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LONG-TERM CHANGES IN SANITARY CONDITIONS AND ZOOPLANKTON COMMUNITY IN THE IMBOASSICA LAGOON (RIO DE JANEIRO, BRAZIL): EFFECTS OF SANDBAR OPENINGS

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Abstract: The present study investigated the intra-ecosystem variability of nutrient enrichment (nitrogen -N- and phosphorus -P-), density of faecal coliforms (*i.e.*, as a proxy of sanitary conditions), and ecological responses of the zooplankton community structure in a tropical urban coastal lagoon, following eutrophication, changes in rainfall, and episodic sandbar openings. Surface waters were monthly taken over 14 years (1992-2005) within the long-term monitoring program ECOlagoas from two sampling stations at the Imboassica lagoon (Northern of the Rio de Janeiro State, Brazil): near a domestic wastewater channel (SEWAGE station), and at the limit to the sea (SANDBAR station). Changes in faecal coliforms and nutrient concentration reduced water quality due to untreated sewage inputs, which was intensified by artificial sandbar openings mainly under low rainfall, such as observed in February 2001. Indeed, a greater depth and subsequent volume of water of the Imboassica lagoon during the acidification period (*i.e.*, attributed to the increased rainfall, and lower frequency of sandbar openings) contributed to dilute the faecal coliform only in the SANDBAR station. In turn, the zooplankton community structure showed that episodic sandbar openings promoted the loss of their functional features derived from a reduction and replacement of species over time, even in the period of lower frequency of sandbar opening and dilution of nutrient concentrations. Our findings indicate that sandbar openings are not the best management practice when facing coastal eutrophication, once it may cause harmful effects on sanitary conditions and ecological community related to zooplankton, mainly in periods of decline in rainfall.

Keywords: Disturb; Ecological indicators; Eutrophication; Faecal coliforms; Tropical Coastal Lagoon.

INTRODUCTION

Coastal lagoons cover approximately 13% of coastlines worldwide (Barnes 1980), showing high productivity (Knoppers 1994) and supporting a wide range of human activities (Newton *et al.* 2014). These transitional ecosystems with high biodiversity (López-Herrera *et al.* 2021) play a critical role to regulate water flow, nutrient fluxes, and organisms from land and inland waters to the ocean (Newton *et al.* 2014). The main environmental ecosystem services of coastal lagoons include water uses, ecological habitat for numerous commercial species, life quality, and income derived from services, such as tourism and recreation (Anthony *et al.* 2009, Ferreira & Freire 2009),

Despite ecological services and uses, human activities in the watershed have resulted in filling up (Millennium Ecosystem Assessment 2005), and nutrient enrichment (Rabalais *et al.* 2009) by deforestation, fertilizers, urban sprawl, and aquaculture (Pérez-Ruzafa *et al.* 2011, García & Muñoz-Vera 2015), especially in developing countries (Fauzi *et al.* 2014). Such conditions promote coastal eutrophication (Middelburg & Levin 2009), one of the most common global change in the last decades (Diaz & Rosenberg 2008), which has resulted in harmful consequences associated with the ecological and sanitary degradation of lagoon waters. The severe eutrophication in urban lagoons derives from the input of organic matter and nutrients from untreated sewage discharges (Esteves 1998, Bettencourt *et al.* 2013), contributing to hypoxia or anoxia, algal blooms, and loss of water quality and biodiversity (Breitburg *et al.* 2018). A common proxy of untreated sewage inputs in aquatic ecosystems is the elevated level of faecal coliforms, obtained from monitoring actions (Pawar 2016).

In developing countries, coastal lagoons have been highly degraded by anthropogenic activities (Esteves *et al.* 2008). One of most common management practices to reduce the sanitary degradation in Brazilian lagoons is the increase of water exchange with the sea by artificial sandbar openings (Suzuki *et al.* 1998, Suzuki *et al.* 2002, Ferreira & Freire 2009, Cezar *et al.* 2015). However, sandbar openings have also resulted in ecological (Crippa *et al.* 2013, Lanés *et al.* 2015) and even sanitary degradation (Bozelli *et al.* 2009, Lopes & Bozelli 2014) whose direct and indirect effects can be alleviated or exacerbated through interactive effects with dynamic environmental drivers. This study used long-term data from two Neotropical lacustrine freshwater systems (Batata Lake, an Amazonian floodplain lake and Imboassica lagoon, an Atlantic coastal lagoon by increasing salinity and reducing the water volume (Fernandes & Esteves 2003). Previous evidence has indicated the effect of changes in nutrient concentrations, salinity, and water transparency after the sandbar opening on ecological communities, indicating a low resilience to this disturbance (Branco *et al.* 2007, Santangelo *et al.* 2007). Another cause of intense biological responses in tropical coastal lagoons is increased rainfall, contributing to higher freshwater inputs from the watershed that contribute to enhance organic acid concentrations and dilute seawaters (Marotta *et al.* 2010a). The subsequent changes in pH and salinity may drive ecosystem structure and function in tropical coastal lagoons, such as involving bacterial, algae, and zooplankton communities (Mouillot *et al.* 2007, Laque *et al.* 2010, MacCord *et al.* 2013, Petruzzella *et al.* 2013).

The Northern coast of Rio de Janeiro State in Brazil has an extensive shoreline with intense human uses and a wide variety of lagoons (Esteves 1998, Marotta *et al.* 2010b, IBGE 2015, da Fonseca *et al.* 2019), which have shown both filling up and eutrophication by growing urbanization associated with untreated sewage inputs and deforestation of the watershed (Fernandes *et al.* 1994, Suzuki *et al.* 1998, Fonseca *et al.* 2019). In the last 30 years, the monitoring program «Ecological Studies of Coastal Lagoons in Northern Rio de Janeiro State» (ECOlagoas Project) coordinated by Prof. Francisco de Assis Esteves has been performed in a tropical urban coastal aquatic ecosystem (Imboassica Lagoon, Macaé City, Rio de Janeiro State), exemplifying a scarce long-term study in a Brazilian lagoon. High nutrient concentrations in Imboassica Lagoon favor both bacterial and picoplanktonic cyanobacteria communities (Kozlowsky-Suzuki & Bozelli 2004) two environmental gradients were observed. One was directly related to entry of marine water (salinity gradient. Artificial sandbar openings have been used as the main mitigation strategy to reduce both aquatic eutrophication and the urban flooding, although more studies are still needed to better understand their relationships with sanitary conditions indicated by faecal coliforms, and ecological responses of the zooplankton community.

In this way, the ECOlagoas long-term monitoring action could improve our understanding on the effects of sandbar openings in coastal lagoons under eutrophication and changes in rainfall. Here we evaluated long-term (14 years) dynamics of nutrient concentrations, density of faecal coliforms (*i.e.*, as a proxy of sanitary conditions), and ecological responses of zooplankton communities, following episodic sandbar openings during eutrophication and acidification periods in the Imboassica lagoon.

MATERIAL AND METHODS

Study area

The coastal lagoon Imboassica is situated in the city of Macaé, Northern region of the state of Rio de Janeiro, Southern Brazil, between the latitudes -23º 25’ and -23º 35’, and longitudes -42º 35’ and -42º 45’ (Figure 1). The predominant land use in the Imboassica Lagoon watershed (area ≈ 55 km^2) is abandoned pasture fields with residual native vegetation, but the lowlands surrounding Imboassica Lagoon are dominated by urban use resulting in nutrient-rich inputs, which have caused eutrophication over the last decades in its waters (Marotta *et al.* 2009). The lagoon is shallow and relatively small in area (Panosso *et al.* 1998) being highly colonized by aquatic macrophytes.

Imboassica Lagoon presents a less eutrophic area influenced by the water exchange (SANDBAR) and a more eutrophic area influenced by domestic discharges (SEWAGE) (Figure 1). The lagoon has been subjected to a series of anthropogenic impacts, namely sewage disposal, openings of the sandbar separating the lagoon from the sea (Table 1), and reduction of its area by landfills.

Study design

Surface waters from both stations were monthly taken throughout 14 years (1992-2005). We used the institutional data repository of the Federal University of Rio de Janeiro (ECOlagoas Project). To assess the influence of contrasting eutrophication levels, accumulated rainfall and frequency of sandbar openings, our dataset was divided in three non-consecutive time periods as described in detail by Marotta *et al.* (2010a). The study periods were (I) Background nutrient levels associated with six sandbar openings (N = 39 months from 1992-1995); (II) Eutrophication associated with only one sandbar opening and drier conditions (N = 35 months from 1999-2001); and (III) Acidification due to increased rainfall associated with only one sandbar opening (N = 23 months from 2003-2005).

Sampling and laboratory analysis

In the field, water column depth was measured with a Secchi disk, salinity with a refractometer or thermosalinometer, and pH with a calibrated

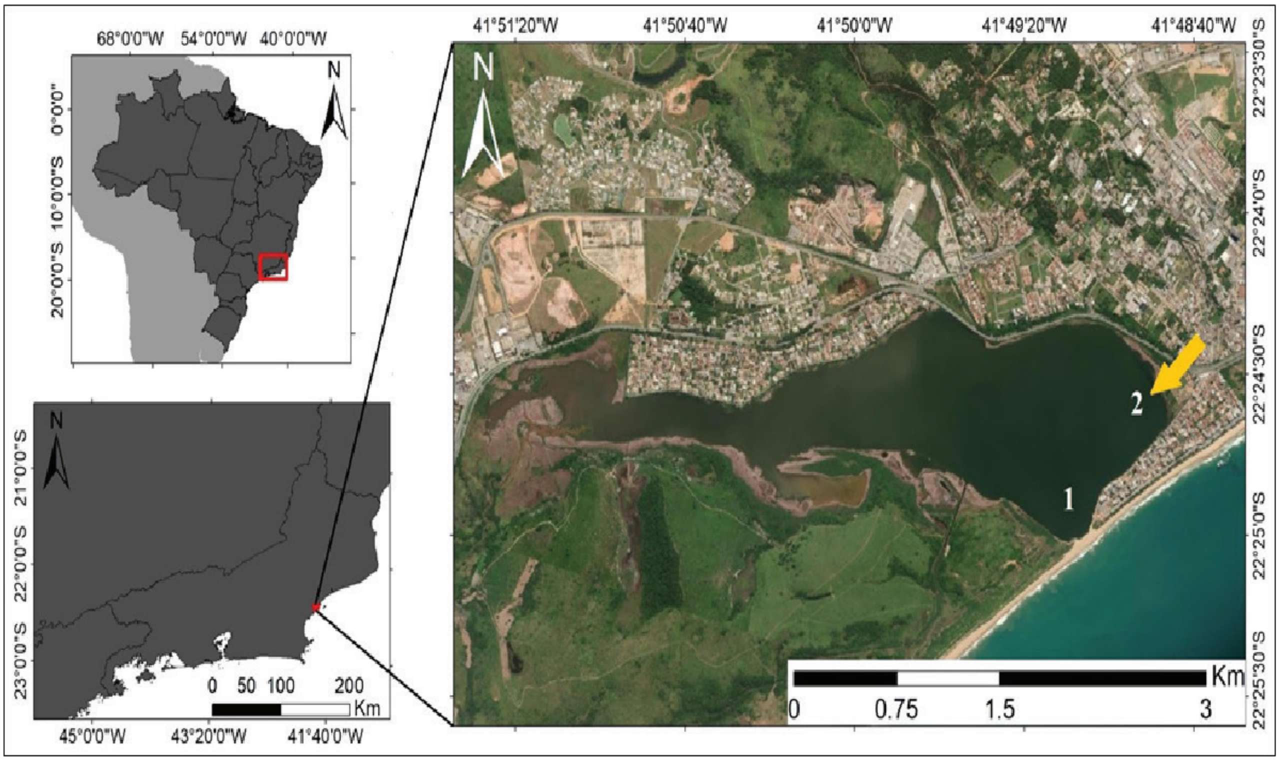

Figure 1. Imboassica Lagoon (municipality of Macaé, State of Rio de Janeiro, Brazil), indicating the stations SANDBAR (1) and SEWAGE (2) and the main non-treated sewage input (yellow arrow). Source: Google images 2021 CNES/Airbus, Maxar Technologies.

Table 1. Events of artificial sandbar openings and mean precipitation in each year during the studied period (1992-2005). Rainfall data provided by INMET (2016).

Year	Number of sandbar openings	Month	References	Precipitation (mm)
1992	1	September	Esteves (1998); Branco *et al.* (2007)	67.65
1993	1	March	Branco *et al.* (2007)	42.18
1994	2	March	Esteves (1998); Branco *et al.* (2007)	69.96
		May		
1995	2	May	Esteves (1998)	67.32
		September	Esteves (1998); Branco *et al.* (2007)	
1996	2	April	Esteves (1998)	52.22
		September		
1997	1	January	Esteves (1998)	60.43
1998	1	February	Esteves (1998)	78.22
1999	no events	-	-	72.35
2000	no events	-	-	57.41
2001	1	February	Bozelli *et al.* 2009	41.46
2002	no events	-	-	70.21
2003	no events	-	-	83.42
2004	no events	-	-	109.92
2005	1	November	Setubal *et al.* 2013	155.17

pHmeter. Surface water samples (~20 cm) were taken and kept in a sterilized flask for faecal coliform, and another for nutrient and chlorophyll-*a* content analysis. In the laboratory, waters samples were filtered for obtaining dissolved nutrients, using Whatman GF/C filters that were kept for chlorophyll-*a* determination. Water samples and filters were frozen until analysis. Total and dissolved N concentrations (TN and DN, respectively) were determined by two methods. We followed the method of Kjeldahl digestion from 1995 to 2000 (Mackereth *et al.* 1979), and the method of nitrate reduction in a cadmium column of a flow injection analyzer (ASIA - Ismatec) after previous oxidation with alkali persulfate solution from 2001-2005. Total and dissolved phosphorus concentrations (TP and DP, respectively) were analyzed by the molybdenum blue reaction, after persulphate oxidation (Golterman *et al.* 1978). Chlorophyll-*a* content was determined in the GF/C filters extracted in ethanol in the dark for 24 h before spectrophotometric determination (Nusch & Palme (1975).

Faecal coliforms (FC) were estimated by the Most Probable Number (MPN) technique, using two different substracts: a lactose broth during the period from 1992 to 1998 and a chromogenic broth from 1999 to 2005. The results were expressed in Most Probable Number per 100 mL (MPN.100 mL^{-1}). The lactose broth results refer to faecal coliform and the chromogenic substract results refer to *Escherichia coli* specifically. Both results will be referred as faecal coliform in MNP/100 mL.

Zooplankton community

In this study, species composition, frequency of occurrence and species richness were used to evaluate the zooplankton community of the Imboassica lagoon. All data were compiled from the published literature available that considered zooplankton community and the openings of sandbar in the Imboassica lagoon over the time interval covered in this study, and further applied to a time series related to the three studied periods.

Statistical analyses

The time series dataset does not attend analyses of variance assumptions (Berry 1987), even after transformations, tested by a normal distribution (Kolmogorov–Smirnov, $p > 0.05$) and homogeneity of variances (Bartlett, $p > 0.05$). We used medians and the 25–75% interquartile range to represent the distribution of values, and non-parametric tests to compare them (Zar 2010). Then, we used the non-parametric Kruskal-Wallis test followed by Dunn's post-test to test the statistical differences ($p < 0.05$) among sampling stations and periods in the 14 years of data in each station.

RESULTS

Considering the 14-year time series, the station SEWAGE showed higher total and dissolved nutrients concentrations, and chlorophyll *a* content than the station SANDBAR, especially in the later periods (eutrophication and acidification) compared with the background (Table 2). In addition, reductions in pH and salinity associated with increases in water depth were observed in both stations during the acidification period (Table 2).

In relation to faecal coliform, lower and less variable values were found in the SANDBAR station than in the SEWAGE station (Figure 2), reaching in median (25-75 % interquartile range) 1.6 (1.3-2.3) and 3.0 (2.3-3.8) MPN.100 mL^{-1}, respectively. In such way, a higher relative frequency of faecal coliform levels below 10^3 MPN.100 mL^{-1} was also observed in SANDBAR, following a slight increase of measurements above 10^4 MPN.100 mL^{-1} in the eutrophication period that contrasted with 100% of values lower than 10^3 MPN.100 mL^{-1} in the acidification period (Figure 3). Faecal coliform levels reduced significantly from the period eutrophication to acidification in the SANDBAR station, while increased significantly from the background to that more eutrophic in SEWAGE ($p < 0.05$, Dunn's post-test; Figure 4).

The dataset of zooplankton community indicated the role of changes in water quality and sandbar openings (Table 3). Seven studies from the literature compilation (Figure 5) demonstrated the dynamics of zooplankton communities in different sampling periods supporting more similarities of species richness in the background and eutrophication periods than in the later acidification period. The species richness was higher in background and eutrophication periods

Table 2. Median and 25-75% inter-quartil range of faecal coliforms (FC), total phosphorous (TP), dissolved phosphorus (DP), total nitrogen (TN), dissolved nitrogen (DN), chlorophyll *a* (Chl *a*), pH, salinity (Sal) and total depth levels in SANDBAR (station 1) and SEWAGE (station 2) at the Imboassica Lagoon in the studied periods (I - Background from 1992 to 1995; II - Eutrophication from 1999 to 2001; III - Acidification from 2003 to 2005). See details on periods in the Method section.

Station	Periods		FC (LogNMP/100ml^{-1})	TP (µmol.l^{-1})	DP (µmol.l^{-1})	TN (µmol.l^{-1})	DN (µmol.l^{-1})	Chl *a* (µg.l^{-1})	pH	Sal	Depth (m)
1	I	Med	1.7	0.7	0.3	40	35.4	3.3	7.9	3	1.2
		(25-75%)	(1.3-2.2)	(0.5-0.8)	(0.3-0.4)	(35-53.6)	(28.6-43.2)	(2.1-11)	(7.7-8.1)	(1.5-6.5)	(0.8-1.8)
		Max	3.7	2.4	1.0	65.7	53.6	59.5	9.0	34	2.3
	II	Med	2.0	1.9	0.4	126.8	72.2	57.4	7.8	1.4	0.8
		(25-75%)	(1.6-2.8)	(1.5-2.3)	(0.3-0.7)	(57.4-181.4)	(35-102.6)	(27.9-105.5)	(8.2-8.6)	(1-18.2)	(0.7-1.1)
		Max	4.0	5.0	1.6	283.7	133.2	234.8	9.5	28.7	1.8
	III	Med	1.3	1.7	0.7	73.5	58.7	11.2	6.8	0.7	1.7
		(25-75%)	(1.3-1.3)	(1-2.4)	(0.6-1.2)	(59-89.4)	(49.5-w71.1)	(6.9-19.5)	(6.3-7.2)	(0.3-1)	(1.6-2)
		Max	2.3	3.7	1.8	130.2	133.0	36.1	8.7	2.9	2.3
2	I	Med	2.0	1.2	0.4	50	42.5	7.4	7.5	2	1.1
		(25-75%)	(1.7-2.7)	(0.7-1.8)	(0.3-0.6)	(41.2-63.2)	(28.6-47.2)	(3.2-13)	(7.2-7.9)	(1-5)	(0.9-1.2)
		Max	4.4	8.0	1.4	92.1	64.3	142.2	9.0	20	1.9
	II	Med	3.1	2.6	0.6	175.9	93.4	61	7.8	1.3	0.7
		(25-75%)	(2.9-3.7)	(2-4)	(0.4-1)	(107.1-232.7)	(55.7-111.1)	(34.1-87.7)	(7.5-8.5)	(0.9-10.7)	(0.4-1)
		Max	4.4	8.0	40.8	476	238	248.8	9.3	26.2	1.3
	III	Med	3.0	2,6	0.9	75.4	62.4	15	6.8	0.7	1.3
		(25-75%)	(2.3-3.2)	(1.8-3.0)	(0.7-1.7)	(57.8-111.8)	(52.3-78.1)	(7.7-26.5)	(6.5-7)	(0.3-1)	(1.2-1.6)
		Max	5.5	3.9	2.0	237.7	156.6	46.3	8.6	2.9	1.7

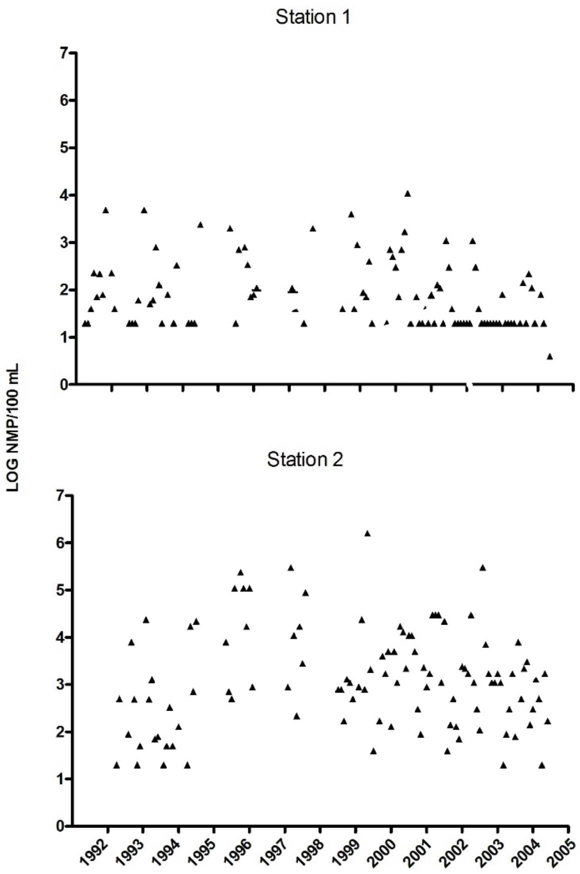

Figure 2. 14-year time series from May of 1992 to October of 2005 of faecal coliform levels in SANDBAR (station 1) and SEWAGE (station 2) at the Imboassica Lagoon.

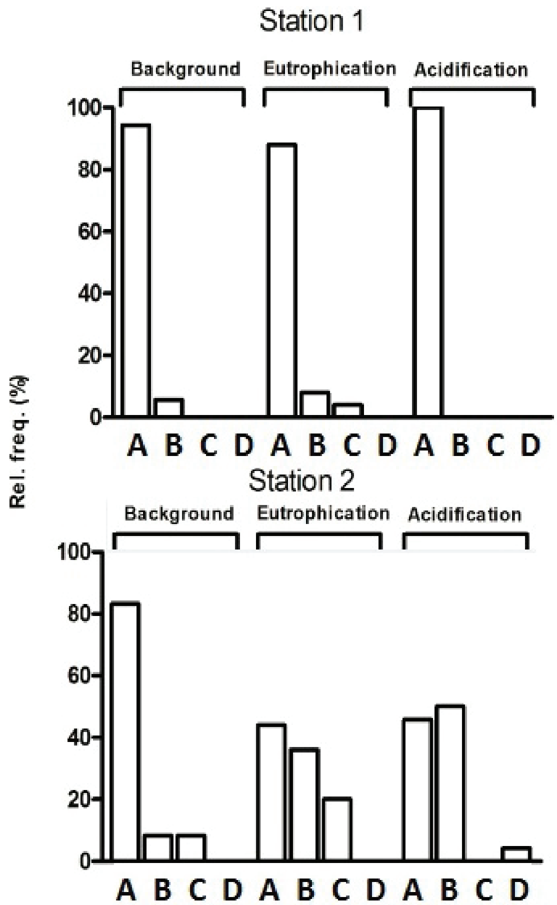

Figure 3. Relative frequency of faecal coliform levels in SANDBAR (station 1) and SEWAGE (station 2) at the Imboassica Lagoon in the periods: I - Background (1992-1995), II - Eutrophication (1999-2001), and III - Acidification (2003-2005). Classes are divided in A<10^3; B=10^3-10^4; C=10^4-10^5; D>10^5 MPNM/100mL. See details on periods in the Method section.

results, 33 and 30 species, respectively. While in the acid period, species richness were 24 and 23, before and after of sandbar openings, respectively (Rocha *et al.* 2004, Setubal *et al.* 2013).

Although the background and eutrophication periods are more similar in terms of species richness, they differed in terms of species composition. As noted, only 7 rotifer, 1 cladoceran and 1 copepod species were frequent in both earlier periods (Table 3). In turn, important changes in the zooplankton community were observed represented by few species with high dominance and high density (*e.g.*, the rotifers *Brachionus calyciflorus*, *Brachionus havanaensis*, and *Keratella tropica*, and cyclopoid copepods) in the eutrophication and acidification periods. The presence of marine and eurihaline species was more frequent in periods of higher salinity, especially (the dominant) *Brachionus plicatilis*, *Brachionus urceolaris* and *Synchaeta* sp. after sandbar openings. Finally, dominance by the rotifers *Keratella tropica* and *Polyarthra* sp. was observed in the acidification period.

DISCUSSION

The ECOlagoas long-term monitoring program in Imboassica Lagoon provided 14-year data of surface water quality in two distinct stations, revealing important intra-ecosystem spatial variability and inter-annual changes in faecal coliform levels, nutrient concentrations, salinity, water depth, and zooplankton community. The maximum faecal coliform level in surface waters in SEWAGE station reached around two times higher than in another tropical polluted coastal lagoon in Rio de Janeiro (Lutterbach *et al.* 2001). The faecal coliform analysis indicated the persistence of most data below the limit levels tolerated for

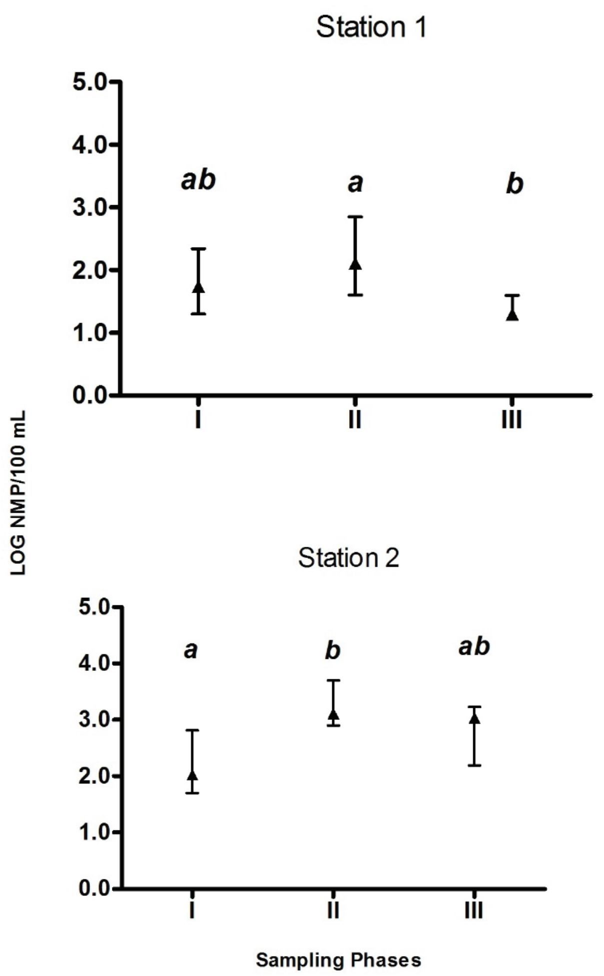

Figure 4. Median and 25-75% inter-quartile range of faecal coliform levels in SANDBAR (station 1) and SEWAGE (station 2) at the Imboassica Lagoon in the studied periods (Background=I; Eutrophication=II; Acidification=III). Statistically significant differences among sampling periods (Background, Eutrophication, and Acidification) are represented by different lower-case letters ($p < 0.05$; Dunn's post-test). See details on periods in the legend of Figure 3 and the Method section.

continental waters (1,000 MPN/100 mL; Figure 2), following microbiological standards from the Brazilian National Council for Environmental Issues (Conselho Nacional do Meio Ambiente-CONAMA; resolution nº 274/2000). However, these results have indicated a significant deterioration of the sanitary conditions by untreated sewage discharges into SEWAGE station of the Imboassica lagoon during the eutrophication period, which was not observed in the SANDBAR. Hence, a significant intra-ecosystem variability of faecal coliform levels between nearby sites was indicated by 14-year medians ~65% higher in SEWAGE station than in the SANDBAR, attributed to the proximity of the main sewage input channel in the east portion.

Reduced water quality reported here is commonly followed by substantial changes in ecosystem functioning processes, such as bacterial respiration and growth (Kümmerer *et al.* 2000, 2004), primary production (Marotta *et al.* 2012) or nitrogen cycling rates (Costanzo *et al.* 2005). The relative frequency (Figure 3) and median values (Figure 4) of faecal coliform levels showed substantial increases from background to eutrophication periods in SEWAGE station, contrasting with substantial decreases from the eutrophication to acidification periods in the SANDBAR. In both stations, median faecal coliform levels were similarly lower during the background period (1992-1995), which could be attributed to lower untreated sewage inputs from less urban areas (Marotta *et al.*, 2009). Another typical cause of physiological constraints that could reduce faecal coliforms is the increased salinity (Gonzalez *et al.* 2010), which was likely derived here from higher frequency of sandbar openings in the background period. This suggests that higher inputs of untreated sewage (*i.e.*, source of nutrients and faecal coliforms) and lower water depth under drier conditions (*i.e.*, reduced dilution capacity) may have contributed not only to the eutrophication after 1999, as reported in previous studies (Marotta *et al.* 2009; Marotta *et al.* 2010), but also to sanitary degradation. Previous studies confirm that artificial sandbar openings associated with untreated sewage discharges drive substantial reductions in water quality and a myriad of other ecosystem properties (Bozelli *et al.* 2009).

In contrast to the higher sanitary degradation in the eutrophication period (1999-2001), the acidification period (2003-2005) showed decreases in faecal coliforms to non-different levels than background (1992-1995) in both stations, which could be attributed to increased water depth and subsequent dilution capacity in response to higher rainfall and the absence of sandbar openings. Additionally, the lower inflow of marine carbonates and higher inputs of terrestrial organic acids could have reduced the water pH in Imboassica lagoon in the later period (Marotta *et al.* 2010a). The role of sandbar openings

Table 3. List of zooplankton taxa and their frequency of occurrence in Imboassica Lagoon. The data were obtained in Rocha *et al.* (2004) and Setubal *et al.* (2013).

Taxa	Frequence			
	I BACKGROUND	II EUTROPHICATION	III ACIDIFICATION	
	1993-1995	2000-2002	Before sandbar opening 2004	After sandbar opening 2005
ROTIFERA				
Ascomorpha sp.	0.0	0.0	0.0	0.1
Asplanchna sieboldi	0.0	0.2	0.1	0.7
Bdelloidea	0.0	0.0	0.2	0.2
Brachionus calyciflorus	0.0	0.3	0.0	0.0
Brachionus caudatus	0.0	0.0	0.3	0.2
Brachionus dimidiatus	0.0	0.3	0.0	0.0
Brachionus falcatus	0.1	0.0	0.0	0.0
Brachionus gessneri	0.0	0.0	0.0	0.0
Brachionus havanensis	0.1	0.4	0.1	0.0
Brachionus patulus	0.0	0.0	0.0	0.0
Brachionus plicatilis	0.6	0.6	0.0	0.7
Brachionus rotundiformis	0.0	0.0	0.0	0.1
Brachionus cf. *urceolaris*	0.0	0.0	0.1	0.6
Collotheca sp.	0.0	0.1	0.0	0.0
Conochilus sp.	0.0	0.0	0.0	0.0
Epiphanes macrourus	0.0	0.2	0.0	0.1
Dipleuchlanis sp.	0.0	0.0	0.0	0.0
Filinia longiseta	0.0	0.1	0.0	0.0
Filinia pejleri	0.0	0.0	0.1	0.2
Filinia terminalis	0.0	0.2	0.0	0.0
Hexarthra sp.	0.9	0.1	0.5	0.7
Keratella cochlearis	0.1	0.0	0.0	0.0
Keratella tropica	0.2	0.4	1.0	0.0
Lecane bulla	0.6	0.0	0.2	0.2
Lecane cornuta	0.0	0.0	0.1	0.0
Lecane curvicornis	0.0	0.0	0.2	0.0
Lecane grandis	0.0	0.1	0.0	0.0
Lecane leontina	0.0	0.0	0.1	0.1
Lecane pertica	0.0	0.0	0.1	0.1
Lecane quadridentata	0.0	0.0	0.0	0.0
Lecane spinulifera	0.0	0.0	0.0	0.0
Lecane stenroosi	0.1	0.0	0.0	0.0
Lecane patella	0.0	0.0	0.0	0.0
Macrochaetus longipes	0.2	0.0	0.0	0.0
Platyas quadricornis	0.0	0.0	0.0	0.0
Polyarthra sp.	0.0	0.0	0.9	0.1
Polyarthra vulgaris	0.1	0.1	0.0	0.0

Table 3. Continues on next page...

Table 3. ...continued

Taxa	Frequence			
	I BACKGROUND	II EUTROPHICATION	III ACIDIFICATION	
	1993-1995	2000-2002	Before sandbar opening 2004	After sandbar opening 2005
Rotaria sp.	0.0	0.0	0.0	0.0
Synchaeta sp.	0.0	0.0	0.0	0.5
Synchaeta sp. 2	0.0	0.0	0.3	0.0
Synchaeta baltica	0.2	0.1	0.0	0.0
Synchaeta bicornis	0.5	0.0	0.0	0.0
Testudinella patina	0.0	0.0	0.2	0.0
Trichocerca bicristata	0.0	0.0	0.0	0.0
Trichocera ruttneri	0.0	0.1	0.0	0.0
Trichocerca sp.	0.2	0.1	0.0	0.0
CLADOCERA				
Anthalona verrucosa	0.0	0.0	0.1	0.3
Bosminopsis deitersi	0.0	0.0	0.4	0.0
Bosmina freyi	0.0	0.0	0.3	0.0
Ceriodaphnia sp.	0.0	0.0	0.2	0.2
Ceriodaphnia cornuta	0.0	0.3	0.0	0.0
Diaphanosoma brevirreme	0.0	0.0	0.4	0.0
Moina minuta	0.1	0.4	0.7	0.6
Leberis davidi	0.0	0.0	0.0	0.1
Chydoridae	0.1	0.0	0.0	0.0
Nicsmirnovius sp.	0.0	0.0	0.0	0.1
COPEPODA				
Acartia cf. *tonsa*	0.0	0.0	0.0	0.1
Acartia tonsa	0.0	0.4	0.1	0.0
Apocyclops procerus	0.0	0.1	0.0	0.0
Mesocyclops cf. *aspericornis*	0.0	0.4	0.0	0.0
Mesocyclops cf. *venezolanus*	0.0	0.0	0.0	0.0
Microcyclops sp.	0.0	0.0	0.0	0.0
Oithona cf. *hebes*	0.1	0.1	0.0	0.0
Paracalanus crassirostris	0.0	0.0	0.0	0.0
Thermocyclops decipiens	0.0	0.4	0.0	0.0
Tropocyclops prasinus	0.1	0.0	0.0	0.0
Non-identified Cyclopoid I	0.0	0.0	0.0	0.0
Non-identified Cyclopoid II	0.0	0.0	1.0	0.5
Non-identified Marine Calanoida	0.1	0.0	0.0	0.0
Non-identified Harpacticoid	0.3	0.2	0.0	0.0
Non-identified Diaptomidae	0.0	0.0	0.0	0.5

Table 3. Continues on next page...

Table 3. ...continued

Taxa	Frequence			
	I BACKGROUND	II EUTROPHICATION	III ACIDIFICATION	
	1993-1995	2000-2002	Before sandbar opening 2004	After sandbar opening 2005
Parasite copepods	0.1	0.1	0.0	0.0
Cyclopoida nauplii	0.9	0.9	1.0	0.4
Calanoida nauplii	0.9	0.8	0.4	0.9
Harpacticoida nauplii	0.7	0.0	0.0	0.0
Cirripedia nauplii	0.3	0.5	0.0	0.0
Cyclopoida juveniles	0.7	0.6	0.9	0.9
Calanoida juveniles	0.7	0.5	0.3	0.7
Harpacticoida juveniles	0.0	0.3	0.0	0.0

and rainfall on nutrient and chlorophyll-*a* concentrations has been reported in other coastal lagoons of the Rio de Janeiro State (Suzuki *et al.* 1998), chemical and biological variables in the Grussai lagoon, and their relationship to ephemeral sand bar openings and to a constant in natura waste water input. The spatial variation in pH, dissolved oxygen, electrical conductivity, total alkalinity and nutrients (*e.g.* soluble reactive silicate, soluble reactive phosphate and ammonium, Suzuki *et al.* 2002), but not on their effects on feacal coliforms levels. Accordingly, planktonic species may be highly and rapidly affected by variations in conditions and resource availability due to the small size and short life cycle, supporting their use as bioindicators of environmental change in monitoring programs (De-Carli *et al.* 2018). Indeed, the return to the functioning and structure of the zooplankton community prior to the openings, depends on the ecological features of the lagoon and its specific composition, and on the magnitude of the event (Attayde & Bozelli 1998, Branco *et al.* 2007, Kozlowsky-Suzuki & Bozelli 2004, Santangelo 2007, Setubal 2013).

In such way, we found substantial responses of the zooplankton community to eutrophication and changes in salinity and water depth

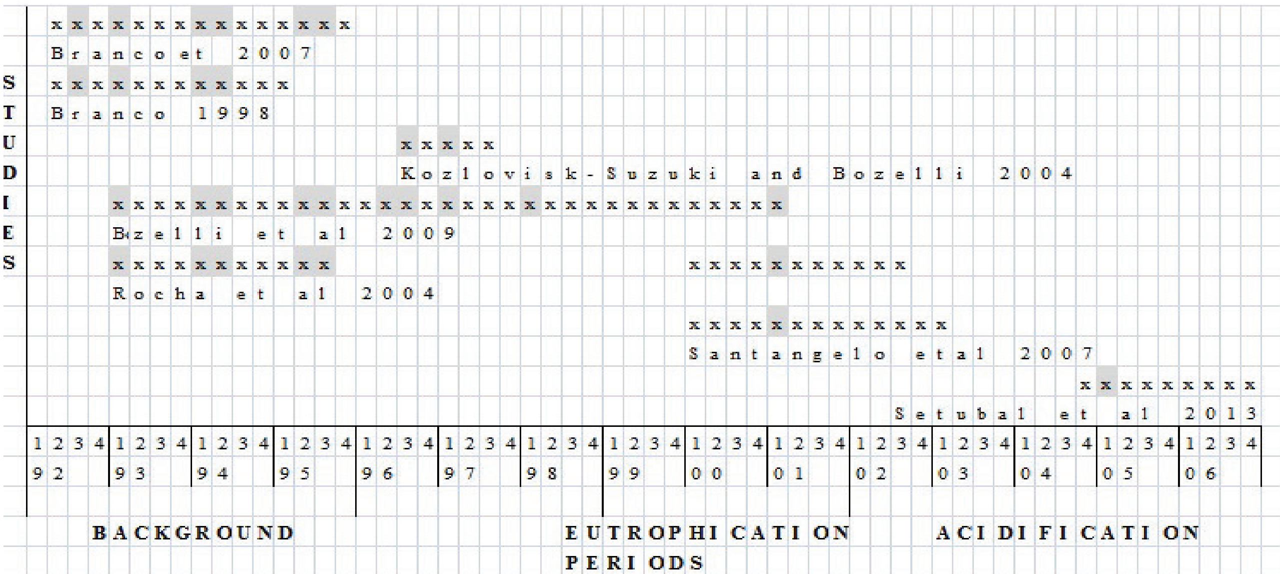

Figure 5. Chronological description, in quarterly periods from 1992 at 2006, of articles on zooplankton made in Imboassica Lagoon during study period. The openings of the sandbar are identified by gray shading.

following sandbar openings, which have led to a shift to dominant species with high salinity tolerance determining low diversity (Table 3). This is supported by changes in zooplankton community of Imboassica lagoon studied over 14 years (Figure 5), confirming important effects of artificial sandbar opening and eutrophication (Melo & Suzuki 1998, Panosso & Esteves 2000, Kozlowsky-Suzuki & Bozelli 2004, Rocha *et al.* 2004). During the period of higher frequency of sandbar openings and less untreated sewage inputs (1992-1995), the successive sandbar openings promoted substantial changes in the zooplankton community, increasing the participation of marine taxa (Branco *et al.* 1998, 2007). Previous studies have also reported significant negative correlations of richness or diversity of the zooplankton community with salinity in the SANDBAR station, such as from 1993 to 1995 and from 2000 to 2002 (Rocha *et al.* 2004). The drastic changes from a strongly eutrophic and oligohaline to a slightly eutrophic and euryhaline condition due to the sandbar opening in February 2001, associated with a low resilience of the zooplankton community (Santangelo *et al.* 2007), may have contributed to considerable loss of species observed after the artificial sandbar opening during the acidification period here (Table 3).

Therefore, coastal management based on ecosystem conservation and economic uses is urgently needed, especially considering human interventions in aquatic environments and their watersheds. Our findings indicate that artificial sandbar openings without sewage treatment can increase risks for sanitary and ecological conditions, suggesting that decreased water volume (*i.e.*, lower dilution capacity) contributes to anthropogenic eutrophication, a still neglected component that may strongly affect the resilience of coastal lagoons to water pollution.

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