Seasonal variations in methane fluxes from two tropical humic coastal lagoons densely colonized by aquatic macrophytes.

Variações sazonais nos fluxos de metano em duas lagoas costeiras húmicas tropicais densamente colonizadas por macrófitas aquáticas.

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DOI:10.21715/GB2358-2812.202539001

ABSTRACT
The emission of methane (CH_4) is an important factor in the Earth's climate and its excessive input into the atmosphere contributes to global warming. Natural wetlands are one of the major sources of CH_4 emission to the atmosphere. This study was carried out to evaluate the seasonal variation in CH_4 fluxes from two tropical coastal lagoons and the difference in the methane efflux from littoral (vegetated) and limnetic (unvegetated) regions. The study was conducted in two dry and one rainy seasons. We measured Potential Methane Fluxes (PMF), Diffusive Methane Fluxes (DMF), CH_4 concentrations in the water column, rainfall, water column depth, water color, dissolved organic carbon (DOC), temperature, salinity, dissolved oxygen (DO), pH, total phosphorus (TP) and chlorophyl a (Chl-a) concentrations. The seasonality of the rainfall regime was the main factor for the seasonal changes in the PMF values, mainly through the alterations in the water column depth showing lower values during the dry period and higher values when filling occurred. The community of aquatic macrophytes contributed significantly to methanogenesis (PMF values) in the littoral region and it was possible to observe seasonal changes in CH_4 dynamics in the littoral and limnetic regions.
Keywords: methane emission, greenhouse effect, organic matter, precipitation, global warming.

RESUMO
A emissão de metano (CH_4) é um fator importante no clima da Terra e seu aporte excessivo na atmosfera contribui para o aquecimento global. As zonas húmidas naturais são uma das principais fontes de emissão de CH_4. Este estudo avaliou a variação sazonal nos fluxos de CH_4 em duas lagoas costeiras tropicais e a diferença no efluxo de metano das regiões litorânea (com vegetação) e limnética (sem vegetação). O estudo foi realizado em duas estações secas e uma chuvosa. Medimos Fluxos Potenciais de Metano (PMF), Fluxos Difusivos de Metano (DMF), concentrações de CH_4 na coluna d'água, precipitação, profundidade da coluna d'água, cor da água, carbono orgânico dissolvido (DOC), temperatura, salinidade, oxigênio dissolvido (DO), pH, concentrações de fósforo total (TP) e clorofila a (Chl-a). A sazonalidade do regime de chuvas foi o principal fator para as mudanças sazonais nos valores de PMF, principalmente através das alterações na profundidade da coluna d'água, apresentando valores mais baixos durante o período seco e valores mais elevados quando o enchimento ocorreu. A comunidade de macrófitas aquáticas contribuiu significativamente para a metanogênese (valores de PMF) na região litorânea e foi possível observar mudanças sazonais em relação à dinâmica do CH_4 nas regiões litorânea e limnética.
Palavras-chave: emissão de metano, efeito estufa, matéria orgânica, precipitação, aquecimento global.

1 INTRODUCTION

Global average surface temperatures, influenced by greenhouse gases, reached unprecedented levels in 2023, exceeding pre-industrial values by 1.45 ± 0.12°C (WMO, 2024). Among greenhouse gases, methane (CH_4) is the second most significant after carbon dioxide (CO_2), responsible for approximately 0.5°C of warming in the 2010s compared to the late 1800s, about two-thirds of the warming caused by CO_2 (IPCC, 2021). The rate of growth in atmospheric CH_4 concentrations has accelerated over the past decade, as a result of the combined increase in fossil fuel and microbial sources (TURNER *et al.*, 2019; JACKSON *et al.*, 2020; YIN *et al.*, 2021).

Regarding microbial sources, CH_4 emissions from wetlands have not been fully assessed in the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (IPCC, 2021), due to limited data availability. However, CH_4 emissions from wetlands are estimated to be increasing, as carbon stocks under anaerobic conditions in these ecosystems are large and highly sensitive to climate change (NISBET *et al.*, 2019). It is estimated that tropical wetlands contribute about one-quarter of total global CH_4 emissions (including both natural and anthropogenic sources), representing approximately half of global wetland emissions, although with considerable uncertainties (BLOOM *et al.*, 2012; SJÖGERSTEN *et al.*, 2014; POULTER *et al.*, 2017; MURGUIA-FLORES *et al.*, 2023). CH_4 emissions from wetlands may exceed anthropogenic emissions over 56% by the end of the 21st century, particularly under global warming scenarios such as RCP2.6 (IPCC, 2021). Under the most pessimistic scenario, RCP8.5, without climate mitigation, tropical CH_4 emissions could grow from 48.36 Tg to 87.37 Tg by 2099 (IPCC, 2021).

CH_4 production occurs in anaerobic environments, such as sediments and anoxic hypolimnion, through methanogenesis, which is the primary anaerobic decomposition pathway of organic matter in freshwater sediments, accounting for 30-80% of carbon mineralization (KUIVILA *et al.*, 1988; BÉDARD; KNOWLES, 1991). Factors such as the input of organic matter into sediments and anoxia in the water column in aquatic ecosystems favor the methanogenesis process (MOBILIAN; CRAFT, 2022). In shallow aquatic environments, aquatic macrophytes play key roles in the CH_4 cycle, providing organic matter, inducing anoxia, and regulating gas exchanges with the atmosphere (WETZEL, 1990; VERHOEVEN *et al.*, 2006; FRODGE *et al.*, 1990; CATTANEO *et al.*, 1998). Under aerobic conditions, CH_4 is oxidized to CO_2 (methanotrophy) (KING; BLACKBURN, 1996), and aquatic macrophytes contribute to this process by oxygenating the sediments and interstitial water, especially in the rhizosphere region (KING, 1994; SORREL *et al.*, 2002; FONSECA *et al.*, 2017).

CH_4 flux in wetlands is naturally highly variable across spatial scales, from meters to kilometers, with the environmental and biological factors influencing this variability still not fully understood (STRÖM *et al.*, 2015; AGUIRREZABALA-CÁMPANO *et al.*, 2022; SØ *et al.*, 2023). In addition to these uncertainties, human activities have significantly altered biogeochemical cycles in tropical wetlands, primarily through changes in land use and climatic conditions (BOUSQUET *et al.*, 2006; HOUGHTON *et al.*, 2012; POULTER *et al.*, 2017). These alterations, especially the use of fertilizers (which increase nitrogen inputs), pollution, and changes in land use and land cover, contribute to the increase in CH_4 emissions from these ecosystems (MURGUIA-FLORES *et al.*, 2023).

In coastal lagoons, CH_4 flux is influenced by abiotic and biotic factors such as temperature, trophic state, sulfate concentration, depth, and the presence of aquatic macrophytes (SEBACHER *et al.*, 1985; VERMA *et al.*, 2002; NAHLIK; MITSCH, 2011; FONSECA-VIANA *et al.*, 2019; FONSECA *et al.*, 2019). In humic coastal lagoons, variables such as water color and dissolved organic carbon (DOC) also affect CH_4 flux, in addition to influencing the ecosystem's metabolism, altering autotrophic and heterotrophic processes (JUUTINEN *et al.*, 2009; SANCHES *et al.*, 2019; ZHANG *et al.*, 2022).

Shallow coastal lagoons on the north coast of Rio de Janeiro present gradients of salinity, water color, and trophic status. The littoral zone of these environments, densely colonized by aquatic macrophytes, plays a crucial role in ecosystem functioning (PANOSSO *et al.*, 1998). This study assessed the diffusive CH_4 flux (DMF) and potential CH_4 flux (PMF) to the atmosphere in two humic coastal lagoons in the north coast of Rio de Janeiro, which have different levels of anthropogenic impact and are densely colonized by aquatic macrophytes such as *Typha domingensis* Pers., *Eleocharis acutangula* (Roxb.) Schult., *Eleocharis interstincta* (Vahl) Roem. & Schult., *Nymphoides humboldtiana* (Kunth) Kuntze, and *Pontederia azurea* Sw.

2 MATERIAL AND METHODS

2.1 STUDY SITE

The study was conducted in Carapebus and Comprida lagoons situated in the Restinga de Jurubatiba National Park, State of Rio de Janeiro, Brazil (Figure 1). The regional climate is warm and humid; the annual average minimum and maximum temperatures are 18.7 and 27.4 °C with lowest precipitation in winter (43.8 mm) and highest in summer (185.8 mm) (FIDERJ, 1977). The lagoons are separated by a sandbar (approximately 100 m) from the Atlantic Ocean. Morphological and limnological characteristics of the lagoons were described in detail by Panosso *et al*. (1998) and Petruccio (1998). Comprida and Carapebus lagoons can be considered as undisturbed with black-coloured water due to humic compounds from the so-called *restinga* (sand-dune habitats in coastal area of Brazil). The littoral regions of coastal lagoons are densely colonized by aquatic macrophytes *Eleocharis interstincta* (Vahl) Roem. & Schult. in Comprida Lagoon and *Typha domingensis* Pers. in Carapebus Lagoon.

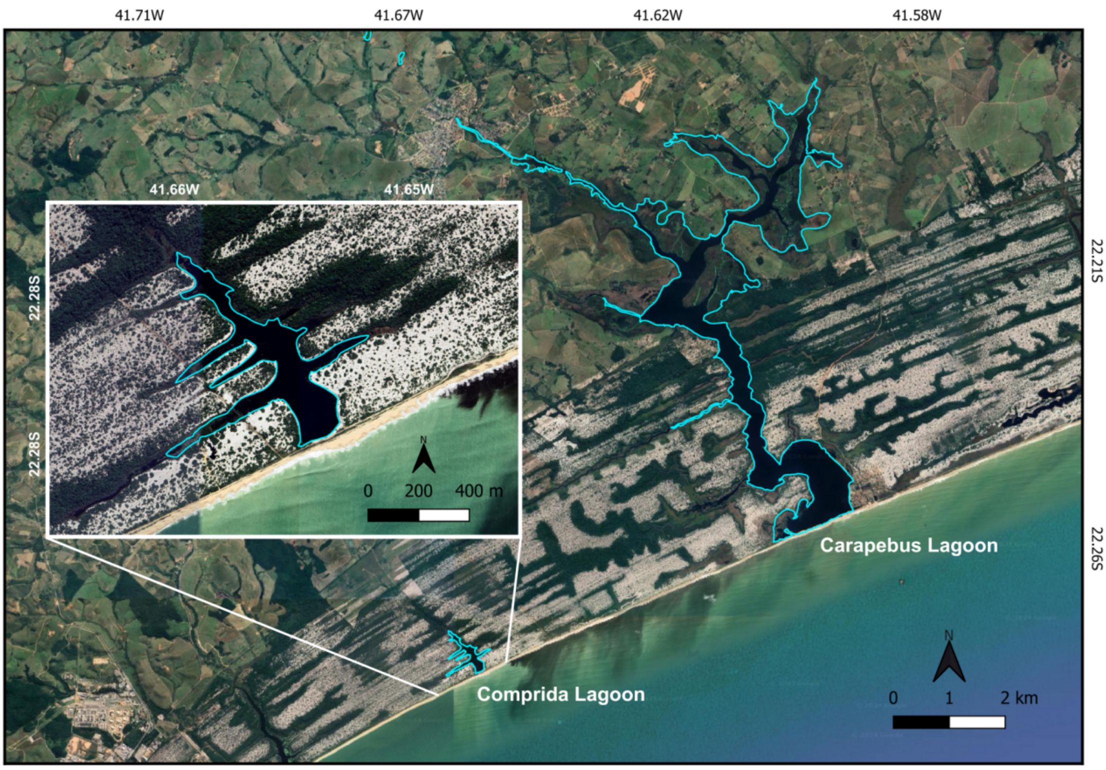

Figure 1 - Regions where the Comprida and Carapebus lagoons are located in Restinga de Jurubatiba National Park.

2.2 ABIOTIC VARIABLES IN THE WATER

The samplings for the determination of rainfall, water column depth, water color and DOC, were carried out from May 2003 to October 2004. The samplings for the determination of temperature, salinity, DO, pH, total phosphorus (TP) and chlorophyl a (Chl-a) were carried out in November 2003, February and May 2004. The rainfall values were obtained from the website of the Instituto Nacional de Meteorologia (INMET, 2023). Water column depth was determined with a Secchi disk. Temperature and salinity were determined with thermosalinometer (YSI 30/10 FT). DO concentrations were determined with an oximeter (YSI 95). pH was determined with a pH meter (Analion PM 608).

For the determination of water color, DOC and TP, and Chl-a concentration, samples of water were collected in polypropylene bottles and transported in refrigeration to the laboratory. In the laboratory, part of the water samples was filtered in GF/F filter for the determination of water color, DOC and Chl-a concentration. Water color was determined by absorbance at 430 nm in an UV-visible spectrophotometer (Beckman DU520). DOC was determined by a carbon analyzer TOC-5000 (Shimadzu Co., Japan). Chl-a concentration was determined after extraction from GF/F filters with 90% ethanol (NUSCH; PALME, 1975). In the fraction of water sample unfiltered, TP concentration was determined by the molybdenum blue reaction after persulphate oxidation according to Golterman *et al*. (1978).

2.3 CH_4 CONCENTRATIONS IN THE WATER AND DIFFUSIVE METHANE FLUXES (DMF)

The samplings for the determination of CH_4 concentrations in the water column and DMF were carried out in November 2003, February and May 2004. To determine CH_4 concentrations, subsurface water samples of 8 mL were collected using plastic syringes and needles (n = 5) and added to glass flasks of 12 mL closed with rubber stoppers, containing the equivalent of 20% of NaCl. CH_4 concentration was obtained using a gas chromatographer (Star 3400 – Varian Co., EUA) and the operation conditions were FID detector temperature of 200°C, injector temperature of 120°C, a 3 m Poropak-N column (80/100 mesh) at 85°C and N_2 as the carrier gas. DMF was estimated using the expression DMF = KCH_4 (Cw - Ceq) (LISS; SLATER, 1974). This expression describes the use of a two-layer model to estimate the fluxes of various gases across the air-water interface, where KCH_4 is the gas transfer velocity of methane at each water temperature, Cw is the dissolved-methane concentration at the lake surface, and Ceq is the equilibrium water-air methane concentration

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2.4 SAMPLING OF SEDIMENT AND POTENTIAL METHANE FLUXES (PMF)

To determine the PMF through the sediment, sediment samples were collected in the limnetic and littoral regions in November 2003, February and May 2004. Sediment cores (n = 5; 4.6 cm inner diameter and 30 cm length) were placed in sediment core incubators filled with bottom water, constituting the microcosms. After one-day of acclimation, each microcosm was closed by cap with rubber septa (Figure 2). The microcosms were incubated in dark chambers at 25 ºC and the CH_4 fluxes between the sediment-water and the headspace were determined from headspace gas sampling. Sampling was carried out through withdrawals of 1 mL aliquots from the headspace between 0 and 60 minutes of incubation, with intervals of approximately 15 minutes. The samples were analyzed for CH_4 concentration using gas chromatography.

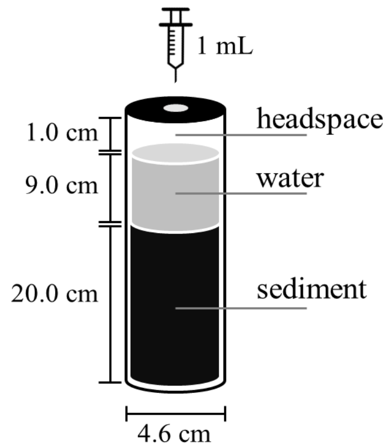

Figure 2 - Scheme of incubation cores for the determination of PMF containing sediment, water and headspace.

2.5 DATA ANALYSIS

The Kruskal-Wallis test was used to compare the variables measured during the dry and rainy periods, followed by Dunn's post hoc test for multiple comparisons with a significance level of $p < 0.05$. Correlation analysis was performed using Spearman's coefficient to assess the monotonic relationships between the DMF and PMF variables among themselves and with the other variables (pH, DO, DOC, water temperature, water depth, TP, chlorophyll a and water color). This was an exploratory analysis aimed at identifying potential patterns or associations between the variables. Correlations with $p < 0.05$ were considered statistically significant. The analyses were performed using JASP 0.19.2 software.

3 RESULTS AND DISCUSSION

The main finding of our study was that the seasonality of the rainfall regime and the consequent change in the depth of aquatic ecosystems (Figure 3) seem to be a determining factor for the sequence of changes in the ecosystem, which culminate in the alteration of the PMF, changing from lower values during the dry period to higher values when filling occurs at the first moment (Figure 3). Once the equilibrium point established by the rainfall regime has been reached, flows begin to vary depending on the consumption of organic matter. The latter is greater at the beginning of the flood, when there is a greater amount of labile organic matter and changes in the reducing conditions of the sediment, and lower later, as the organic matter becomes more refractory (Figure 3). With a new dry period, the lagoon becomes shallower and PMF remains low. At this point, aquatic macrophytes develop and organic matter accumulates in the surrounding sandbank, until new filling occurs and the cycle restarts. But this sequence becomes more marked when there is a long period of drought, as observed in the present study.

The results of PFM in Comprida and Carapebus lagoons showed significant spatial and temporal variation (Figure 3), following variations in the rainfall regime. In Comprida Lagoon, the littoral region showed significant differences ($p < 0.05$) in relation to the limnetic region during the rainy season sampling (February 2004) reaching values of 3044 ± 480 and 125 ± 128 $\mu mol.m^{-2}.day^{-1}$, respectively. Carapebus Lagoon showed significant differences ($p < 0.05$) between the littoral and limnetic regions also in the rainy season (November 2003), reaching values of 24180 ± 26060 and 490 ± 460 $\mu mol.m^{-2}.day^{-1}$, respectively; and in the beginning of the dry season (May 2004), reaching values of 20000 ± 15070 and 2010 ± 2520 $\mu mol.m^{-2}.day^{-1}$, respectively. Despite the increase in PMF values in the limnetic region in May 2004, no significant differences were observed ($p > 0.05$) in relation to November 2003 e February 2004 for both environments. On the other hand, the littoral region of Comprida Lagoon showed a significant increase ($p < 0.05$) in PMF values in February and May 2004 in relation to November 2003.

Comparing the PFM between the two lagoons (Figure 3), the differences were not significant between the limnetic regions ($p>0.05$). In relation to the littoral region, Carapebus Lagoon presented a significantly higher CH_4 flux ($p<0.05$) in relation to Comprida Lagoon in the periods of November 2003 and May 2004. Santos Neves *et al*. (2011) observed the positive effect of eutrophication and the presence of *T. domingensis* on increasing the concentration of CH_4 in the sediment and water column in a study conducted in constructed wetlands, corroborating the results of this study. Furthermore, Marinho *et al*. (2010) observed a lower C:N:P ratio in the sediment colonized by *T. domingensis* in relation to that of *E. interstincta* in Cabiúnas Lagoon, localized in the same region, showing a better quality of the detritus of *T. domingensis*, which could promote higher rates of methanogenesis. The results of these studies indicate the importance of the quality of OM for CH_4 emission in aquatic ecosystems. Therefore, the high values of PMF (Figure 3) observed in the Carapebus Lagoon in relation to the Comprida Lagoon may be explained by the differences in the quality of OM available in the two environments.

The highest values of PMF in the littoral regions of both coastal lagoons (Figure 3) demonstrated the importance of aquatic macrophytes in providing more favorable conditions for methanogenic organisms, as a source of substrates and ensuring anaerobic conditions essential for methanogenesis. Mann and Wetzel (2000) observed the possibility of changes in the chemical composition of pore water due to the presence of aquatic macrophytes. These changes in the chemical composition of the sediment, particularly in the concentration of DOC in pore water, can favor a series of processes, including methanogenesis. In our study, the correlation of PMF was made with the DOC in the water column, showing no significant correlation in Carapebus Lagoon ($p > 0.05$) and a negative correlation in Comprida Lagoon ($rho = -0.661$, $p = 0.007$). The correlation of PMF with DOC should be interpreted with caution, as other environmental factors, such as DOC consumption by other organisms, may also influence the results. Several studies have demonstrated the importance of aquatic macrophytes as a source of substrates for methanogenic organisms through the decomposition of their detritus and the release of root exudates (WHITING; CHANTON, 1993; DANNENBERG; CONRAD, 1999; BERGMAN *et al*., 2000; KAKU *et al*., 2000; GRASSET *et al*., 2019; BODMER *et al*., 2024). Fonseca *et al*. (2015) observed higher methane production in the littoral region in relation to the limnetic region in Comprida Lagoon, showing the importance of aquatic macrophytes detritus to methanogenesis. Fonseca *et al*. (2004) also observed higher CH_4 concentrations in the sediment colonized by aquatic macrophytes in relation to the limnetic region in Cabiúnas Lagoon, which also indicated the importance of aquatic macrophytes detritus to methane production.

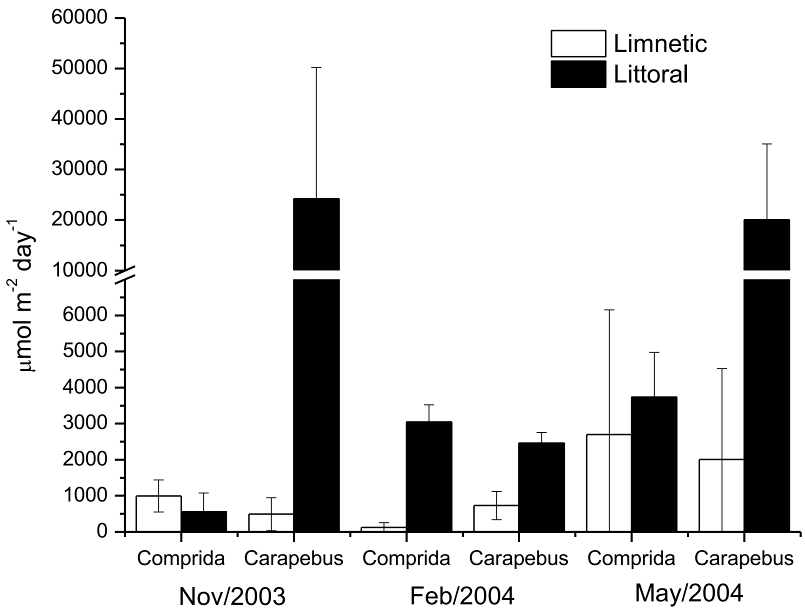

Figure 3 - PMF values in limnetic and littoral regions of Comprida and Carapebus lagoons in November 2003, February and May 2004. Bars = standard deviations.

Another consequence of the rainfall regime was the variation in the average depth of both ecosystems. Following the increase in rainfall, the water depth in Comprida Lagoon increased from 1.7 to 2.8 m, relative to the period from January to October 2003; and Carapebus Lagoon showed an increase in water depth from 2.8 to 3.7 m, from November 2003 to July 2004 (Figure 4). The increase in water depth at the sampling stations of both lagoons may have been another important factor contributing to the increase in PMF. The water table level has been identified as a key factor in modulating methane emissions (EVANS *et al*., 2021), promoting a significant increase in the supply of organic matter (OM) to the sediment, resulting from the death of aquatic macrophytes (SANTOS *et al*., 2006). During the dry period, from February to September 2003, when the lowest water depth values were observed, submerged aquatic macrophytes developed in the limnetic regions (unpublished data), a fact that was especially notable in Carapebus Lagoon. However, from September 2003 onwards, with an increase in rainfall, the lagoons began to fill. This filling led to the mortality of submerged aquatic macrophytes and also the flooding of vegetation and adjacent terrestrial detritus (visual observation), which likely provided more substrates for decomposer microorganism communities. Furthermore, with greater depth, the mixing of the water column, influenced by wind action, probably decreased in these ecosystems, creating more reducing conditions favorable to methanogenesis. According to Yavitt *et al*. (1987), the proportion of substrate transformed into CH_4 is influenced by changes in the anaerobic conditions of the sediment, and the redox potential may vary in the environment. In this context, we observed that in Comprida Lagoon, the correlation between PMF and depth was negative in the limnetic region (rho = -0.567, p = 0.028), with PMF values decreasing as depth increased, which could be explained by the buffering effect of depth on CH_4 fluxes (MARTÍNEZ-EIXARCH *et al*., 2024). In the littoral region, however, the correlation was positive (rho = 0.661, p = 0.007), probably due to the death of aquatic macrophytes, which are abundant in this region and increase the availability of organic matter. On the other hand, in Carapebus Lagoon, no correlations between PMF and depth were observed.

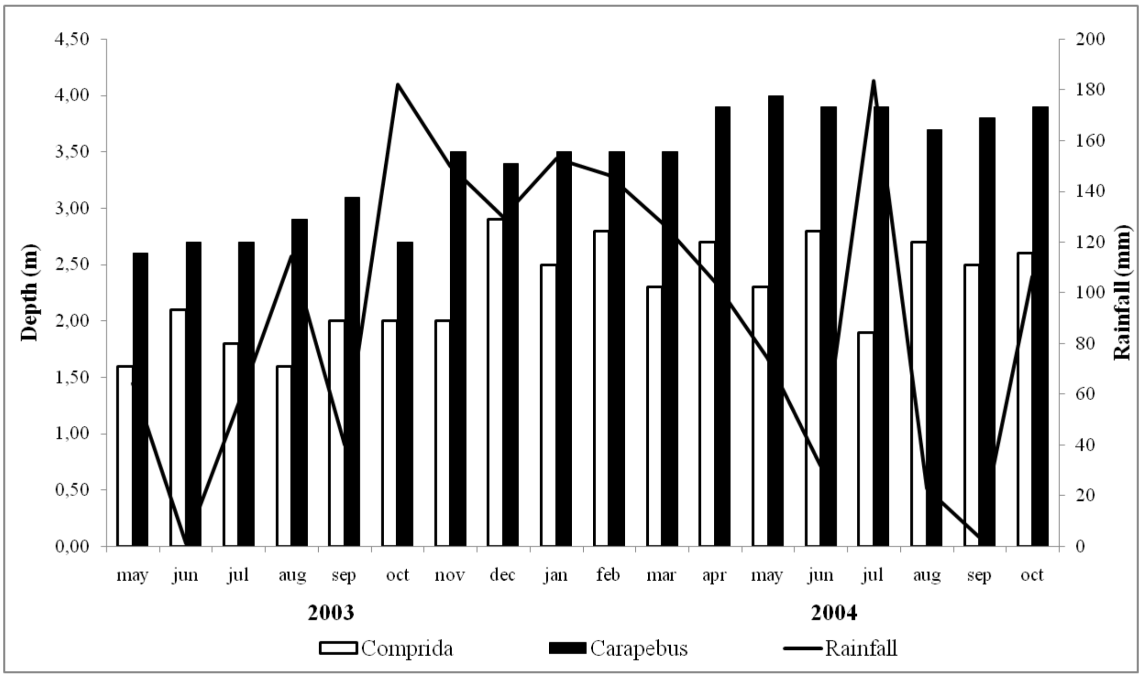

Figure 4 - Depth (m) in Comprida and Carapebus lagoons and rainfall (mm) in the sampled region from May 2003 to October 2004 (INMET, 2023).

Regarding the concentration of TP and Chl-a in the water column, Carapebus (Table 1A) and Comprida (Table 1B) lagoons have oligotrophic and dystrophic characteristics, respectively. TP and Chl-a concentrations were not significantly different (p > 0.05) between sampling periods in both environments. Several studies in different aquatic ecosystems demonstrated the importance of increasing nutrient concentrations, i.e., artificial eutrophication, in the production of CH_4 in the sediment (MARINHO, 2004; MARINHO *et al.*, 2009; FURLANETTO *et al*., 2012; GONSALVES *et al*., 2011; SANTOS NEVES *et al*., 2011; PETRUZZELLA *et al.*2013). In addition, the trophic state of aquatic ecosystems influences the potential for CH_4 fluxes through the water column. (SCHRIER-UIJL *et al*., 2011). In our study, in the littoral region of Comprida Lagoon, PMF showed a positive correlation with TP (rho = 0.661, p = 0.007). The increase in the amount of phosphorus may have favored the quality of the organic matter available to methanogens, resulting in an increase in PMF (BEAULIEU *et al*., 2019). On the other hand, in the limnetic region, a negative correlation was observed between PMF and TP (rho = -0.567, p = 0.028), with PMF increasing as TP decreased. The limnetic region is a more open area of the lagoon, which makes the correlations more complex, since several other environmental factors may have influenced both PMF and TP values. In the Carapebus Lagoon there was no correlation between PMF and TP ($p > 0.05$). The concentration of Chl-a is also an important parameter, as it reflects not only the eutrophication process in an aquatic ecosystem, but also how much labile OM will be available in both the water column and sediment. In the case of sediment, the deposition of OM of phytoplankton origin can enhance anaerobic processes (GRASSET *et al.*, 2018). Studies on seasonal and spatial variations in the concentration of CH_4 in the water of the Carapebus Lagoon showed significantly positive correlations of this gas with the concentration of Chl-a (MARINHO *et al.*, 2003). However, in this study, the only positive correlation observed between PMF and chlorophyll a occurred in the littoral region of Comprida Lagoon (rho = 0.756, p = 0.001). Since chlorophyll a has a phytoplanktonic origin, it is possible that there was an increase in the availability of labile organic matter from these organisms, which, as a result, may have favored methanogenic activity and, consequently, methane flux.

Table 1 - Abiotic variables in Comprida (A) and Carapebus (B) lagoons.

A									
Years	Periods	CH_4 µM	Temp. (ºC)	Sal.	DO ($mg.L^{-1}$)	TP (µM)	Chl a ($\mu g.L^{-1}$)	Depth (m)	pH
2003	Dry	0.12±0.04	23±2	0.2±0.1	7.9±0.4	0.47±0.15	1.78±0.46	1.9±0.2	5.6±0.3
2003/2004	Rainy	0.53±0.33	27±2	0.1±0.1	5.2±2.7	0.59±0.45	2.18±1.79	2.1±0.5	4.8±0.5
2004	Dry	0.13±0.02	23±2	0.2±0.1	6.6±1.1	0.57±0.09	2.81±2.12	2.5±0.3	4.1±0.3

B									
Years	Periods	CH_4 µM	Temp. (ºC)	Sal.	DO ($mg.L^{-1}$)	TP (µM)	Chl a ($\mu g.L^{-1}$)	Depth (m)	pH
2003	Dry	0.11±0.06	24±2	7±1	8.9±0.4	0.79±0.29	5.56.02	2.8±0.2	8±0.6
2003/2004	Rainy	0.57±0.24	28±2	4±1	6.8±0.6	0.85±0.74	4.39±3.21	3.6±0.1	7.6±0.5
2004	Dry	0.26±0.20	24±1	2±0.3	7.7±0.3	0.68±0.27	6.07±6.68	3.9±0.1	7.2±0.2

Regarding the water color (Figure 5) and the concentration of DOC (Figure 6), a significant increase ($p<0.05$) was observed between the dry and rainy period of 2003, which remained high until the dry period of 2004 in both lagoons. Despite the increase in water color and DOC concentration, in Comprida Lagoon we did not observe a significant correlation between these variables ($p>0.05$). The brown color of the water observed in Comprida Lagoon is often associated with the presence of humic and fulvic acids, which are derived from the decomposition of organic matter in aquatic environments, but the relationship between color and DOC is not strictly causal because other factors can affect water color. It is important to highlight that approximately 90% of the DOC concentration present in the water of Comprida Lagoon is composed of humic substances of allochthonous origin from the surrounding *restinga* vegetation (SUHETT *et al.*, 2004). Humic substances are refractory to decomposition and can be deposited, increasing the supply of OM in the sediment (CROSSEY, 1978; STEINBERG, 2003). The sediment from Comprida Lagoon, despite having high concentrations of OC and TN, is composed of low quality OM due to its humic origin (PETRUCIO; FARIA, 1998). Such composition tends to hinder the decomposition processes, determining a slower rate of decomposition of OM in the sediment of the Comprida Lagoon (FONSECA *et al.*, 2015). In opposition to these results, high concentrations of CH_4 were observed in the sediment of a small dystrophic shallow lake in the south of Brazil, where the authors attributed the results to high concentrations of TOC, TN and TP and values of DO lower than 2 $mg.L^{-1}$ (FURLANETTO *et al.*, 2012), contrasting with values of DO higher than 8 $mg.L^{-1}$ in Comprida Lagoon (ENRICH-PRAST *et al.*, 2004).

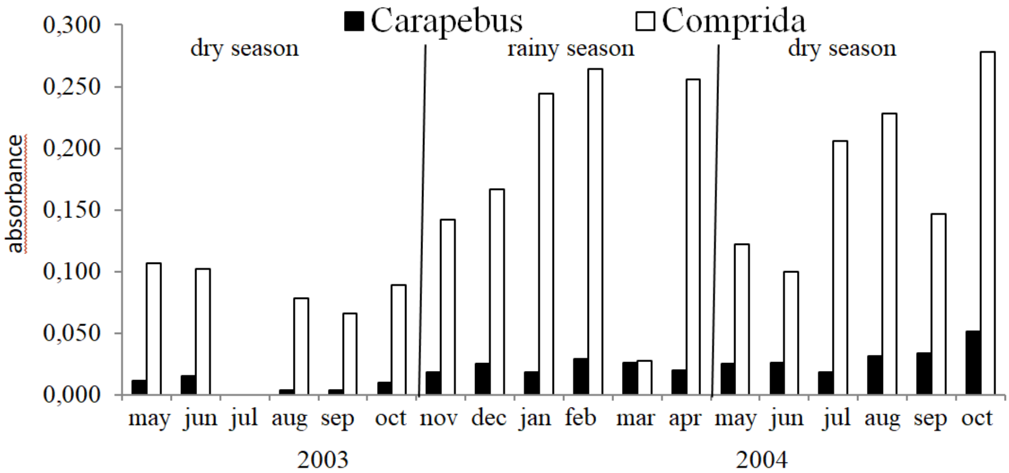

Figure 5 - Monthly water color values in Comprida and Carapebus lagoons.

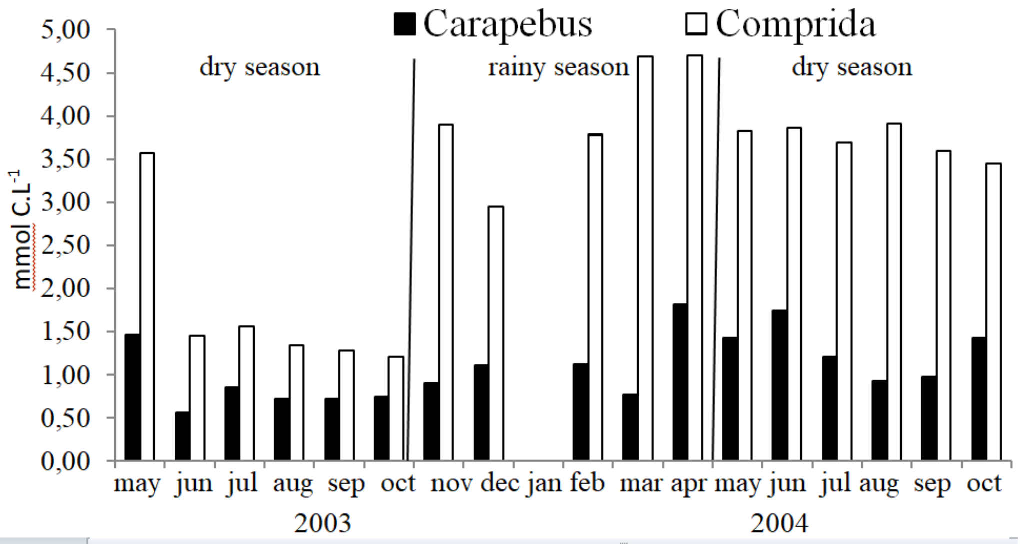

Figure 6 - Monthly values of DOC concentration of Comprida and Carapebus lagoons.

In Carapebus Lagoon, no correlation was observed between water color and DOC concentrations either ($p > 0.05$). Probably, the highest PMF values observed in Carapebus Lagoon can be attributed to the greater biomass of *T. domingensis* compared to the biomass of *E. interstincta* in the Comprida Lagoon (visual observation), as the greatest differences found between the lagoons occurred in the littoral region. Furthermore, Marinho *et al*. (2010) observed higher stoichiometric ratios C:N, C:P and N:P in the sediment colonized by *E. interstincta* compared to the sediment colonized by *T. domingensis* in the Cabiúnas Lagoon, located in the same region, indicating a better quality of the detritus of *T. domingensis*. On the other hand, Fonseca *et al*. (2017) observed greater potential methane production in *E. interstincta* stands compared to *T. domingensis* in the Cabiúnas Lagoon. However, in the same study, the authors reported the absence of a lag phase in the potential methane production in the *T. domingensis* stand, indicating a greater intensity of methane production at the beginning of the sediment incubation in relation to the *E. interstincta* stand. The results of these studies corroborate the higher PMF values observed in the littoral region of the Carapebus Lagoon in the present study.

Some studies suggest a negative effect on methanogenic activity in the sediment of aquatic ecosystems colonized by aquatic macrophytes through their oxygenation via the root system (CONRAD, 2009; SUTTON-GRIER; MEGONIGAL, 2011). Such processes lead to an increase in methanotrophy, through the supply of oxygen in a region with high methane amounts (CHRISTENSEN *et al*., 2003; WHALEN, 2005). The decrease in methanogenesis and the increase in methanotrophy occur in microhabitats close to the root system (rhizosphere) and may not be sufficient to attenuate the ebullition emission in the sediment as a whole (TORRES-ALVARADO *et al*, 2005).

The DMF in the limnetic region showed seasonal variation, likely due to the balance between methanogenesis and methanotrophy. In this study, methanogenesis was assessed based on PMF values (Figure 7). Thus, the reduction in PMF between November 2003 and February 2004 does not account for the significant decrease in DMF. This decline may be attributed to a potential increase in methanotrophy, possibly due to deeper water columns, higher temperatures, and more aerobic conditions (Table 1). Notably, larger reductions in DMF values were observed in Comprida Lagoon. This trend was also evident in May 2004, where, despite an increase in DMF values, the rise was more pronounced and was also observed in Carapebus Lagoon. Although PMF values were similar in the limnetic region in May 2004, DMF values were significantly higher in Comprida Lagoon. These results suggest a possible increase in methanotrophic activity within the water column of Comprida Lagoon during this period.

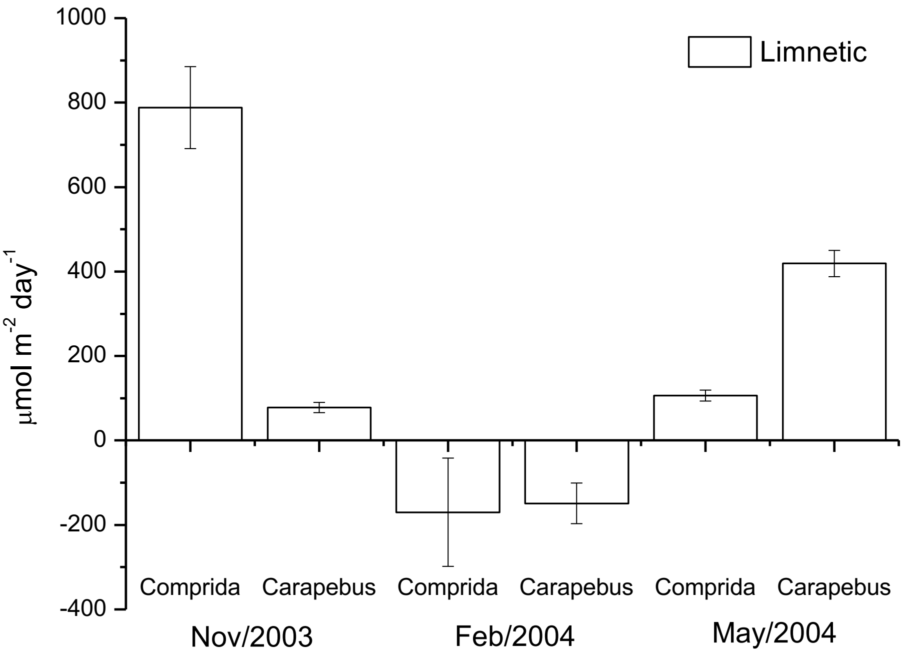

Figure 7 - DMF values in limnetic region of Comprida and Carapebus lagoons in November 2003, February and May 2004. Bars = standard deviations.

In both lagoons, the correlations observed involving DMF and other variables suggest the existence of causal relationships associated with increase in precipitation and, consequently, the increase in the depth of the water column. In Comprida Lagoon, the increase in depth correlated with the increase in color (rho = 0.500, p = 0.041) and DOC concentrations (rho = 0.660, p = 0.004). In Carapebus Lagoon, positive correlations were also observed between depth and color (rho = 0.800, p < 0.001) and depth and DOC (rho = 0.575, p = 0.020). These correlations in both environments indicate inputs of allochthonous organic material from the surrounding restinga (FARJALLA *et al.*, 2009; SUHETT *et al.*, 2007, SUHETT *et al.* 2013). Additionally, increases in depth and color also correlated with the increase in CH_4 concentrations (rho = 0.657, p = 0.004 and rho = 0.567, p = 0.022, respectively) in Comprida Lagoon, suggesting that the input of allochthonous DOC favored methanogenesis, increasing CH_4 concentration. Furlanetto *et al.* (2012) observed higher CH_4 concentrations in a dystrophic lake, such as Comprida Lagoon, compared to an eutrophic and an oligotrophic lake, attributing the results to the accumulation of allochthonous organic matter in the sediment, which promotes methanogenesis. Furthermore, in both environments, the increase in temperature correlated positively with the increase in CH_4 concentrations (Comprida Lagoon: rho = 0.502, p = 0.040; Carapebus Lagoon: rho = 0.755, p < 0.001). The relationship between temperature and CH_4 concentrations is not yet well established in the literature, with some studies indicating that the increase in temperature directly influences the increase in CH_4 concentrations due to a stimulus of methanogenesis (MARINHO *et al.*, 2009; METJE; FRENZEL, 2005; YVON-DUROCHER *et al.*, 2014; YUAN *et al.*, 2024), while other studies suggest that temperature increase does not alter or even decreases CH_4 concentrations, implying that at higher temperatures, methane oxidation could balance, or even exceed, methane production (SHELLEY *et al.*, 2015; FUCHS *et al.*, 2016). In our study, it is lickely that there was an increase in CH_4 production, favored by the rise in temperature, which caused increased CH_4 concentrations. In Carapebus Lagoon, the rise in temperature positively correlated with the increase in DMF (rho = 0.501, p = 0.041), and in Comprida Lagoon, both temperature and CH_4 concentrations positively correlated with DMF (rho = 0.620, p = 0.008 and rho = 0.755, p < 0.001, respectively). These relationships strengthen the argument that CH_4 production increased due to the rise in temperature, and consequently led to an increase in DMF.

Another relevant aspect in both environments was the reduction in salinity due to precipitation. In Comprida Lagoon, the decrease in salinity showed a negative correlation with the increase in color (rho = -0.482, p = 0.050), corroborating the argument of allochthonous DOC input with the entry of rainwater and resulting in the dilution of salts in the environment. In Carapebus Lagoon, this effect was more evident, as the reduction in salinity showed strong negative correlations with the increase in depth (rho = -0.868, p < 0.001) and color (rho = -0.830, p < 0.001), in addition to a moderate correlation with the increase in DOC (rho = -0.636, p = 0.006).

4 CONCLUSION

In the present research, the seasonality of the rainfall regime seemed to be the main factor for the sequence of changes in the functioning of the ecosystem related to the PMF. The rainfall regime determined the variation in water depth and, consequently, the alteration in the PMF, changing to lower values during the dry period to higher values when filling occurs at the first moment. It was possible to confirm the importance of emergent aquatic macrophytes in terms of CH_4 dynamics in shallow aquatic ecosystems such as coastal lagoons. We observed that this community contributed significantly to methanogenesis (PMF values) . in the littoral region. Furthermore, it was possible to observe seasonal changes in relation to CH_4 dynamics in the littoral (PMF) and limnetic (PMF and DMF) regions. In the case of DMF values, the influence of methanotrophy can be highlighted. Water temperature, water depth, concentrations of DOC, TP, chlorophyll a, water color, pH and DO are relevant factors for CH_4 dynamics, which are closely related to climate factors. Therefore, research on climate change, particularly studies focused on changes in rainfall patterns, is of considerable importance.

5 ACKNOWLEDGEMENTS

The authors would like to thank to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Financiadora de Estudos e Projetos (Finep) and Petróleo Brasileiro S. A. (PETROBRAS) for financial support. The authors also thank to Instituto de Biodiversidade e Sustentabilidade, Universidade Federal do Rio de Janeiro, Macaé,RJ (NUPEM/UFRJ) and the team at the Limnology Laboratory/UFRJ.

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