

Greenhouse gas (CO₂, CH₄) exchange between the atmosphere and freshwater bodies in the south of Vietnam

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Abstract: *The role of lakes/reservoirs in the global carbon cycle remains controversial due to the coexistence of methanogens and methanotrophs in this ecosystem type. The study aims to compare greenhouse gas (CH₄ and CO₂) emissions between three reservoirs (Trị An, Dầu Tiếng, and Buôn Tua Srah) and two natural lakes (Lắk and Bàu Trắng), associated with the influence of water physicochemical properties on the emission quantities. Field data were collected in October 2020 and April 2021, coinciding with the wet and dry seasons, respectively. An autoanalyzer ultraportable gas analyzer was used to measure the rates of greenhouse gas fluxes exchanged between the water bodies and the atmosphere in a transparent floating chamber at one Hz frequency within five to eleven hours, depending on the weather condition. Water quality parameters, including pH, temperature, conductivity, turbidity, ORP, and DO were measured hourly. The results indicated that CO₂ dominated the total carbon emission quantities in the lakes and reservoirs. The CH₄ and CO₂ amounts released hourly were higher in the natural lakes relative to the reservoirs and remarkably lower during the dry season compared to the wet season. Trị An reservoir functioned as a carbon sink in both seasons, with significantly higher influxes in the wet season. The CO₂:CH₄ ratios ranged drastically between the water bodies, and the low values of these ratios suggested a higher contribution of CH₄ to the total carbon emissions in the natural lakes. The DO and ORP values were low, implying contamination in these water bodies. Oxygen competition probably resulted in the decreased population size of photosynthetic organisms, which in turn, could lead to a reduced rate of hourly carbon emission during the dry season. These findings may affirm the contribution of microalgae and other photosynthetic microorganisms to the role of carbon sink/source of a freshwater body.*

Keywords: carbon emission; greenhouse gases; carbon sink; carbon source

1. Introduction

Natural lakes and reservoirs, as substantial components of biogeochemical cycles, are considered crucial regulators in carbon emission and absorption processes at global, national, and regional scales (Barros et al. 2011; Kumar et al. 2019; Wen et al. 2017). Despite only comprising a slight fraction of the Earth's surface (~3.7%), the global inland waters emit a large amount of CO₂ and CH₄ (estimated at ~2,100 and ~130 Tg.C.yr⁻¹, respectively) into the atmosphere, notably contributing to the global carbon budget (Raymond et al. 2013; Kumar et al. 2022; Sun et al. 2021; Tranvik et al. 2009). Carbon emissions from these ecosystems primarily result from both aerobic and anaerobic degradations of organic matter, driven by diverse and complex microbial communities (Kumar et al. 2019). Anoxic sediments due to continuous inundation of water bodies, combined with abundant organic matter sources, are favorable for methanogens' activities, enhancing CH₄ production (Tranvik et al. 2009; Barros et al. 2011). The majority of CH₄ generated

in hypolimnetic sediments is oxidized to CO₂ by methanotrophs, whereas CH₄ generation in epilimnetic sediments is mainly responsible for CH₄ emission from water bodies (Tranvik et al. 2009). On the other hand, inland waters are regarded as important carbon sinks thanks to their carbon sequestration ability via primary production in aqueous environments and organic carbon sedimentation (Phyoe and Wang 2019; Alikhani and Karbin 2019). The estimated global organic carbon burials in natural lake and reservoir sediments were ~30–70 and ~160–200 Tg.C.yr⁻¹, respectively (Phyoe and Wang 2019). The carbon release and storage processes occur in parallel within lentic ecosystems, but the amounts vary remarkably within and between water bodies, depending on various factors, e.g., depth, surface area, age, trophic state, water physicochemical properties, benthic zone conditions, sediment composition and yield, and oxygen exposure duration (Wen et al. 2017; Phyoe and F Wang 2019; Borges et al. 2022; Barros et al. 2011; Heyang Sun et al. 2021; Amit Kumar et al. 2019, 2022). In other words, the flux rates and magnitudes are highly powered by the inland water characteristics and environmental conditions. Indeed, many studies indicated that analyses based on algorithms extrapolating the emissions for surveyed water bodies might lead to either over- or under-estimations owing to the discrepancies across various regional scales (Li Siyue et al. 2018; Phyoe and Wang 2019; Jia et al. 2022; Wen 2017; DelSontro 2018). Therefore, in the context of dramatic increases in anthropogenic activities and climate change, the role of lakes and reservoirs as carbon sinks or sources remains at the center of debate (Phyoe and Wang 2019; Jia et al. 2022). Consequently, to identify specific methods for regulating the carbon sink and source mechanisms of water bodies, it is essential to examine exchanged carbon fluxes in relation to environmental factors at regional and local scales.

Vietnam is one of the countries most vulnerable to climate change, but greenhouse gas assessments have only received attention in recent years, with studies that mostly focused on agricultural emissions (Espagne et al. 2021). In spite of the large potential contribution to the national carbon budget from a vast network of reservoirs and lakes (World Bank Group 2018), no research on the exchanged carbon quantities in these ecosystems has been documented in Vietnam. Meanwhile, the rapid development and land-use changes, particularly the rise in reservoir construction for hydropower and irrigation (World Bank Group 2018), could alter the carbon balance. Further, differences in structures of artificial water bodies (dependent on use purposes) and geographic features result in the distinct characteristics of lakes and reservoirs in Vietnam. Thus, regional data scarcity would induce uncertain evaluations, making it difficult to propose suitable solutions for emission reductions.

This study, for the first time, determines and compares CO₂ and CH₄ emission fluxes between lakes and reservoirs in southern Vietnam, coupled with water physicochemical properties influencing the emissions. The study was expected to not only clarify the roles of investigated water bodies as well as driving factors for their sink or source capacity, but also help improve understandings of CO₂ and CH₄ emission dynamics in lentic ecosystems. Additionally, the findings would provide a scientific basis for developing appropriate and efficient management strategies to minimize GHG emissions from freshwater bodies, contributing to global climate change mitigation efforts aligned with Vietnam's net-zero commitment.

2. Study area

The investigations conducted in this case study are highly representative in term of bioclimatic features in the geographic region, between 11°02' - 12°26' N and 106°10' - 108°26' E, extending from the coastal to mountainous landscapes where exist many reservoirs of different size, varying from dozens thousand to dozens hectares as illustrated in Figure 1. The study area relies on three climate zones according to Köppen-Geiger climate classification (Beck et al. 2018) where a large part of the forest is dense and rich in broad-leaved evergreens and semievergreens, subtropical species are restricted in elevation above 1000m (Thai 1993). These are the natural and man-made water reservoir for irrigation or power generation purposes. On a national scale, Lák is the second-largest natural lake, while Trĩ An ranks as the largest man-made reservoir in terms of both water volume and surface area. All main characteristics of five study areas are listed in table 1.

Tab. 1. Main characteristics of the studied water bodies and drainage basins.

Study site	Water reservoir			Drainage basin			In-reservoir activity
	Surface area (km ²)	Mean water depth (m)	Origin/ Start in operation/ purpose	Topography Landscape and landcover	Hydrologic system	Mean annual precipitation And temperature (max-min)	
Dầu Tiếng	270	10	Constructed, operating since 1985 Irrigation	25-30m, Ancient terrace, old alluvium Mix annual plants and semi evergreen forest	Exoheic	1800 – 2200 mm, 20.5-36°C (Aw)*	floating fish farms, sand mining
Trị An	323	20	Constructed, operating since 1984 Hydropower	50-170m, Mountain - highland (basalt and metamorphic rocks), Mix perennial plantations and broad-leaved evergreen forest	Exoheic	1.700 - 2.500mm, 15-36°C (Am)*	floating fish farms
Buôn Tua Srah	37	35	Constructed, operating since 2011 Hydropower	500-1800m mountain-highland (basalt and metamorphic rocks), Mix evergreen forest and annual plantations	Exoheic	1800-1.900 mm 17.6-33.6 °C (Aw)*	floating fish farms
Lắk	6.2	1.5	Natural Recreation/ tourism	430-1400m Mountain (metamorphic rock) –alluvial floodplain Mix annual plantations evergreen forest	Exoheic	1.900 - 2.100mm 17.6-33.6 °C (Aw)*	Tourism, fishing catch
Bàu Trắng	0,7	15	Natural Recreation/ tourism	60-80m Coastal sand dunes, patchy shrubs	Endoheic	1.070 mm 12.4-32.6 °C (Aw)*	Tourism, fishing catch

*Climate zones: Am - tropical, monsoon; Aw - tropical savannah; Cwb - temperate, dry winter, warm summer, (Beck et al. 2018).

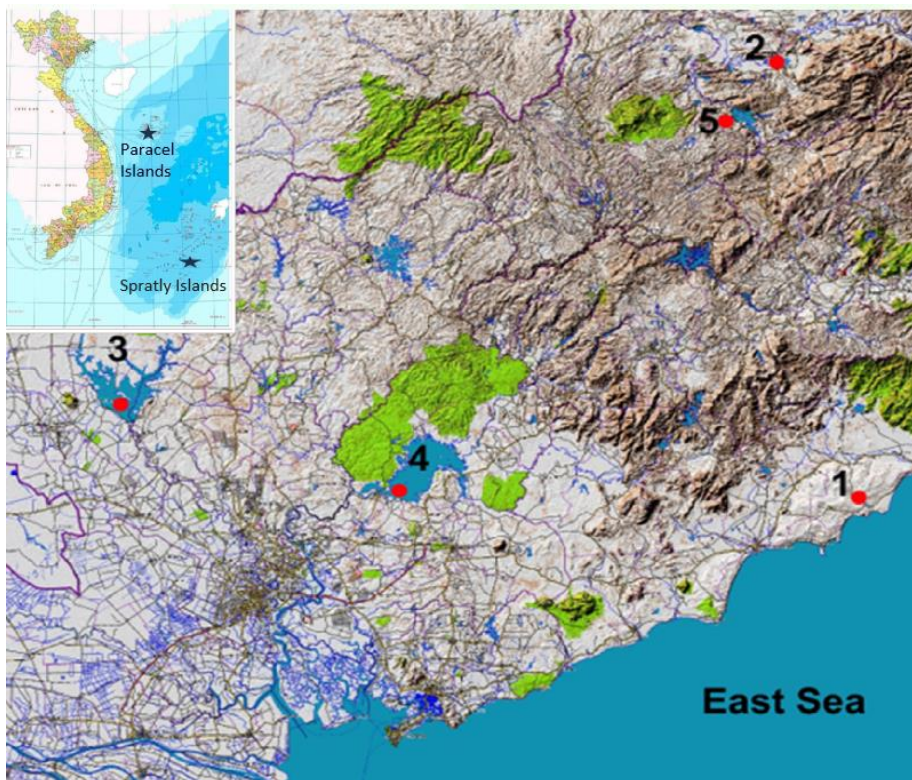


Fig. 1. Study sites marked by red points and numbers. 1 – Bàu Trắng lake; 2 – Lắc; 3 – Dầu Tiếng reservoir; 4 – Trị An reservoir; 5 – Buôn Tua Srah reservoir

3. Methodology

The size of water bodies and hydrological conditions influence gas diffusion from organic matter stored both at the bottom and within the water column. Therefore, our investigation employed a strategy of measuring gas fluxes alongside biochemical sampling throughout the water column. Additionally, climate variations played a significant role in these processes. Three to seven sampling points were deployed in each lake, depending on the shape and size of the lake. Samplings and collection of greenhouse gas flux rates were conducted in October 2020 and April 2021, corresponding to the wet and dry seasons (Table 2).

Tab. 2. Locations and weather conditions on sampling days at each surveyed water body.

Site	Location	Weather	
		Wet season	Dry season
Dầu Tiếng	11°26'48"N-106°22'17"E	Sunny and windy	Sunny
Trị An	11°06'18"N-107°02'57"E	Sunny	Sunny, light and short rain
Lắc	12°25'30"N-108°11'15"E	Heavy rain	Sunny
Buôn Tua Srah	12°15'26"N-108°04'40"E	Windy	Sunny
Bàu Trắng	11°03'49"N-108°25'28"E	Sunny and windy	Sunny

Measurement Equipment and Data Collection Process

Greenhouse gas fluxes from water surfaces were measured using an Ultraportable Greenhouse Gas Analyzer (UGGA-LGR) connected to floating static chambers. The diel cycle of CO₂ and CH₄ flux was estimated by calculating the linear gas accumulation rate in the chambers. Simultaneously, water physicochemical parameters (pH, temperature, conductivity, turbidity, oxidation-reduction potential (ORP), and dissolved oxygen) were monitored using a 90-FLT water quality logger. The analyzer provided accurate CO₂ and CH₄ concentrations, corrected for water vapor influence, with detection ranges of 1–20,000 ppm for CO₂ and 0.01–100 ppm for CH₄. Water vapor concentration is used to calculate the 'dry' concentrations

of CO₂ and CH₄ - the gas concentrations after removing the influence of water vapor, using the device's internal calculation formula.

The device is connected to an acrylic chamber (30 cm x 30 cm x 40 cm) attached to a buoy to float on the water's surface by two ports for the inlet and outlet of gas. Gas is pumped from the floating chamber to the measurement device for GHG concentration analysis and subsequently returned to the floating chamber. The cycle is repeated, resulting in a cumulative curve showing the temporal variations in concentrations. Measurements were conducted at 1 Hz continuously for five to eleven hours, depending on weather conditions. Data collected were displayed in real-time on a smartphone connected to the measurement device. The concentrations were converted to flux rate in accordance with the following formula.

$$F = \frac{V \times P}{R \times S \times (T_{air} + 273.15)} \times \left(\frac{Mt - Mo}{dt} \right)$$

Where F is the exchange rate; V is the floating chamber's volume; S is the chamber's area; P and T are the gas's pressure and temperature, respectively; Mt is the gas concentration at the end of the measurement (ppm); Mo is the gas concentration at the beginning of the measurement (ppm); dt is the duration of the measurement (minutes) and R is the ideal gas constant. The exchange rates were calculated for each hour and presented as g.m⁻².h⁻¹ before averaging for daytime and night.

Data Analysis

The exchange rates, presented as g.m⁻².h⁻¹, were averaged for daytime and night for further analysis. Data distributions were tested using the Shapiro-Wilk test. The discrepancy in flux rates and environmental characteristic variables between reservoirs and natural lakes, as well as between the seasons, were examined by one-way ANOVA. The relationships between the water's physicochemical parameters and emission rates were assessed using univariate correlation analyses. All statistical analyses and hypothesis testing were performed using Statgraphic software with a 95% confidence level.

4. Results

Physico-chemical properties of the surface water

The minimum, maximum, and average values of the surface water physico-chemical properties are presented in Table 3. The water temperatures were significantly higher in the dry season than in the wet season (p < 0.01) in all surveyed water bodies, leading to the decline of ORP in the dry season (p < 0.01). No significant difference in the water temperatures was recorded between daytime and night-time. However, the water temperatures tended to be remarkably higher in the reservoirs compared to the natural lakes (p < 0.01). The turbidity values showed no difference between the two seasons (p > 0.05). The highest turbidity was recorded at LẮk lake, followed by the values acquired at Dầu Tiếng reservoir (Table 3). These two turbidity values differed significantly from those found at Bàu Trắng, Buôn Tua Srah, and Trị An reservoirs (p < 0.05).

Tab. 3. The minimum, maximum, mean, and standard deviation values of the physicochemical properties in the surveyed water bodies in the wet and dry seasons. *: p < 0.05; **: p < 0.01; ns: non-significant.

		Season	min	max	average	sd
Temperature (°C)	Dầu Tiếng	wet	27.6	27.6	27.60	0.00
		* dry	29.0	30.4	29.80	0.61
	Trị An	wet	26.6	27.4	27.04	0.29
		** dry	29.3	30.0	29.60	0.29
	Tua Srah	wet	24.2	24.8	24.50	0.42
		** dry	27.3	29.5	28.16	0.84

	Lák	wet	23.7	24.8	24.26	0.37
		** dry	25.4	27.9	26.27	0.81
	Bàu Trắng	wet	26.7	27.1	26.84	0.14
		** dry	28.8	29.2	29.12	0.14
Turbidity (NTU)	Dầu Tiếng	wet	9.1	9.1	9.10	0.00
		* dry	17.3	23.8	21.38	2.94
	Trị An	wet	9.0	29.3	20.52	6.85
		** dry	3.5	6.5	4.98	0.97
	Tua Srah	wet	7.1	7.6	7.35	0.35
		** dry	2.3	5.4	3.79	0.98
	Lák	wet	19.2	30.5	22.73	3.97
		** dry	95.0	104.0	101.13	2.80
	Bàu Trắng	wet	0.2	3.8	3.27	1.08
		** dry	3.7	5.6	4.53	0.59
DO (mg.L⁻¹)	Dầu Tiếng	wet	0.95	9.83	5.92	3.68
		ns dry	5.03	7.79	6.96	1.29
	Trị An	wet	7.94	11.31	9.99	1.21
		** dry	6.37	7.40	6.82	0.36
	Tua Srah	wet	6.53	6.60	6.57	0.05
		ns dry	6.23	7.23	6.74	0.41
	Lák	wet	5.63	8.06	6.54	0.88
		ns dry	4.72	7.91	6.05	1.32
	Bàu Trắng	wet	3.69	5.62	4.77	0.76
		** dry	6.29	8.56	7.42	0.71
ORP (mV)	Dầu Tiếng	wet	-	-	-	-
		- dry	-62	166	67.86	51.52
	Trị An	wet	25	193	90.75	74.71
		ns dry	-62	69	27.63	41.26
	Tua Srah	wet	210	224	216.00	7.21
		** dry	92	146	113.75	17.72
	Lák	wet	151	199	180.57	20.74
		** dry	27	127	88.56	36.19
	Bàu Trắng	wet	146	193	171.88	18.91
		** dry	-43	60	-17.78	35.59
pH	Dầu Tiếng	wet	6.50	8.90	7.70	1.69
		ns dry	7.26	7.26	7.26	0.00
	Trị An	wet	9.12	9.68	9.38	0.24
		** dry	8.33	8.63	8.51	0.13
	Tua Srah	wet	7.33	7.40	7.37	0.05
* dry		7.85	8.81	8.20	0.35	

LẮk ns	wet	7.46	9.06	8.07	0.56
	dry	7.31	9.55	8.04	0.82
Bàu Trắng **	wet	7.44	7.77	7.64	0.11
	dry	8.78	9.18	8.93	0.11

Although the DO values were higher in the dry season, they were not significantly different from the wet season ($p > 0.05$). The higher DO values were recorded during the daytime, but the average showed no difference from the night-time ones ($p > 0.05$). The DO values significantly differed between the water bodies ($p < 0.01$), with the maximum and minimum acquired at Trị An reservoir and Dầu Tiếng reservoir, respectively. In general, the mean values of DO from the reservoirs were higher than the natural lakes, but the difference was not statistically different ($p > 0.05$). The ORP values significantly changed between the seasons, with the drastically higher in the wet season ($p < 0.01$) and were analogous between day and night ($p > 0.05$). The ORP values were much higher in the reservoirs compared to the natural lakes ($p < 0.01$). The pH values were relatively stable at Dầu Tiếng reservoir and LẮk Lake, while there was a considerable difference between the seasons at Trị An, Bùn Tua Srah, and Bàu Trắng (Table 3).

Emission quantities of CO₂ and CH₄ from the water bodies

CH₄

The range of CH₄ and CO₂ fluxes and their average values are presented in Table 4. The methane emissions from all surveyed water bodies were consistently higher in the dry season. However, the significant seasonal difference was recorded only in the Dầu Tiếng reservoir and Bàu Trắng ($p < 0.01$). During the monitoring year, the surveyed reservoirs and natural lakes acted as CH₄ sources, with the mean rate fluctuating between 0.002 ± 0.01 mg CH₄.m⁻².h⁻¹ and 2.485 ± 2.005 mg CH₄.m⁻².h⁻¹ at Dầu Tiếng reservoir in the wet season and Bùn Tua Srah reservoir in the dry season, respectively. Nonetheless, a meager influx of CH₄ (-0.1119 ± 0.043 mg CH₄.m⁻².h⁻¹) was recorded at the Dầu Tiếng reservoir in the dry season (Table 4).

Tab. 4. The minimum, maximum, mean, and standard deviation values of the CH₄ and CO₂ flux rates in the surveyed water bodies in the wet and dry seasons. *: $p < 0.05$; **: $p < 0.01$; ns: non-significant.

		Season	min	max	average	sd
CH ₄ (mg.m ⁻² .h ⁻¹)	Dầu Tiếng **	wet	0.001	0.004	0.002	0.001
		dry	-0.153	-0.059	-0.119	0.043
	Trị An ns	wet	0.106	0.998	0.527	0.351
		dry	0.297	1.939	0.932	0.561
	Tua Srah ns	wet	0.356	2.389	1.394	0.843
		dry	0.937	6.463	2.485	2.005
	LẮk ns	wet	0.360	0.646	0.556	0.106
		dry	0.128	1.945	1.012	0.806
	Bàu Trắng **	wet	0.794	3.189	1.605	0.839
		dry	2.368	11.183	5.603	3.104
CO ₂ (mg.m ⁻² .h ⁻¹)	Dầu Tiếng ns	wet	-439	3371	1341.0	1306.0
		dry	-1792	2039	456.2	1391.4
	Trị An **	wet	-845	-342	-634.9	191.7
		dry	-318	11	-120.6	98.1
	Tua Srah ns	wet	483	2281	1118.5	635.4
		dry	-205	3072	285.3	1127.5

Lắk	wet	-174	313	16.0	183.6
	dry	-283	95	-130.3	159.1
Bàu Trắng	wet	371	1176	719.1	302.2
	dry	-347	-128	-215.1	76.2

The average values of CH₄ flux rate from the reservoirs were 0.525 ± 0.725 mg CH₄.m⁻².h⁻¹ and 1.213 ± 1.575 mg CH₄.m⁻².h⁻¹ in the wet and dry seasons, respectively. The CH₄ flux rates from the reservoirs were significantly lower compared to the natural lakes ($p < 0.01$). The mean flux rates of CH₄ at the natural lakes were 1.120 ± 0.808 mg CH₄.m⁻².h⁻¹ in the wet season and 3.307 ± 3.228 mg CH₄.m⁻².h⁻¹ in the dry season. The CH₄ flux rates varied remarkably between the three reservoirs ($p < 0.01$), with the minimum and maximum values of CH₄ acquired at the Dầu Tiếng and Buôn Tua Srah reservoirs, respectively (Table 4), and this tendency was consistent in both seasons. Of the natural lakes, the mean flux rates of CH₄ were compellingly higher at the Bàu Trắng relative to the Lắk lake ($p < 0.01$). Similar to the reservoirs, the difference in the CH₄ flux rates between the Bàu Trắng and the Lắk lake was tremendous in the dry season. Although the CH₄ emissions from all surveyed reservoirs and natural lakes tended to be higher during the daytime in both seasons, there was no significant difference in the CH₄ flux rates between day and night ($p > 0.05$). The contributions of CH₄ to the total carbon exchanged were meager and varied between 0.00065 and 16.7%. The CH₄: total C ratios were higher at the natural lakes. In the wet season, these ratios were *ca.* 4 times higher at the natural lakes compared to the reservoirs, but the difference strongly decreased in the dry season (Figure 4). The contributions of CH₄ to the total carbon exchange were remarkably higher in the dry season compared to the wet season in both types of surveyed water bodies, which might be related to the oxidization of CH₄ to CO₂.

CO₂

The emission quantities of CO₂ between the surveyed water bodies and the atmosphere were consistently lower in the dry season compared to the wet season (Table 4). However, the significant difference was recorded only at Trị An reservoir and Bàu Trắng ($p < 0.01$). Dầu Tiếng and Buôn Tua Srah reservoirs acted as CO₂ sources in both seasons, while Trị An reservoir was always a CO₂ sink (Table 4). On the contrary, the natural lakes seasonally shifted between the CO₂ sink and source. In the wet season, the Lắk lake and Bàu Trắng were the CO₂ emission sources with the mean flux rates of 16 ± 183.6 mg CO₂.m⁻².h⁻¹ and 719.1 ± 302.2 mg CO₂.m⁻².h⁻¹, respectively. These natural lakes turned into CO₂ sinks in the dry season with the mean flux rates of -130.3 ± 159.1 mg CO₂.m⁻².h⁻¹ at the Lắk lake and -215.1 ± 76.2 mg CO₂.m⁻².h⁻¹. The mean flux rate of CO₂ tended to be higher in the reservoirs (0.4112 ± 1.1225 mg CO₂.m⁻².h⁻¹) compared to the natural lakes (0.0788 ± 0.4325 mg CO₂.m⁻².h⁻¹). Nevertheless, the difference between the water body groups was insignificant ($p > 0.05$).

5. Discussion

Variation in CH₄ flux rates

The results of our study concurred with Soued et al. (2022) that the reservoirs are sources of CH₄ emissions in both seasons. The variation range of CH₄ flux rates was from 0.001 to 11.183 mg CH₄.m⁻².h⁻¹, in agreement with Beaulieu et al. (2020) and Kemenes et al. (2007). Nevertheless, the CH₄ flux rates from the reservoirs in the South of Vietnam were higher than those reported by Yang et al. (2023) in a temperate river-reservoir system in the North of China. The discrepancy could be attributed to the higher level of eutrophication in tropical reservoirs (Lewis 1996), which promotes the CH₄ formation (Schrier-Ujil et al. 2010). The higher rates of CH₄ emission in tropical inland freshwater bodies were also claimed by Sanches et al. (2019).

In the dry season, the Dầu Tiếng reservoir acted as a CH₄ sink with a meager influx (Table 4). The water level in Dầu Tiếng drastically reduced in the dry season, and the exposed bottom was occupied by agricultural activities, especially grazing. Enteric fermentation of cattle raised in the pasture probably amplified the atmospheric CH₄ concentration (Saunas et al. 2016), which subsequently allowed the diffusion

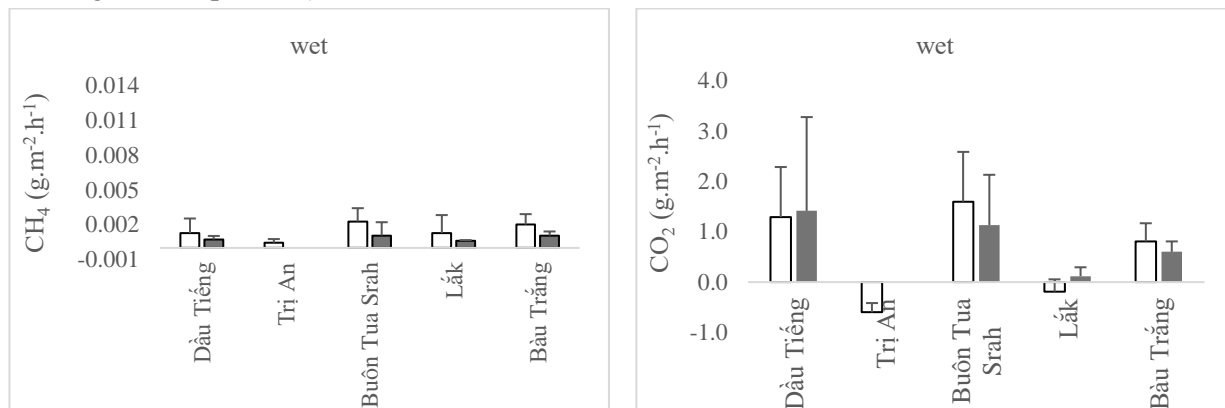
of CH₄ to the flooded area where the measurements were taken. Methane emissions from the Buôn Tua Srah reservoir were consistently greater than Trị An and Dầu Tiếng, and the disparity was more conspicuous in the dry season (Table 4). The exposure of the reservoir's beds, along with the disturbance caused by agricultural activities in the dry season, led to the more aerobic status of the beds in Trị An and Dầu Tiếng and inhibited the methanogenesis which is rigorously limited in reducing conditions (Calabrese et al. 2021). On the contrary, water in the Buôn Tua Srah reservoir was maintained at high levels throughout the year. The predominance of reducing conditions could favor the methanogens and result in the high flux rates of CH₄ emissions. In addition, constructed in 2001 and accomplished in 2011, Buôn Tua Srah was younger than Dầu Tiếng and Trị An, which were accomplished in 1981 and 1988, respectively. The higher rates of CH₄ emission from younger reservoirs were announced by Barros et al. 2011.

Data presented in Table 4 showed that the CH₄ emission rates from the reservoirs were significantly lower than the natural lakes ($p < 0.01$), and the flux rates at Bàu Trắng were remarkably more extensive than the Lák lake ($p < 0.01$). Similar to the reservoirs, the difference in the CH₄ flux rates between the two natural lakes was more apparent in the dry season and could be ascribed to the critical changes in water level between the seasons. Bàu Trắng is constantly inundated, while the Lák lake is also exposed in the dry season and subject to various human activities, including agricultural production and tourism, e.g., boat rowing or elephant riding, which perhaps introduced oxygen into the lake's bed and inhibited the methanogenesis. According to the field observation, the hydrophytic community was the most abundant at Bàu Trắng. The emergent parts of hydrophytes could directly transport CH₄ into the atmosphere instead of being oxidized in the water (Bodmer et al. 2024; Ge et al. 2024) and could account for the highest CH₄ flux rates at Bàu Trắng relative to the other surveyed water bodies.

The CH₄ emission flux rates were persistently higher during the daytime compared to the night-time in both seasons and both groups of the monitored water bodies (Figure 2), coinciding with the findings of Siczko et al. 2020. Light increased CH₄ emission rates (Thottathil et al. 2018) by inhibiting methanotrophs' growth and activities (Dumestre et al. 1999). Moreover, photosynthesis performed by aquatic plants and phytoplanktons could impede the oxidation of CH₄ to CO₂ (Murase and Sugimoto 2005).

Variation in CO₂ flux rates

The results of our study showed that the range of CO₂ flux rates from the three reservoirs was greater than those delineated by Beaulieu et al. 2020 and Macklin et al. 2018, probably due to the high temperature and level of eutrophication. However, we agreed with Macklin et al. 2018 that the mean rate of CO₂ emitted from the reservoirs was higher than from the natural lakes, though the difference between the two groups was insignificant ($p > 0.05$).



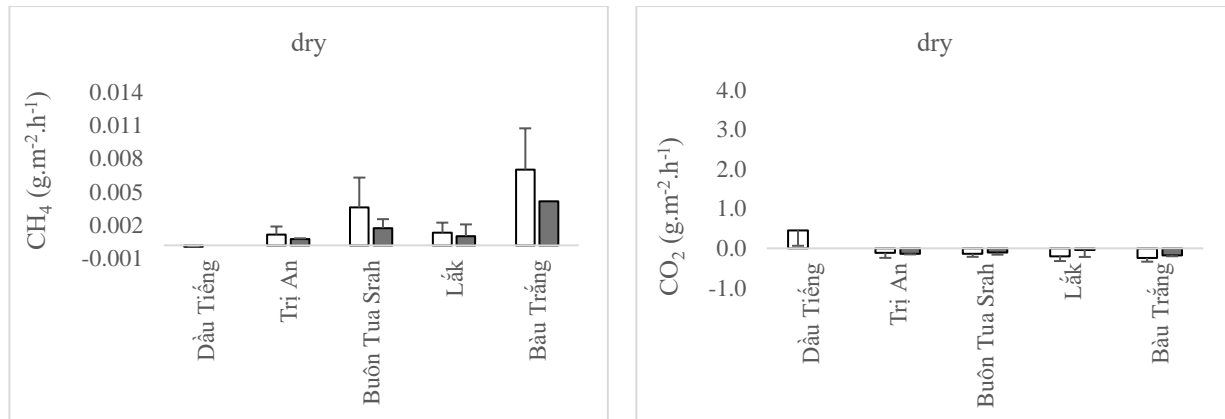


Fig. 2. Temporal variation of CH₄ and CO₂ flux rates at the surveyed water bodies in the wet and dry seasons.

Of the reservoirs, the highest CO₂ flux rates were acquired at Dầu Tiếng and followed by Buôn Tua Srah, while Trị An acted as a CO₂ sink in both seasons (Table 4). As mentioned previously, the Buôn Tua Srah reservoir is younger than Trị An and Dầu Tiếng. Thus, it is expected to emit more CO₂ than the others. Nevertheless, our study proved that water management and human activities in the reservoirs' beds remarkably affected the CO₂ flux rates. The exposure and agricultural production in the Dầu Tiếng reservoir's bed in the dry season stimulated the organic matter decomposition and boosted the CO₂ emissions. Although Dầu Tiếng and Buôn Tua Srah were consistently the sources of CO₂, the CO₂ flux rates strongly decreased in the dry season (Table 4), proving the contribution of photosynthesis performed by hydrophytes, which was presumably partly suppressed by the low temperature and solar radiation levels in the wet season, to the CO₂ exchange with the atmosphere. The negative fluxes of CO₂ recorded in Trị An reservoir, otherwise, could not comprehensively reflect the context of CO₂ exchange between this water body in the atmosphere. The higher density of phytoplanktons and diatoms in the wet season at Trị An (Vũ Cẩm Lương 2006), especially the increase in green algae density in the wet season (Trần Thị Hoàng Yến et al. 2019), accompanied by the solar illumination during the daytime (Table 1), could interpret the higher values of CO₂ influxes in the wet season at this reservoir.

Influence of the physicochemical properties on the fluxes of CH₄ and CO₂

Located on the plateau of the Southeastern, the water temperatures at the Lắc Lake were lower than the other water bodies (Table 3). Its CO₂ flux rates were also the lowest (Table 4), implying the influence of water temperatures on the rates of CO₂ exchange between the water bodies and the atmosphere. Contrary to Natchimuthu et al. (2014), our results agreed with Marotta et al. (2009) that the CO₂ flux rates positively related to the water temperatures though significant correlations were confined in the wet season ($p < 0.05$; $r = 0.6674$ and 0.7710 at the reservoirs and the natural lakes, respectively). In the dry season, the availability of high-intensity solar radiation and temperature simultaneously promoted the processes of production (photosynthesis) and consumption (respiration, organic matter decomposition) of CO₂ and led to indistinctiveness in the correlation between the water temperatures and CO₂ flux rates. The more substantial emissions of CO₂ resulting from the increase in temperatures were approved by the positive correlation between DO and CO₂ ($p < 0.05$ and $r = 0.8643$ and 0.8970 at the reservoirs and natural lakes, respectively), which showed that the dissolved oxygen was consumed for the respiration and organic matter decomposition to release CO₂ in the water. Nonetheless, the correlations between DO and CO₂ were divergent between the reservoirs and natural lakes in the dry season. When pooling the data by the exposure and inundation in the dry season, the significant correlation between DO and CO₂ flux rates was acquired only in the group of the inundated water bodies (Buôn Tua Srah and Bàu Trắng) ($p < 0.01$ and $r = -0.7990$). This finding proved that the exposure of the beds decisively affected the CO₂ fluxes exchanged between the water bodies and the atmosphere. The soil disturbance caused by tillage and the organic matter decomposition favored by the aerobic conditions augmented the CO₂ emitted into the atmosphere, which subsequently diffused into the water, in addition to the influx via photosynthesis. Thus, the negative correlation between DO and CO₂ flux

rates could be attributed to the less important contribution of diffusion compared to the internal processes of CO₂ production in the consistently inundated water bodies.

The correlations between turbidity values and CO₂ flux rates were similar in the reservoirs and natural lakes, but the curves' directions differed from the wet to dry seasons. The increase in turbidity led the CO₂ fluxes to more negative values in the wet season ($p < 0.05$, $r = 0.6291$ and 0.7833 at the reservoirs and natural lakes, respectively) but stronger CO₂ emission in the dry season, although significant correlation was found at the reservoirs only ($p < 0.05$ and $r = 0.9548$). The higher turbidity in the wet season was probably related to the accretion of phytoplanktons, which was advocated by the significant positive correlation between DO and turbidity in the dry season ($p < 0.01$ and $r = 0.8395$). Furthermore, the tendency of the variations in tandem of turbidity and DO in the wet season was also found at the reservoirs ($p > 0.05$). More advanced levels of nutrient mobilization to the water bodies in the wet season could account for the higher density of phytoplanktons and make the water more turbid. According to Trần Thị Hoàng Yến et al. (2019), the expansion of the green algae community at Trĩ An reservoir in the wet season corresponded with the higher levels of phosphorus. Phytoplankton's photosynthetic activities led to CO₂ flux toward the negative values and turned the water body into a CO₂ sink. In the dry season, probably due to the drastically low water levels, the turbidity values were easily affected by soil disturbances, and when accompanied by the reduced nutrient concentrations (Trần Thị Hoàng Yến et al. 2019), photosynthesis was inhibited, leading to higher rates of CO₂ emissions.

The ORP values were meager in all of the surveyed water bodies (Table 3), implying poor water quality. Significant correlation between the ORP and CO₂ flux rated was recorded only at the natural lakes in the dry season ($p < 0.05$ and $r = 0.5940$), proving that increased water quality could promote the aerobic decomposition of organic matter and enhance the CO₂ release to the atmosphere. The CO₂ flux rates consistently correlated with the pH values in both seasons and at both groups of the surveyed water bodies ($p < 0.05$ and $r = -0.7459$ at the reservoirs and -0.8881 at the natural lakes). The amendment of CO₂ was recognized to reduce water pH values (Cupp et al. 2017). Moreover, the concentrations of H⁺ reacting to CO₂ in the water increase with the reduction of pH values, resulting in low DO values. The correlations between DO and pH were also claimed by our results, with the correlation coefficients acquired at the reservoirs being 0.7713 and 0.7155 in the wet and dry seasons ($p < 0.05$), respectively. The correlation coefficients recorded at the natural lakes were 0.8308 in the wet season and 0.9200 in the dry season ($p < 0.01$).

The influence of temperatures on methanogens and methanotrophs differed between the reservoirs and natural lakes. In both seasons, the increase in water temperature led to higher rates of CH₄ emissions at the reservoirs, although a significant correlation was found in the dry season only ($p < 0.05$ and $r = -0.6878$). Meanwhile, warmer water at the natural lakes tended to amplify the CH₄ flux rates ($p < 0.01$ and $r = 0.8340$ and 0.7675 in the wet and dry seasons, respectively). Higher temperatures were postulated to enhance CH₄ emissions (Palma Silva et al. 2013; Natchimuthu 2014) by suppressing methane oxidation (Fenibo 2023). Furthermore, methane could be produced in oxic water surfaces in the presence of chlorophyll and light (Grossart et al. 2011; Beaulieu et al. 2019). The highly significant positive correlation between DO and CH₄ flux rates at the natural lakes in the dry season ($p < 0.01$ and $r = 0.7355$) corresponding with the high temperatures demonstrated the critical contribution of temperature to methanogenesis. Oxic production of methane at the water surface was recorded only in the dry season at the natural lakes due to the absence of a significant correlation between DO and CH₄ flux rates in the wet season. Antagonistically, the CH₄ flux rates at the reservoirs constantly exhibited negative correlations with DO in both seasons (Figure 3), showing that methanogenesis was hindered in aerobic conditions.

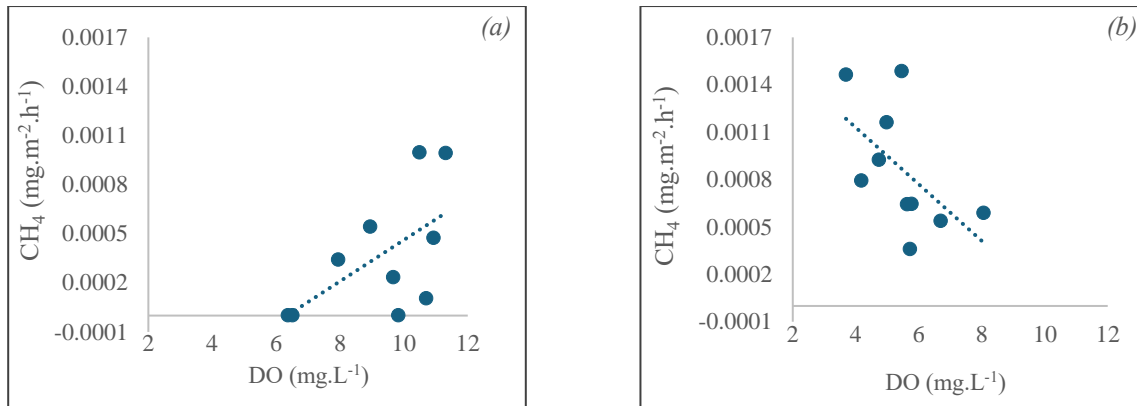


Fig. 3. Correlations between DO and CH₄ flux rates at the (a) reservoirs and (b) natural lakes in the wet season.

No correlations were found between the water turbidity and CH₄ flux rates in any surveyed water body. However, the tendency of the hostile relations between the CH₄ flux rates and ORP values implied the restraint of methanogenesis by clean water with high oxidation levels. The decrease in CH₄ production at acidic pH resulted from the decrease in methanogens' activities under acidic conditions, which was attributed to the inhibition of aerobic digestion (Yu You et al. 1997). All of the surveyed water bodies were alkaline (Table 3). According to Latif et al. 2014 and Gross and Cravotta III 2016, the solubility of CH₄ increased with the increase in water pH, helping to explain the positive correlation between pH and CH₄ flux rates ($p < 0.05$ and $r = 0.6170$ and 0.6002 in the wet and dry seasons, respectively).

The CH₄ and CO₂ flux rates negatively correlated with each other in the dry season ($p < 0.01$ and $r = -0.6873$ at the reservoirs and -0.7702 at the natural lakes). The correlation coefficient was higher at the constantly inundated water bodies ($p < 0.01$ and $r = -0.9276$) compared to the one exposed in the dry season ($p < 0.01$ and $r = -0.7457$). These negative correlations might refer to higher rates of methane oxidation relative to methane production. Oxidation of methane is favored in deep waters (Weber et al. 2019) as CH₄ could be easily consumed by methanotrophs living in oxic water (Henneberger et al. 2015; Sawakuchi et al. 2016). In the wet season, when all of the surveyed water bodies were full of water, the positive correlations between CH₄ and CO₂ probably implied a similarity in methane production and oxidation rates.

6. Conclusion

All surveyed water bodies were the sources of CH₄ emissions in both seasons. However, the Dầu Tiếng reservoir acted as a CH₄ sink with a meager influx in the dry season. The CH₄ emission rates from the reservoirs were significantly lower than those from natural lakes. Dầu Tiếng and Buôn Tua Srah reservoirs acted as CO₂ sources in both seasons, while Trị An reservoir was always a CO₂ sink. The natural lakes seasonally shifted between the CO₂ sink and source. The contributions of CH₄ to the total carbon exchange were higher at the natural lakes compared to the reservoirs. The surveyed water bodies were unhealthy because of the low DO and ORP values. The flux rates of CH₄ and CO₂ were ruled over by water quality, water level, and the photosynthesis of aquatic creatures and were drastically affected by human activities in the reservoirs and lakes' beds.

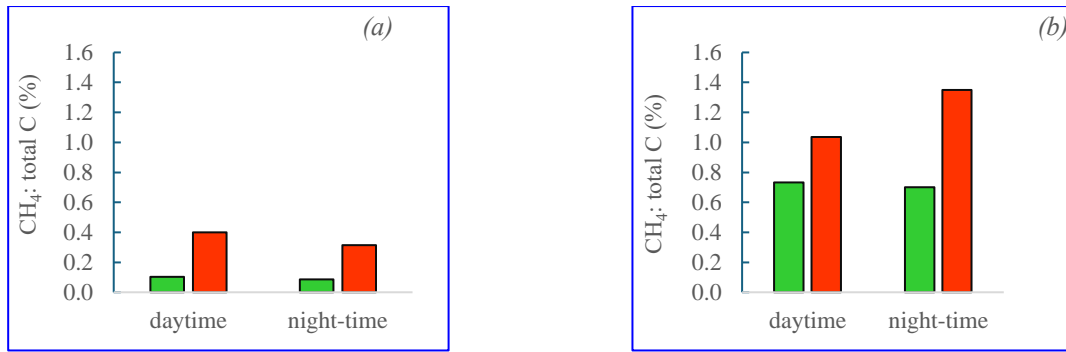


Fig. 4. The contribution of CH₄ to the total carbon flux rates in the (a) wet and (b) dry season. The green and red columns represent the values achieved in the reservoirs and natural lakes.

Acknowledgements

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