biomass in the ECs and the ZLs sites was higher than that in the OPs and TNs sites, and the former two sites had increased CH_4 release into the atmosphere. In general, numerous studies indicate that vegetation is a key factor of CH_4 release in wetlands and is attributed to primary production, which supplies organic matter to the sediment and induces the production of CH_4 by methanogenic bacteria [41,42]. For example, Furlanetto et al. [43] reported that higher CH_4 emissions in eutrophic lakes were attributed to higher organic matter concentration, resulting from higher primary production rates. Other studies indicated that CH_4 emissions were positively correlated with net primary production in two lakes [3,32]. Our results reveal that the invasive plants strongly enhance freshwater CH_4 emissions through an increase in plant productivity, thus contributing to global warming. Therefore, to reduce CH_4 emissions, we suggest the extensive removal of water hyacinth in lakes through wetland protection and restoration projects.

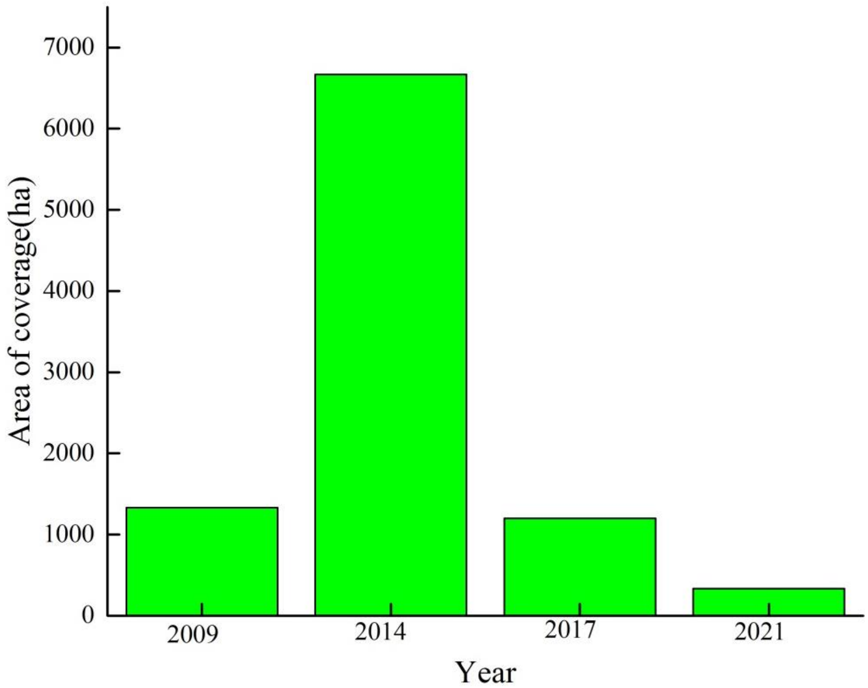


Figure 8. The area covered with water hyacinth in Hong Lake.

CH_4 is produced in sediment under anoxic conditions by methanogens and is released into the atmosphere through three pathways, including ebullition, diffusion and plant-mediated emissions [3,44,45]. Two studies showed that lower DO concentrations in water overlaying the sediment in the lake and marsh resulted in higher CH_4 production [46,47] and greater CH_4 emissions [10,48]. In the present study, the mean DO concentration at the four sites of the lake, from highest to lowest, was as follows: OPs > TNs > ECs > ZLs (Figure 3e). Thus, lower DO concentrations were observed in surface water with areas covered by macrophytes, which may have caused an increase in CH_4 emission fluxes at the ZLs and the ECs, compared with the TNs and Ops (Figures 4 and 5). The results indicate that CH_4 emissions had no significant correlation with DO concentration in the lake water, but the emissions decreased with increasing DO concentration in the lake water (Figure 7). For example, Bolpagni et al. [49] reported that the oxygen saturation in a stand of *T. natans* was lower than that in control areas that were devoid of plants, indicating vegetation could lead to a reduction in anoxic conditions and an increase in CH_4 emissions, although the aerenchyma in the plants may contribute to the transport of CH_4 from the water column into the atmosphere. In contrast, Attermeyer et al. [10] reported that the lower DO concentrations in the surface water of areas covered by *E. crassipes* led to a significantly lower flux of CH_4 emissions compared with that of open water, because the CH_4 in the surface water beneath the vegetation was oxidised by methanotrophic bacteria. Thus, the effect of DO concentrations in water on CH_4 emissions requires further study.

Air and water temperatures are important factors that limit the seasonal variation in CH_4 emissions [6,8,32,50]. It is well-established that methanogenesis in lake sediments increases exponentially with temperature because of the increased microbial activity at higher temperatures [10,51,52]. Figure 4 shows that the highest CH_4 emission fluxes occurred in June and July (Summer) at the three sites (ECs, OPs and TNs), whereas the lowest were seen in December (Winter). Figure 6a indicates that CH_4 emissions increase exponentially with air and water temperatures in Hong Lake (N = 40, $p < 0.01$), but R^2 was much lower. Although the highest CH_4 emissions occurred in April (Spring) for the ZLs site, the results suggest that other factors affect the CH_4 emissions at Hong Lake, such as water depth, plant growth and the availability of organic matter in sediments [6,45,53].

Water depth or the water table level in wetlands is usually a major factor affecting the spatial and temporal variation in the CH_4 emission flux [42,48,53]. We observed a negative correlation between CH_4 emission fluxes and water depth at all sites; however, R^2 was also much lower (Figure 6b). The results are consistent with the findings of several previous studies [8,53]. Because Hong Lake is a shallow lake with a mean water depth of 1.5 m [28], the variation in water depth in the lake from April to December ranged from 48 cm to 293 cm (Figure 3c). However, emergent plants, including *Z. latifolia* and *N. nucifera* plants, which were more dominant in the ZLs site compared with the other three sites, could extend their root systems into deeper and more anaerobic sediment and transport CH_4-rich gas into the atmosphere [53].

5. Conclusions

In this study, we determined how the invasive water hyacinth weed affects CH_4 emissions in subtropical Chinese lakes. The results indicate that CH_4 emissions in the zones invaded by water hyacinth were 20%–220% higher than those in the exotic-plant-free areas, because of the higher productivity of the invasive water hyacinth. The CH_4 emission fluxes at Hong Lake ranged from -5.38 mg m^{-2} h^{-1} (a sink of atmospheric CH_4) to 102.68 mg m^{-2} h^{-1} (a larger source of atmospheric CH_4). In addition, the results indicate that CH_4 emissions exhibited a weaker correlation with water temperature, water depth and dissolved oxygen concentration. Therefore, it is essential to further intensively study the CH_4 emissions of lakes in tropical and subtropical regions.

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References

1. Downing, J.A.; Prairie, Y.T.; Cole, J.J.; Duarte, C.M.; Tranvik, L.J.; Striegl, R.G.; McDowell, W.H.; Kortelainen, P.; Caraco, N.F.; Melack, J.M.; et al. The global abundance and size distribution of lakes, ponds, and impoundments. *Limnol. Oceanogr.* **2006**, *51*, 2388–2397. [CrossRef]
2. Verpoorter, C.; Kutser, T.; Seekell, D.A.; Tranvik, L.J. A global inventory of lakes based on high-resolution satellite imagery. *Geophys. Res. Lett.* **2014**, *41*, 6396–6402. [CrossRef]
3. Bastviken, D.; Cole, J.J.; Pace, M.L.; Tranvik, L.J. Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate. *Glob. Biogeochem. Cycl.* **2004**, *18*, 1–12. [CrossRef]
4. Bastviken, D.; Tranvik, L.J.; Downing, J.A.; Crill, P.M.; Enrich-Prast, A. Freshwater Methane Emissions Offset the Continental Carbon Sink. *Science* **2011**, *331*, 50. [CrossRef]
5. IPCC. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In *Climate Change 2021: The Physical Science Basis*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021; pp. 1–2391.
6. Aben, R.C.H.; Barros, N.; van Donk, E.; Frenken, T.; Hilt, S.; Kazanjian, G.; Lamers, L.P.M.; Peeters, E.T.H.M.; Roelofs, J.G.M.; Domis, L.N.D.S.; et al. Cross continental increase in methane ebullition under climate change. *Nat. Commun.* **2017**, *8*, 1682. [CrossRef] [PubMed]
7. Yang, H.; Xie, P.; Ni, L.; Flower, R.J. Underestimation of CH_4 Emission from Freshwater Lakes in China. *Environ. Sci. Technol.* **2011**, *45*, 4203–4204. [CrossRef] [PubMed]
8. Natchimuthu, S.; Sundgren, I.; Gålfalk, M.; Klemedtsson, L.; Crill, P.; Danielsson, Å.; Bastviken, D. Spatio-temporal variability of lake CH_4 fluxes and its influence on annual whole lake emission estimates. *Limnol. Oceanogr.* **2015**, *61*, S13–S26. [CrossRef]
9. Johnson, M.S.; Matthews, E.; Du, J.; Genovese, V.; Bastviken, D. Methane Emission from Global Lakes: New Spatiotemporal Data and Observation-Driven Modeling of Methane Dynamics Indicates Lower Emissions. *J. Geophys. Res. Biogeosci.* **2022**, *127*, e2022JG006793. [CrossRef] [PubMed]
10. Attermeyer, K.; Flury, S.; Jayakumar, R.; Fiener, P.; Steger, K.; Arya, V.; Wilken, F.; van Geldern, R.; Premke, K. Invasive floating macrophytes reduce greenhouse gas emissions from a small tropical lake. *Sci. Rep.* **2016**, *6*, 20424. [CrossRef] [PubMed]
11. Marotta, H.; Pinho, L.; Gudasz, C.; Bastviken, D.; Tranvik, L.J.; Prast, A.E. Greenhouse gas production in low-latitude lake sediments responds strongly to warming. *Nat. Clim. Change* **2014**, *4*, 467–470. [CrossRef]
12. Pickard, A.; White, S.; Bhattacharyya, S.; Carvalho, L.; Dobel, A.; Drewer, J.; Jamwal, P.; Helfter, C. Greenhouse gas budgets of severely polluted urban lakes in India. *Sci. Total Environ.* **2021**, *798*, 149019. [CrossRef] [PubMed]
13. Pu, Y.; Zhang, M.; Jia, L.; Zhang, Z.; Xiao, W.; Liu, S.; Zhao, J.; Xie, Y.; Lee, X. Methane emission of a lake aquaculture farm and its response to ecological restoration. *Agric. Ecosyst. Environ.* **2022**, *330*, 107883. [CrossRef]
14. Palma-Silva, C.; Marinho, C.C.; Albertoni, E.F.; Giacomini, I.B.; Barros, M.P.F.; Furlanetto, L.M.; Trindade, C.R.T.; Esteves, F.D.A. Methane emissions in two small shallow neotropical lakes: The role of temperature and trophic level. *Atmos. Environ.* **2013**, *81*, 373–379. [CrossRef]
15. Villamagna, A.M.; Murphy, B.R. Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): A review. *Freshw. Biol.* **2010**, *55*, 282–298. [CrossRef]
16. Ding, J.; Ren, W.; Fu, W.; Zhang, G. Water hyacinth in China: Its Distribution, Problems and Control Status. In *Biological and Integrated Control of Water Hyacinth, Eichhornia Crassipes*; Julien, M.H., Hill, M.P., Center, T.D., Jianqing, D., Eds.; Australian Centre for International Agricultural Research: Canberra, ACT, Australia, 2001; pp. 29–32.
17. Owens, C.S.; Madsen, J.D. Low temperature limits of water hyacinth. *J. Aquat. Plant Manag.* **1995**, *33*, 63–68.
18. Hu, W.; Salomonsen, J.; Xu, F.-L.; Pu, P. A model for the effects of water hyacinths on water quality in an experiment of physico-biological engineering in Lake Taihu, China. *Ecol. Model* **1998**, *107*, 171–188. [CrossRef]
19. Rai, D.N.; Munshi, J.D. The influence of thick floating vegetation (Water hyacinth: *Eichhornia crassipes*) on the physic-chemical environment of a fresh water wetland. *Hydrobiologia* **1979**, *62*, 65–69. [CrossRef]
20. Wilson, J.R.; Holst, N.; Rees, M. Determinants and patterns of population growth in water hyacinth. *Aquat. Bot.* **2005**, *81*, 51–67. [CrossRef]
21. Zhang, T.; Ban, X.; Wang, X.; Cai, X.; Li, E.; Wang, Z.; Yang, C.; Lu, X. Analysis of nutrient transport and ecological response in Honghu Lake, China by using a mathematical model. *Sci. Total Environ.* **2017**, *575*, 418–428. [CrossRef] [PubMed]
22. Zhou, W.C.; Shi, Y.H.; Pan, L. Current status and controlling strategies of water pollution in Honghu Lake wetland in Jianghan plain of Middle Reaches of Yangtze River. *Wetl. Sci. Manag.* **2019**, *15*, 31–34. (In Chinese)
23. Han, M.; Dsouza, M.; Zhou, C.; Li, H.; Zhang, J.; Chen, C.; Yao, Q.; Zhong, C.; Zhou, H.; A Gilbert, J.; et al. Agricultural Risk Factors Influence Microbial Ecology in Honghu Lake. *Genom. Proteom. Bioinform.* **2019**, *17*, 76–90. [CrossRef] [PubMed]

24. Tong, C.; Morris, J.T.; Huang, J.; Xu, H.; Wan, S. Changes in pore-water chemistry and methane emission following the invasion of *Spartina alterniflora* into an oliogohaline marsh. *Limnol. Oceanogr.* **2017**, *63*, 384–396. [CrossRef]
25. Yin, S.; An, S.; Deng, Q.; Zhang, J.; Ji, H.; Cheng, X. *Spartina alterniflora* invasions impact CH_4 and N_2O fluxes from a salt marsh in eastern China. *Ecol. Eng.* **2015**, *81*, 192–199. [CrossRef]
26. Zhang, Y.; Ding, W.; Cai, Z.; Valerie, P.; Han, F. Response of methane emission to invasion of *spartina alterniflora* and exogenous n deposition in the coastal salt marsh. *Atmos. Environ.* **2010**, *44*, 4588–4594. [CrossRef]
27. Banik, A.; Sen, M.; Sen, S.P. Methane emissions from water hyacinth-infested freshwater ecosystems. *Chemosphere* **1993**, *27*, 1539–1552. [CrossRef]
28. Wang, Z.; Du, Y.; Yang, C.; Liu, X.; Zhang, J.; Li, E.; Zhang, Q.; Wang, X. Occurrence and ecological hazard assessment of selected antibiotics in the surface waters in and around Lake Honghu, China. *Sci. Total Environ.* **2017**, *609*, 1423–1432. [CrossRef] [PubMed]
29. Bellido, J.L.; Tulonen, T.; Kankaala, P.; Ojala, A. CO_2 and CH_4 fluxes during spring and autumn mixing periods in a boreal lake (Pääjärvi, southern Finland). *J. Geophy. Res.* **2009**, *114*, G04007.
30. Wang, H.; Lu, J.; Wang, W.; Yang, L.; Yin, C. Methane fluxes from the littoral zone of hypereutrophic Taihu Lake, China. *J. Geophys. Res. Earth Surf.* **2006**, *111*, D17. [CrossRef]
31. Gondwe, M.J.; Masamba, W.R.L. Spatial and temporal dynamics of diffusive methane emissions in the Okavango Delta, northern Botswana, Africa. *Wetl. Eco. Manag.* **2014**, *22*, 63–78. [CrossRef]
32. Xing, Y.; Xie, P.; Yang, H.; Ni, L.; Wang, Y.; Rong, K. Methane and carbon dioxide fluxes from a shallow hypereutrophic subtropical Lake in China. *Atmos. Environ.* **2005**, *39*, 5532–5540. [CrossRef]
33. Fernandez, J.M.; Townsend-Small, A.; Zastepa, A.; Watson, S.B.; Brandes, J.A. Methane and nitrous oxide measured throughout Lake Erie over all seasons indicate highest emissions from the eutrophic Western Basin. *J. Great Lakes Res.* **2020**, *46*, 1604–1614. [CrossRef]
34. Eugster, W.; DelSontro, T.; Sobek, S. Eddy covariance flux measurements confirm extreme CH_4 emission from a Swiss hydropower reservoir and resolve their short-term variability. *Biogeosciences* **2011**, *8*, 2815–2831. [CrossRef]
35. Abril, G.; Guérin, F.; Richard, S.; Delmas, R.; Galy-Lacaux, C.; Gosse, P.; Tremblay, A.; Varfalvy, L.; Dos Santos, M.A.; Matvienko, B. Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). *Glob. Biogeochem. Cycl.* **2005**, *19*, GB4007. [CrossRef]
36. Lu, S.; Wang, S.H.; Yuan, W.B.; Wen, Y.L. Lake environment evolution of Honghu and consideration on development of wetland ecological industry. *Ecol. Econ.* **2009**, *218*, 157–159. (In Chinese)
37. Zhou, Y.; Song, K.; Han, R.; Riya, S.; Xu, X.; Yeerken, S.; Geng, S.; Ma, Y.; Terada, A. Nonlinear response of methane release to increased trophic state levels coupled with microbial processes in shallow lakes. *Environ. Pollut.* **2020**, *265*, 114919. [CrossRef] [PubMed]
38. Sun, H.; Yu, R.; Liu, X.; Cao, Z.; Li, X.; Zhang, Z.; Wang, J.; Zhuang, S.; Ge, Z.; Zhang, L.; et al. Drivers of spatial and seasonal variations of CO_2 and CH_4 fluxes at the sediment water interface in a shallow eutrophic lake. *Water Res.* **2022**, *222*, 118916. (In Chinese) [CrossRef] [PubMed]
39. Peixoto, R.B.; Marotta, H.; Bastviken, D.; Enrich-Prast, A. Floating Aquatic Macrophytes Can Substantially Offset Open Water CO_2 Emissions from Tropical Floodplain Lake Ecosystems. *Ecosystems* **2016**, *19*, 724–736. [CrossRef]
40. Mwamburi, J. Spatial variations in sedimentary organic matter in surficial lake sediments of Nyanza Gulf (Lake Victoria, Kenya) after invasion of water hyacinth. *Lakes Reserv. Sci. Policy Manag. Sustain. Use* **2016**, *21*, 94–113. [CrossRef]
41. Whiting, G.J.; Chanton, J.P. Primary production control of methane emission from wetlands. *Nature* **1993**, *364*, 794–795. [CrossRef]
42. Juutinen, S.; Alm, J.; Larmola, T.; Huttunen, J.T.; Morero, M.; Martikainen, P.J.; Silvola, J. Major implication of the littoral zone for methane release from boreal lakes. *Global Biogeochem. Cycl.* **2003**, *28*, 1–11. [CrossRef]
43. Furlanetto, L.M.; Marinho, C.C.; Palma-Silva, C.; Albertoni, E.F.; Figueiredo-Barros, M.P.; de Assis Estevesb, F. Methane levels in shallow subtropical lake sediments: Dependence on the trophic status of the lake and allochthonous input. *Limnologica* **2012**, *42*, 151–155. [CrossRef]
44. Capone, D.G.; Kiene, R.P. Comparison of microbial dynamics in marine and freshwater sediments: Contrasts in anaerobic carbon catabolism. *Limnol. Oceanogr.* **1998**, *33*, 725–749. [CrossRef]
45. Ding, W.; Cai, Z.; Tsuruta, H.; Li, X. Key factors affecting spatial variation of methane emissions from freshwater marshes. *Chemosphere* **2003**, *51*, 167–173. [CrossRef]
46. Flury, S.; McGinnis, D.F.; Gessner, M.O. Methane emissions from a freshwater marsh in response to experimentally simulated global warming and nitrogen enrichment. *J. Geophys. Res. Earth Surf.* **2010**, *115*, G1. [CrossRef]
47. Maruya, Y.; Nakayama, K.; Sasaki, M.; Komai, K. Effect of dissolved oxygen on methane production from bottom sediment in a eutrophic stratified lake. *J. Environ. Sci.* **2023**, *125*, 61–72. [CrossRef] [PubMed]
48. Zhou, W.; Cui, L.; Wang, Y.; Li, W. Methane emissions from natural and drained peatlands in the Zoigê, eastern Qinghai-Tibet Plateau. *J. Forestry Res.* **2017**, *28*, 539–547. [CrossRef]
49. Bolpagni, R.; Pierobon, E.; Longhi, D.; Nizzoli, D.; Bartoli, M.; Tomasellli, M.; Viaroli, P. Diurnal exchanges of CO_2 and CH_4 across the water–atmosphere interface in a water chestnut meadow (*Trapa natans* L.). *Aquat. Bot.* **2007**, *87*, 43–48. [CrossRef]
50. Xiao, Q.; Zhang, M.; Hu, Z.; Gao, Y.; Hu, C.; Liu, C.; Liu, S.; Zhang, Z.; Zhao, J.; Xiao, W.; et al. Spatial variations of methane emission in a large shallow eutrophic lake in subtropical climate. *J. Geophys. Res. Biogeosci.* **2017**, *122*, 1597–1614. [CrossRef]

51. Zeikus, J.G.; Winfrey, M.R. Temperature limitation of methanogenesis in aquatic sediments. *Appl. Environ. Microb.* **1976**, *31*, 99–107. [CrossRef] [PubMed]
52. Duc, N.T.; Crill, P.; Bastviken, D. Implications of temperature and sediment characteristics on methane formation and oxidation in lake sediments. *Biogeochemistry* **2010**, *100*, 185–196. [CrossRef]
53. Hirota, M.; Tang, Y.; Hu, Q.; Hirata, S.; Kato, T.; Mo, W.; Cao, G.; Mariko, S. Methane emissions from different vegetation zones in a Qinghai-Tibetan Plateau wetland. *Soil Biol. Biochem.* **2004**, *36*, 737–748. [CrossRef]