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Research Article

Living and dead Foraminifera as bioindicators in Saquarema Lagoon System, Brazil

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ABSTRACT. The understanding of the differences between living (L) and dead (D) benthic foraminiferal assemblages and all the factors that might lead their distribution should be a key to characterize the environmental and paleoenvironmental changes accurately. Population dynamics and dissimilarities of biological nature (the differences in turnover rate and seasonal alterations in standing stock) can cause significant divergences between the L and D foraminiferal assemblages. This study compares L and D foraminifera to evaluate the sediment quality of the Brazilian Saquarema Lagoon System (SLS) using biogeochemical proxies and predict how coastal ecosystems are responding to the combined effects of eutrophication and pollution pressure and areas where the paleoenvironmental studies can be performed. The SLS is a transitional environment where total organic carbon, proteins, and dissolved oxygen are the main factors controlling the distribution of foraminiferal assemblage. The high values of biopolymers (carbohydrates, lipids, and proteins) in SLS indicate a very impacted environment with long water residence time. The low values of species richness, Shannon-Weaver diversity, and evenness for both L and D foraminiferal assemblages are a consequence of fluctuating conditions in the SLS. Due to low salinities, agglutinated species and *Quinqueloculina seminula* can occur in the most confined areas, and *Ammonia parkinsoniana*, *Cribroelphidium excavatum*, *Cribroelphidium poeyanum*, and *Elphidium gunteri* characterized the area with the highest marine influence. Although in most of the SLS the taphonomic processes modified the original assemblage, in some regions the thanatocoenosis corresponds to the biocenosis. These areas can be considered the most suitable for future paleoenvironmental and paleoclimatic studies.

Keywords: foraminifera, environmental quality, trophic state, marine pollution, coastal lagoon, neontology.

INTRODUCTION

Transitional waters-bodies such as coastal lagoons with close connections to the sea are typically characterized by strong seasonal cycles resulting from periodical rainfall and wind-forcing events that affect the circulation and the residence time of water (Kjerfve, 1994; Prado *et al.*, 2014).

In Brazil, the formation of coastal lagoons was associated with eustatic oscillation processes during the

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Quaternary (Knoppers *et al*., 1999) which can be observed at all shorelines, but mainly in Rio de Janeiro and the Rio Grande do Sul States (Esteves, 1998).

The Brazilian Saquarema Lagoon System (SLS) is connected with oceanic water through the Barra Franca Channel (Fig. 1), an artificial channel stabilized with engineering works in Saquarema Lagoon. A small portion of mangroves occurs in the northern margin of the Urusussanga and Jardim Lagoon (Belart *et al*., 2017; Dias *et al*., 2017). The Urussanga Lagoon, surrounded by swamps, receives the outflow of three rivers: Mato Grosso (or Rocandor), Tingui and Jundiá. The Seco River drains in the Jardim and the Saquarema lagoons and receives the input of fresh water from the Padre and Bacaxá rivers (Moreira, 1989). In the region, the weather is warm and moist and characterized by rainy season in summer with annual precipitation between 1,000-1,500 mm (Barbiere & Coe-Neto, 1999).

The silting and organic matter accumulation generates high anthropic/natural impact in all Rio de Janeiro lagoons. These processes have accelerated in the last decades by deforestation, erosion related to agricultural activities and disordered population growth in most of the drainage basins. Some of the main impacts in this environment are impairment of water quality by effluent discharges without treatment, and changes in hydrologic balance in the last decades, assigned to engineering works such as the work to stabilize the communication channel with the ocean (Knoppers *et al*., 1999).

Coastal areas have traditionally been occupied by human civilization for the development of cities, industries and other activities promoting environmental stress (Agardy & Alder, 2005). The excessive discharges of nutrients from domestic and industrial effluents, combined with urban and agricultural runoff determine the enrichment of organic and inorganic nutrients in paralic ecosystems (Borja *et al*., 2012; Silva *et al*., 2013). These inputs intensify the eutrophication process, which is considered the main factor of stress in the coastal and marine environments (Meyer-Reil & Koster, 2000).

In the last decades, Foraminifera have been widely used as a proxy to describe coastal environments (Frontalini & Coccioni, 2007; Frontalini *et al*., 2009; Laut *et al*., 2011; Martins *et al*., 2013, 2015, 2016a, 2016b; Nesbitt *et al*., 2015). Foraminifera is commonly used as bioindicators because they have a short life cycle, which provides quick response to environmental changes, and are abundant, most diversified, with widespread distribution and specific ecological requirements (Murray, 2006; Laut *et al*., 2016a). The distribution of benthic foraminifera is controlled by many factors, such as temperature, salinity, dissolved oxygen, sediment grain size (Murray, 1991, 2001) and changes in the quality and amount of nutrients (Murray, 2006). Sediment characteristics strongly influence their distribution: they are more abundant in finer sediments but they are also influenced by sediment pollution (Bhalla & Nigam, 1986; Alve & Olsgard, 1999: Frontalini & Coccioni, 2007; Martins *et al*., 2013, 2015).

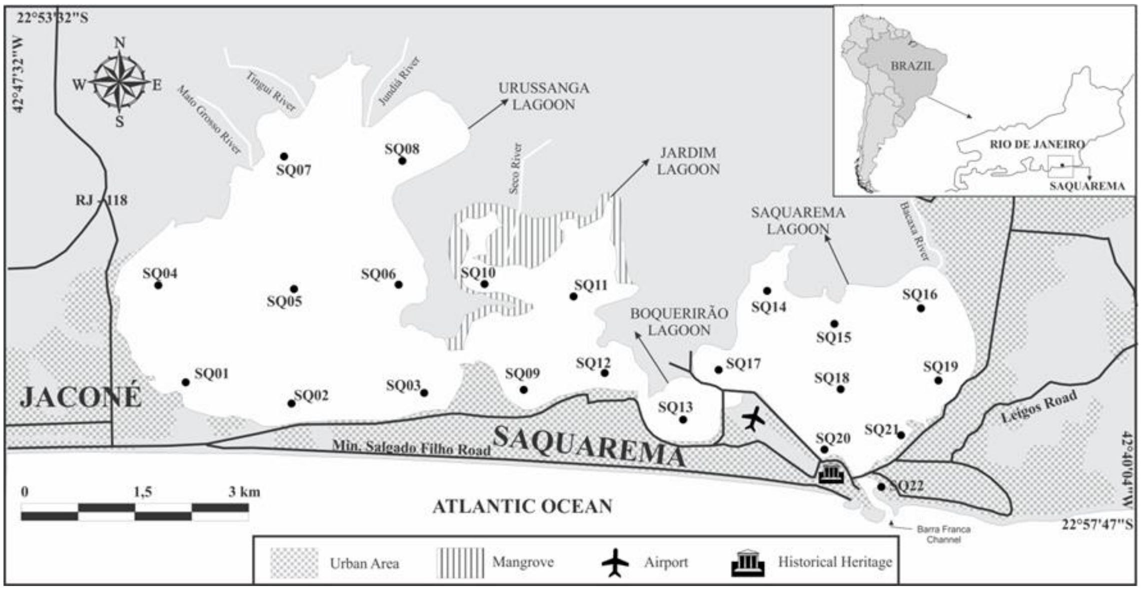

Figure 1. Localization map of studied stations in the Saquarema Lagoon System.

The knowledge about foraminiferal biodiversity in the Brazilian southeast coast was based on total assemblages (Vilela *et al.*, 2003; Leipnitz *et al.*, 2014; Clemente *et al.*, 2015). These studies can lead to bias environmental interpretations because after death foraminiferal tests are exposed to taphonomic processes, such as transport, breaking and dissolving of carbonates.

The studies of Raposo *et al.* (2016) and Belart *et al.* (2017) were the only ones in Rio de Janeiro lagoons based exclusively on living assemblages. Both of them have considered a checklist of lagoonal foraminiferal species without an ecological approach. However, the number of living species was lower than that in total foraminiferal assemblages implying possible seasonal differences and/or the occurrence of allochthonous taxa which corroborates the hypothesis that the absence of a study that separates living individuals from the dead might lead to wrong environmental and paleoenvironmental interpretations.

The understanding of the differences between living (L) and dead (D) benthic foraminiferal assemblages and the factors that contribute to their distribution should be a key to accurate interpretations of paleoenvironmental changes (Goineau *et al.*, 2015). The abundance and composition of L-assemblage vary over short time periods throughout the year in response to both specific-seasonal reproduction and environmental parameters (Murray, 1991). Population dynamics and dissimilarities of biological nature (differences in turnover rate and seasonal alterations in standing stock) can cause significant divergences between the L and D foraminifera (*e.g.*, Jorissen & Wittling, 1999; De Stigter *et al*., 2007; Duros *et al*., 2014).

This study represents the first contribution to compare the L and D benthic foraminiferal assemblages and the sediment quality in the Saquarema Lagoon System (SLS) using biogeochemical proxies, as well as to predict how coastal ecosystems are responding to the combined effects of eutrophication and pollution pressure. Through these analyzes will allow recognizing the sectors where there is the highest preservation of foraminifera tests, thus delimiting priority areas for the paleoenvironmental studies.

MATERIALS AND METHODS

Study area

The Saquarema Lagoon System (SLS) is a tropical coastal ecosystem located in southeastern Brazil in the Rio de Janeiro State (22°55'-22°56'S, 42°35'-42°29'W). It has an area of 21.2 km^2, which extends approximately 11.8 km along the coast with an average depth of less than 2.0 m (Belart *et al*., 2017; Dias *et al*., 2017). This system is composed of four large connected lagoons (Fig. 1): Urussanga (12.6 km^2), Jardim (2 km^2), Boqueirão (0.6 km^2) and Saquarema (6 km^2).

This work is based on the analysis of sediment samples collected in 22 stations in SLS on March 2013 (Fig. 1), each sampled station was geo-referenced with a GPS (model GPSMAP® 78S). The methodology of sampling, data acquisition related to physical and chemical parameters (*e.g.*, temperature, salinity, pH and dissolved oxygen (DO) content in surface water) and benthic foraminifera, as well as granulometric and geochemical data, such as total organic carbon (TOC), total sulfur (TS) and TOC/TS ratio are described by Dias *et al*. (2017).

Stained sediment samples were washed over sieves with mesh openings of 500 and 63 µm. The residual fraction in each sieve was dried at 50°C, and the foraminiferal specimens were concentrated from the remaining sediment by flotation in trichloroethylene (Belart *et al*., 2017). All foraminiferal stained (living specimens) and unstained tests (dead specimens) were picked, identified, and counted under stereoscopic microscopic at 80x magnification. At least, 100 living (L) and 100 dead (D) individuals were counted per sample (Fatela & Taborda, 2002). The number of specimens found in the three replicates was therefore averaged. The generic taxonomical classification of Loeblich & Tappan (1988), 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 using the World Register of Marine Species (WoRMS, 2014). Diversity was calculated using the Shannon index (H'), expressed by the formula: $H' = \sum p_i \ln(p_i)$. The formula calculated the mean evenness (or homogeneity): $J' = H' \ln(S)^{-1}$, using the software MVSP.

Organic matter compounds

The total biopolymer concentration (BPC) consisting of lipids (LIP), proteins (PTN) and carbohydrates (CHO) were determined. These variables were analyzed in the sediment according to the methodology described by Dias *et al*. (2017) in the Laboratory of Palynofacies & Organic Facies of the Federal University of Rio de Janeiro (FURJ). The relative enrichment of biopolymers was evaluated through several parameters: PTN, CHO, LIP, BPC and PTN/CHO.

Interpolation maps

The maps shaped with ArcMap 10.5 and the Spline with Barriers (SWB) tool were configured with cell size 15 and 0 of a smooth factor, for this study in accordance to Dias *et al*. (2017). The interpolation shows the spatial distribution of the parameters concentration inside the lagoon and spatial distribution of ecological indexes and Foraminifera species. Coordinates are provided in WGS84.

Statistical analysis

Only samples with foraminiferal number >100 in L and D assemblages were considered for statistical analyses. Detrended Correspondence Analysis (DCA) was used to correlate the multiple environmental variables and their influence on ecological relationships and distribution of L and D assemblages. DCA analysis was performed in PCord 5.0 Software and based on the Relative Euclidean Distance for calculation of variance coefficient. DCA analysis was based on the relative abundance of L and D foraminifers' species (Appendix 1), as well as the physical and chemical parameters (pH, DO and salinity) and geochemical data such as BPC, CHO, LIP, PTN, TOC, and TS. Before the DCA analysis, these data were standardized to the square root of 0.5 to decrease the difference between the parameters scale.

Q-mode Cluster Analysis (CA) using the relative abundance of all species identified (Appendix 1) and based on the Euclidian Distance with Ward Linkage was applied to order the stations in groups with similar characteristics regarding L- and D-foraminifera. All data were normalized with the square root of 0.5 before the statistical analysis in PCord 5.0 software.

RESULTS

Water parameters

The water temperature showed small variations in the SLS. The highest and lowest temperature values (47.9 and 24.9°C) were recorded at stations SQ07, located near the mangrove fringe on the north bank of the Urussanga Lagoon, and SQ20 close to the communication channel between the Saquarema Lagoon and the Atlantic Ocean, respectively (Table 1).

The lowest and highest values of salinity (30.7 and 43.3) were measured at stations SQ08, in the Urussanga Lagoon, and SQ18, near Barra Franca Channel, respectively (Table 1). The highest pH value (8.7) was recorded in stations SQ02, SQ03 and SQ09 in the Urussanga Lagoon and the lowest (7.8) in SQ20 from the Saquarema Lagoon (Table 1). The maximum value of DO (8.3 mg L^{-1}) was recorded in the SQ03 station from the Urussanga Lagoon and the minimum (5.5 mg L^{-1}) in SQ10 station from the Jardim Lagoon (Table 1).

Grain-size and organic matter analysis

Clay fraction ranged from 16.1% to 44.95% in stations SQ09 and SQ07, respectively, and silt from 42.8% to 80.2% in stations SQ08 and SQ04, respectively (Table 1). The predominant grain size fraction in SLS surface sediments was silt, but in the stations located near the Barra Franca Channel and in SQ03 station located on the south bank of the Urussanga Lagoon sandy fractions dominated.

The minimum TOC recorded value was 0.09% in SQ22 station located in the communication channel with the Atlantic Ocean and maximum 21.5% in SQ10 station located on the Jardim Lagoon (Table 1). The highest value of TS (4.95%) was recorded in SQ08 station located on the northern bank of the Urussanga Lagoon, situated near the Mato Grosso River's mouth and the lowest in stations SQ20 and SQ21 (0.02%) from Saquarema Lagoon (Table 1). The ratio TOC:TS varied between 16.2 and 0.431 in stations SQ20 and SQ22, respectively.

The highest BPC content (32.96 mg C g^{-1}) was found in SQ02 station located on the south bank of Urussanga Lagoon, and the lowest value was found in SQ22 (1.78 mg C g^{-1}). The maximum PTN value was recorded in SQ10 station (4.64 mg C g^{-1}) and the minimum in the SQ22 station (0.45 mg C g^{-1}). The highest and the lowest average CHO content was recorded in the Boqueirão (21.7 mg C g^{-1}) and the Saquarema Lagoon (14.4 mg C g^{-1}), respectively. The highest average LIP content was found in the Jardim Lagoon (5.45 mg C g^{-1}) followed by the Boqueirão Lagoon (4.48 mg C g^{-1}). The lowest average value (3.02 mg C g^{-1}) of LIP was found in the Saquarema Lagoon.

Living and dead foraminiferal assemblages

A total of 3,493 specimens belonging to 8 species and 3,430 specimens belonging to 9 species were picked and identified in the L and D assemblages, respectively (Fig. 2). The lowest L-foraminifera density (102 ind 50 mL^{-1}) was found in SQ04. In the other stations, the L-foraminifer density ranged from 140 ind 50 mL^{-1} in the inner portion of the Jardim Lagoon (SQ11) to 399 ind 50 mL^{-1} in the Saquarema Lagoon (SQ20) (Fig. 2).

The D-foraminifera density ranged from 115 ind 50 mL^{-1} in SQ04 to 338 ind 50 mL^{-1} in SQ18 (Saquarema Lagoon). No L-foraminifera were found in SQ02, SQ03, SQ04, SQ05, SQ6, SQ07 and SQ22 (Fig. 2). In the stations SQ01, SQ03, SQ05, SQ06, SQ07, and SQ22 the D-foraminifera were absent.

For L-assemblages, the H' index values ranged from 0.2 to 1.4; the lowest and highest values were found in SQ08 at the Urussanga Lagoon and in SQ09 at the Jardim Lagoon, respectively. For D-assemblages, the H' index values varied between 0.6 and 1.6 in SQ08 (Urussanga Lagoon) and SQ12 (Jardin Lagoon), respectively (Fig. 2). The J' values varied between 0.2-0.9 and 0.6-0.9 for the L and D assemblages, respectively (Fig. 2).

Table 1. Geographic coordinates of stations, grain size, total organic carbon (TOC; %), total sulphur (TS; %), carbohydrates (CHO; mg C g^{-1}), lipids (LIP; mg C g^{-1}), proteins (PTN; mg C g^{-1}), total biopolymeric carbon (BPC; mg C g^{-1}) are presented. This table also shows salinity (Sal), pH, dissolved oxygen (O_2; mg L^{-1}) and temperature (T, °C) measured at each sampling station.

	Long (W)	Lat (S)	O2 (mg L^{-1})	pH	T (°C)	Sal	PTN (mg C g^{-1})	CHO (mg C g^{-1})	LPI (mg C g^{-1})	BPC (mg C g^{-1})	TOC (%)	TS (%)	Sand (%)	Silt (%)	Clay (%)
SQ01	42°35’5.63”	22°55’27.90”	7.3	8.5	26.3	32.8	3.5	11.9	2.8	18.2	11.9	3.4	1.5	71.6	26.8
SQ02	42°34’19.55”	22°55’37.83”	7.8	8.7	25.8	33.5	2.4	25.9	3.0	31.4	10.2	3.7	5.0	70.9	24.1
SQ03	42°33’30.27”	22°55’33.00”	8.3	8.7	26.6	33.1	2.7	4.6	1.6	8.9	0.5	0.1	99.9	0.0	0.1
SQ04	42°35’16.65”	22°54’56.30”	7.4	8.6	27.7	33.3	3.0	13.9	3.3	20.2	12.7	4.5	0.7	80.2	19.1
SQ05	42°34’23.95”	22°54’55.19”	7.8	8.6	27.7	31.6	2.6	19.8	3.3	25.7	10.7	4.2	2.3	70.3	27.4
SQ06	42°33’25.69”	22°54’45.95”	6.7	8.5	28.3	31.2	2.7	14.2	3.3	20.2	10.1	4.6	0.3	60.3	39.4
SQ07	42°34’35.83”	22°53’59.91”	7.2	8.4	47.9	31.1	2.8	23.4	3.1	29.3	9.4	4.6	1.9	53.2	45.0
SQ08	42°33’27.18”	22°53’46.68”	7.0	8.4	27.6	30.7	3.4	13.3	2.9	19.6	11.9	5	10.3	55.3	34.4
SQ09	42°32’22.21”	22°55’25.49”	7.9	8.7	26	33.8	2.7	21.5	3.4	27.6	8.4	3.3	25.7	57.6	16.7
SQ10	42°32’45.95”	22°54’39.60”	5.5	8.2	26.8	33.5	4.6	10.3	3.6	18.5	21.5	3.4	13.4	56.9	29.7
SQ11	42°32’0.49”	22°54’44.77”	5.9	8.2	27.6	31.0	2.8	20.1	3.7	26.7	9.3	3.9	13.2	48.9	37.9
SQ12	42°31’42.99”	22°55’17.95”	6.1	8.5	27.8	31.8	2.6	24.7	3.4	30.8	8.4	3.1	1.1	66.8	32.1
SQ13	42°31’4.91”	22°55’37.92”	6.1	8.6	27.5	32.4	2.7	19.3	3.1	25.1	6.5	2.9	17.4	57.6	25.0
SQ14	42°30’26.15”	22°54’44.39”	6.9	8.4	26.9	34.3	2.7	19.8	2.7	25.1	5.2	3.0	4.1	74.1	21.8
SQ15	42°29’46.12”	22°54’57.39”	7.2	8.5	26.1	34.5	2.3	21.3	2.5	26.1	5.1	2.8	3.2	75.5	21.3
SQ16	42°29’11.66”	22°54’47.40”	.07	8.6	26	34.0	2.4	20.1	3.0	25.5	4.0	2.8	2.9	73.8	23.3
SQ17	42°30’49.99”	22°55’8.12”	7.2	8.5	26	34.0	2.6	24.0	2.8	29.4	5.3	2.4	13.5	57.1	29.4
SQ18	42°29’41.91”	22°55’23.36”	6.4	8.4	25.4	43.3	2.1	22.7	2.2	27.0	4.0	2.2	25.3	42.8	31.9
SQ19	42°28’59.72”	22°55’14.20”	6.5	8.5	26.1	34.1	2.7	21.5	3.5	27.8	4.2	1.7	6.4	73.6	20.1
SQ20	42°29’56.69”	22°55’46.96”	6.4	7.8	24.9	34.5	2.0	3.1	0.7	5.8	0.3	0	100	0	0
SQ21	42°29’19.20”	22°55’36.72”	6.8	8.4	26.4	34.0	2.2	5.7	1.1	9.1	0.2	0	100	0	0
SQ22	42°29’32.31”	22°56’0.11”	6.7	8.2	25.7	34.3	0.4	1.1	0.2	1.7	0.1	0.2	100	0	0

The dominant families in both assemblages were Ammoniidae and Elphidiidae (Rotaliida Order, Rotalioidea Superfamily). *Ammonia tepida* and *Ammonia parkinsoniana* were the most abundant species throughout the lagoonal system, followed by *Cribroelphidium excavatum* both in L and D-assemblages (Fig. 3).

Ammonia tepida was present in L-assemblages in all stations (Fig. 3). The highest density of this species in L-assemblages was found along the Saquarema margin (48 ind 50 mL^{-1} in SQ21 and 318 ind 50 mL^{-1} in SQ20) and in the Urussanga Lagoon in station SQ08 (up to 165 ind 50 mL^{-1}). In D-assemblages, *A. tepida* reached the highest densities in the Saquarema Lagoon (up to 173 ind 50 mL^{-1}) and lowest values in the Urussanga Lagoon (1-21 ind 50 mL^{-1}) (Fig. 3).

Ammonia parkinsoniana was found in all stations in both L and D-assemblages. The highest density values of *A. parkinsoniana* both in L and D-assemblages were identified in the northern margin of the Saquarema Lagoon (110 tests). In the northern part of the Urussanga Lagoon (SQ08), the density of *A. parkinsoniana* in L-assemblages reached 7 ind 50 mL^{-1} to in D-assemblage to 134 ind 50 mL^{-1}. *Cribroelphidium excavatum* was present along the Saquarema and Jardim lagoons in both L and D-assemblages (Fig. 3).

This species reached the highest density in L-assemblage, at station SQ21 (201 ind 50 mL^{-1}) and in D-assemblage at station SQ13 (63 ind 50 mL^{-1}). *Cribroelphidium poeynum* was found in the L^{-1} assemblage only in SQ20 with low density (6 ind 50 mL^{-1}) but in D-assemblage was distributed in Saquareama, Jardim, Boqueirão and Urussanga lagoons with a density ranging from 4-11 ind 50 mL^{-1}. *Elphidium gunteri* (Elphidiidae Family) was restricted to the north margin in Saquarema, Boqueirão and Jardim lagoons with density values between 4-56 ind 50 mL^{-1} (Fig. 4). *Quinqueloculina seminula* (Hauerinidae family) was found only in the Urussanga and Jardim lagoons both in L and D-assemblages (Fig. 4). The highest densities of *Q. seminula* in D-assemblage were reached in the Jardim Lagoon and the western part of the Urussanga Lagoon. *Buliminella elegantissima* (Buliminellidae family) was found only in D-assemblage at stations SQ10 and SQ15 in Jardim and Saquarema lagoons, respectively. A few agglutinated species (Order Lituolida) including *Ammotium salsum* (D-assemblages) *Haplophragmoides wilberti* (L-assemblages) and
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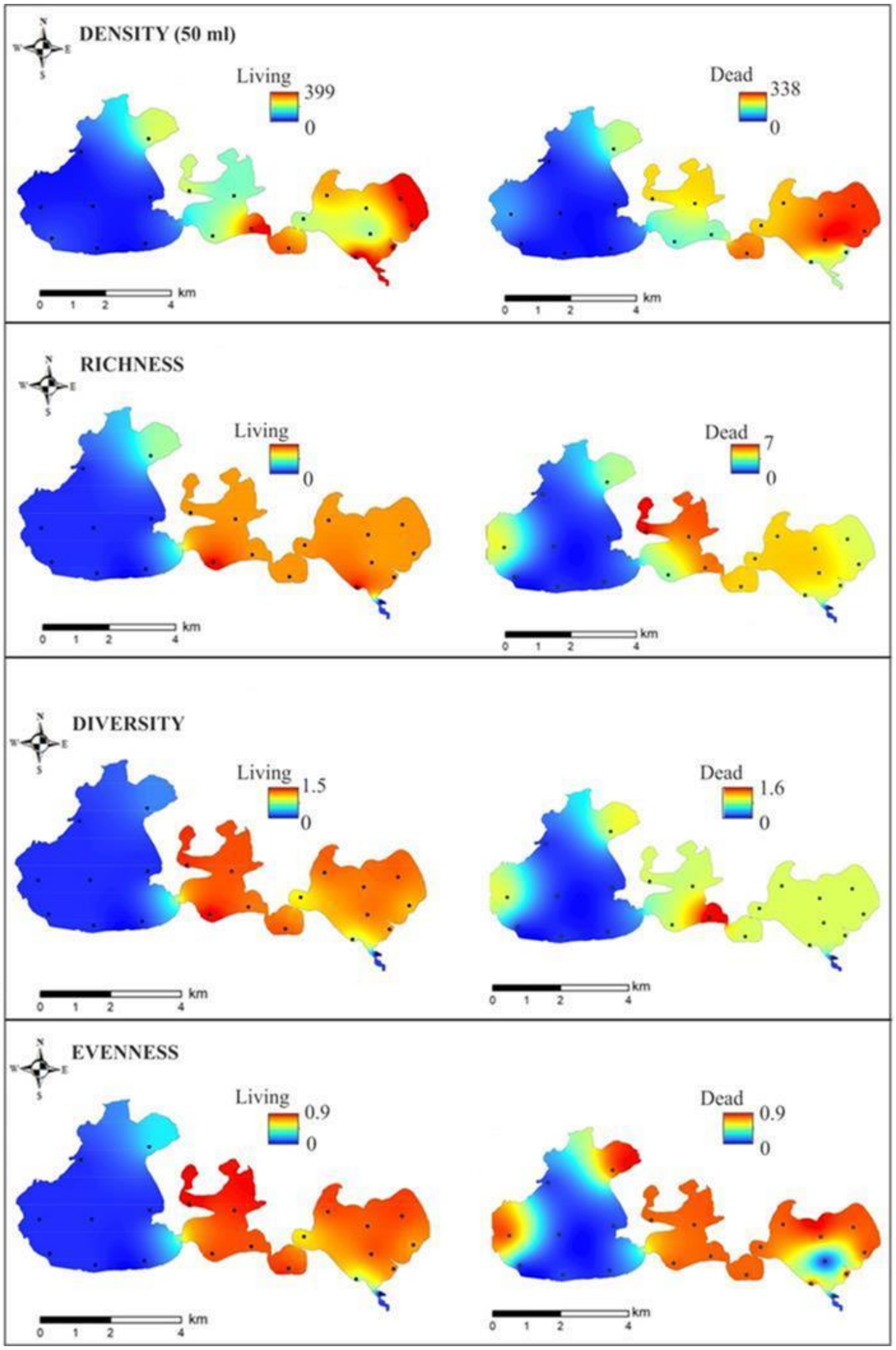

Figure 2. Distribution of living and dead foraminiferal density (ind 50 mL^{-1}), species richness, diversity of Shannon and evenness in SLS.

Trochamminita salsa (both L and D assemblages) were exclusively identified in the Urussanga Lagoon (SQ04).

Statistical analyses

The DCA analysis (Fig. 5) with 81% variance coefficient for the axis 1 and 14% for the axis 2 shows that the agglutinated species (*A. salsum*-D, H. Wilbert-L, and *T. salsa*-L and D) and *Q. seminula* (L and D) were related to higher values of TOC, TS, Temperature, PTN, DO and LIP values (axis 1). *Ammonia tepida*-D and *A. parkinsoniana*-L were associated with higher values of salinity, CHO, and sandy sediments, as well as, *C. excavatum* and *C. gunteri* (in axis 1). *Elphidium poeyanum* in both L- and D-assemblages was related to

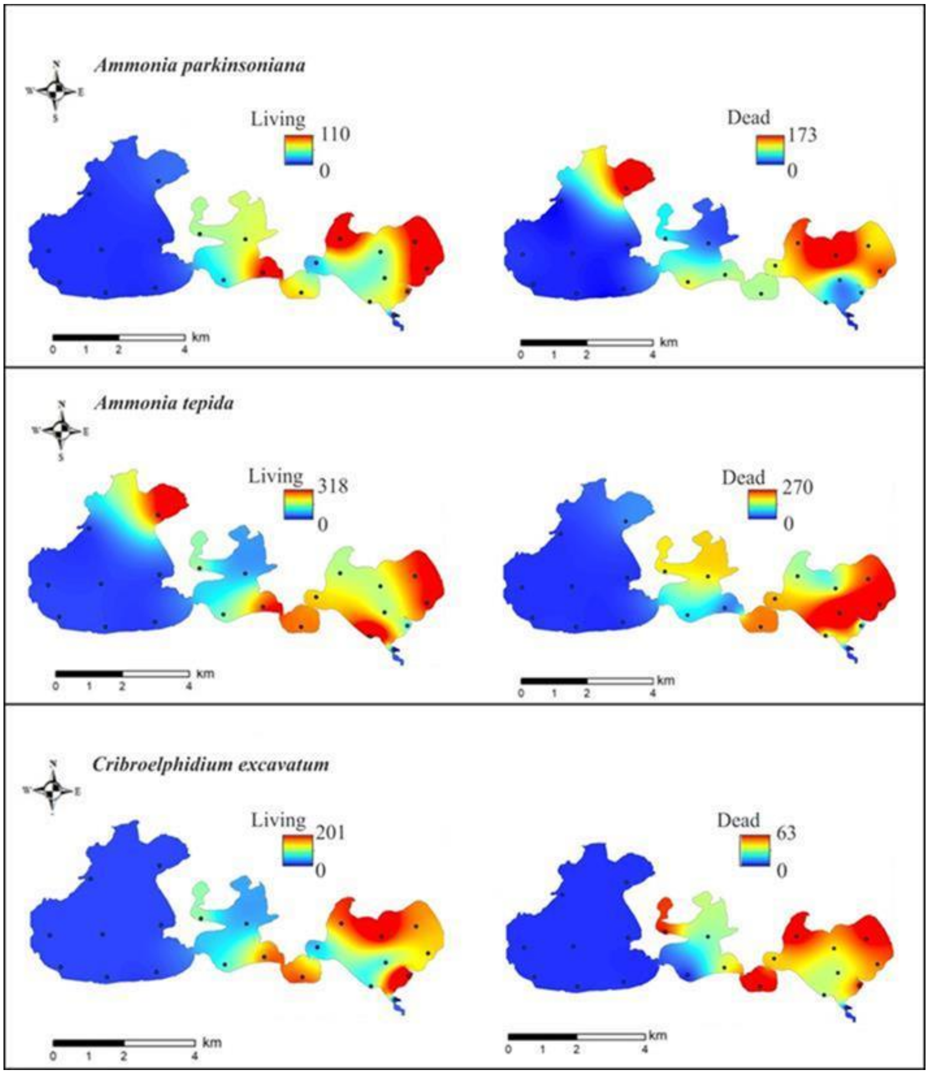

Figure 3. Species distribution of living and dead density (ind 50 mL^{-1}) of *A. parkinsoniana*, *A. tepida* and *C. excavatum* in SLS.

sand fraction, in axis 2. On the other hand, *A. tepida*-L and *A. parkinsoniana*-D were linked to axis 2 and the increase of clay fraction, TOC, TS, Temperature, PTN, DO and LIP (Fig. 5).

The Q-mode cluster analysis allowed the identification of five groups of stations in SLS considering 78% of similarity (Fig. 6). Group I is represented by stations SQ21-L and SQ21-D; Group II by stations SQ09-L, SQ09-D, SQ10-L, SQ12-L, SQ12-D, SQ13-L, SQ14L, SQ14-D, SQ15-L, SQ15-D, SQ19-L, SQ16-L and SQ18-L; Group III by stations SQ08-L, SQ08-D, SQ17-L, SQ20-L; Group IV by stations SQ11-L, SQ11-D, SQ13-D, SQ10-D, SQ16-D, SQ17-D, SQ18-D,SQ19-D, SQ20-D; and Group V by station SQ04-L and SQ04-D.

DISCUSSION

Bottom hydrodynamic and bathymetry of the SLS

Teodoro *et al*. (2010) suggested that the dominance of silty fractions indicates reduced velocities of bottom water currents as occurs in the SLS, except in the Saquarema Lagoon where sandy sediment and low values of TOC dominate (Dias *et al*., 2017). Thus the hydrodynamic regime seems to be more intense in the Saquarema Lagoon due to the proximity to the ocean connection through the Barra Franca Channel, strong tidal currents, and winds. On the other hand, the Urussanga Lagoon is considered the most confined region of the SLS, where the predominance of muddy sediments and high TOC content were founded.

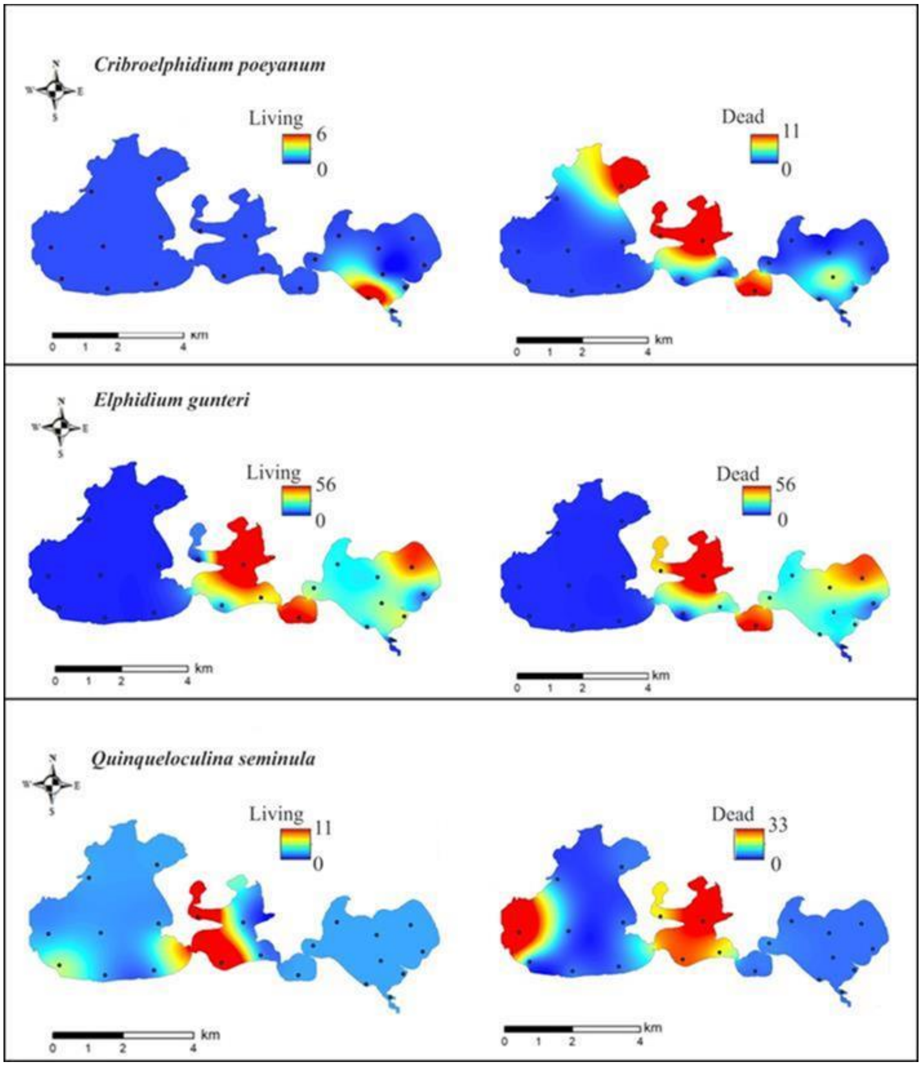

Figure 4. Species distribution of living and dead density (ind 50 mL^{-1}) of *C. poeyanum*, *E. gunteri* and *Q. seminula* in SLS.

According to Dias *et al*. (2017), sandy sediments are more common in shallow areas with depth less than 0.5 m. It was possible to identify an increase of this sediment fraction in much of the southern SLS margin at depths greater than 1 m. These sandy sediments might have been supplied by the wind, by removal, transportation, and deposition from the dunes fields.

Environmental characterization

The surface water physical and chemical variations were low in SLS during the sampling period except for the water temperature, and they were entirely different from those found by Lacerda & Gonçalves (2001). The highest values of salinity found in the Saquarema Lagoon (station SQ18) are the consequence of sea water inflow and high evaporation rate. In this lagoon, powerful tidal currents associated with strong winds favor the accumulation sandy sediments in its central area (Dias *et al*., 2017). According to the Venice System, and considering the salinity variation (means of 33.3), the SLS can be considered a euryhaline environment (Smayda, 1983).

The temperature showed a direct relationship with the hydrodynamic and bathymetry of the lagoon since the shallower regions such as SQ07 (<30 cm) had the highest values but the average temperature found in SLS was in agreement with Bruno (2013). The DO values recorded in SLS were higher than that found in other Rio de Janeiro lagoons, such as the Maricá Lagoon (Oliveira *et al*., 1955; Guerra *et al*., 2011) and the Araruama Lagoon (Debenay *et al*., 2001) in Araruama City. The range of the DO values indicates that the SLS is a favorable environment for the establishment of aerobic organisms of several trophic levels. These high values of DO can be favorited by the action of the wind in a shallow water body. The sediment

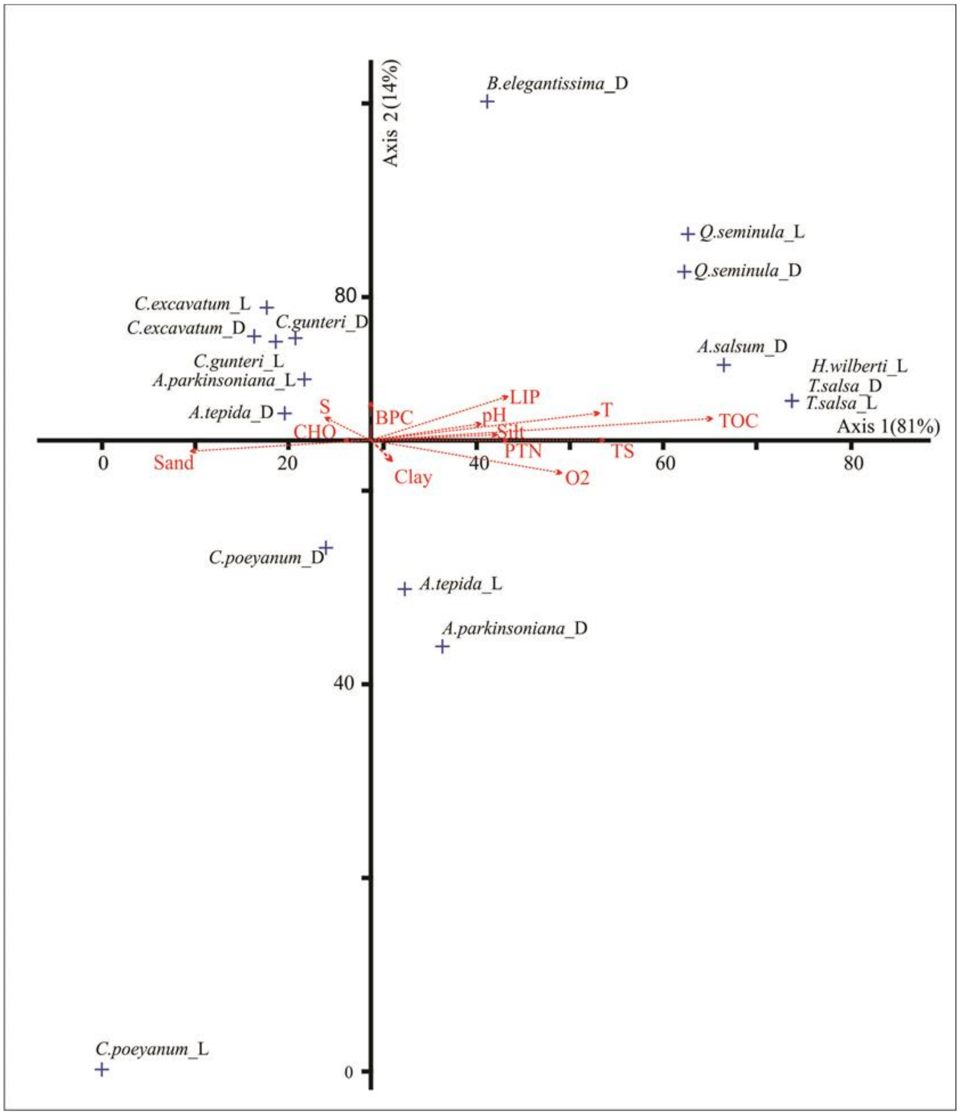

Figure 5. DCA analysis relating the living (L) and dead (D) Foraminifera species with the abiotic parameters in SLS. BPC: the total of biopolymers, CHO: carbohydrates, LIP: lipids, PTN: proteins, TS: total sulfur, TOC: total organic carbon, S: salinity, T: temperature.

had basic pH (7.8 to 8.7) in all the analyzed stations on the contrary to what has been recorded by Lacerda & Goncalves (2001).

Sedimentology and geochemistry

The highest average TOC content found in the Jardim Lagoon (9.53%) is related to the presence of peat in SQ10 station (Dias *et al.* 2017). According to Mendonça-Filho *et al.* (2003) sediments with TOC content >2.5% and high organic matter accumulation rate may be associated with dysoxic-anoxic conditions. In the SLS, the TS values ranged between 0.02-4.95 percent. Using the same methodology of analysis, Clemente *et al.* (2015) and Martins *et al.* (2015) recorded mean TS values of 1.4% in the Guanabara Bay (Rio de Janeiro) and 0.04% in the Bizerte Lagoon (Tunisia), respectively. Laut *et al.* (2016a) found values ranging between 0.04% and 1.73% in the Itaipu Lagoon (Rio de Janeiro). The TS in SLS was higher than those recorded in these areas but was lower than that found in the Santos Estuary (São Paulo), an area highly polluted from industrial and domestic sewage and where the average value was 6.03% (Siqueira *et al.*, 2006).

The biopolymers content in marine and estuarine environments is used for the characterization and interpretation of the origin of organic matter accumulated in sediments (Silva *et al.*, 2011). For instance, Cotano & Villate (2006) noticed that the organic matter

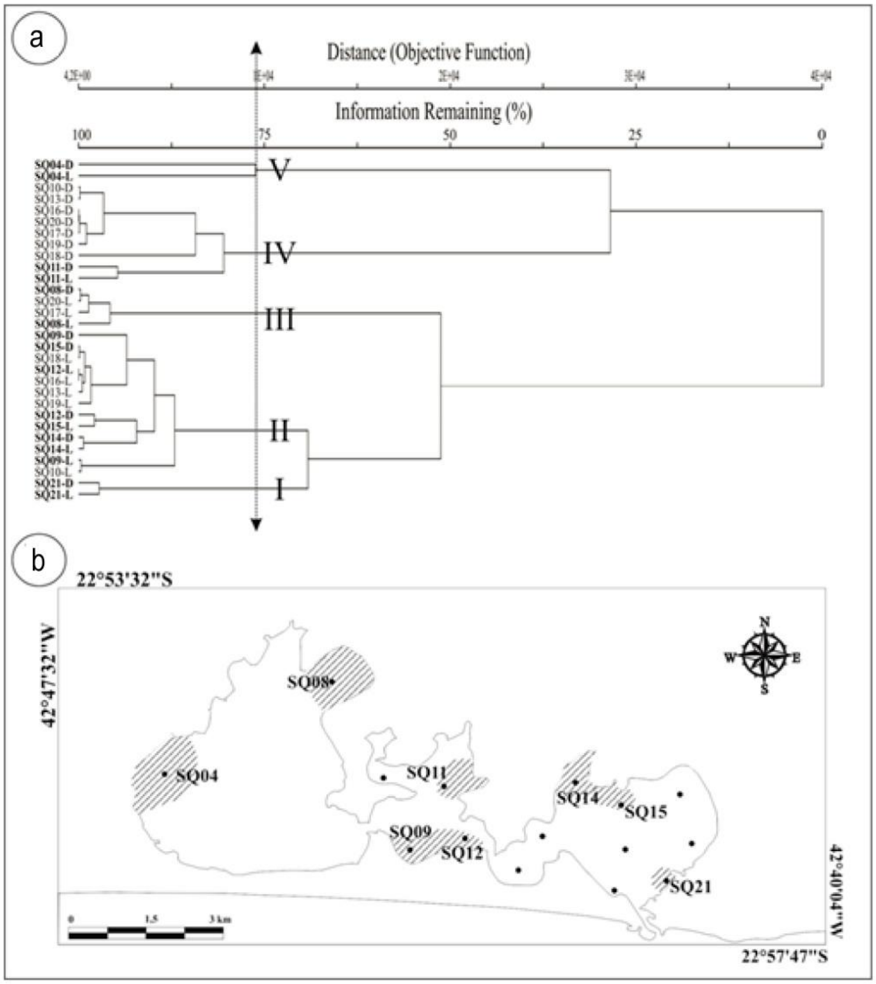

Figure 6. Q-mode Cluster Analysis of stations in the SLS based on relative abundance of living (L) and dead (D) foraminifera (Appendix 2). a) Five groups were defined considering 78% of similarity. In bold are the stations where the L- and D-assemblages compose the same group, b) the distribution map of the stations where the L and D-assemblages have at least 78% similarity according to the cluster analysis results.

provided by domestic liquid effluents and other anthropogenic activities could have high concentrations of PTN and LIP, whereas organic matter from a phytoplanktonic origin and vegetal detritus may have high CHO content. The highest carbohydrate value was found in the SQ02 station (25.9 mg C g^{-1}), near the south margin of the Urussanga Lagoon that has a small mangrove swamp and in the center of all the lagoons of SLS (Dias *et al*., 2017). In lagoons suffering anthropic impacts, the increase of LIP concentrations may be associated with the increment of recalcitrant substances originated by fluvial inputs or sewage (Laut *et al*., 2016a). The highest concentrations of LIP were identified in the most urbanized margin of the Saquarema Lagoon (Dias *et al*., 2017). The PTN decomposition is faster than CHO, and, therefore, only new material, recently deposited, presents high PTN values (Fabiano *et al*., 1995; Laut *et al*., 2016a, 2017). However, in SLS, the high PTN values found in the north margin of the Jardim Lagoon (Dias *et al*., 2017) suggest a natural source from mangrove and peat region.

Characterization of living foraminiferal assemblages

Foraminiferal richness commonly documented for coastal lagoons vary, in general, between twenty and thirty species (Fatela & Taborda, 2002; Laut *et al*., 2007), much higher than that found in the SLS. The species richness identified in L-assemblages of the SLS was lower than recorded in other lagoons of southeastern Brazil. For instance, Vilela *et al*. (2011) recognized 52 foraminiferal species in the Rodrigo de Freitas Lagoon; Bomfim *et al*. (2010) identified 22 species in the Maricá Lagoon and; Debenay *et al*.

(2001) found of 74 species in the Araruama Lagoon. However, these studies were based on the total assemblage, which may incorporate allochthonous species. The low richness of L-assemblages might also be a consequence of periodic variations due to the seasonal reproduction of the species and differential life cycles.

Their geographical position may explain the higher richness and density values of L-assemblages in stations SQ19 and SQ20. These stations were located close to the Barra Franca Channel that promotes the greater exchange of marine water and high-quality food supplied from the ocean. The relatively low foraminiferal H' diversity found in the SLS can be compared to other Brazilian coastal regions, such as the Rodrigo de Freitas Lagoon (Vilela *et al*., 2011) and the Maricá Lagoon (Bomfim *et al*., 2010) that ranged from 0.88 to 2.5, respectively. In these studies were however analyzed only total assemblages (living+dead). Martins *et al.* (2016a) and Delavy *et al.* (2016) using living foraminifera reported diversity values between 0.75 and 1.7 in the inner area of the Guanabara Bay. The values at SLS can be attributed to several factors including the untreated domestic sewage input and the long residence time (or renewal) of water. According to Alves (2003), the water residence time can reach up 58 days in the Urussanga Lagoon and 20 days in the Saquarema Lagoon. The SLS long water residence time, even for the Saquarema Lagoon that is directly connected with the ocean, suggests that the artificial Barra Franca Channel may not be sufficient for water renewal in SLS required for the establishment of large diversified foraminiferal assemblages.

In the SLS, changes in the composition of the L-assemblages, from predominantly calcareous species close to sea channel to an increase of agglutinated species in confined regions, can be observed. *Haplophragmoides wilberti* and *T. salsa* in the L-assemblages were restricted to the most confined areas in the Boqueirão Lagoon (SQ04). These dominant species, as suggested by several authors, is very resistant to salinity changes and reported as dominant in transitional environments such as coastal lagoons (Laut *et al*., 2012, 2016a, 2017; Martins *et al*., 2015).

According to Hayward *et al.* (1996), *C. excavatum* is distributed preferably in coastal environments, where conditions of high salinity, nitrogen, and phosphate prevail. This species is also considered bioindicators of eurytopic conditions by several authors because of their ability to live in a wide variety of habitats and to tolerate a wide range of environmental conditions. It has been recorded in several lagoons of Brazil and around the world (Debenay *et al*., 2002; Vilela *et al*., 2003; Laut *et al*., 2012; Martins *et al*., 2015; Belart *et al*., 2017). *Cribroelphidium excavatum* is also common in estuarine systems like Potengi River in northeastern of Brazil (Souza *et al*., 2010) and Paraiba do Sul River, Rio de Janeiro State (Laut *et al*., 2011).

Ammonia parkinsoniana was reported as a dominant species in the total foraminifera assemblages (living+dead) in several lagoons of Rio de Janeiro: the Maricá Lagoon (Bomfim *et al*., 2010), the Rodrigo de Freitas Lagoon (Vilela *et al*., 2011) and the Araruama Lagoon (Debenay *et al*., 2001). This species shows eurytopic behaviors because it was reported in others coastal lagoons with very distinct environmental conditions, such as the Bizerte Lagoon (Tunisia) and associated to the significant and sustainable flux of high-quality nutrients (Martins *et al*., 2015). In the SLS, *A. parkinsoniana* was found in almost all stations, but reached the highest abundance at stations close to the connection with the ocean, under the higher marine influence related to physical and chemical parameters and food quality.

In addition to *A. parkinsoniana*, the DCA also suggests other bioindicators of higher marine influence: *C. excavatum*, *C. poeyanum*, and *E. gunteri* (Fig. 5). These species are the most spatially represented in the lagoon system. However, their abundance increased under relatively low temperatures, TOC, PTN and LIP values and relatively high salinities and CHO. These species also have a eurytopic behavior since several authors have also reported them in the world (Frontalini *et al*., 2009, 2010, 2013; Laut *et al*. 2016a; Martins *et al*. 2016a, 2016b).

The DCA results also point out that *A. tepida* is related to confined areas and regions with higher temperature, TOC, PTN and LIP but to relatively low BPC content. The results confirmed the adaptive behavior of this species that was present in L-assemblage of all the analyzed stations, in different values of salinities, temperatures, and pH. *Ammonia tepida* is commonly founded in transitional environments under pollution stress from natural or anthropogenic sources (Laut *et al*., 2016a; Martins *et al*., 2016a, 2016b). This species was also found in other lagoons in Italy, such as Orbetello Lagoon (Tuscany, the coast of Tyrrhenian Sea), Lake Varano (Southern Italy), and the Santa Gilla Lagoon (Cagliari) related to the most confined areas (Frontalini *et al*., 2009). The proliferation of this species in coastal environments is favored by the reduced competition in hypo- and hypersaline environments since it is a euryhaline species (Murray, 1991).

Species belonging to Miliolida Order are stenohaline and have low resistance to low concentrations of oxygen (Todd & Brönnimann, 1957). However, *Q. seminula* can be considered characteristic of mixohaline and brackish environments (Ruiz *et al*., 2005; Laut *et al*., 2014). In some tropical ecosystems like SLS, this species is associated with sediment of high organic matter and water with high dissolved oxygen level (Clemente *et al*., 2015; Laut *et al*., 2016a; Martins *et al*., 2016a).

Comparison between living and dead foraminiferal assemblages

The distribution of L and D assemblages was significantly different. These differences may be related to the hydrodynamic conditions or seasonal variations in the community structure in SLS. The analysis of data suggests that the Jardim Lagoon was the depocenter of empty foraminiferal tests. In this lagoon, the density and richness of L-assemblage were higher in the southern margin, and the D-assemblage was higher in the northern. The exception was the station SQ12 in the south of the Jardim Lagoon where the ecological indexes were similar between L and D assemblages.

The species *A. parkinsoniana*, *A. tepida* and *C. excavatum* are the most representative species in the region because they are distributed along to SLS in D and L assemblages. However, *A. tepida* and *A. parkinsoniana* would be used with care as bioindicators in paleoenvironmental studies at SLS because in DCA they present opposite position between L and D. The opposite distribution in the DCA might suggest post-mortem transport effect. *Ammonia tepida* was transported from the most confined to the marine influence area, and *A. parkinsoniana* followed the opposite direction.

The agglutinant species *H. wilberti* (L), *T. salsa* (L and D) and the calcareous *Q. seminula* (L and D) are the bioindicators of low-energy regions in SLS because responded positively in the DCA to higher TOC, TS, temperature, PTN and DO values. These species are commonly found in the inner portion of bays (Phleger, 1957), lagoons (Bomfim *et al*., 2010; Debenay *et al*., 2001) and mangroves (Debenay *et al*., 2004; Woodroffe *et al*., 2005). Some authors like Donnici *et al*. (2012) and Debenay *et al*., (2015) reported that miliolids as *Q. seminula* were favored by environments with greater hydrodynamics and oxygenated waters, which did not occur in the SLS. These species were found in confined regions in L and D. *Haplophragmoides wilberti* might not be useful as a bioindicator of confined areas for paleoenvironmental studies at SLS. This species was not found in D-assemblage, and this suggests the action of taphonomic processes. In the other hands, the bioindicators of high hydrodynamic were *E. poeyanum* and *C. gunteri* that are associated in DCA to sand and CHO in L and D-assemblages.

The cluster analysis identified regions in SLS showing the most substantial difference between L and D assemblages. The most significant differences can be observed between Group II (mostly composed by L-assemblage), Group III (only composed by L-assemblage) and Group IV (mostly composed by D-assemblage). The distribution of these groups was in the central region of the Saquarema Lagoon (SQ16, SQ17, SQ18, SQ19, and SQ20), the Boqueirão Lagoon (SQ13) and north of the Jardim Lagoon (SQ10). The exceptions were the stations SQ09, SQ12, SQ14, SQ15 (Group II) and SQ11 (Group IV) that were represented both in L and D assemblages in the same groups.

The high similarity (78%) occurred with the stations SQ04 and SQ21 that formed isolated groups in the dendrogram. Thus, only a few regions in the SLS presented the preservation of biocenosis (L-assemblage) as indicated in Figure 6. These regions should be prioritized in paleoenvironmental studies because the thanatocoenosis (D-assemblage) shares great similarity with biocenosis. The results indicated that environmental studies based on total assemblage are not recommended in the SLS because the taphonomic processes are very active.

CONCLUSIONS

The SLS, a transitional environment, was characterized and TOC, biopolymers, grain-size, and DO were identified as the main factors responsible for the distribution of foraminiferal assemblage. The high values of TOC and TS suggest that this environment has suffered natural and anthropogenic pressures. The high values of biopolymers indicate a very impacted environment with long water residence time. The species richness in L-assemblages was very low compared to other Brazilian coastal regions and dominated by species with eurytopic behavior such as *A. tepida*, *A. parkinsoniana*, and *C. excavatum*. The species *H. wilberti* was only recognized in L-assemblages next the mangrove fringe, whereas *B. elegantissima* and *A. salsum* were solely identified in the D-assemblage. These differences between L and D-assemblage indicate transport, dissolution, and seasonality in the system. The composition of assemblages in the SLS reflected the reduction of marine gradient influence. The agglutinated species and *Q. seminula* were bioindicators of most confined areas, and *A. parkinsoniana*, *C. excavatum*, *C. poeyanum*, and *E. gunteri* characterized the most marine influenced areas. The species *A. tepida* and *A. parkinsoniana* cannot be considered as bioindicators of hydrodynamic in paleoenvironmental studies in the SLS as both were transported after death. The cluster analysis showed that only a few regions in each lagoon present right conditions of preservation of biocenosis. The results of this analysis indicated the best regions for the application of paleoenvironmental studies and that the studies with total assemblages do not represent the biotic conditions in the SLS.

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Appendix 1. Abundance and ecological index of foraminifera from Saquarema Lagoon System (L: represent the living assemblage, and D: dead assemblage).

	Ammonia parkinsoniana	*Ammonia tepida*	*Ammotium salsum*	*Buliminella elegantissima*	*Cribroelphidium excavatum*	*Cribroelphidium poeyanum*	*Elphidium gunteri*	*Haplophragmoides wilberti*	*Quinqueloculina seminula*	*Trochamminita salsa*
SQ01_D	0	0	0	0	0	0	0	0	0	0
SQ01_L	0	1	0	0	0	0	0	6	6	7
SQ02_D	0	0	0	0	0	0	0	0	0	0
SQ02_L	0	0	0	0	0	0	0	0	0	0
SQ03_D	0	0	0	0	0	0	0	0	0	0
SQ03_L	0	0	0	0	0	0	0	0	0	0
SQ04_D	0	3	27	0	0	0	0	0	33	2
SQ04_L	0	0	0	0	0	0	0	0	0	0
SQ05_D	0	0	0	0	0	0	0	0	0	0
SQ05_L	0	0	0	0	0	0	0	0	0	0
SQ06_D	0	0	0	0	0	0	0	0	0	0
SQ06_L	0	0	0	0	0	0	0	0	0	0
SQ07_D	0	0	0	0	0	0	0	0	0	0
SQ07_L	0	0	0	0	0	0	0	0	0	0
SQ08_D	21	134	0	0	0	8	0	0	0	0
SQ08_L	7	165	0	0	0	0	0	0	0	0
SQ09_D	44	70	0	0	0	0	0	0	17	0
SQ09_L	22	65	0	0	23	0	7	0	38	0
SQ10_D	110	38	0	2	56	7	23	0	11	0
SQ10_L	37	72	0	0	30	0	0	0	44	0
SQ11_D	109	12	0	0	23	11	56	0	21	0
SQ11_L	44	28	0	0	12	0	56	0	0	0
SQ12_D	19	55	11	0	33	0	12	0	11	0
SQ12_L	84	156	0	0	59	0	23	0	0	0
SQ13_D	145	54	0	0	63	8	37	0	0	0
SQ13_L	54	145	0	0	63	0	37	0	0	0
SQ14_D	82	102	4	0	62	0	11	0	0	0
SQ14-L	102	82	0	0	62	0	11	0	0	0
SQ15_D	82	173	0	1	38	0	21	0	0	0
SQ15_L	33	84	0	0	82	0	11	0	0	0
SQ16_D	160	84	0	0	58	0	32	0	0	0
SQ16_L	84	160	0	0	58	0	32	0	0	0
SQ17_D	130	66	0	0	40	0	15	0	1	0
SQ17_L	17	118	0	0	14	0	15	0	0	0
SQ18_D	270	25	0	0	29	4	10	0	0	0
SQ18_L	36	83	0	0	22	0	16	0	0	0
SQ19_D	173	110	0	0	48	0	4	0	0	0
SQ19_L	110	173	0	0	48	0	4	0	0	0
SQ20_D	82	38	0	0	29	0	13	0	0	0
SQ20_L	47	318	0	0	23	2	9	0	0	0
SQ21_D	40	36	0	0	58	0	13	0	0	0
SQ21_L	76	48	0	0	201	0	21	0	0	0
SQ22_D	0	0	0	0	0	0	0	0	0	0
SQ22_L	0	0	0	0	0	0	0	0	0	0

Appendix 2. Absolute abundance of foraminifera from Saquarema Lagoon System (L: represent the living assemblage, and D: dead assemblage).

	Ammonia parkinsoniana	*Ammonia tepida*	*Ammotium salsum*	*Buliminella elegantissima*	*Cribroelphidium excavatum*	*Cribroelphidium poeyanum*	*Elphidium gunteri*	*Haplophragmoides wilberti*	*Quinqueloculina seminula*	*Trochamminita salsa*
SQ01_L	0	1	0	0	0	0	0	6	6	7
SQ04_D	0	3	27	0	0	0	0	0	33	2
SQ08_D	134	21	0	0	0	8	0	0	0	0
SQ08_L	7	165	0	0	0	0	0	0	0	0
SQ09_D	70	44	0	0	0	0	0	0	17	0
SQ09_L	22	65	0	0	23	0	7	0	38	0
SQ10_D	38	110	0	2	56	7	23	0	11	0
SQ10_L	37	72	0	0	30	0	0	0	44	0
SQ11_D	12	109	0	0	23	11	56	0	21	0
SQ11_L	44	28	0	0	12	0	56	0	0	0
SQ12_D	55	19	11	0	33	0	12	0	11	0
SQ12_L	84	156	0	0	59	0	23	0	0	0
SQ13_D	54	145	0	0	63	8	37	0	0	0
SQ13_L	54	145	0	0	63	0	37	0	0	0
SQ14_D	102	82	4	0	62	0	11	0	0	0
SQ14-L	102	82	0	0	62	0	11	0	0	0
SQ15_D	173	82	0	1	38	0	21	0	0	0
SQ15_L	33	84	0	0	82	0	11	0	0	0
SQ16_D	84	160	0	0	58	0	32	0	0	0
SQ16_L	84	160	0	0	58	0	32	0	0	0
SQ17_D	66	130	0	0	40	0	15	0	1	0
SQ17_L	17	118	0	0	14	0	15	0	0	0
SQ18_D	25	270	0	0	29	4	10	0	0	0
SQ18_L	36	83	0	0	22	0	16	0	0	0
SQ19_D	110	173	0	0	48	0	4	0	0	0
SQ19_L	110	173	0	0	48	0	4	0	0	0
SQ20_D	38	82	0	0	29	0	13	0	0	0
SQ20_L	47	318	0	0	23	2	9	0	0	0
SQ21_D	36	40	0	0	58	0	13	0	0	0
SQ21_L	76	48	0	0	201	0	21	0	0	0