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Living benthic Foraminifera from the Saquarema lagoonal system (Rio de Janeiro, southeastern Brazil)

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Abstract: Transitional environments such as coastal lagoons with narrow connections to the sea are ecosystems very sensitive to natural or anthropogenic pressures. They are biodiversity hotspots and for this reason it should be studied and preserved. This study lists the benthic Foraminifera species from the Saquarema lagoonal system (SLS), Rio de Janeiro state, Brazil. This complex ecosystem consists of four large connected lagoons, namely Urussanga, Jardim, Boqueirão, and Saquarema. A poorly diversified benthic foraminiferal assemblage was documented from most of the lagoon system and consisted of only eight species belonging to three orders and four families. The relatively low species richness of the SLS compared to other Brazilian coastal lagoons might be explained by several factors including domestic sewage input and the long residence time of water.

Key words: impacted ecosystem; coastal lagoons, transitional environments lagoons

INTRODUCTION

Transitional environments, such as coastal lagoons with narrow connections to the sea, are strongly influenced by seasonal cycles. These cycles resulting from periodical rainfall and storm–forcing events alter physical and chemical parameters, circulation, and residence time (or renewal) of water (Kjerfve 1994). Like coastal marine ecosystems, transitional environments are affected by active processes that promote the establishment of environmental and ecological gradients. These environments occupy 13% of coastal areas in the world (Barnes 1980) and support a range of highly valued ecological services (Anthony et al. 2009). In addition, transitional environments are among the most biologically productive environments of our planet and harbor a rich and unique biodiversity (Esteves et al. 2008; Whitfield et al. 2008).

Tropical coastal lagoons are, however, among the most threatened ecosystems on Earth due to multiple disturbances, including habitat alterations (Bulleri & Chapman 2010), climate change (Anthony et al. 2009; Clausen & Clausen 2014), and various anthropogenic perturbations (McKinney et al. 2010). Climate change, in addition to anthropogenic pertubations such as artificial opening of sandbars and building of drainage canals, can promote, for instance, drying and salinization (Esteves et al. 2008). Gomez Gesteira (2003) characterizes water residence time as an important physical variable in estuaries and coastal lagoons and a useful tool for studying the quality of its waters.

In the last decades, Foraminifera have been widely used as a proxy to describe the quality of coastal environments (Laut et al. 2011; Martins et al. 2013, 2015a). Foraminifera are commonly used as bioindicators because their short life cycles offer insight into rapid environmental changes (Murray 2006). Generally, they fossilize in sediments and provide important paleoenvironmental information (Murray 2006). The distribution of benthic Foraminifera is controlled by many factors, such as temperature, salinity, dissolved oxygen, sediment grain size or substrate (Murray 1991, 2001), and changes in the

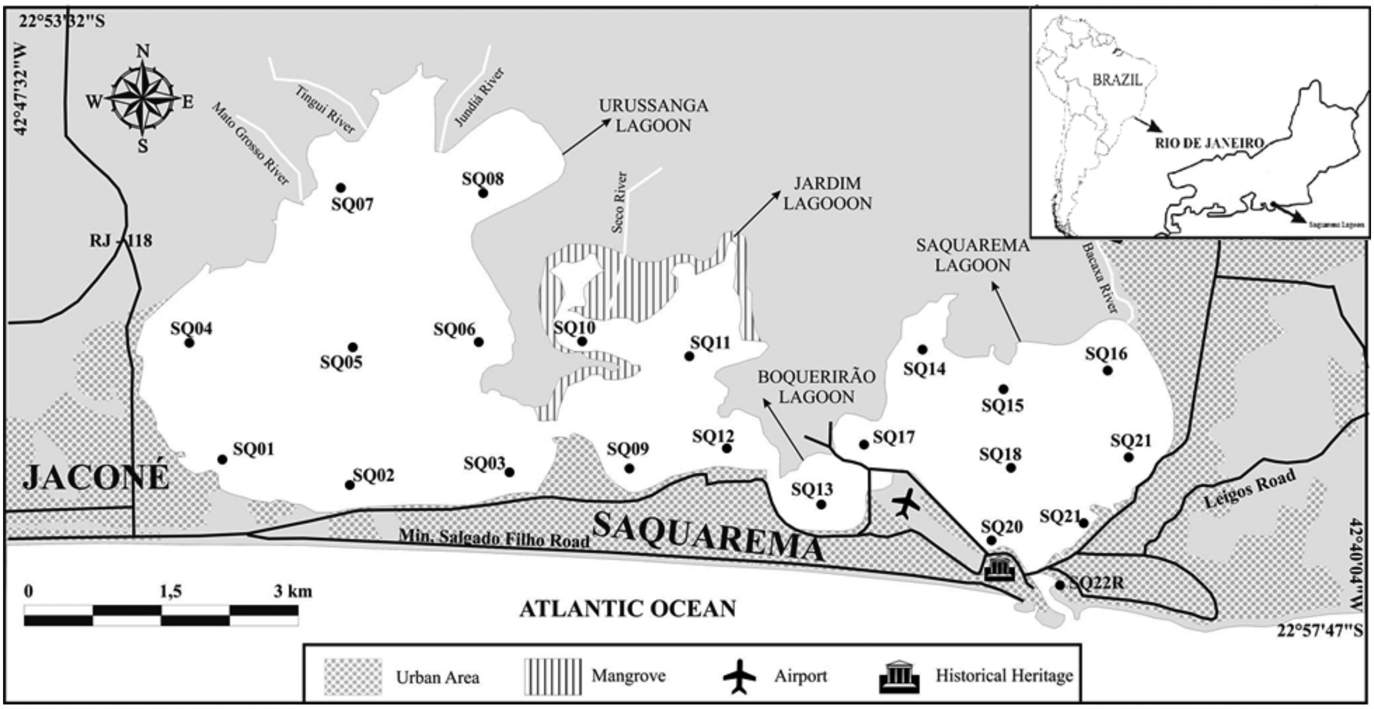

Figure 1. Location of the study area and sampling stations in the Saquarema lagoonal system, Rio de Janeiro state, Brazil.

quality and amount of nutrients (Gooday 2003; Murray 2006). Some species colonize the oxide sediment interface, but others tolerate very depressed levels of oxygen and episodic anoxia conditions (Bernhard & Sen Gupta 1999). Sediment characteristics are one of the principal determinants of their distribution; benthic Foraminifera live more abundantly in silty and clayey sediments. However, Foraminifera are also can be influenced by sediment pollution (Bhalla & Nigam 1986; Alve & Olsgard 1999; Frontalini & Coccioni 2008; Martins et al. 2013, 2014, 2015a, b). The aim of this study is to characterize the living benthic foraminiferal assemblages on surface sediments from the SLS in order to serve as a background to future ecological and paleoecological studies, as well as contribute to research on the biodiversity and distribution of Foraminifera throughout Brazilian coastal lagoons.

MATERIALS AND METHODS

Study site

The SLS is located in Rio de Janeiro state, southeast Brazil, between 22°55′S and 22°56′S, and 042°35′W to 042°29′W (Figure 1). The lagoon system covers an area of ca. 21.2 km^2 and extends for ca. 11.8 km along the coast; it has an average depth not greater than 2.0 m. The SLS consists of four large connected lagoons, namely Urussanga (12.6 km^2), Jardim (2 km^2), Boqueirão (0.6 km^2), and Saquarema (6 km^2). Urussanga Lagoon is border by swamps to the north and receives the water from the Mato Grosso (or Roncador), Tingui, and Jundiá rivers. The Jardim Lagoon, which is surrounding by swamps, receives the input from the Rio Seco. The Saquarema Lagoon, receives the discharge of Bacaxá River and mangroves fringe the north bank (Bruno 2013). The Boqueirão Lagoon has no inflowing rivers (Moreira 1989). The climate in the entire state of Rio de Janeiro is warm and humid with a rainy summer season, a dry winter season, the average rainfall is between 1,000 and 1,500 mm/year (Barbiére & Coe–Neto 1999). The climate in SLS is sub–humid, with prolonged periods of drought, and high temperatures (Carmouze & Vasconcelos 1992). Climatic conditions are also influenced by the Serra do Mato Grosso in the west whose orographic processes effect primarily the rivers that discharge into Urussanga Lagoon (Carmouze & Vasconcelos 1992; Barros 2003). This lagoonal–coastal complex ecosystem is connected to the ocean through Barra Franca Channel. This channel is artificial with its margins stabilized by stone blocks. According to IBGE (2002, 2008), the human population of Saquarema grew 72.2% between 1990 (37,888 inhabitants) and 2001 (59,938 inhabitants), and included 31,623 households although 47.97% were not occupied year–round. In 2007, population of Saquarema increased to 62,174 inhabitants (IBGE 2008), indicating the growth in 2012 of about 24.6%. This uncontrolled urbanization surrounding Saquarema, coupled with the natural effects of silting in Barra da Franca Channel, have effectively increased domestic sewage in the lagoon and intensified the environmental disturbance (Bruno 2013).

Sediment collection

Twenty–two stations were selected in 2013 for collecting sediment samples in the SLS at a water depth between 0.5 and 3 m. (Figure 1; Table 1). Three replicates of surface sediment were collected from each station using an Ekman Grab.

Table 1. Location of the sampling stations in the Saquarema Lagoonal system.

Station	Longitude (W)	Latitude (S)
SQ01	42°35′05.63″	022°55′27.90″
SQ02	42°34′19.55″	022°55′37.83″
SQ03	42°33′30.27″	022°55′33.00″
SQ04	42°35′16.65″	022°54′56.30″
SQ05	42°34′23.95″	022°54′55.19″
SQ06	42°33′25.69″	022°54′45.95″
SQ07	42°34′35.83″	022°53′59.91″
SQ08	42°33′27.18″	022°53′46.68″
SQ09	42°32′22.21″	022°55′25.49″
SQ10	42°32′45.95″	022°54′39.60″
SQ11	42°32′00.49″	022°54′44.77″
SQ12	42°31′42.99″	022°55′17.95″
SQ13	42°31′04.91″	022°55′37.92″
SQ14	42°30′26.15″	022°54′44.39″
SQ15	42°29′46.12″	022°54′57.39″
SQ16	42°29′11.66″	022°54′47.40″
SQ17	42°30′49.99″	022°55′08.12″
SQ18	42°29′41.91″	022°55′23.36
SQ19	42°28′59.72″	022°55′14.20″
SQ20	42°29′56.69″	022°55′46.96″
SQ21	42°29′19.20″	022°55′36.72″
SQ22	42°29′32.31″	022°56′00.11″

At least three 50–ml replicates of the first few centimeters of surface sediment were sampled at each site for analyses.

Sediments were stored in ethanol stained with Rose Bengal (2 g of Rose Bengal in 1,000 ml alcohol) to differentiate living Foraminiferas from dead specimens (Murray & Bowser 2000).

Sediment analysis

Stained sediment samples were washed over sieves having mesh openings of 500 and 63 μm. The residual fraction in each sieve was dried at 50°C and the Foraminifera were removed from the remaining sediment by flotation in trichloroethylene, using the difference in density (Martins et al. 2015a). All stained Foraminifera were picked out from the sample, identified, and counted under stereoscopic microscopic at 80× magnification. As close as possible, 100 living individuals per sample were counted, but in some samples, fewer living specimens were found. The number of specimens found in the triplicates were therefore averaged (Table 2).

The generic taxonomical classification of Loeblich & Tappan (1987), and specific concepts of Boltovskoy et al. (1980), Debenay et al. (2002), and Martins & Gomes (2004) were followed. After identification, the names of species were checked against the World Register of Marine Species (WoRMS 2014). The specimens were stored in micropaleontological slides and archived following the methods of Schönfeld et al. (2012) in the Laboratory of Micropaleontology, Universidade Federal do Estado do Rio de Janeiro. Images of selected specimens of each species were made using scanning electron microscopy (EVO MA10, Zeiss).

RESULTS

A total of 10,459 living benthic foraminiferal specimens belonging to eight species were collected and identified. The species belong to three orders and four families (Table 2). A total of 6,094 specimens (58.3% of the total of living individuals) assigned to five species were found in Saquarema Lagoon, while 1,389 specimens (13.3% of the total of living individuals) belonging to four species were from Boqueirão Lagoon, 2,400 specimens (22.9% of the total of living individuals) belonging to five species were from Jardim Lagoon, and 576 specimens (5.5% of the total of living individuals) belonging to four species were from Urussanga Lagoon. The dominant families in the SLS were Rotaliidae and Elphidiidae.

The stations SQ19 and SQ20, nearest to Barra Franca Channel (Saquarema Lagoon), showed the greatest number of individuals and species. Samples from stations SQ01, SQ02, SQ03, SQ05, SQ06, SQ07, and SQ22 did not show living Foraminifera.

The family Rotaliidae showed the highest value of richness and was highly abundant in the Saquarema, Boqueirão, and Jardim lagoons. *Ammonia tepida* (1698 specimens) and *A. parkinsoniana* (753 specimens) had the highest abundance throughout the lagoonal system, followed by *Cribroelphidium excavatum* (697 specimens). *Ammonia tepida* was found in almost all stations, except at SQ04.

Agglutinated species of the order Lituolida, family Haplophragmoididae (*Haplophragmoides wilberti* and *Trochamminita salsa*), were exclusively found in Urussanga Lagoon, at station SQ04 near the fringe of mangroves. *Quinqueloculina seminula* (family Hauerinidae) was found only in the Urussanga and Jardim lagoons (stations SQ04, SQ09, and SQ10).

Table 2. Relative abundance of specimens for each foraminiferal species recorded in the samples analyzed in the Saquarema lagoonal system, Rio de Janeiro state, Brazil.

Stations	Number of Tests (150 ml)	Number of Species	*Ammonia parkinsoniana*	*Ammonia tepida*	*Crielphidium excavatum*	*Cribroelphidium poeyanun*	*Elphidium gunteri*	*Haplophragmoides wilberti*	*Quinqueloculina seminula*	*Trochamminita salsa*
SQ04	60	4	–	5	–	–	–	30	30	35
SQ08	516	2	4.1	95.9	–	–	–	–	–	–
SQ09	365	5	14.2	41.9	14.8	–	4.5	–	24.5	–
SQ10	549	4	20.2	39.3	16.4	–	–	–	24.0	–
SQ11	420	4	31.4	20	8.6	–	40	–	–	–
SQ12	966	4	26.1	48.4	18.3	–	7.1	–	–	–
SQ13	897	4	18	48.5	21.1	–	12.4	–	–	–
SQ14	771	4	39.7	31.9	24.1	–	4.3	–	–	–
SQ15	630	4	15.7	40	39	–	5.2	–	–	–
SQ16	1002	4	25.1	47.9	17.4	–	9.6	–	–	–
SQ17	492	4	10.4	72.0	8.5	–	9.1	–	–	–
SQ18	471	2	22.9	52.9	14	–	10.2	–	–	–
SQ19	1005	5	32.8	51.6	14.3	–	1.2	–	–	–
SQ20	1197	4	11.7	79.7	5.8	0.5	2.3	–	–	–
SQ21	1380	4	22	13.9	58.1	–	6	–	–	–

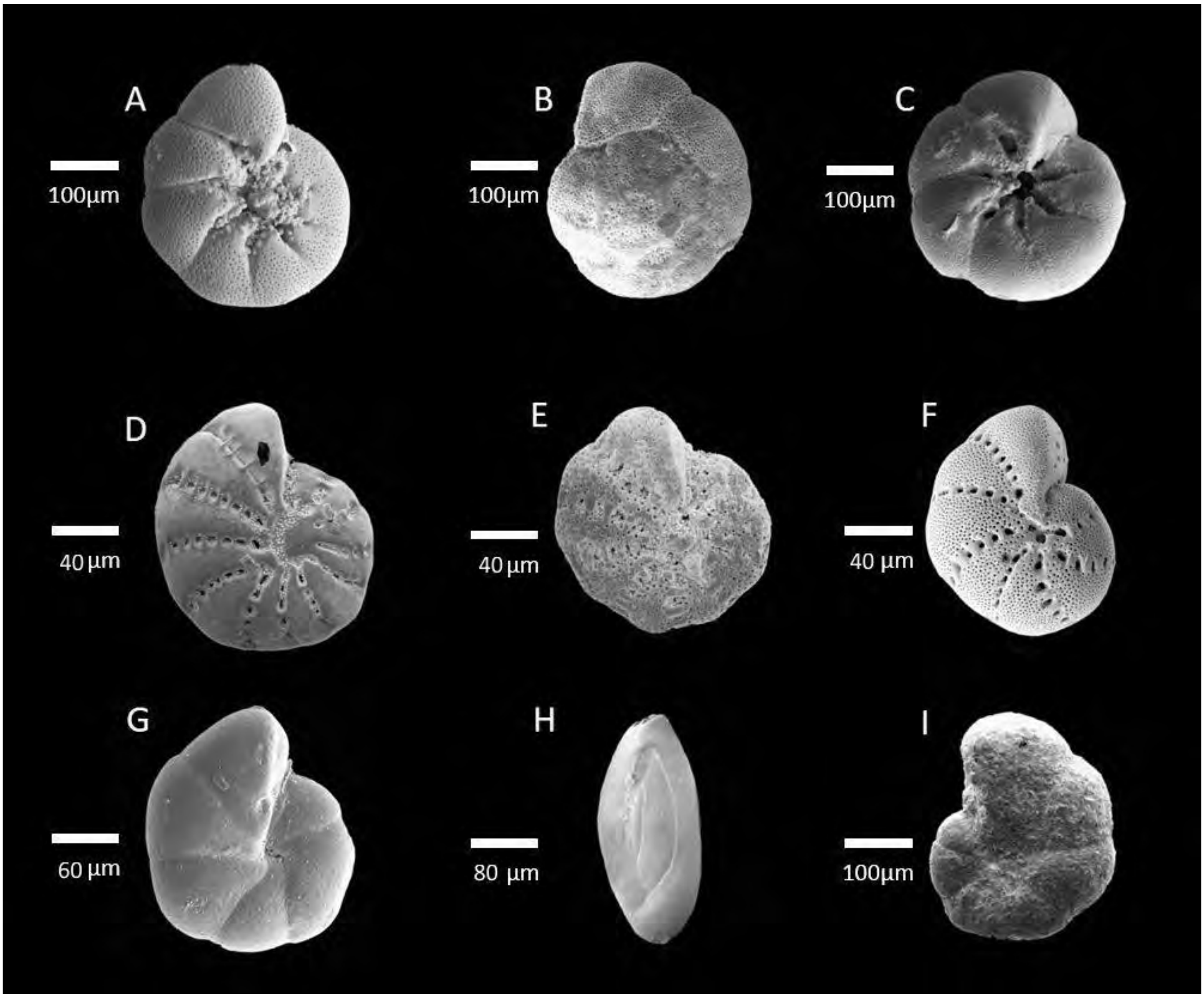

Figure 2. Foraminiferal species identified at Saquarema Lagoonal System. **A.** *Ammonia parkinsoniana* (ventral view). **B.** *Ammonia parkinsoniana* (dorsal view). **C.** *Ammonia tepida*. **D.** *Cribroelphidium excavatum.* **E.** *Cribroelphidium poeyanum*. **F.** *Elphidium gunteri.* **G.** *Haplophragmoides wilberti.* **H.** *Quinqueloculina seminula*. **I.** *Trochamminita salsa*.

List of the species — systematic classification

Kingdom Chromista
Subkingdom Harosa
Infrakingdom Rhizaria
Phylum Foraminifera
Order Rotaliida
Family Rotaliidae

Ammonia parkinsoniana (d'Orbigny, 1839): Figure 2A, B.

Species voucher: F–AMPA–SQ19

Description: Test planoconvex, low trochospiral, outline circular, peripheral margin slightly rounded; wall yellow to yellow–brown, coarsely perforate on the spiral side, septal sutures limbate, spiral sutures depressed in the final whorl; on umbilical side, sutures depressed and leading into an umbilical cavity that may be filled with a knob; aperture a narrow slit at base of chamber.

Ammonia tepida (Cushman, 1926): Figure 2C.

Species voucher: F–AMTE–SQ12

Description: test low trochospiral, spiral side evolute, umbilical side involute, periphery rounded to lobate, wall calcareous; aperture an interiomarginal and extraumbilical. It is characterized by lacking umbilical plugs and beading, fluting or furrowing on either side.

Family Elphidiidae

Cribroelphidium excavatum (Terquem, 1875): Figure 2D.

Species voucher: F–CREX–SQ16

Description: Test circular in outline, somewhat compressed, peripheral margin rounded and slightly lobate; chambers inflated, 7–10 in final whorl; wall smooth, transparent or opaque, radial; sutures gently curved, depressed, often covered with pustules; fossettes of variable size and shape; umbilici concave, covered with pustules; aperture formed by series of holes at base of smooth apertural face.

Cribroelphidium poeyanum (d'Orbigny, 1826): Figure 2E.

Species voucher: F–CRPO–SQ20

Description: test relatively small, laterally compressed, planispiral involute, umbilical regions slightly depressed, with 10–11 rapidly enlarging chambers in the last whorl and rounded periphery, suture very depressed and marked by short and narrow septal bridges. Wall calcareous, finely perforated, pustules are rarely present in the umbilical depression or on the apertural face. Aperture multiple and basal and some additional pores may be present on the apertural face.

Elphidium gunteri Cole, 1931: Figure 2F.

Species voucher: F–ELGU–SQ14

Description: Test subcircular to ovate in outline, expanded in umbilical area, peripheral margin broadly rounded; chambers slightly inflated, 10–13 in final whorl; wall radial, translucent to opaque, with large pores; sutures radial, deeply depressed with numerous fossettes lined with pustules; retral processes thick and distinct; umbilici with one or several knobs; aperture composed of various holes on and at base of apertural face, bordered by distinct rims.

Order Lituolida
Family Haplophragmoididae

Haplophragmoides wilberti Andersen, 1953: Figure 2G.

Species voucher: F–HAWI–SQ04

Description: Test involute, circular in outline, weakly lobate, peripheral margin rounded; 6–8 triangular chambers in final whorl planispirally involved; wall smooth, shiny, finely agglutinate with much cement, yellow–gray; sutures slightly depressed, straight to sigmoid; aperture a small and low arch with a narrow projecting lip.

Trochamminita salsa (Cushman & Bronnimann, 1948): Figure 2I.

Species voucher: F–TRSA–SQ04

Description: Test free, planispirally enrolled at least in the early stage, later chambers irregular in form and arrangement, sutures radial in early part, slightly depressed, periphery rounded, peripheral outline lobulated; wall thin, brownish, with fine to coarse quartz grains on a proteinaceous base; aperture areal, one or more rounded to irregular openings in the lower part of the apertural face, each surrounded by a distinct lip.

Order Miliolida
Family Hauerinidae

Quinqueloculina seminula (Linnaeus, 1758): Figure 2H.

Species voucher: F–QUSE–SQ09

Description: test elongate, in quinqueloculine mode, with rounded periphery. Aperture is a large elongate opening with a simple elongated tooth. Wall calcareous, imperforate and porcelaneous, surface smooth.

DISCUSSION

Foraminiferal species richness commonly documented for coastal lagoons vary between 20 and 30 species (Fatela & Taborda 2002; Laut et al. 2007; Raposo et al. 2016). The species richness in the Saquarema Lagoonal System (8 species) was lower recorded from other southeastern Brazilian lagoons. Accordingly, Vilela et al. (2011) recognized 52 foraminiferal species in Rodrigo de Freitas Lagoon, Bomfim et al. (2010) identified 22 species in Maricá Lagoon, and Debenay et al. (2001) found of 74 species in Araruama Lagoon. However, these studies were done using the full assemblage (live and dead specimens), which may not represent the totality of the living species, because dead Foraminifera can be transported into lagoons. Raposo et al. (2016) was the first to use exclusively record an assemblage of benthic Foraminifera based solely on live specimens and found 35 species in Itaipu Lagoon at Niterói (Rio de Janeiro state).

Ammonia parkinsoniana, *A. tepida* and *C. excavatum* were the most frequent species in the SLS. Several authors have suggested that these species are very resistant to salinity changes and thus are dominant in transitional environments (Boltovskoy 1965; Martins et al. 2015; Laut et al. 2016a, b; Raposo et al. 2016). *Ammonia parkinsoniana* was also dominant in Maricá Lagoon (Bomfim et al. 2010), Rodrigo de Freitas Lagoon (Vilela et al. 2011), and Araruama Lagoon (Debenay et al. 2001).

The areas of the SLS with dominance of *A. parkinsoniana* (found at almost all stationsbut with greatest dominance at SQ14 and SQ21 in Saquarema lagoon) are typically brackish water environments that demonstrates the influence of freshwater in this system (Martins et al. 2015). However, this species shows eurytopic behavior because it was reported in others coastal lagoons with very different environmental conditions, such as Bizerte Lagoon (Tunisia), which is hypersaline and with a large and sustainable flux of high quality nutrients (Martins et al. 2015). In the SLS, *A. parkinsoniana* was found at almost all stations, but showed higher abundance at stations closer to lagoon mouth where nutrients and energy exchanges are greatest.

Ammonia tepida is commonly encountered in restricted environments under stress of pollution from natural or anthropogenic sources (Vilela et al. 2004; Yanko et al. 1994, 1999; Alve 1995; Culver & Buzas 1995; Sousa et al. 1997; Bonetti et al. 1997; Debenay et al. 2000, 2001; Van der Zwaan 2000; Raposo et al. 2016). In Rio de Janeiro state, it was the dominant species in Guanabara Bay and Itaipu Lagoon. This species was also found in in Italy, such as the Laguna di Orbetello (Tuscany), Lago di Varano (Apulia) and Stagno di Santa Gilla (Sardinia), all in the most confined areas (Frontalini et al. 2009, 2010, 2014).

According to Hayward et al. (1996), *C. excavatum* is prefers coastal environments, where high salinity, nitrogen, and phosphate prevail. Bruno (2012) linked the occurrence of *C. excavatum* to restricted marine influence next to the artificial channel in Lagoa de Maricá, Rio de Janeiro state. This species is believed to be cosmopolitan because it has been recorded in several lagoons of Brazil and around the world (Debenay et al. 2001; Vilela et al. 2004; Laut et al. 2012; Martins et al. 2015). *Cribroelphidium excavatum* is also common in estuarine systems such as in the Rio Potengi, northeastern of Brazil (Souza et al. 2010), and in Rio Paraiba do Sul, Rio de Janeiro state (Laut et al. 2011). In the SLS, this species was found in almost all samples collected near the mouth and also in more confined areas, suggesting its eurytopic behavior.

The highest representation of agglutinated species and reduced number of tests in Lagoa de Maricá were related to hyposaline conditions by Bomfim et al. (2010). These authors explained the absence of marine species in the lagoon by the limited tidal transport and water exchange with the ocean. Similar conditions were encountered in the SLS, where these agglutinated species were found only in the most confined areas, near the mangrove fringe, with little marine influence.

The higher species richness and greater number of specimens at stations SQ19, SQ20, and SQ21 in SLS may be explained by their position next to the Barra Franca Channel, which provides greater exchange of nutrients and water from the ocean.

The relatively low foraminiferal diversity of the SLS compared to other Brazilian coastal lagoons might be explained by the discharge of untreated domestic sewage and the long residence time of water. Indeed, according to Alves (2003), the residence time can be as much as 58 days in Urussanga Lagoon, the most confined area of the SLS, and about 20 days in Saquarema Lagoon, which is nearest to the mouth. The long residence time of even the Saquarema Lagoon might suggest that the artificial channel may not provide sufficient flow of nutrients required for the establishment of larger assemblages of Foraminifera in the SLS.

Kaiho (1994) related that the increase in the flux of organic debris commonly leads to a decrease in dissolved oxygen in underlying water. Variations in the abundance of oxygen–sensitive morphologic groups may reflect changes in dissolved oxygen content. As the SLS suffers from the discharge of domestic sewage, low levels of dissolved oxygen may be a determining factor that influences the distribution of benthic Foraminifera in this lagoon system and may have caused the disappearance of its Foraminifera fauna.

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