OECOLOGIA BRASILIENSIS
Farjalla, V.F.; Faria, B.M.; Esteves, F.A. & Bozelli, R.L. 2001. Bacterial density and biomass, and relations with abiotic factors, in 14 coastal lagoons of Rio de Janeiro State. pp. 65-76. In: Faria, B.M.; Farjalla, V.F. & Esteves, F.A. (eds). *Aquatic Microbial Ecology in Brazil.* Series Oecologia Brasiliensis, vol. IX. PPGE-UFRJ. Rio de Janeiro, Brazil.

BACTERIAL DENSITY AND BIOMASS, AND RELATIONS WITH ABIOTIC FACTORS, IN 14 COASTAL LAGOONS OF RIO DE JANEIRO STATE

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Resumo

Densidade e biomassa bacteriana, e relações com as variáveis abióticas, em 14 lagoas costeiras do Estado do Rio de Janeiro. O objetivo desta pesquisa foi avaliar a densidade e a biomassa bacteriana na coluna d'água de 14 lagoas costeiras do Estado do Rio de Janeiro. Além disso, as variáveis bacterianas foram correlacionadas com os valores de clorofila *a* e com variáveis abióticas, como salinidade e concentração de nutrientes. Foram observados altos valores de densidade e biomassa bacteriana nestas lagoas, principalmente em lagoas com alta salinidade. Nestas lagoas salgadas, também observamos uma forte dominância de bastonetes longos, que contribuem com os altos valores de biomassa. Nós concluímos que, durante o período estudado, estas lagoas com alta salinidade podem ser consideradas ambientes extremos, selecionando poucas espécies de bactérias que podem viver nelas. Há uma forte correlação entre a densidade e a biomassa bacteria com a concentração de fósforo nestas lagoas. Nenhuma outra correlação foi encontrada entre os valores de biomassa bacteriana e densidade bacteriana com outros fatores abióticos ou concentração de clorofila *a*. Neste caso, o fósforo pode ser considerado o principal nutriente limitante ao crescimento bacteriano na maioria destas lagoas. Estas lagoas costeiras apresentaram altas concentrações de carbono orgânico dissolvido (COD), porém concentrações similares não resultaram em colorações semelhantes da água. Foi concluído que o COD destas lagoas têm origens diferentes, o que pode interferir na utilização deste pela comunidade bacteriana.

Palavras-chave: biomassa bacteriana, densidade bacteriana, lagoas costeiras, salinidade, concentração de nutrientes.

Abstract

The aim of this study was to evaluate the bacterial density and biomass in the water column of 14 coastal lagoons of Rio de Janeiro State. Furthermore, we relate these bacterial variables with chlorophyll *a* concentrations and abiotic factors, such as salinity and concentration of nutrients. High values of bacterial density and biomass were observed in these lagoons, mainly in lagoons with high salinity. In salty lagoons, we also observed a strong dominance of long rods, which contribute to the high biomass observed. We conclude that, during the period observed, these lagoons with high salinity can be considered extreme environments, selecting few species of bacteria that could live there. There is a strong correlation between bacterial density and biomass with phosphorus concentration in these lagoons. No other correlation among bacterial density and biomass with abiotic factors or chlorophyll *a* were found. Thus, in this case, phosphorus can be considered the main limiting nutrient to bacterioplankton in most of these coastal lagoons. These coastal lagoons presented high concentrations of dissolved organic carbon (DOC), but similar concentrations did not result in similar water color. We conclude that the DOC from these lagoons must have different origins, which can interfere in its utilization by the bacterial community.

Key-words: bacterial biomass, bacterial density, coastal lagoons, salinity, nutrient concentration.

Introduction

Bacteria are widely regarded as an important component of aquatic ecosystems, and their function and metabolism have been exhaustively studied in the last two decades (Søndergaard, 1997). This fact is related mainly with the establishment of the "microbial loop" concept by Pomeroy (1974), and lately by Azam (1983). As per this concept, bacteria assimilate the DOC in the water and convert it to biomass or to CO_2, during the respiration process. Bacteria can also be predated by protozoa and zooplankton organisms, establishing an important link between the dissolved nutrients and the higher trophic levels. In this case, bacteria are considered secondary producers of aquatic ecosystems and their production can be higher than primary production in some environments (Cole *et al.*, 1988; Simon *et al.*, 1992). However, despite their importance as freshwater reservoirs, only few studies related to bacterial metabolism were performed in tropical aquatic ecosystems, with just few of them were performed in coastal lagoons.

Coastal lagoons are important aquatic ecosystems to the surrounding human communities, as a source of water, food (fish, crabs, shrimps), or as a leisure area. In Brazil, tropical coastal lagoons are present, mainly, in Rio de Janeiro, Rio Grande do Sul and some northeast States. These lagoons are formed by sedimentation of bays or river estuaries, or by emergence of the water table, and are characterized by a sandbar, which separates them from the ocean (Esteves, 1998). The disruption of the sandbar by human action or by natural forces, such as the wave action or an excessive filling up of the lagoon, promotes changes between freshwater and marine water, with direct effects on the homeostasis of the ecosystem. Thus, the alterations promoted by sandbar opening, such as increase in salinity, are important abiotic factors in these lagoons, regulating the biotic communities of the lagoon, including the bacterial community (Caumette, 1992).

Salty lagoons are particularly interesting to microbial ecology, since large organisms disappear early in the salinity gradient, and predominantly or exclusively microbial communities are found in environments with high salinity (Pedrós-Alió *et al.*, 2000). Ecological studies in these environments have been limited to descriptions of the peculiar organisms found at different salinities (halophilic and halotolerant microorganisms and microbial mats), with attention to their respective salinity ranges, but with little concern in quantification of their biomass and activities (Rodríguez-Valera *et al.*, 1981; Cohen & Rosenberg, 1989). Study of the bacterial community in salty lagoons also provides an additional advantage, since the microbial food web in these ecosystems is short, formed only by prokaryotic function, and the microbial loop paradigm can be easily tested. Furthermore, salty lagoons can be considered extreme environments, and are actually a focus of considerable attention due to the increase of widespread distribution of extreme environments, related to global climatic changes (see review Fenchel *et al.*, 1998).

Lagoons with low salinity and low depth are usually characterized by large stands of aquatic macrophytes. According to Wetzel (1990), in small lakes, the aquatic macrophytes, as well as the surrounding vegetation, drive the metabolism of the ecosystem, mainly as sources of carbon (Wetzel, 1990). This important extra source of carbon allows for an increase in bacterial biomass, especially in comparison with oceanic waters (Simon *et al.*, 1992). Therefore, a great fraction of the DOC found in these environments is related to the high concentrations of humic substances originated in the process of decomposition of the surrounding vegetation (Wetzel, 1993), resulting in the dark color of some of these coastal lagoons.

In this paper, we describe the bacterial numbers and biomass in 14 coastal lagoons and relate them to some abiotic variables, such as salinity and nutrients concentration, water color and chlorophyll *a* concentrations.

Material and Methods

This study was performed in 14 lagoons located in the Restinga de Jurubatiba National Park (Fig. 1), in the North of Rio de Janeiro State, Brazil (22° - 22° 30' S and 41° 15' - 42° W). Water samples were collected, in April/2000, in 2 L plastic bottles previously rinsed with HCl 10% and deionized water and we measured, in each lagoon, the water temperature, electrical conductivity and salinity with YSI conductivimeter (model 30SET).

The samples were kept in constant temperature and, in the laboratory, we measured the pH and alkalinity with an Analion pHmeter (model PM-603) and the absorbance at 430 nm, as an indication of water color. We also fixed 18 ml of each sample with buffered formaline (final concentration, 3.7%) for bacterial density and biomass measurements.

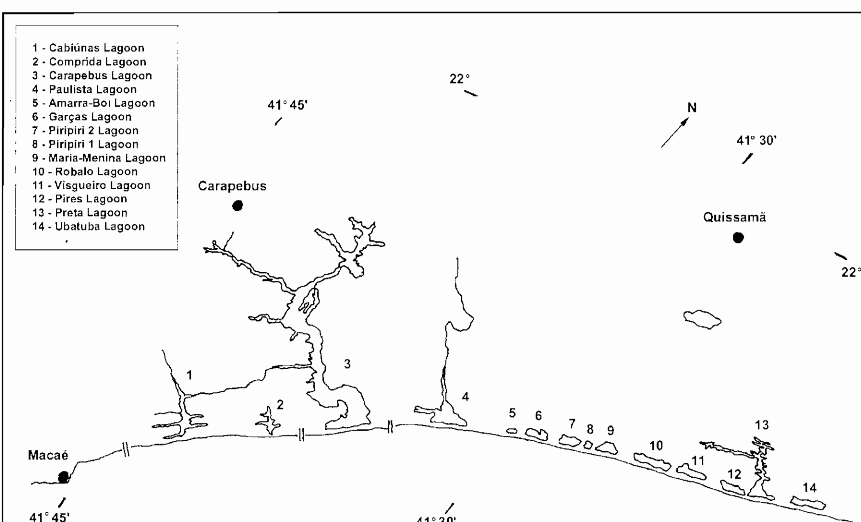

Figure 1. Schematic map of localization of 14 studied lagoons.

The water samples were filtered in GF/C 47 mm filters for chlorophyll *a* and nutrient analyses. Chlorophyll *a* was extracted with Ethanol 90% and measured through the absorbance at 665 nm (Nusch & Palme, 1975). Total dissolved nitrogen concentrations were obtained through digestion at 320 °C and distillation, in accordance to Mackereth *et al.* (1978). Total dissolved phosphorus measurements were made by autoclaving and formation of ammonium molibdate (Golterman *et al.* 1978). Dissolved organic carbon (DOC) measurements were made by Pt-catalysed, high-temperature combustion using a Shimadzu TOC-5000 total carbon analyzer. In this case, the samples were purged with HCl (2 M, final pH~2) to minimize the effect of high salinity in some lagoons.

For obtaining bacterial density and biomass data, we used the methods proposed by Hobbie *et al.* (1977) and Fry (1988), respectively. Therefore, slides stained with acridine orange (final concentration of 0.01%) were prepared and the bacteria counted and measured in an epifluorescence microscope (Axiovert Zeiss Universal), with the use of an ocular micrometer, at a 1600-fold magnification. The bacteria were divided in three separate classes (rods, cocci, and vibrios), and at least 300 bacteria or 30 fields per slide were counted. Controls were made with sterilized water and when these controls reached values above 1% of the values found in the samples, they were discarded and the slides were prepared again. Randomly, in each slide, approximately 10% of the counted bacteria were measured, considering the three separate classes. The biovolume was estimated as proposed by Fry (1990) and converted to biomass through the conversion factor of 308 fg C μm^{-3} proposed by Fry (1988).

Results

These coastal lagoons comprise a large spectrum of concentration of salts, conductivity, pH values and water color (Table 1). Visgueiro lagoon showed the higher values of salinity (71.4 ‰), approximately twice as high as the adjacent ocean (35 ‰). On the other hand, Cabiúnas, Comprida, Carapebus, Paulista and Amarra-Boi lagoons showed concentrations of salts lower than 1‰. The conductivity values have also shown a large variation, related mainly to concentration of salts ($R^2 = 0.99$, $p < 0.05$). Water temperature was high during the sampling time in which the lowest value (27.3 °C) was found in Paulista lagoon and the highest value (38.4 °C) in Robalo lagoon. We found the lowest pH value in Amarra-Boi lagoon (3.91) and the highest pH value in Visgueiro lagoon (9.55). On the other hand, absorbance at 420 nm was highest in Amarra-Boi lagoon (0.315) and lowest in Visgueiro lagoon (0.005), showing a negative correlation with pH values ($R^2 = 0.85$, $p < 0.05$).

Chlorophyll *a* and nutrient concentration also varied among these lagoons (Table 1). Chlorophyll *a* concentrations were generally low in these lagoons, except in Preta lagoon (136.44 $\mu g\ l^{-1}$). The lowest concentration of nutrients was found in Cabiúnas lagoon whereas the highest concentration of DOC was found in Visgueiro lagoon (7.46 mM C) and the highest concentrations of dissolved nitrogen (DN) and dissolved phosphorus (DP) were found in Robalo lagoon (146.3 μM N and 3.32 μM P). NP ratio varied from 591:1 in Garças lagoon to 44:1 in Robalo lagoon.

Table 1. Measurements of salinity, conductivity, temperature, pH, water color, DOC, DN, DP and chlorophyll *a* measurements in the 14 coastal lagoons. ND - Not determinated.

Lagoons	Salinity (‰)	Conduct. (mS cm^{-2})	Temp. (°C)	pH	Abs 430nm	DOC (mM)	DN (μM)	DP (μM)	NP ratio	Chl a (μg l^{-1})
Cabiúnas	0.1	0.4	ND	6.72	0.060	1.05	30.6	0.10	306:1	1.36
Comprida	0.1	0.1	ND	4.34	0.181	3.11	62.2	0.16	389:1	3.27
Carapebus	0.2	0.4	ND	7.63	0.031	1.57	63.3	0.35	181:1	2.33
Paulista	0.3	0.6	27.3	6.99	0.094	2.27	65.5	0.34	193:1	1.33
Amarra-Boi	0.2	0.4	34.6	3.91	0.315	7.04	138.9	0.38	366:1	3.75
Garças	8.2	14.3	31.9	9.25	0.077	4.68	141.9	0.24	591:1	6.32
Periperi 2	41.0	61.3	29.3	8.82	0.032	3.84	80.8	0.39	207:1	2.69
Periperi 1	32.4	50.0	33.4	8.84	0.032	5.28	144.1	0.62	232:1	5.73
Maria Menina	24.0	38.0	31.7	8.21	0.066	3.70	114.6	0.93	123:1	7.70
Robalo	37.3	56.8	34.8	8.91	0.020	3.44	146.3	3.32	44:1	0.83
Visgueiro	71.4	99.5	34.0	9.55	0.005	7.46	133.2	1.69	79:1	1.44
Pires	28.9	44.9	32.8	9.19	0.021	2.19	97.2	1.20	81:1	9.08
Preta	29.5	45.4	28.6	9.27	0.034	3.45	63.2	0.82	77:1	136.44
Ubatuba	14.3	23.3	29.1	8.96	0.010	1.54	111.4	0.47	237:1	7.34

These lagoons showed bacterial numbers varying between 0.76 * 10^{10} to 5.16 * 10^{10} cells l^{-1} and bacterial biomass varying between 0.45 to 14.32 mg C l^{-1}, respectively the highest and lowest values in Paulista and Visgueiro lagoons (Table 2). In lagoons with high values of salinity (except Piripiri 1, 2 and Maria Menina lagoons), we observed a strong dominance of rods (73 - 97 %) among the other bacterial classes. On the other hand, we observed an equilibrium among classes in lagoons with low concentration of salts (Table 2).

Table 2. Bacterial density and biomass in the 14 coastal lagoons.

Lagoons	% rods in bacterial numbers	% cocci in bacterial numbers	% vibrios in bacterial numbers	bacterial numbers * 10^{10} céls l^{-1} (SD)	% rods in bacterial biomass	% cocci in bacterial biomass	% vibrios in bacterial biomass	Bacterial Biomass mg C l^{-1}
Cabiúnas	41.3	17.6	41.1	0.89 (0.22)	57.4	5.5	36.4	0.61
Comprida	47.3	22.6	28.9	0.77 (0.13)	47.9	12.0	38.2	0.48
Carapebus	47.6	19.1	32.3	1.05 (0.18)	56.9	8.7	32.4	0.70
Paulista	51.6	20.3	28.8	0.76 (0.21)	56.8	6.7	36.2	0.45
Amarra-Boi	50.1	37.0	12.7	3.84 (0.44)	55.4	13.1	31.1	2.03
Garças	45.3	12.0	45.9	3.29 (0.42)	39.0	3.3	55.1	2.61
Periperi 2	25.1	25.8	43.2	1.48 (0.87)	24.7	8.1	58.9	1.10
Periperi 1	37.4	13.3	39.0	1.72 (0.37)	34.6	3.4	48.2	1.39
Maria Menina	44.2	13.9	41.2	2.87 (0.59)	67.1	2.1	30.0	3.18
Robalo	96.9	2.7	0.4	3.74 (0.22)	99.2	0.4	0.4	7.85
Visgueiro	95.7	2.9	1.3	5.16 (0.83)	98.6	0.2	1.2	14.32
Pires	94.6	4.3	1.1	3.83 (0.32)	98.8	0.3	0.9	9.81
Preta	80.8	2.5	16.7	4.06 (0.38)	90.6	0.4	8.9	5.64
Ubatuba	72.7	10.0	16.8	1.52 (0.37)	82.7	1.6	15.4	2.28

A strong correlation between bacterial numbers ($R^2 = 0.80$; $p < 0.005$) and biomass ($R^2 = 0.87$; $p < 0.05$) with DP concentration was found. No other correlation was found among bacterial numbers and biomass with other abiotic measurements. Bacterial numbers and biomass also presented a strong correlation between them ($R^2 = 0.86$; $p < 0.005$).

Discussion

From the 80's on, after the establishment of the microbial loop paradigm, bacteria were recognized as important producers in aquatic ecosystems, mainly in oligotrophic ecosystems, where the phytoplankton primary production is low. In these 14 lagoons, we observed low concentrations of chlorophyll *a* (Table 1), varying between 0.83 to 9.07 μg Chl *a* l^{-1} (except Preta lagoon), characterizing most of these lagoons as oligo or mesotrophic (Vollenweider & Kerekes, 1980). In this case, bacteria might be important producers in these ecosystems, sustaining part of the zooplankton and fish biomass, through the microbial loop food chain.

In aquatic ecosystems, bacteria can be limited by a large number of factors, divided in top-down and bottom-up factors. Top-down factors are related mainly to predation by higher trophic levels (protozoa, zooplankton) and to cellular lysis by virus action (Bergh et al., 1989; Stabell, 1996; Christoffersen *et al.*, 1997; Jürgens *et al.*, 1997), while bottom-up factors are related with limitation by low concentration of some nutrient, usually DOC, nitrogen or phosphorus (Elser *et al.*, 1995; Kirchman & Rich, 1997; Cotner *et al.*, 1997) or, more rarely, by low temperatures (Felip *et al.*, 1996). Billen *et al.* (1990) and Pace & Cole (1994, 1996) showed that bottom-up factors are main factors regulating bacteria, especially in oligotrophic aquatic ecosystems. We observed in these lagoons an unbalance between the ratios of the three main nutrients (DOC, DN and DP) with high concentrations of DOC and DN when compared with DP concentration. It can also be observed in the high NP ratios observed in these ecosystems (Table 1). According to Farjalla (1998), bacterial production in Carapebus, Comprida e Cabiúnas lagoons are limited by the low concentrations of phosphorus. We also found a strong correlation between bacterial density and DP concentration, as well as bacterial biomass and DP concentration, in these 14 lagoons ($R^2 = 0.80$ and 0.86, respectively). Thus, phosphorus seems to be the most important bottom-up factor, regulating bacterial communities in coastal lagoons of Rio de Janeiro State. However, other factors, as temperature, salinity, DOC origins and biotic factors should be important in the control of bacterial communities in these lagoons.

Most of the 14 lagoons studied here are temporary, with a reduction in the water level during dry months. At this time, there is an accumulation of salt and nutrients in few centimeters of water column. In April, the sampling month, several lagoons, namely Ubatuba, Pires, Visgueiro, Robalo, Maria Menina, Periperi 1, Garças and Amarra-Boi, presented water columns restricted to few centimeters. In these lagoons, there is a great increase in the water temperature during the day, due to the small water column and the high salinity, which increase the water heat capacity. This can be observed by the high water temperature in these lagoons (Table 1) during the sampling time (~11:00). It has been reported that this increase in the water temperature might cause several changes in bacterial metabolism, such as an increase of bacterial production.

We also observed high concentrations of DOC in these lagoons, with values achieving 7.46 mM DOC (~80 mg C l^{-1}) in Visgueiro lagoon. These concentrations are considered very high, especially when compared with aquatic ecosystems considered humic (Tranvik, 1989; Amblard *et al.*, 1995; Lindell *et al.*, 1995). However, there is no correlation between DOC concentration and water color in these lagoons. Thus, lagoons with similar DOC concentrations did not present the same water color, and the DOC from these lagoons might have different origins.

Lagoons with low salinity (Cabiúnas, Comprida, Carapebus, Paulista and Amarra-Boi) usually present large stands of aquatic macrophytes, dominated by *Typha domingensis*, *Eleocharis interstincta*, *Nymphaea ampla* and *Potamogeton stenostachys* (Farjalla *et al.*, 1999). These lagoons are also surrounded by "restinga" vegetation, a shrub vegetation located in coarse sandy soil. Due to the sandy soil, the decomposition products of "restinga" plants are percolated to the lagoons by the rain action. These products, generally humic substances, together with the humic substances originated in the decomposition of aquatic macrophytes, account for the dark color characteristic of these lagoons (Table 1). Thus, in lagoons with low salinity, the DOC is originated in the decomposition of aquatic macrophytes and restinga vegetation, being composed mainly of humic substances. On the other hand, lagoons with high salinity also showed high concentrations of DOC; however this did not result in the darkening of water color. These lagoons are all temporary, and the DOC might be originated by phytoplankton exudates, mainly by the layer of cells above the sediment. This carbon is concentrated during the drawdown period, explaining the high concentration not associated with dark color.

The salt concentration is also an important factor in the structure of bacterial communities of aquatic ecosystems. According to Pedrós-Alió *et al.* (2000), increases in salinity resulted in an increase in biomass of prokaryotes, with a maximum activity of both phyto-and bacterioplankton found at a salinity around 100 ‰. Changes in bacterial composition have also been recorded through the isolation of pure cultures from different saltern ponds (Rodríguez-Valera *et al.*, 1981). Thus, halotolerant bacteria predominate with the increase in salinity, being substituted by halophilic bacteria and halophilic archaea (Oren, 1990ab). The progressive increase in salinity makes each lagoon a more extreme environment than the former and this, according to ecological theory, should cause a decrease in the number of species present, and increase the endemism.

We observed high bacterial densities in these coastal lagoons, archiving 5 * 10^{10} cells l^{-1} in Visgueiro lagoon, and the higher densities found generally in salty lagoons (Table 2). These values of bacterial densities are close to the upper limit to bacterial densities found in the literature for freshwater ecosystems (Pedrós-Alió & Guerrero, 1991) and they are similar to the values found in other saline environments (10^{10} to 10^{11} cells l^{-1}, Oren, 1990ab; Pedrós-Alió *et al.*, 2000). We have also observed high values of bacterial biomass, with the higher values found in salty lagoons. These values are linked with the high bacterial density but mainly with the high bacterial biovolume, associated with the dominance of long rods in these ecosystems (Table 2). Based on the proportion among the three main classes of bacteria (rods, cocci, vibrios), bacterial diversity is slightly lower in lagoons with high salinity when compared with lagoons with low salinity. Lagoons with high salinity can be considered extreme environments, with only few species able to exploit these ecosystems and the decrease in bacterial diversity is expected (Fenchel *et al.*, 1998). Pedrós-Alió *et al.* (2000) also found large dominance of long rods and square-shaped archaea (mean cellular size of 0.72 μm^3) in saltern ponds of Barcelona.

However, how can these lagoons have high concentrations of carbon and high bacterial biomass? Are bacteria inactive in these ecosystems? Farjalla (1999), studying the bacterial density, biomass and secondary productivity in Cabiúnas, Comprida e Carapebus lagoons suggested that DOC accumulates in these ecosystems mainly due to low efficiency of the microbial loop in these ecosystems. In this case, the bacteria might be limited by low concentrations of phosphorus or by the low quality of DOC molecules, resulting in accumulation of DOC which is not mineralized nor used by other trophic levels by predation on bacteria.

Finnaly, we suggest further research on the bacterial metabolism in these ecosystems, focusing on bacterial production, biomass and respiration (BGE measurements). It will be also important to study the bacterial diversity in these ecosystems, mainly in the salty lagoons, to better understand which bacteria can live in these extreme environments and how their food web works.

Acknowledgments

The authors thank Paulo Roberto Brum for improvements in English translation and CNPq and PETROBRAS for financial support during this research. Vinicius Farjalla especially thanks CNPq for PhD schollarship during this research.

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