

# Magnitude and variability of methane production and concentration in tropical coastal lagoons sediments

Magnitude e variabilidade da produção e concentração de metano no sedimento de lagoas costeiras tropicais

Antonella Petruzzella<sup>1</sup>, Claudio Cardoso Marinho<sup>1</sup>,

Lúcia Fernandes Sanches<sup>1</sup>, Murilo Minello<sup>2</sup> and Francisco de Assis Esteves<sup>1</sup>

<sup>1</sup>Laboratório de Limnologia, Departamento de ecologia, Centro de Ciências da Saúde – CCS, Universidade Federal do Rio de Janeiro – UFRJ, Cidade Universitária, Ilha do Fundão, CP 68020, CEP 21940-540, Rio de Janeiro, RJ, Brazil

e-mail: antonellabio@gmail.com; clcamar@biologia.ufrj.br; luciafernandessanches@yahoo.com.br; festeves@biologia.ufrj.br

<sup>2</sup>Instituto Federal de Educação, Ciência e Tecnologia do Rio de Janeiro – IFRJ, Campus Arraial do Cabo, Rua José Pinto de Macedo s/n, Prainha, CEP 28930-000, Arraial do Cabo, RJ, Brazil  
e-mail: murilo.minello@ifrj.edu.br

**Abstract: Aim:** Coastal wetlands are potential zones for methane (CH<sub>4</sub>) production. The present study aims to evaluate the spatial variation of CH<sub>4</sub> production and concentration in ten tropical coastal lagoons, the influence of aquatic macrophytes on the sediment CH<sub>4</sub> concentration and how the magnitude of these potential CH<sub>4</sub> production rates compare to those in other ecosystems. **Methods:** Sediments were sampled in ten coastal lagoons, with one site in the limnetic region and another site in aquatic macrophyte stands when they were present in the littoral region. We measured the CH<sub>4</sub> production as a potential rate, and CH<sub>4</sub> concentration was directly measured from sediment samples. **Results:** The highest potential CH<sub>4</sub> production (PMP) rates were found in alkaline and hypersaline lagoons. However, Cabiúnas, which is a freshwater lagoon densely colonized by aquatic macrophytes, also exhibited a high PMP rate. We also observed that the sediment CH<sub>4</sub> concentration in the littoral region was higher than in the limnetic region in all of the investigated lagoons except Paulista, which presented the opposite pattern. The PMP rates observed in the studied lagoons were low compared to other aquatic ecosystems. **Conclusion:** Our results suggest that the sediments of saline lagoons are important CH<sub>4</sub> production sites, and in general, aquatic macrophytes have a positive influence on methanogenesis, which was evident based on the CH<sub>4</sub> concentrations present in the sediments of these lagoons. Further studies should focus on the processes underlying the CH<sub>4</sub> patterns observed in the tropical coastal lagoons, especially concerning the coupling between CH<sub>4</sub> production and concentration.

**Keywords:** methanogenesis, organic matter, littoral region and methane concentration.

**Resumo: Objetivo:** Áreas alagadas costeiras são zonas potenciais para produção de metano (CH<sub>4</sub>). O presente estudo tem como objetivo avaliar a variação espacial da produção e concentração de CH<sub>4</sub> em dez lagoas costeiras tropicais, a influência de macrófitas aquáticas na concentração de CH<sub>4</sub> no sedimento e como a magnitude dessas taxas de produção potencial de CH<sub>4</sub> é em comparação com outros ecossistemas. **Métodos:** Os sedimentos foram amostrados em dez lagoas costeiras, com um ponto na região limnética e outro ponto nos bancos de macrófita aquática, quando estas estavam presentes na região litorânea. Nós medimos a produção de CH<sub>4</sub> como uma taxa potencial e a concentração de CH<sub>4</sub> foi diretamente medida das amostras de sedimento. **Resultados:** As maiores taxas de produção potencial de CH<sub>4</sub> (PPM) foram encontradas em lagoas alcalinas e hipersalinas. Contudo, Cabiúnas, que é uma lagoa de água doce densamente colonizada por macrófitas aquáticas também exibiu alta taxa de PPM. Nós também observamos que a concentração de CH<sub>4</sub> do sedimento na região litorânea foi mais alta que na região limnética em todas as lagoas investigadas, exceto Paulista, que apresentou o padrão oposto. As taxas de produção de CH<sub>4</sub> observadas nessas lagoas estudadas foram baixas comparadas com outros ecossistemas aquáticos. **Conclusão:** Nossos resultados sugerem que os sedimentos de lagoas salinas são importantes sítios produtores de CH<sub>4</sub>, e em geral, macrófitas aquáticas tem uma influência positiva na metanogênese, o que foi evidente baseado nas concentrações de CH<sub>4</sub> presentes nos sedimentos dessas lagoas. Estudos adicionais deveriam focar nos processos subjacentes aos padrões do CH<sub>4</sub> observados nas lagoas costeiras tropicais, especialmente preocupando-se com o acoplamento entre produção e concentração de CH<sub>4</sub>.

**Palavras-chave:** metanogênese, matéria orgânica, região litorânea e concentração de metano.

## 1. Introduction

Methane ( $\text{CH}_4$ ) production in aquatic environments has drawn special attention in the recent years, because the relative increase of  $\text{CH}_4$  in the atmosphere since pre-industrial time is approximately 150%, compared to 35% for  $\text{CO}_2$  (IPCC, 2007). Furthermore, the global warming potential for  $\text{CH}_4$  is 25 times higher than that of  $\text{CO}_2$  (over a 100 year period - (IPCC, 2007)).  $\text{CH}_4$  is produced biologically by methanogenesis, which is the pathway for mineralizing organic carbon compounds in anoxic conditions and substrate availability (Segers, 1998; Laanbroek, 2010). Methanogenic microorganisms perform this process, generally *Archaea*, which only occurs in anaerobic environments, such as the sediment of aquatic environments, where methanogenesis is one of the most important processes of organic matter (OM) degradation (Schulz and Conrad, 1995).

Coastal wetlands are potential zones for the production of  $\text{CH}_4$  (Purvaja and Ramesh, 2001), but the overall ecological factors governing these rates could be very distinct among locations (Gonsalves et al., 2011). Several environmental factors may influence methanogenesis, such as salinity, temperature, pH and microbial interactions with other anaerobic metabolic groups, such as iron ( $\text{Fe}^{3+}$ )-reducing bacteria, acetogenic bacteria and sulfate-reducing bacteria (Marinho et al., 2012). Additionally, the presence of aquatic macrophytes has been pointed as a factor that significantly influences  $\text{CH}_4$  dynamics (Whiting and Chanton, 1993; Fonseca et al., 2004; Laanbroek, 2010).

Coastal aquatic ecosystems are generally shallow, allowing substantial development of aquatic macrophytes (Esteves, 2011). The presence of these plants promotes direct and indirect influences on  $\text{CH}_4$  dynamics. First, they are a source of OM to methanogens (Neue et al., 1997), which can increase  $\text{CH}_4$  production (Conrad, 2007). Second, aquatic macrophytes act on  $\text{CH}_4$  oxidation, a process that is the reverse of methanogenesis. The roots and rhizomes of macrophytes enhance sediment oxygenation, which allows the growth of the methanotrophic bacteria responsible for the oxidation of  $\text{CH}_4$  into  $\text{CO}_2$  (King, 1994). Third, aquatic macrophytes works as a route to release  $\text{CH}_4$  to the atmosphere, through their internal system for gas transport (Boon and Sorrell, 1995; Yavitt and Knapp, 1995; Kulshreshtha et al., 2000). Using this route the  $\text{CH}_4$  can release direct from the sediment to the atmosphere without contact with the water column. Thus, the same ecosystem could have

patches with different  $\text{CH}_4$  production dynamics and  $\text{CH}_4$  concentrations, according to the presence of aquatic macrophytes.

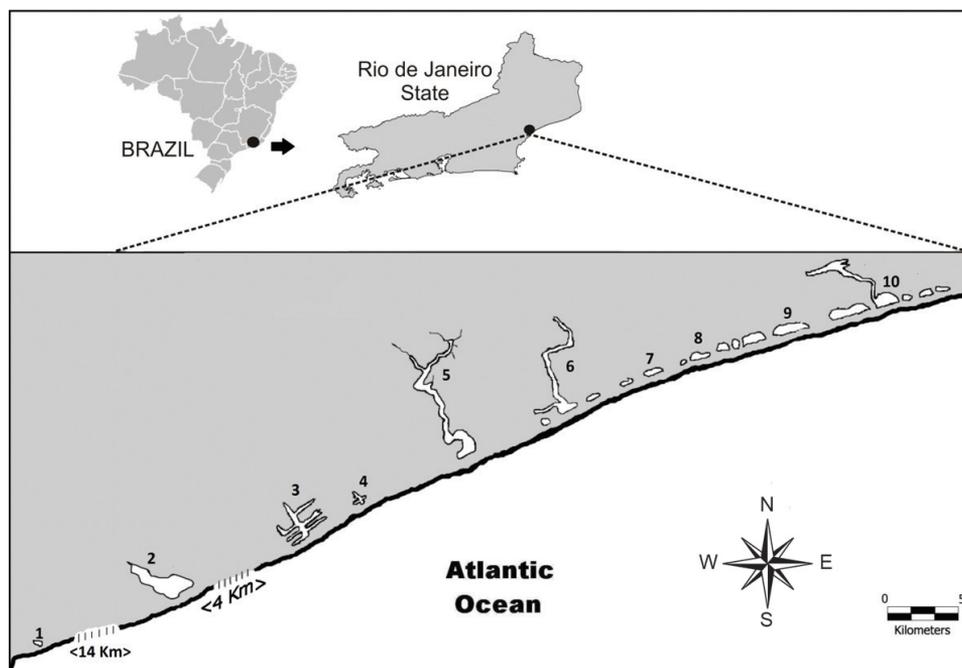
Another important feature of coastal aquatic environments is their proximity to the sea, which can profoundly modify the water chemistry, especially in terms of pH and salinity (Smith, 1994). Methanogens are often found in a wide range of environments, and these organisms have evolved several strategies that enable them to survive and proliferate in environments of varied ionic composition and salinity, ranging from freshwater to hypersaline habitats (Zinder, 1993; Martin et al., 1999). However, competition for substrate with sulfate-reducers tends to be higher in coastal environments, where the sulfate concentration is increased due to proximity to the sea. In these ecosystems, sulfate reduction may be favored over methanogenesis, because sulfate reduction is more energetically advantageous in relation to the substrates common to both of the types of microorganisms (Lyimo et al., 2002), diminishing the overall potential of coastal lagoons for  $\text{CH}_4$  production.

Studies of the dynamics of  $\text{CH}_4$  production and concentration in the sediments of aquatic coastal environments have become more important as the concentration of this greenhouse gas has increased in the atmosphere throughout the years (Zaiss, 1996; Furtado et al., 2002; Fonseca et al., 2004). In general, the wetlands are considered the main natural source of the atmospheric  $\text{CH}_4$  (Wuebbles and Hayhoe, 2002) that currently contributes approximately 20% to the global warming effect (Neue et al., 1997). Through extensive field sampling, the present study aims to evaluate: (1) the variation of  $\text{CH}_4$  production and concentration in ten coastal aquatic ecosystems (2) the spatial variation of sediment  $\text{CH}_4$  concentration due to the occurrence of aquatic macrophytes and (3) how the magnitude of these potential  $\text{CH}_4$  production rates compares to other ecosystems.

## 2. Material and Methods

### 2.1. Study area

This study was conducted in 10 coastal lagoons located in the northern region of the state of Rio de Janeiro, Brazil ( $22^\circ\text{-}22^\circ 30' \text{ S}$  and  $41^\circ 15'\text{-}42^\circ \text{ W}$  – Figure 1). Eight of the lagoons are situated at the Restinga de Jurubatiba National Park (Cabiúnas, Comprida, Carapebus, Paulista, Garças, Piripiri, Visgueiro and Preta lagoons), and the remaining



**Figure 1.** Map illustrating the geographical position of the 10 coastal lagoons. The lagoons are numbered as follows: 1) Iodada, 2) Imboassica, 3) Cabiúnas, 4) Comprida, 5) Carapebus, 6) Paulista, 7) Garças, 8) Piripiri, 9) Visgüeiro and 10) Preta.

two are in the urban areas of the cities of Macae and Rio das Ostras (Imboassica and Iodada lagoon, respectively). The climate of the region is characterized as tropical sub-humid/humid; the mean annual temperature varies from 24.7 °C to 21.4 °C, and the mean annual precipitation is 1000 mm (INMET, 2003).

These lagoons were formed by movements of marine transgression and regression during glacial and interglacial periods, and are characterized by a sandbar that separates them from the sea (Esteves, 2011). Although these coastal lagoons resulted from the same process, their geneses were different, resulting in a wide range of inland aquatic ecosystems with different sizes, morphometries, water chemistry, landscape positions and trophic status (Caliman et al., 2010). All of the studied lagoons are shallow, not exceeding 3.0 m water depth and present substantial natural differences in their limnological parameters, particularly in terms of salinity, pH and sulfate and nutrient concentrations (Table 1). Moreover, the Cabiúnas, Carapebus, Comprida, Imboassica, Iodada and Paulista lagoons exhibited areas colonized by aquatic macrophytes, and the most frequently observed species were *Typha domingensis* Pers., *Eleocharis interstincta* (Vahl) Roem. & Schult., *Nymphaea ampla* Salisb. and *Potamogeton stenostachys* K. Schum.

## 2.2. Sampling

The sediment samples reported in this article were collected using acrylic core tubes during December of 2002. One site was collected in the limnetic region of all of the lagoons. In the Cabiúnas, Carapebus, Comprida, Imboassica, Iodada and Paulista lagoons, we also sampled one additional site within aquatic macrophyte stands in the littoral region. The littoral region in all of these lagoons was dominated by *Typha domingensis* stands, except for Comprida, which was predominantly colonized by *Eleocharis interstincta* stands.

## 2.3. Potential CH<sub>4</sub> production of the sediment (PMP)

The sediment sampled in the cores was put into plastic bags and kept in a refrigerator (5 °C) for 2 days until the incubation. Six grams of the sediment collected was transferred to 25 ml flasks, and 3 ml of water from the lagoon was added. The flasks (n=7) were closed with rubber stoppers, and the residual CH<sub>4</sub> and O<sub>2</sub> was removed by flushing with N<sub>2</sub> for 1 min, creating an anoxic and CH<sub>4</sub> free condition. The flasks were incubated statically in the dark in a constant temperature (25±0.5 °C) for 5 days. The CH<sub>4</sub> concentration in the headspace was measured by GC analysis (VARIAN Star 3400 – Varian Co., USA), with a FID detector temperature of

**Table 1.** Limnological parameters (depth, salinity, pH, pore water sulfate concentration and total nitrogen and phosphorus levels in water and N:P ratio) of the ten investigated coastal lagoons.

Lagoons	Depth (m)	Salinity (‰)	pH	Sulfate (mM)	Total Nitrogen ( $\mu\text{M}$ )	Total Phosphorus ( $\mu\text{M}$ )	N:P
Imboassica*	1.10	2.5	7.52	0.71	40.07	1.28	31
Iodada	1.80	0.1	5.16	0.33	-	-	-
Cabiúnas*	2.30	0.5	6.81	0.97	55.59	0.36	154
Comprida*	1.10	0.1	4.83	0.31	64.53	0.53	122
Carapebus*	0.80	4.1	7.48	2.41	66.95	0.62	108
Piripiri*	1.10	69.1	8.58	4.26	83.45	1.02	82
Paulista*	1.60	3.3	4.19	4.01	48.45	0.45	108
Garças*	0.10	1.5	3.55	6.64	121.29	1.84	66
Preta*	0.60	100	8.40	1.56	43.07	1.33	32
Visgueiro*	0.10	160	8.28	1.01	45.64	2.09	22

\*Mean total nitrogen and phosphorus. The data were collected between July 2000 and February 2003 (Enrich-Prast et al., 2004).

220 °C, an injector temperature of 120 °C, a 1 m Poropak-Q column (60/100 mesh) at 85 °C and  $\text{N}_2$  as the carrier gas.

#### 2.4. $\text{CH}_4$ concentration in the sediment

Sediment samples (5 mL) were collected using plastic syringes (n=3). The samples were stored in 25 ml flasks with 5 mL of NaOH (4%) to inhibit biological activity and expel the methane from the pore water (Casper, 1992). The flasks were closed with rubber stoppers and then shaken. The  $\text{CH}_4$  concentration in the flasks' headspace was measured as described previously earlier in the PMP section.

#### 2.5. Other measurements

The salinity was measured using a portable salinity, conductivity and temperature analyzer (YSI 30/10 FT), pH was measured using an Analion pH meter PM608, and depth was measured using a Secchi disc. The sulfate concentration in the sediment pore water was determined by the formation of barium sulfate (APHA, 1998). The remaining data were obtained from the Brazilian Long Term Ecological Research Program (PELD-LTER- site 5) and the ECOLAGOAS Project database.

#### 2.6. Data analyses

After testing for normality (using a Kolmogorov-Smirnov test) and homogeneity of variance, nonparametric analyses were used when a normal distribution was not observed. All of the statistical analyses were computed with GraphPad Prism 5.0 for Windows. We assumed a significant level of  $\alpha=0.05$  to indicate statistically significant difference.

Differences in potential  $\text{CH}_4$  production (PMP) rates among all of the lagoons were evaluated using

a Kruskal-Wallis one-way analysis of variance (ANOVA). We used Dunn's post-hoc test to evaluate differences among the lagoons. Differences among the sediment  $\text{CH}_4$  concentrations of the ten lagoons were tested using one-way ANOVA with a Tukey post-hoc test. We also investigated differences in the sediment  $\text{CH}_4$  concentration between the limnetic and littoral regions (aquatic macrophytes stands) for all of the lagoons that exhibited extensive aquatic macrophyte stands: the Cabiúnas, Carapebus, Comprida, Imboassica, Iodada and Paulista lagoons. A paired t-test was used to compare the means among these observations.

### 3. Results

The limnological parameters measured in the ten investigated coastal lagoons are presented in Table 1. All of the lagoons were shallow (0.10-2.30 m) and did not exceed 2.5 m water depth, which is characteristic of this ecosystem type as previously described. The salinity values varied considerably among the lagoons, ranging from freshwater (<5.0‰) to hypersaline (>40‰). Almost all of the studied lagoons are freshwater bodies, except Piripiri, Preta and Visgueiro, which exhibit salinity values greater than seawater (35‰), reaching levels up to 100‰ (Table 1). We found the highest pH values in these hypersaline environments, exceeding 8. The lowest pH values were found in the Garças, Paulista, Comprida and Iodada lagoons, ranged from 3.55 to 5.16 (Table 1). The pore water sulfate concentration varied from 0.3 mM in Comprida to 6.64 mM in Garças Lagoon. The total nitrogen concentration in the water ranged from 40.07  $\mu\text{M}$  in Imboassica Lagoon to 121.19  $\mu\text{M}$  in Garças Lagoon (Table 1), where the values were considerably higher

than in the other lagoons. The total phosphorus in the water ranged from 0.36  $\mu\text{M}$  in Cabiúnas to 2.09  $\mu\text{M}$  in Visgueiro Lagoon. The Imboassica, Preta and Visgueiro lagoons presented the lowest N:P ratios of 32, 31 and 22, respectively, whereas Cabiúnas had the highest ratio, reaching 154.

### 3.1. Potential $\text{CH}_4$ production rates of nine coastal lagoons

The PMP of Comprida Lagoon was not included in the statistical analyses, thus, only nine coastal lagoons were considered. Figure 2 shows a wide PMP variation among the lagoons, ranging from undetectable in Garças Lagoon to 4.33  $\text{nmol CH}_4 \text{ g}^{-1} \text{ day}^{-1}$  in Visgueiro Lagoon. Visgueiro exhibited the greatest  $\text{CH}_4$  production rate of all of the lagoons, but the rate was not significantly different from that in Preta, Piripiri, Imboassica and Cabiúnas. In addition, there was no significant difference in PMP among Carapebus, Paulista, Imboassica, Garças and Iodada, which showed low  $\text{CH}_4$  production rates.

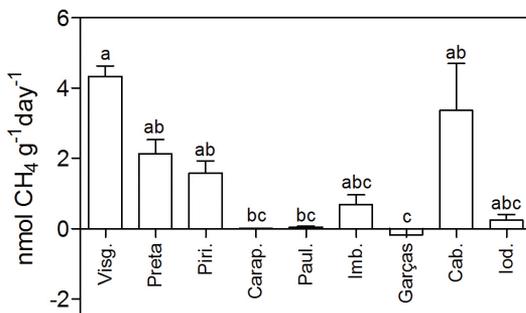
### 3.2. Sediment $\text{CH}_4$ concentration

#### 3.2.1. Differences among the ten coastal lagoons

The mean pore water  $\text{CH}_4$  concentration of the ten coastal lagoons ranged from 8.13  $\mu\text{M}$  in Imboassica Lagoon to 420.63  $\mu\text{M}$  in Preta Lagoon (Figure 3A). The former was significantly different from the others, and the remaining lagoons were all statistically similar (Figure 3A).

#### 3.2.2. Differences between the limnetic and littoral region (aquatic macrophytes stands)

The pore water  $\text{CH}_4$  concentration measured in the limnetic region and within aquatic macrophyte stands varied considerably between the two regions (Figure 3B). Iodada Lagoon had the greatest

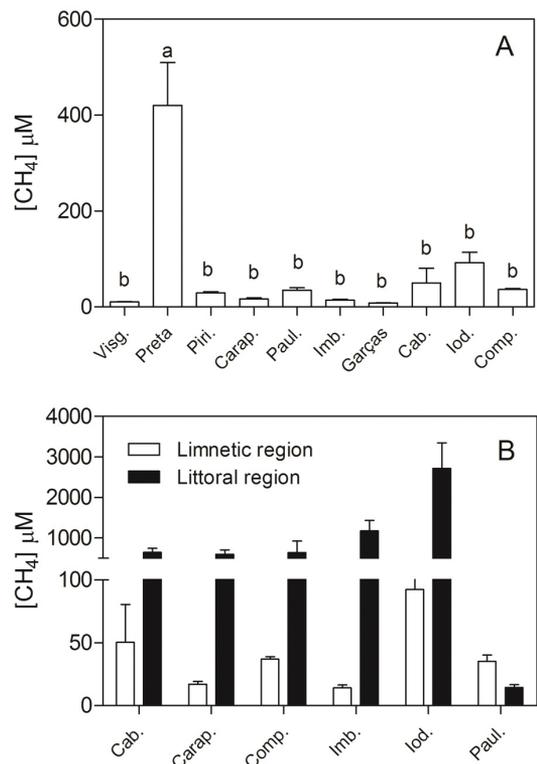


**Figure 2.** Potential  $\text{CH}_4$  production rates of nine coastal lagoons. Visg.–Visgueiro, Preta–Preta, Piri.–Piripiri, Carap.–Carapebus, Paul.–Paulista, Imb.–Imboassica, Garças–Garças, Cab.–Cabiúnas and Iod.–Iodada.

sediment  $\text{CH}_4$  concentration, with 2712.03  $\mu\text{M}$  in the littoral region. Imboassica Lagoon did not show the highest littoral region  $\text{CH}_4$  concentration values, but these values were eighty three times higher than those in the Imboassica limnetic region. Overall, the  $\text{CH}_4$  concentration in the littoral region was significantly different and higher than that in the limnetic region in all of the investigated lagoons except Paulista, which presented the opposite pattern (Figure 3B).

## 4. Discussion

Hypersaline and freshwater lagoons can be found side-by-side, depending on the particular drivers of hydrological balance, such as local precipitation, watershed inflow, evaporation rate and seawater influence (Kjerfve, 1994), which demonstrates that salt balance is intimately related to, but not limited to, water balance (Smith, 1994).



**Figure 3.** Sediment  $\text{CH}_4$  concentrations in pore water. **A**– Ten coastal lagoons. Visg.–Visgueiro, Preta–Preta, Piri.–Piripiri, Carap.–Carapebus, Paul.–Paulista, Imb.–Imboassica, Garças–Garças, Cab.–Cabiúnas, Iod.–Iodada and Comp.–Comprida. **B**– Difference between the limnetic and littoral regions of all of the lagoons that contain aquatic macrophyte stands. The lagoons are named as follows: Cab.–Cabiúnas, Carap.–Carapebus, Comp.–Comprida, Imb.–Imboassica, Iod.–Iodada and Paul.–Paulista. The bars indicate the means  $\pm$ SEMs.

The salinity also influences the pH, and most known methanogens are neutrophilic, suggesting that pH constrains  $\text{CH}_4$  production in wetlands. Our results indicated that the highest PMP rates were found in alkaline and hypersaline lagoons. However, some studies that quantitatively assessed the pH influence on methanogenesis in wetlands do not confirm a positive relationship between pH and  $\text{CH}_4$  production rates (Dunfield et al., 1993; Bergman et al., 1998). In addition to high pH values, high primary productivity and high sulfate concentrations are characteristic of many hypersaline aquatic systems (Oren, 2002). Sulfate concentrations are high in coastal lagoons compared to freshwater systems (only 100–200  $\mu\text{M}$ ) but lower in relation to seawater and estuarine systems (20–30 mM) (Capone and Kiene, 1988). Our results suggest that the present sulfate concentration of the coastal lagoons evaluated in this study does not affect methanogenesis because, high  $\text{CH}_4$  production values were found in the lagoons with high sulfate concentrations, highlighting the diminished importance of competition between the methanogenesis and sulfate reduction metabolic pathways in these systems, which is unexpected (Lovley et al., 1982; Oremland and Poucin, 1982).

High sulfate reduction rates have been measured in hypersaline brines, microbial mats and aquatic sediments at salinities exceeding 20‰ (Brandt et al., 2001; Daffonchio et al., 2006). Although some studies indicate that sulfate concentrations might not constrain  $\text{CH}_4$  production, sulfate-reducing bacteria usually compete with methanogens, inhibiting  $\text{CH}_4$  production by lowering the hydrogen partial pressure below a threshold level necessary for hydrogen utilization by methanogens (Lovley et al., 1982; Boone, 1991). In contrast, our results indicate that the Vigueiro, Preta and Piripiri lagoons showed the greatest PMP rates, suggesting that the competition between these two groups of bacteria is weak, which can be explained by the presence of noncompetitive substrates, such as betaine, trimethylamine and methylated sulfides (Zinder, 1993). Noncompetitive substrates result from organisms' osmoregulatory strategies which consist of an intracellular accumulation of inorganic ions, such as sodium ( $\text{Na}^+$ ), to survive in salt water. However, high concentrations of inorganic ions often have deleterious effects; thus, these ions are progressively replaced by organic solutes that are produced within organismal cells' (Martin et al., 1999). Therefore, organisms that inhabit high salinity conditions can favor the

accrual of these organic solutes, which are used only by methanogens (Martin et al., 1999; Boone, 1991). In addition, the salt influence inhibits the colonization by aquatic macrophytes (Glenn et al., 1995). Without shading by aquatic macrophytes, the benthic compartment can be colonized by microalgae and other microorganisms forming a microbial mat. The Vigueiro and Piripiri lagoons exhibit microbial mats, which can possibly increase the OM input in the system and provide substrates for methanogenesis (Enrich-Prast et al., 2004). Moreover, C:N:P ratios are significant in several important ecological processes, such as litter decomposition (Güsewell and Gessner, 2009). In the present research, the low N:P ratio value in the water of Vigueiro Lagoon (Table 1), can also explain the highest PMP rates observed there, as a function of the labile OM input via particulate deposition in the water column.

In contrast to the hypersaline systems, Cabiúnas is a freshwater lagoon that is densely colonized by aquatic macrophytes and has high PMP rate. The effect of macrophytes on  $\text{CH}_4$  dynamics is well investigated, and their presence may explain some of the PMP results found for this particular system. Aquatic macrophytes contribute as suppliers of organic material through root exudates and plant litter production, which can account for 50% of the nutrients and OM input in an entire aquatic system (Wetzel, 2001). Ding et al. (2002) noted that labile organic carbon for  $\text{CH}_4$  production is mainly derived from plant litter, which can be more resistant to decomposition, such as emergent macrophytes, or be more labile, such as floating leaves or submerged macrophytes (Farjalla et al., 1999). We believe that OM inputs via macrophytes may subsidize microbiological process in sediments, favoring oxygen consumption and supporting methanogenesis. Particularly in this sampling year, Cabiúnas Lagoon was vastly colonized by the submerged macrophyte *Potamogeton stenostachys*, and according to Brum and Esteves (2001), this macrophyte species detritus decomposes five times faster than regular emergent macrophyte species that are, usually dominant in these systems. Therefore, because *Potamogeton stenostachys* is a labile OM source and abundant in the sediment of Cabiúnas Lagoon, it possibly altered the OM input into the sediment, enhancing methanogenesis. Our results consistently indicate a positive influence of the presence of aquatic macrophytes, which is also corroborated by the comparison between limnetic and littoral region pore water  $\text{CH}_4$  concentrations

in our study and others (Chan et al., 2002; Bastviken et al., 2010; Neves et al., 2011). Almost all of the lagoons showed much higher sediment  $\text{CH}_4$  concentrations in the littoral region than in the limnetic region. Such differences have also been reported by Fonseca et al. (2004) in the Cabiúnas Lagoon, who measured high  $\text{CH}_4$  concentrations in sediments colonized by macrophytes such as *Typha domingensis*.

An interesting pattern observed in the present study is that high production rates are not always followed by a high  $\text{CH}_4$  concentration in sediments. In the limnetic region, the pore water  $\text{CH}_4$  concentration, even in the lagoons that showed high PMP rates, was relatively lower and not significantly different among the lagoons, except for Preta Lagoon. We believe that other factors can influence the  $\text{CH}_4$  concentration. The  $\text{CH}_4$  produced in anaerobic sediments of these ecosystems, can be oxidized in the aerobic zone by methanotrophic bacteria, or even anaerobically, often related to sulfate reduction (Schubert et al., 2010; Meulepas et al., 2010). During this process, these organisms consume large amounts of  $\text{CH}_4$ , a process that has been a biogeochemical enigma for many years regarding anoxic marine sediments. Nearly 90% of the  $\text{CH}_4$  produced in anoxic marine sediments is recycled through anaerobic oxidation processes (Hinrichs et al., 2000). Anaerobic  $\text{CH}_4$  oxidation in freshwater systems could be possible if sulfate concentrations reach approximately 1 mM (Segers, 1998), a requirement that is met by the coastal lagoons in the present study. In

summary, the sediment  $\text{CH}_4$  concentration results from the balance between methanogenesis and methanotrophy (aerobic or anaerobic oxidation). The low depth of the water column in Visgueiro Lagoon and other shallow aquatic bodies can favor mixing due to wind action, causing system oxygenation, which can result in high  $\text{CH}_4$  oxidation and/or inhibition of the  $\text{CH}_4$  production in the surface sediments. Such a process could, also explain the high PMP rates and low pore water  $\text{CH}_4$  concentration in the sediments of the lagoons studied here.

Rates of PMP have been determined in a large number of studies in various natural wetlands, rice fields and other ecosystems. The available data (Table 2) suggest that rice paddy soils are the greatest producers, perhaps due to the large amount of available organic carbon and anaerobic conditions, a hypothesis that is also corroborated by other studies (Reeburgh, 1996; Yang and Chang, 1998). Compared to other ecosystems, the  $\text{CH}_4$  production rates observed in the studied lagoons were low. For the shallow Arabian Sea, researchers observed  $\text{CH}_4$  production of  $150 \text{ nmol g}^{-1} \text{ day}^{-1}$ ,  $95 \text{ nmol g}^{-1} \text{ day}^{-1}$  in a mangrove estuary and a surprisingly high rate of  $36 \text{ nmol g}^{-1} \text{ day}^{-1}$  in the sandy beach sediments. Marinho et al. (2012) also investigated the  $\text{CH}_4$  production rate in mangroves, and their results were similar to what we found in some coastal lagoons. Zaiss (1996) found  $87 \text{ nmol g}^{-1} \text{ day}^{-1}$  in a freshwater lagoon. However, the greatest PMP rate of a freshwater lagoon (Cabiúnas) in our study was only  $3.36 \text{ nmol g}^{-1} \text{ day}^{-1}$ . In an earlier study

**Table 2.** Comparison of the potential methane production (PMP) rates from different ecosystem types.

Ecosystem Type	Sediment PMP rates at 25 °C ( $\text{nmol CH}_4 \text{ g}^{-1} \text{ day}^{-1}$ )	References
Salt marsh	1.3	Zaiss, 1996
Vigueiro Lagoon	4.33	Present study
Zoige alpine wetland, Tibet	1.75*	Tian et al., 2011
Ace lake, Antarctica	2.5	Franzmann et al., 1991
Mangrove Coroa Grande, Brazil	2.7 to 3.2	Marinho et al., 2012
Arabian Sea – Shallow Arabian Sea	150	Gonsalves et al., 2011
Mangrove estuary	95	Gonsalves et al., 2011
Sandy beach	36	Gonsalves et al., 2011
Rice paddy soils, Philippines	999*	Yao et al., 1999
Italy	1250*	Yao et al., 1999
Hudson Bay lowland – <i>Sphagnum</i> -dominated peatland	10	Dunfield et al., 1993
Sedge-dominated peatland	≈12	
Swedish lakes	0.037 to 3.99*	Duc et al., 2010
Freshwater Lagoon	87	Zaiss, 1996
Cabiúnas Lagoon	3.36	Present study
Cabiúnas Lagoon	n.d.	Furtado et al., 2002

\*Temperature of the incubation: 30°C.

performed by Furtado et al. (2002) in the same lagoon, PMP was undetectable, possibly due to the absence of substrates. However, in general, regions colonized by aquatic macrophytes often exhibit high PMP rates (Dunfield et al., 1993).

Methane production is an important environmental issue in the context of concerns about global climate change. The relative contributions of different natural sources to global atmospheric methane emissions are 76% from wetlands, 11% from termites, 8% from oceans and 5% from hydrates (IPCC, 2001). Despite the fact that wetlands only occupy 3.8% of the earth's land surface (Aselmann and Crutzen, 1989), they have an important role in CH<sub>4</sub> dynamics. Our results suggest that the sediments of saline lagoons are important CH<sub>4</sub> production sites, and aquatic macrophytes generally have a positive influence on methanogenesis, which was evident in the CH<sub>4</sub> concentration in the sediments. Although our study does not provide all of information that we need to explain differences in CH<sub>4</sub> production rates and concentrations, we were able to provide a fundamental background on the main environmental factors acting on these particular systems. Due to the environmental complexity usually associated with these aquatic ecosystems, further studies should focus on the processes underlying the CH<sub>4</sub> patterns observed in these systems, especially regarding the coupling between CH<sub>4</sub> production and concentration.

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