Foraminifera as indicators of environmental changes promoted by dredging in tidal channels from Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil
Foraminíferos como indicadores das mudanças ambientais promovidas pela dragagem nos canais de maré do Sistema Lagunar Maricá-Guarapina, Rio de Janeiro, Brasil

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Abstract

To mitigate the anthropogenic impacts on the coastal lagoons, public managers have been implementing different approaches, such as dredging and opening channels to increase the circulation of the marine waters and improve the system's environmental quality. This study aims to investigate the effects of these approaches (opening and dredging of channels) in the Maricá-Guarapina Lagoonal System, using the relationship between foraminifera and environmental parameters before (2013) and after (2019) these interventions on the environment. After the interventions, data showed a significant increase in the marine influence on the lagoon system. The effects of seasonality could be identified by the reduction of sandy sediments related to the decrease in rainfall between the two analysed periods. The ecological indexes for foraminifera increased in 2019 due to the higher efficiency of water renewal in the lagoons. *Ammonia tepida*, *Ammonia parkinsoniana* and *Elphidium excavatum* were the most constant species in both sampling periods. *Quinqueloculina seminulum* was replaced by *Ammotium morenoi* and *Ammotium cassis* after the interventions as a result of changes in the distribution of muddy sediments in the lagoons. The Assemblage *E. excavatum* was correlated with higher salinity levels and showed an extension of its range within the lagoons. The same occurred with the Assemblage *Paratrochammina guaratibaensis*, which indicated high hydrodynamic. On the other hand, Assemblage *A. tepida*, related to the most impacted area, was distributed in all the innermost lagoons, and after the dredging its distribution was reduced.

Keywords: Coastal monitoring; anthropogenic environmental change; tropical lagoons.

Resumo

Para mitigar os impactos antropogênicos nas lagoas costeiras, os gestores públicos vêm implementando diferentes abordagens, como a dragagem e a abertura de canais para aumentar a circulação das águas marinhas e melhorar a qualidade ambiental do sistema. Este estudo tem como objetivo investigar os efeitos dessas abordagens (abertura e dragagem de canais) no Sistema Lagunar Maricá-Guarapina, utilizando a relação entre foraminíferos e parâmetros ambientais antes (2013) e após (2019) essas intervenções no ambiente. Após as intervenções, os dados demonstraram um aumento significativo da influência marinha sobre o sistema lagunar. Os efeitos da sazonalidade puderam ser identificados pela redução de sedimentos arenosos relacionados à diminuição da pluviosidade entre os dois períodos analisados. Os índices ecológicos da comunidade de foraminíferos aumentaram em 2019 devido à maior eficiência de renovação da água nas lagoas. *Ammonia tepida*, *Ammonia parkinsoniana* e *Elphidium excavatum* foram as espécies mais constantes em ambos os períodos de amostragem. *Quinqueloculina seminulum* foi substituída por *Ammotium morenoi* e *Ammotium cassis* após as intervenções, como resultado do aumento de áreas com sedimentos lamosos nas lagoas. A assembleia *E. excavatum* foi correlacionada com níveis mais altos de salinidade e demonstrou a extensão da influência da maré dentro das lagoas. O mesmo ocorreu com a assembleia *Paratrochammina guaratibaensis* que indicou as áreas de mais alta hidrodinâmica. A assembleia *A. tepida* foi relacionada às áreas mais impactadas, ocorrendo nas áreas mais internas, e apresentou retração após as obras de dragagem.

Palavras-chave: Monitoramento costeiro; mudanças ambientais antropogênicas; lagunas tropicais..

1. Introduction

Several coastal regions worldwide are under an accelerated process of environmental degradation and modification of natural landscape. This scenario is driven by intensive human activities, whose effects can be observed in countless coastal environments such as lagoons, mangroves, dunes, beaches, coral reefs, and

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others (Esteves et al. 2008). Among the most threatened ecosystems, the tropical coastal lagoons are one the most vulnerable, making conservation fundamental since they provide essential services and ecosystem resources, such as nurseries for several species, food sources, resting areas for continental and marine organisms, high biological productivity, and rich biodiversity (Santos 1970; Belart et al. 2017; Silva & Mussi 2019). Such characteristics encourage human development around these lagoons, which often occurs without urban planning, especially in the Neotropical regions, where the demography is more accentuated in the coastal zone (Esteves et al., 2008).

Coastal lagoons are geologically ephemeral environments (Kjerfve 1994) and extremely sensitive to natural factors such as climate change, local tectonic activity or by human interference such as landfills, changes in the drainage basin, and others (Lanzoni and Seminara 2002). The prolonged residence time of water in these environments makes them more susceptible to the concentration and deposition of pollutants, and also to eutrophication processes (Miranda et al. 2002; Carloni et al. 2010).

The increase in water circulation promoted by opening artificial channels has been a measure frequently used to improve water quality and biological productivity in coastal lagoons (Dionisio et al. 2000; Suzuki et al. 2002). Some researchers argue that the construction or dredging channels may be considered a palliative measure and harmful due to the fast displacement of biota from freshwater or brackish water to marine organisms' colonization, that changes completely the structure and functions of original community (Pérez-Ruzafa et al. 1991, Sfriso et al. 2003; Young & Potter 2003). In contrast, for other researchers (Hernéndez-Arana and Ameneyro-Angeles, 2011), these interventions result in beneficial effects with the reconfiguration of the water body as an estuarine behaviour (formation of salinity gradients) and the consequent increase in biodiversity level that is lower in environments with eutrophic and confined characteristics.

In recent decades, the coast of Rio de Janeiro State (Fluminense coast) has been the target of intense urban expansion, disorderly growth, and exponential increase in local population density, generating changes in the watersheds, in the use of the soil and its resources, and also the increase in waste production that is discharged directly into lagoonal bodies (Souza et al. 2010; Cruz et al. 1996).

In this context, the Maricá-Guarapina Lagoon System (MGLS), located approximately 50 km north of Rio de Janeiro city is an important coastal system composed of four lagoons connected by channels (Maricá, Barra, Padre, and Guarapina) that have been affected by several anthropic impacts over time (Laut et al. 2019). A historical review of the trophic state of the coastal lagoons from Rio de Janeiro published by Silva & Molisani (2019) reveals that this lagoon system achieved the worst results of the entire coastal region between 1980 and 2014. The high level of organic matter in MGLS greatly impacted the distribution of the benthic community, causing the lowest values of abundance, richness and diversity on the foraminifera, and ostracods in 2013 (Laut et al. 2021).

Among the four lagoons, the most alarming situation occurs with Maricá Lagoon (the most confined area in the system), which receives a large load of raw sewage from the urban area of Maricá city (Toledo et al. 2021). The Maricá Lagoon has the Itaipuaçu Channel which connects it to the Atlantic Ocean. However, this extensive channel does not promote good water renewal (Cruz et al. 2010). On the other hand, the Guarapina Lagoon, which receives mainly pollutants from agricultural waste, has the best water renewal by connectivity with the sea through the Ponta Negra channel (Souza et al. 2013). Laut et al. (2019 and 2021) report that the Ponta Negra Channel is inefficient in renewing the entirety of the waters of Guarapina Lagoon, presenting areas with an accelerated eutrophication process.

Toledo et al. (2021) when presenting an overview of the MGLS, reported the recurring phenomena of algal bloom/eutrophication and fish mortality mainly in the Maricá and Barra lagoons and warned of the need for mitigation measures for these problems. In recent years, the city of Maricá has implemented dredging projects in the fluvial channels and the lagoons as an objective to mitigate low oxygenation and flooding during the summer (Prefeitura de Maricá 2021). The Ponta Negra Channel was also dredged in 2018 making the lagoon system navigable but the persistence of fish mortality events led the city government to open a new channel in Barra Lagoon. The changes were visible after the channel opening according to local fishermen interviewed, but a few days later the channel was closed naturally being necessary to perform a mechanical reopening. Due to their intermittence, the maintenance and permanence of these channels depend on efforts and permanent monitoring, to promote an effective water exchange with the ocean.

Studies using local biota to understand the effects of interventions in lagoon channels have been recommended and widely used (Buss et al. 2003). For this purpose, benthic foraminifera have great potential, once they have shown efficiency in characterising water bodies, with several advantages when compared to macrofauna groups (Bouchet et al. 2007; Alve et al. 2009). The main characteristics of foraminifera used as environmental bioindicators include: their high density and diversity, which allow a reliable assessment without the need for large volumes of sediment; short life cycles turn them able to respond quickly to environmental changes; and a high degree of specialisation that demands specific ecological requirements (Murray 2006; Schönfeld et al. 2012; Leipnitz et al. 2014). In addition, the possibility of preserving their shells in the sediment allows generating useful paleoenvironmental information to understand the evolution of ecosystems, making paleoclimatological and paleoecological reconstructions possible (Murray 2006; Raposo et al. 2016; Belart et al. 2018; Bouchet et al. 2007).

Despite recent scientific advances, foraminifera are not part of the national environmental guidelines and standards for biomonitoring. For the implementation of these organisms in environmental monitoring, it is fundamental the contribution of researchers with a consensus about standardised methodologies which take into account the specific conditions of each environment and the great diversity of ecological regions (Sousa et al. 2020; Bouchet et al. 2012). Unfortunately, studies of this type are still scarce in many places in the world, including Brazil. In most regions there is no database before the environmental impacts and human interventions (Bouchet et al. 2012). Specifically, for MGLS, there is previous data collected in 2013 (Laut et al. 2021) before the intervention works in the channels, which allows the application of these organisms for biomonitoring the possible anthropogenic impacts. Thus, this study aims to identify the environmental changes in the Maricá-Guarapina Lagoonal System using the relationship between environmental variables and the foraminifera distribution. Also, this study contributes to the knowledge of biodiversity and ecological relations of foraminifera of the Neotropical region, and provides data to use in environmental monitoring programs.

2. Regional Settings

The MGLS is located on the southeast of Brazil (22°52’ 23°00’ S e 43°00’ 42°45’ W) in Maricá coast (Rio de Janeiro State) and consists of four circular lagoons connected by channels (Maricá – 17.9 km^2, Barra – 7.58 km^2, Padre - 1.44 km2 and Guarapina 6.43 km2) that together comprise nowadays 33.35 km^2 in area. These lagoons are part of the coastal plain formed since the Pleistocene from the deposition of sediments on the Pre-Cambrian basement (Perrin 1984; Silva et al. 2014). Its limits are determined by the Atlantic Ocean (south) and by the Tiririca (west) and Ponta Negra (east) Coastal Range in the city of Maricá (Fig.1). The drainage basin consists of three main sub-basins (total 330 km2): Vigário River Basin; Ubatiba River, which its mouth is in Maricá Lagoon; and Caranguejo River Basin with its mouth located in Guarapina Lagoon (Comitê Gestor da Região Hidrográfica da Baía de Guanabara e dos Sistemas Lagunares de Maricá e Jacarepaguá, 2006).

The range of the spring tide in Rio de Janeiro is less than 1.5 m (DHN, 2022), conditioning the coast to a micro-tide regime. The Maricá coast is dominated by incidence waves from SE associated with good weather conditions, and from S and SE, during the occurrence of storms caused by the occasional passage of cold fronts, when waves can reach 3 m high at breaking point (Muehe 1979; Silva et al. 2008a). These waves occasionally overcome the sand barrier during storms of greater magnitude, depositing sediments directly in the lagoons (Silva et al. 2008b). This phenomenon (overwash) is currently more frequent in Barra de Maricá (Fig. 1), where the barrier is narrower (Silvestre et al. 2015). The climate of the MGLS region is tropical humid type to semi-humid with annual temperature around 23 °C, and the precipitation value comprises around 1,100 and 1,500 mm/year. The main factor that influences its characteristic climate is the tropical air masses with oceanic and continental origins (Barroso-Vanacôr et al. 1994).

Barbiére (1985) described the bathymetry of MGLS as follows: Maricá lagoon has a maximum depth of 2.0 m and a mean of 1.0 m; Barra and Padre Lagoons represent the shallower part of the system since 70% of its area have depths of 0.5 m; Guarapina lagoon is the deepest with depths ranging from 2.0 to 5.0 m in deep. The sedimentation rate measured in the system through ^{210}Pb isotope is 0.28 cm/year close to the Itaipuaçu channel, 0.36 cm/year close to the mouth of the Mumbuca River (Fernex et al. 1992), and 0.4 cm/year in the central area (Marques et al. 1995). According to Silva et al. (2021), the central section of MGLS should increase sediment thickness by around 40 cm over the next 100 years, reducing the depth from approximately 1 to 1.5 m. Laut et al. (2019) used the classification proposed by Hedgpeth (1951) for salinity in MGLS and observed the existence of a gradient marked by a decrease in salinity from Guarapina to Maricá. According to the authors, Guarapina and Padre lagoons are strong mesohaline systems (mean salinity between 10 and 18); Barra Lagoon is a weak mesohaline system (mean salinity between 1.8 – 18); and Maricá Lagoon is a freshwater system (salinity <1.8).

The silt is the predominant grain size class in the bottom of the lagoonal system. Muddy sediments were found in the central areas of Guarapina and Maricá lagoons and at the northern region of Barra Lagoon (Laut et al. 2019). According to Fernex et al. (1992), the sandy sediments are common in shallow zones with a water column of less than 50 cm mainly found along the lagoonal margins and at the entrance of Guarapina Lagoon and at Padre Lagoon (Laut et al. 2019). Sandy barriers represent the main source of sand for the lagoons through wind reworking and washover deposits (Silva et al. 2021; Silvestre et al. 2021). The bottom sediments of MGLS receive organic matter from mixed sources while the main source is the autochthonous organic matter produced by phytoplanktonic and vegetal detritus from the mangrove fringe. The organic matter from anthropogenic sources is more evident in Padre Lagoon. Still, the central regions of Maricá, Barra and Guarapina lagoons have a low capacity for oxidation which should evolve into an ever-increasing stage of eutrophication (Laut et al. 2019).

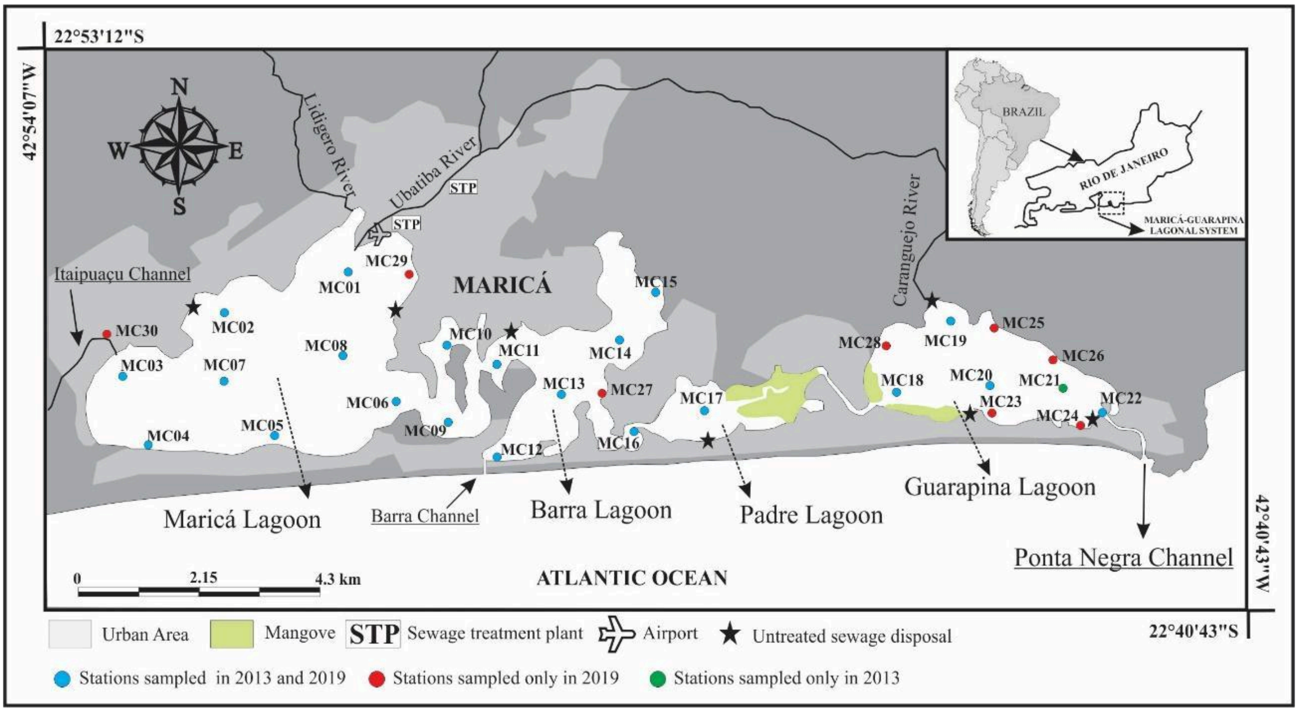

Figure 1. Study area and sampling stations in Maricá-Guarapina Lagoon System, Rio de Janeiro, Brazil. Note urban and mangrove area, untreated sewage points observed and other important areas are also indicated (Datum: WGS 94 zone 23S).

Until the 1950s, opening the sandy bar to the sea was a natural process in storm events, or it was provided by the fishermen when the waters reached the maximum flooding in Maricá Lagoon (Mello & Vogel 2017). However, in 1951, Ponta Negra Channel was constructed to connect the Guarapina Lagoon to the ocean due to the Governmental Sanitation Program in Rio de Janeiro. The construction of the channel aims to limit flooding during the rainy season and avoid malaria focus. This work brought drastic environmental changes to the system, such as reducing regional fishing productivity and decreasing the water body (Amador 1985). However, today, the channel does not have an efficient function to promote water change by tidal flood. The MGLS has been operated by the flood system in rainy periods (Cruz 2010). Ponta Negra is a channel with a very limited hydraulic section due to silting, and probably, the effective hydraulic area does not reach 20 m² (Laut et al. 2019).

3. Material and Methods

3.1 Sampling

The sampling at MGSL was carried out in July 2019 (meridional winter) following the same methods applied in March 2013 (meridional autumn) by Laut et al. (2021), aiming to maintain accuracy when comparing both sample periods. In 2019 were established 29 sampling stations; among these, 21 were carried out in the same places as in 2013 (Laut et al. 2021), and 8 were placed as extra points to have greater area coverage and better data resolution (Fig. 1). Station MC21 cannot be sampled in 2019 due to navigation issues. The sampling process was carried out using Ekman Grab while collecting ~100 g of sediments for grain size analysis. For foraminifera analysis, 50 ml of sediments was collected in triplicate (three different grab throws) from the first 1 cm of sediment and stained with Rose Bengal solution to identify living organisms (Schönfeld et al. 2012). Temperature (T), salinity (Sal) and pH data were measured using a multiparameter probe model YSI 6600V2 in the water-sediment interface using a van Dorn water sample.

3.2 Grain size analysis

Grain size analysis were performed on the samples (100 g) were: 1) washed with deionized water to remove soluble salts; 2) dried in an oven at 60 ºC and weighed; 3) treated with hydrochloric acid (HCl) and hydrogen peroxide (H2O2) to remove, respectively, carbonates and organic particles; 4) dried in an oven at 60 ºC and weighed after each previous step; 5) sieved using a Ro-tap system with mesh openings of 2.00 mm; 1.41 mm; 1.00 mm; 0.71 mm; 0.50 mm; 0.35 mm; 0.25 mm; 0.177 mm; 0.125 mm; 0.083 mm and 0.063 mm. Particles smaller than 0.063 mm (silt and clay) were analysed by the Pipette sampling method, which is based on Stokes' law. The grain size classification system proposed by Shepard (1954) was adopted for sediment classification.

3.3 Foraminiferal analysis

The sediment was washed on 63 µm and 500 µm sieves and dried at 50°C. The foraminiferal specimens were hand-picked on fractions between 63-500 µm, according Boltovskoy (1965), using a stereomicroscope with 80x magnification. In this study, only living foraminifera (stained) were considered. Only the samples with a minimum of 100 living specimens were used for statistical analysis (Fatela & Taborda 2002).

The absolute abundance in the stations was determined by averaging the number of specimens in the three replicates (Raposo et al. 2018). Species that occurred in just one station, with less than 4% relative abundance, were also removed from the statistical analysis to avoid noise. Foraminiferal genera were taxonomically classified following Loeblich & Tappan (1987). The identification at the species level was based on several publications, notably Todd & Brönnimann (1957), Boltovskoy et al. (1980), Laut et al. (2012, 2017a) and Raposo et al. (2016). The identity of species and genera was checked through the World Marine Species Database (WoRMS, 2022). Ecological indexes such as density (mean among the three replicates - FD) and species richness (S), Shannon's diversity (H') and equitability (J') were used in the data interpretation. The software MVSP 3.1 was used to calculate H' and J.

3.4 Interpolation maps

The maps were created with the ArcMap Pro 2.7 software and the Spline with Barriers (SWB) tool configured with cell size 15 and 0 smooth factors according to Belart et al. (2017) and Laut et al. (2017b, 2019, 2022). The interpolation shows the spatial distribution of abiotic and biotic analysed variables in both sample periods (2013 and 2019). The coordinates were provided in the Universal Transverse Mercator (UTM), zone 23S, in the WGS84 datum.

3.5 Statistical analysis

The relative abundances of all living foraminiferal species in each sample were calculated and used for statistical analysis. The abiotic data (temperature, salinity, pH and grain size) were transformed by the square root of 0.5 before statistical analysis. The Detrended Correspondence Analysis (DCA) was applied to determine the relationships among benthic foraminiferal species and sample stations with abiotic parameters. Cluster analysis (CA) in Q-mode and R-mode allowed us to evaluate the similarities among samples from two sampling periods to identify sub-environments based on species distribution and abundance. The cluster generated using the relative abundance of all living foraminiferal was performed using Ward's method with Euclidean distance coefficient for Q-mode and the r-Pearson distance coefficient for R-mode. The DCA and CAs were performed in PCord 5.

4. Results

4.1 Abiotic parameters

The physical-chemical and sedimentological parameters of the MGLS showed significant differences between the sampling carried out in 2013 and 2019 (Table 1). The salinity in 2013 ranged from 0.1 - 20.0 (mean 5.1) in the MGLS (Table 1). The lowest values of water salinity were recorded in Maricá Lagoon (mean of 0.5), varying from 0.1 (MC01) next to the Ubatiba river mouth, and 1.0 (MC06) in the channel with Barra Lagoon. The Guarapina Lagoon had the highest mean of salinity (17.2) among the lagoons. This lagoon had the highest salinity values (20), recorded at stations MC20, MC18 and MC21 (Fig. 2; Table 1), located near the lagoon mouth and margins. The temperature in 2013 ranged from 27.6°C to 33.1°C (mean 29.4°C) in the MGLS; the mean temperature was 29.9 ºC in Maricá Lagoon, 29.4 ºC in Barra Lagoon, 30.2 ºC in Padre Lagoon, and 28.4 ºC in Guarapina Lagoon. The station located at Ubatiba River mouth (MC01) had the highest temperature (33.1 °C), and the lowest temperature (27.6 °C) was recorded in the channel connecting Maricá and Barra lagoons (MC06) (Fig.2). The pH values in 2013 ranged from 8.2 (station MC12) to 9.5 (station MC01) in MGLS (Table 1; Fig. 2).

The salinity in 2019 ranged from 12.5 to 29.2 (mean 18.3) in the MGLS (Table 1). The lowest values of water salinity were recorded in Maricá Lagoon (mean of 13.7), varying from 12.5 (MC29) to 16.3 (MC06). The Guarapina Lagoon had the highest mean of salinity (25.2) among the lagoons. This lagoon had the highest salinity value (29.2) recorded in the station MC22 (Fig. 2; Table 1) in the Ponta Negra channel. The temperature in 2019 (Table 1) ranged from 22.2°C to 25.3°C (mean 23.7°C) in the MGLS, and the mean temperature was 23.2 ºC in Maricá Lagoon, 24.3 ºC in Barra Lagoon, 22.9 ºC in Padre Lagoon, and 24.0 ºC in Guarapina Lagoon. The station located in the transitional area between Maricá and Barra lagoons (MC011) had the highest temperature (25.3°C); the lowest temperature (22.2°C) was recorded in the Itaipuaçu channel (MC30) (Fig.2). The pH values in 2019 ranged from 8.7 (station MC25) to 7.2 (stations MC06 and MC10) in MGLS (Table 1; Fig. 2).

In 2013, sand was the dominant sediment grain-size class in the Southeast margin of Maricá Lagoon, the Southwest margin of Barra Lagoon, Ponta Negra Channel, and Padre Lagoon. The predominance of the sand fraction was also presented in the mouth of the Ubatiba and Caranguejo rivers (Fig. 3). The stations MC01, MC05, MC06 in Maricá Lagoon, MC12 and MC16 in Barra Lagoon, MC17 in Padre Lagoon and MC22 in Guarapina Lagoon showed 100% of sand in 2013 (Tab 01). In 2019, none of the stations presented 100% sand, but the pattern of distribution and dominance was practically the same as in 2013. The exception was the station MC17 in Padre Lagoon where muddy sediment dominates, with only 10.7% of sand (Fig. 3, Table 1). The stations MC12 (93.3%) and MC14 (94%) in Barra Lagoon and MC22 (95%), MC23 (92.4%), and MC24 (92.8) presented the highest percentage of sand in 2019. The silt fraction in 2013 was dominant in the west zone of Maricá and Guarapina lagoons and the central and inner region of Barra Lagoon (Fig. 3). The stations MC08 (87%) in Maricá Lagoon, MC13 (91%), MC14 (91.8%) and MC15 (90.8%) in Barra Lagoon and MC18 (86.6%) and MC18 (82.8%) in Guarapina Lagoon showed the highest percentage of silt in 2013 (Table1).

Table 1. Abiotic parameters from Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil, in 2013 and 2019 (Lat = latitude, Long = longitude, Sal = salinity, T = temperature, * extra points acquired during 2019).

Lagoon	Samples	Lat (S)	Long (W)	2013						2019					
				Sal	T (°C)	pH	Sand (%)	Silt (%)	Clay (%)	Sal	T (°C)	pH	Sand (%)	Silt (%)	Clay (%)
Maricá	MC01	22°55'44.54"	42°50'27.35"	0.1	33.1	9.5	100	0	0	12.6	23.1	7.5	43.5	33.2	23.3
	MC02	22°56'0.14"	42°51'44.00"	0.2	29.7	8.9	17.4	81.2	1.4	12.7	23.3	8.2	72.4	14.7	12.9
	MC03	22°56'44.73"	42°52'51.11"	0.3	30.7	8.91	21.6	78.1	0.3	12.6	23.1	8.1	62.5	21.1	16.4
	MC04	22°57'25.87"	42°52'33.92"	0.6	30.3	9.09	48.8	51.2	0	12.6	22.9	8	51.7	27.4	20.9
	MC05	22°57'18.12"	42°51'3.96"	0.9	28.1	8.7	100	0	0	12.8	23	8.3	95.5	0.8	3.7
	MC06	22°56'57.18"	42°49'54.45"	1	27.6	8.73	100	0	0	16.3	22.9	7.2	77	9.2	13.8
	MC07	22°56'52.55"	42°51'47.00"	0.5	29.9	8.7	13.4	79.8	6.8	14.1	22.5	7.7	58.5	17.6	23.9
	MC08	22°56'19.44"	42°50'33.28"	0.5	28.3	8.7	2.9	87.0	10.1	12.6	22.5	7.7	50.7	26.3	23.0
	* MC29	22°55'39.02"	42°49'45.19"	-	-	-	-	-	-	12.5	23.0	7.5	43.5	19.9	36.6
	* MC30	22°56'23.24"	42°52'57.13"	-	-	-	-	-	-	15.4	23.2	7.3	4.0	35.8	60.2
	Minimum			0.1	28.1	8.7	2.9	0	0	12.5	22.5	7.2	4.0	0.8	3.7
	Maximum			1.0	33.1	9.5	100	81.2	10.1	16.3	23.3	8.3	95.5	35.8	60.2
	Mean			0.5	29.7	8.9	50.5	47.2	2.3	13.4	23.0	7.8	55.9	20.6	23.5
	Standard deviation			0.3	1.7	0.3	40.2	37.8	3.7	1.3	0.3	0.4	23.2	10.2	14.7
Barra	MC09	22°57'10.85"	42°49'12.46"	0.5	28.9	8.6	36.6	63.4	0	15.0	24.6	7.8	3.7	62.6	33.7
	MC10	22°56'24.96"	42°49'17.08"	1.4	29.7	8.9	32.1	67.9	0	15.3	24.5	7.2	19.8	42.7	37.5
	MC11	22°56'36.77"	42°48'40.26"	1.9	29.0	8.3	36.6	63.4	0	16.6	25.3	7.4	36.3	12.4	51.3
	MC12	22°57'31.54"	42°48'40.88"	3.1	28.0	8.2	100	0	0	17.9	24.6	7.4	93.3	0.7	6.0
	MC13	22°57'7.35"	42°48'12.06"	1.7	29.6	8.7	7.5	91.1	1.4	17.6	24.5	7.5	40.9	31.7	27.4
	MC14	22°56'27.55"	42°47'31.45"	2.0	30.1	8.9	4.8	91.8	3.4	17.3	24.7	7.5	94.5	0.2	5.3
	MC15	22°55'52.69"	42°47'3.52"	2.7	30.5	9.2	5.8	90.8	3.4	17.7	24.6	7.6	6.3	66.9	26.8
	MC16	22°57'21.75"	42°47'4.99"	1.8	31.4	9.3	100	0	0	17.5	22.3	7.6	8.0	39.9	52.1
	* MC27	22°57'0.47"	42°47'35.71"	-	-	-	-	-	-	16.9	24.6	7.5	45.8	11.9	42.3
	Minimum			0.5	28.0	8.3	4.8	0	0	15.0	22.3	7.2	3.7	0.2	5.3
	Maximum			3.1	31.4	9.3	100	91.8	3.4	17.9	25.3	7.8	93.3	66.9	52.1
	Mean			1.9	29.7	8.8	40.4	58.6	1.0	16.9	24.4	7.5	38.7	29.9	31.4
	Standard deviation			0.7	1.0	0.4	36.7	35.7	1.4	1.0	0.8	0.2	32.9	23.7	16.2
Padre	MC17	22°56'41.23"	42°45'7.60"	8.0	29.0	9.3	100	0	0	18.1	22.9	7.5	10.7	24.6	64.7
Guarapina	MC18	22°56'57.65"	42°44'21.49"	20.0	28.1	9.0	13.4	86.6	0	23.1	24.1	8.2	12.8	35.4	51.8
	MC19	22°56'3.58"S	42°43'42.04"	16.0	29.1	9.1	79.6	20.4	0	23.9	24.6	8.7	14.5	42.5	43.0
	MC20	22°56'44.92"	42°43'16.05"	10.0	27.8	9.2	17.2	82.8	0	26.0	24.0	8.4	16.1	49.7	34.2
	MC21	22°56'51.67"	42°42'25.13"	20.0	28.5	9.2	76.4	23.6	0						
	MC22	22°57'16.50"	42°41'46.56"	20.0	28.4	9.1	100	0	0	29.2	23.3	8.3	95.0	0.8	4.2
	* MC23	22°57'5.56"	42°43'14.96"	-	-	-	-	-	-	24.2	24.0	8.3	92.4	0.9	6.7
	* MC24	22°57'10.16"	42°42'26.66"	-	-	-	-	-	-	25.5	24.1	8.6	92.8	0.8	6.4
	* MC25	22°56'13.28"	42°43'11.49"	-	-	-	-	-	-	24.6	24.1	8.7	59.2	22.4	36.9
	* MC26	22°56'35.87"	42°42'35.52"	-	-	-	-	-	-	26.4	23.8	8.3	25.5	44.0	30.5
	* MC28	22°56'26.18"	42°44'6.02"	-	-	-	-	-	-	24.2	24.4	8.6	44.6	16.0	39.4
	Minimum			8.0	27.8	9.0	13.4	0	0	18.1	22.9	7.5	10.7	0.8	4.2
	Maximum			20.0	29.1	9.3	100	86.6	0	29.2	24.6	8.7	95.0	49.7	64.7
	Mean			15.7	28.5	9.1	64.4	35.6	0	24.5	23.9	8.4	46.4	23.7	31.8
	Standard deviation			5.0	0.5	0.1	35.9	35.9	0	2.7	0.5	0.3	34.0	17.9	19.3

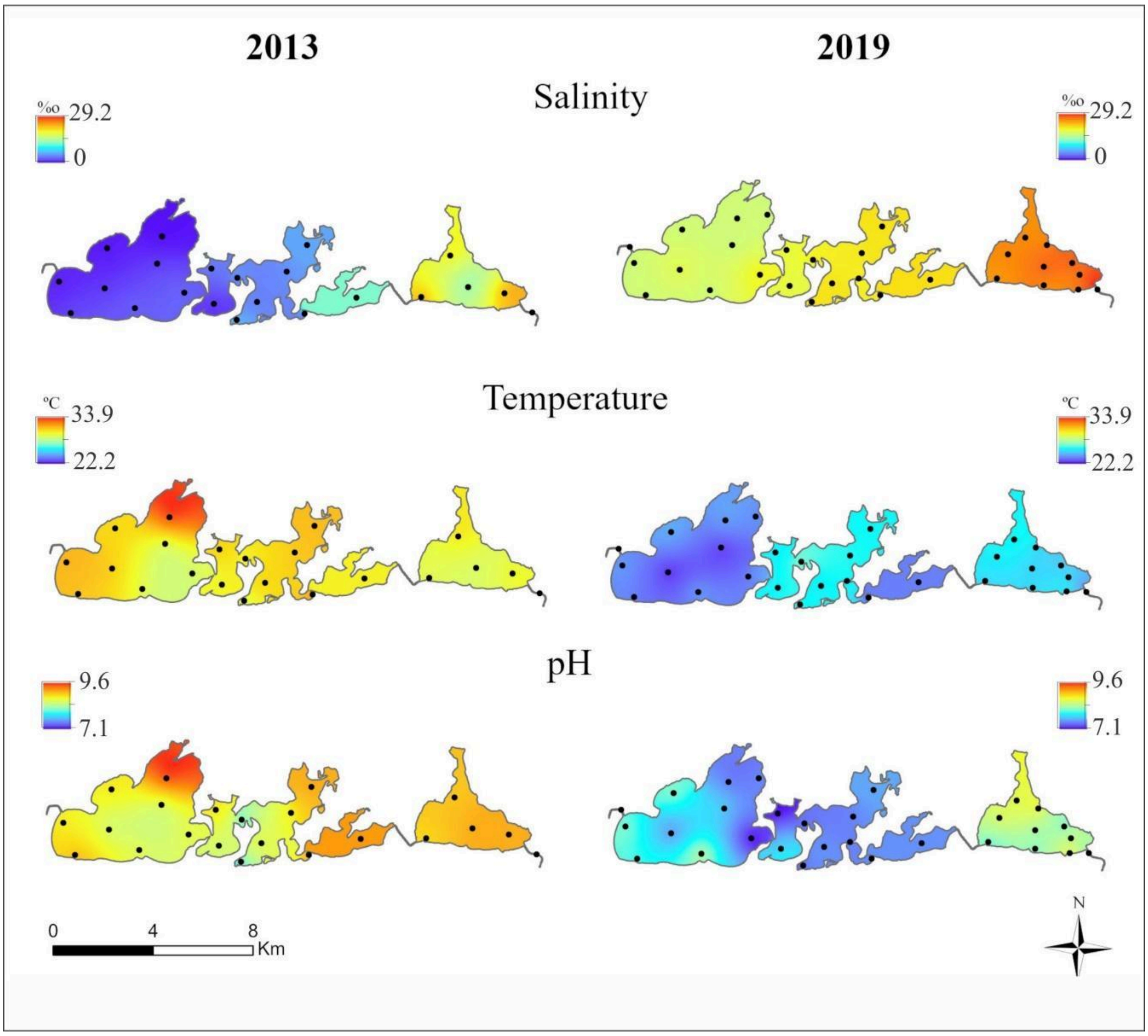

Figure 2. Distribution of bottom water parameters from the Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil in 2013 and 2019.

The clay percentages in 2013 were low in MGLS with higher concentration in the central area of Maricá Lagoon and in the central and inner region of Barra Lagoon (Fig. 3). The stations MC07 (6.8%) and MC08 (10.1%) in Maricá Lagoon showed the highest percentage of clay in 2013. In 2019, there was an increase in the values and distribution of clay in the MGLS, in which the highest values were in the central and inner regions of Barra Lagoon, Padre Lagoon and west region of Guarapina Lagoon (Fig. 3). The stations MC30 (60.2%) in Maricá Lagoon, MC11 (51.3%), MC16 (52.1%) in Barra Lagoon, MC17 (64.7%) in Padre Lagoon and MC18 (51.8%) in Guarapina presented the highest percentage of clay in 2019.

Following Shepard´s classification (1954), on MGLS, nine granulometric classes were recognized in both sampling times: sand, silt, sandy silt, silty-sand, sand-silt-clay, clayey-sand, clayey-silt, silt clay, and sand clay. In 2013, sand was distributed in the north margin of Guarapina (MC19 and MC21) and Maricá lagoons (MC01), next to Ponta Negra Channel (MC22), in the southern region of Barra (MC12 and MC16) and Maricá lagoons (MC05 and MC06), and Padre Lagoon (MC17). In 2019, the sand class was restricted to the south margin of Guarapina (MC23 and MC24), Barra (MC12), and Maricá lagoons (MC05 and MC06), next to Ponta Negra Channel (MC22), and central-north region of Barra (MC14). The silt class was distributed in the central-south region of Guarapina (stations MC18, MC19 and MC20), central-north region of Barra Lagoon (MC13, MC14 and MC15), and central-west region of Maricá Lagoon (MC02, MC03, MC07 and MC08). The sandy silt class occupies the transitional region between Maricá and Barra lagoons (MC09, MC10 and MC11). The western area of Maricá Lagoon (MC02, MC03 and MC07) and central-east of Barra Lagoon (MC27) showed silty-sand class. The sand-silt-clay class occupied the central north of Maricá Lagoon (MC01, MC08 and MC29), the south margin of Maricá Lagoon (MC04), the central north region of Barra Lagoon (MC10 and MC13), and north margin of Guarapina Lagoon (MC25, MC26 and MC28). The stations MC09 and MC15 in Barra Lagoon and MC20 in the central Guarapina Lagoon presented clayey-silt. The station MC30 in Itaipuaçu Channel, south of Barra Lagoon (MC16), Padre Lagoon (MC17), and the inner region of Guarapina Lagoon (MC18) presented silt clay. The station MC11 in the Barra Lagoon was the only one with sand clay (Fig. 4).

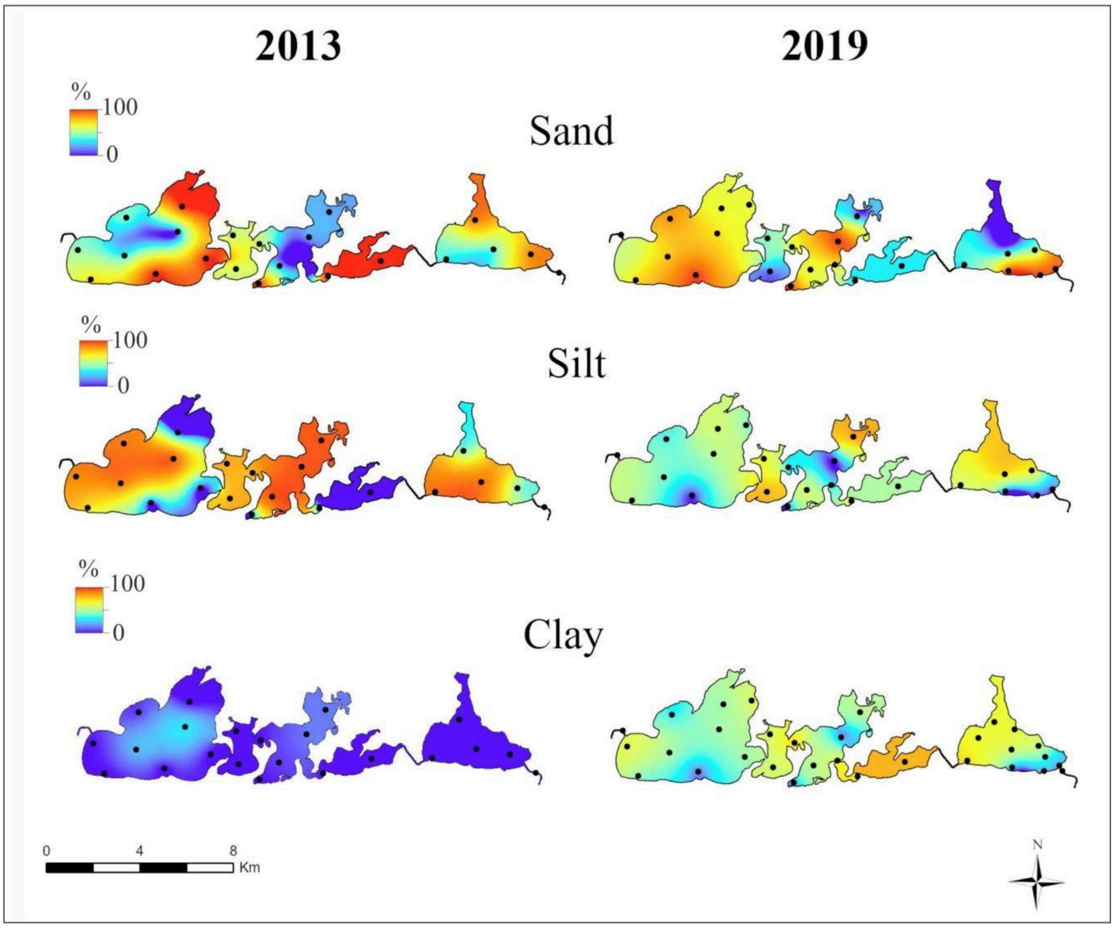

Figure 3. Distribution of grain size in Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil in 2013 and 2019.

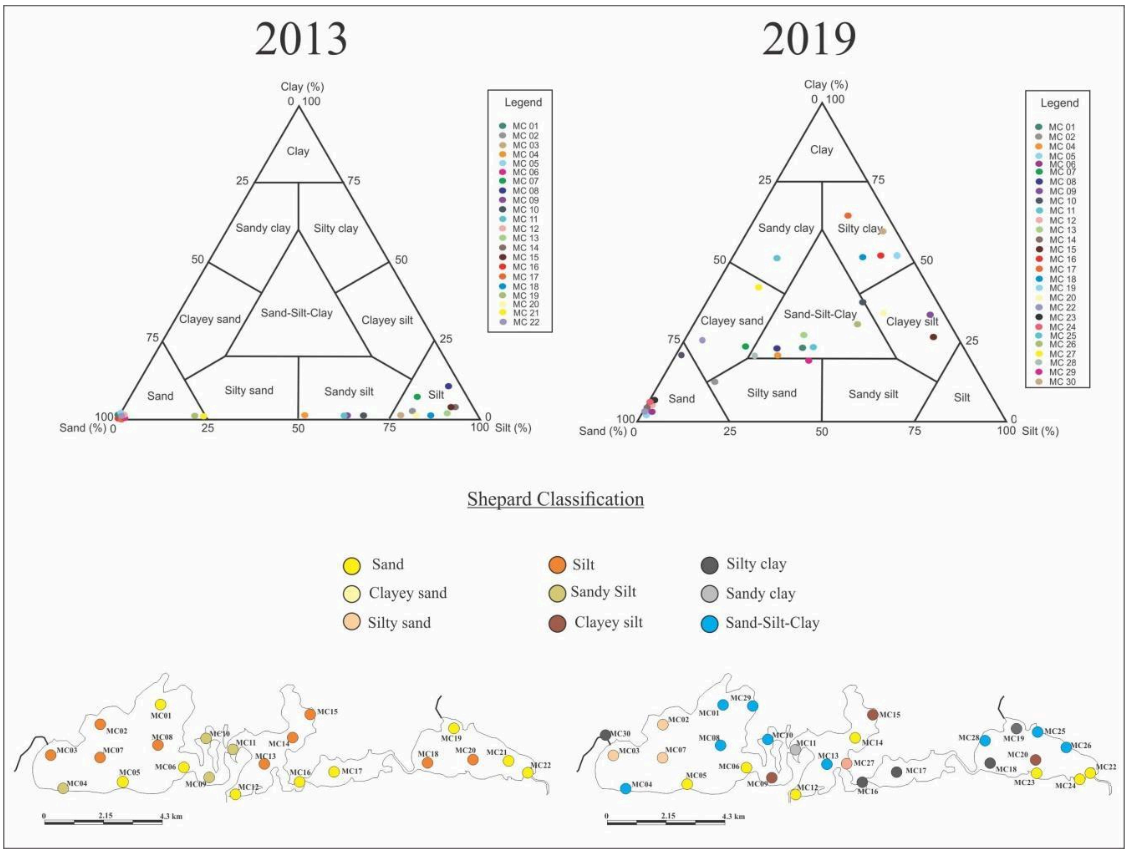

Figure 4. Ternary diagram based on Shepard's classification (1954) and distribution of the granulometric classes in Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil in 2013 and 2019.

4.2 Biotic Data

In the 2013 sampling, 17 living species of foraminifera were identified in 14 stations, and in 2019, 18 species were identified in 17 stations (Table 3 and 4). In 2013, living foraminifers were absent on stations MC02, MC05, MC06, MC07, and MC08 in Maricá Lagoon, and MC09, MC10 and MC13 in Barra Lagoon. In 2019, the same was observed on stations MC01, MC02, MC05 and MC06 in Maricá Lagoon, MC10, MC11, MC13, MC14, MC15, MC16 in Barra Lagoon and MC21, MC22 and MC28 in Guarapina Lagoon (Table 3 and 4).

The foraminifera density (FD) was low in most of the stations of 2013 (<200 specimens/50 ml), with the highest values in the southwest of Maricá Lagoon and the north of Guarapina Lagoon (Fig. 5). In stations MC04, MC12, MC16 and MC19 the FD were >1,500 specimens/50 ml (Table 2). In 2019, the highest values of FD were in the central-north area of Guarapina Lagoon, and the lowest were in Maricá and Padre lagoons (Fig. 5). The highest values were observed in the stations MC19, MC20, and MC25 (66,960, 5,342 and 47,340, respectively); the lowest occurred in MC03, MC09 and MC12 (53, 108 and 109, respectively) (Table 3).

The lowest foraminiferal richness (S) in 2013 was found in Maricá Lagoon (MC01, MC03) and the north of Barra Lagoon (MC14), while the highest ones (7 species) were restricted to the southwest of Maricá Lagoon (MC04) and the central region of Guarapina Lagoon (MC19 and MC20) (Table 2 and Fig. 5).

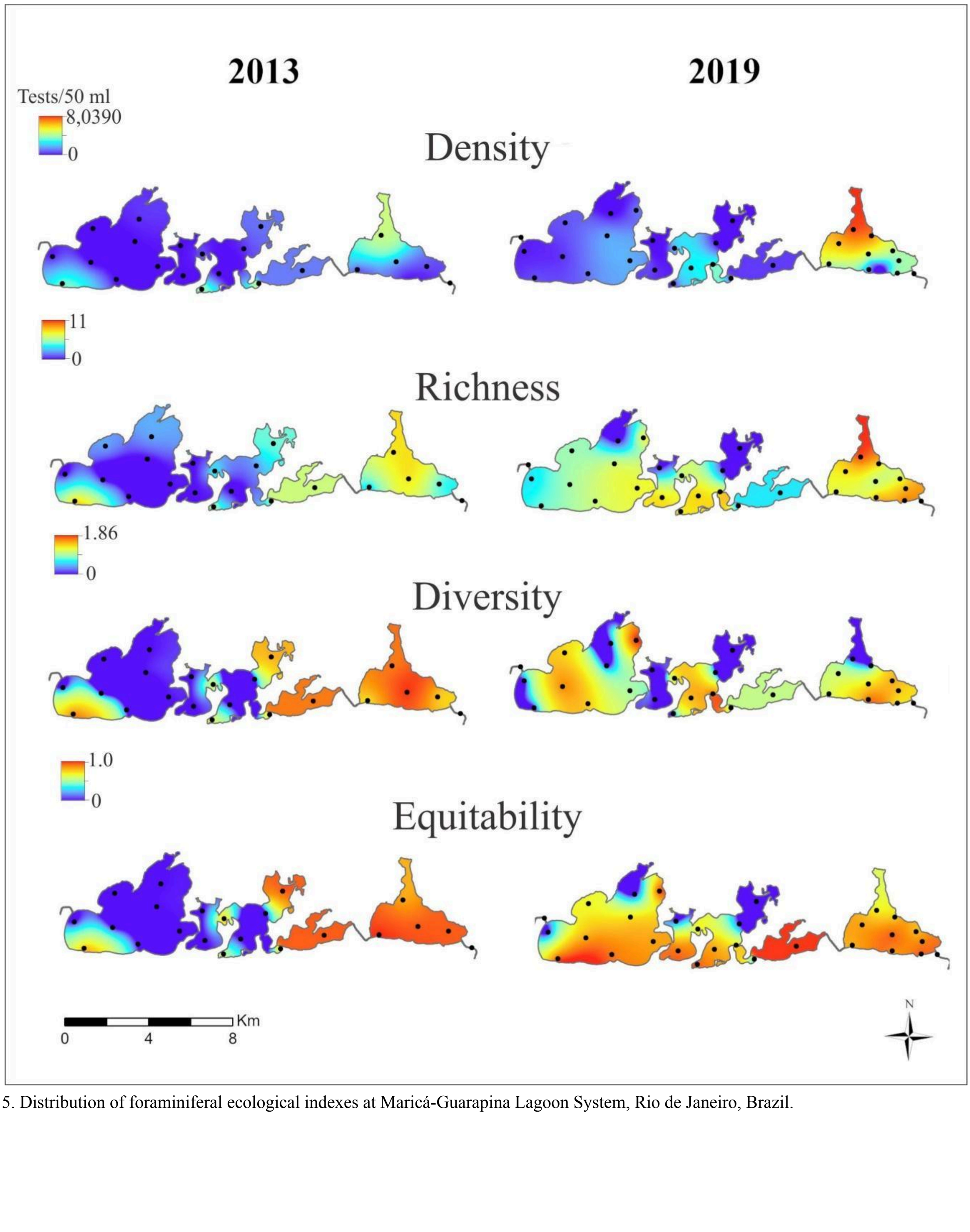

Figure 5. Distribution of foraminiferal ecological indexes at Maricá-Guarapina Lagoon System, Rio de Janeiro, Brazil.

The foraminiferal distribution from 2019 was similar to 2013, except at the station MC16 (Barra Lagoon) and MC17 (Padre Lagoon) which presented the lowest values (Fig. 5). The highest S in 2019 were in MC19, MC24, MC23 and MC25 (11, 10 and 8 species, respectively) in Guarapina Lagoon (Table 3 and Fig. 5).

Table 2. Foraminifera data from 2013, in the Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil.

	MC 01	MC 03	MC 04	MC 11	MC 12	MC 14	MC 15	MC 16	MC 17	MC 18	MC 19	MC 20	MC 21	MC 22
Density (specimens/50 ml)	110	109	1,500	180	2,300	102	300	3,780	340	220	4,040	620	180	340
Richness (S)	1.0	1.0	7.0	2.0	4.0	1.0	3.0	4.0	5.0	2.0	7.0	7.0	3.0	6.0
Diversity (H´)	-	-	1.2	0.3	0.4	-	1.0	0.7	1.4	0.7	1.4	1.8	0.9	1.1
Equitability (J)	-	-	0.6	0.5	0.3	-	0.9	0.5	0.9	1.0	0.7	0.9	0.9	0.6
Ammobaculites dilatatus	-	-	1.1	-	-	-	-	-	-	-	-	-	-	-
Ammonia parkinsoniana	-	-	-	11.1	3.3	-	13.3	9.5	11.1	-	4.6	26.7	-	-
Ammonia tepida	-	-	54.3	88.9	91.7	-	46.7	78.8	33.3	-	16.4	13.3	-	5.9
Ammotium morenoi	-	-	1.1	-	-	-	-	-	5.6	-	-	-	-	-
Arenoparrella mexicana	-	-	24.5	-	-	-	-	-	-	42.1	-	-	-	5.9
Caronia exilis	-	-	-	-	-	-	-	-	-	-	0.7	-	-	-
Elphidium excavatum	-	-	-	-	4.2	100	-	10.6	38.9	-	36.2	-	55.6	-
Elphidium discoidale	-	-	-	-	-	-	-	-	-	-	2.0	-	-	-
Entzia macrescens	-	-	-	-	-	-	-	-	11.1	-	-	-	-	-
Haynesina germanica	-	-	-	-	-	-	-	-	-	-	4.6	-	-	-
Paratrochammina guaratibaensis	-	-	-	-	-	-	-	-	-	57.9	35.5	2	-	5.9
Pseudononion japonicum	-	-	-	-	-	-	-	-	-	-	-	20	33.3	-
Pyrgo oblonga	-	-	-	-	-	-	-	-	-	-	-	6.7	11.1	-
Quinqueloculina seminulum	100	100	16	-	0.8	-	40	1.1	-	-	-	6.7	-	5.9
Textularia earlandi	-	-	-	-	-	-	-	-	-	-	-	-	-	70.6
Trochamminita salsa	-	-	2.1	-	-	-	-	-	-	-	-	-	-	-
Warrenita palustris	-	-	1.1	-	-	-	-	-	-	-	-	6.7	-	5.9

In 2013, the H' diversity index was equal to 0 in the stations with only one species (MC01 and MC03 – *Quinqueloculina seminulum*; MC14 – *Elphidium excavatum*). The lowest H´ diversity values were observed in stations MC11 and MC12 in Barra Lagoon, which were 0.3 and 0.4, respectively. The highest H' diversity values were found in MC17 in Padre Lagoon and MC19 and MC20 in Guarapina Lagoon, which ranged between 1.4 – 1.8 (Table 2 and Fig. 5). The highest J' equitability values were found between the stations MC17 and MC21, which ranged between 0.7 and 1.0, and the lowest were in MC12 (Table 2 and Fig. 5).

In 2019, the H' values were usually higher than those found in 2013 (Fig. 5). The lowest H' values were observed in station MC17 in Padre Lagoon, which was 0.7, and MC08 in Maricá Lagoon, which was 0.8. The highest H' value was in MC24 in Guarapina Lagoon, which was 2.0 (Table 3). The highest J' values in 2019 were in MC12 and MC24, which were 1.0 and the lowest were in MC08 and MC19, which were both 0.5 (Table 3 and Fig. 5).

In 2013, *Ammonia tepida* was the most constant species (64% of stations), with relative abundance between 5.9 – 91.7%, followed by *Q. seminulum* (57% of stations) with relative abundance between 0.8 – 100% and *Ammonia parkinsoniana* (50% of stations) with relative abundance between 4.6 – 26.7% (Table 2). The most constant agglutinated foraminiferal species was *Paratrochammina guaratibaensis* (28% of stations) with relative abundance between 2 – 57.9% followed by *Arenoparrella mexicana* (21% of stations) with relative abundance between 5.9 – 42.1% and *Warrenita palustris* (21% of stations) with relative abundance between 1.1 – 6.7% (Table 2). The species *Ammobaculites dilatatus* and *Trochamminita salsa* were present only in the Maricá Lagoon (MC04), *Elphidium discoidale* (MC19), *Caronia exilis* (MC18 and MC22), *Haynesina germanica* (MC19), *P. guaratibaensis* (MC18, MC19, MC20 and MC22), *Pseudononion japonicum* (MC20 and MC21), *Pyrgo oblonga* (MC19 and MC21) and *Textularia earlandi* (MC22) were present only in Guarapina Lagoon, and *Entzia macrescens* (MC17) was present only in Padre Lagoon (Table 2).In 2019, 7 species which were not present in 2013 (*Ammobaculites exiguus, Ammotium cassis, Cribrolphidium gunteri, Miliammina fusca, Miliolinella subrotunda, Polysaccammina hipohalina and Trochammina inflata*) which were not found previously, were present in MGLS. Conversely, 6 species identified in 2013 (*E. dicoidale, H. germanica, P. japonicum, T. earlandi and W. palustris*) were absent in 2019.

The agglutinated species *A. morenoi* was the most constant species in 2019 (76% of stations), with relative abundance between 1.3 - 72%, followed by calcareous *A. tepida* (70% of stations) with relative abundance between 1.7 – 66.6%, *E. excavatum* (70% of stations) with relative abundance between 3.3 – 58.8%, and *A. parkinsoniana* (64% of stations) with relative abundance between 1.0 – 47.4% (Table 3).

Table 3. Foraminifera data from 2019, in the Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil in 2019.

	MC 03	MC 04	MC 07	MC 08	MC 09	MC 12	MC 17	MC 18	MC 19	MC 20	MC 23	MC 24	MC 25	MC 26	MC 27	MC 29	MC 30
Density (specimens/50 ml)	53	173	116	506	108	109	115	2,895	66,960	5,342	569	2,245	47,340	38,39	1,410	195	193
Richness (S)	2	3	4	5	7	7	2	6	11	5	8	10	8	6	7	6	7
Diverstity (H')	-	1	0.9	0.8	1.6	1.7	0.7	1.2	1.1	1.4	1.6	2	1.1	1.1	1	1.5	1.2
Equitability (J)	-	0.9	0.7	0.5	0.8	1	0.9	0.6	0.5	0.8	0.7	1	0.5	0.6	0.5	0.8	0.6
Ammobaculites dilatatus	-	13.9	8.3	16.8	5.0	14.2	-	-	-	-	-	-	0.5	-	13.4	1.7	-
Ammobaculites exiguus	-	2.3	-	5.9	-	7.1	-	-	1.0	-	-	8.2	-	-	2.5	-	-
Ammonia parkinsoniana	-	-	5.5	-	-	7.1	-	3.0	1.0	-	13.4	3.3	0.5	1.04	3.3	11.8	47.4
***Ammonia* spp.**	-	-	-	-	-	-	-	-	4.0	3.4	1.3	6.6	11.0	-	-	-	-
Ammonia tepida	-	-	66.6	-	10.0	-	-	56.0	6.2	34.4	18.0	5.5	7.0	9.9	1.7	20.3	34.2
Ammotium cassis	50.0	9.3	-	1.9	-	-	-	-	-	-	-	1.1	-	-	3.3	-	-
Ammotium morenoi	50.0	69.7	19.4	74.2	5.0	28.5	-	7.7	1.3	-	2.5	9.4	-	-	72.3	35.6	5.2
Arenoparrella mexicana	-	4.6	-	0.9	-	-	-	-	-	-	-	-	-	-	-	15.2	-
Caronia exilis	-	-	-	-	-	-	-	-	0.2	-	-	-	-	-	-	-	-
Cribroelphidium gunteri	-	-	-	-	15.0	7.1	-	7.1	3.2	-	4.5	-	0.1	-	-	-	5.2
Elphidium excavatum	-	-	-	-	45.0	-	41.2	25.	13.6	23.6	41.0	32.0	58.8	17.71	3.3	15.2	5.2
Entzia macrescens	-	-	-	-	-	-	-	-	-	-	-	2.2	-	-	-	-	-
Miliammina fusca	-	-	-	-	-	-	-	-	-	-	-	13.2	-	-	-	-	-
Miliolinella subrotunda	-	-	-	-	10.0	28.5	-	-	1.3	11.5	3.85	3.4	4.2	8.33	-	-	-
Paratrochammina guaratibaensis	-	-	-	-	10.0	-	58.8	1.19	61.7	25.0	10.9	6.1	12.6	56.25	-	-	2.6
Polysaccammina hipohalina	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-	-
Quinqueloculina seminulum	-	-	-	-	-	-	-	-	0.5	-	0.64	-	0.5	0.52	-	-	-
***Quinqueloculina* spp.**	-	-	-	-	-	-	-	-	4.9	1.3	3.85	8.3	4.7	6.25	-	-	-
Trochammina inflata	-	-	-	-	-	7.14	-	-	-	-	-	-	-	-	-	-	-
Trochamminita salsa	-	-	-	-	-	-	-	-	-	0.7	-	-	-	-	-	-	-

The other most constant agglutinated foraminiferal species were *P. guaratibaensis* (59% of stations) with relative abundance between 1.2 – 56.2%, *A. dilatatus* (41% of stations) with relative abundance between 0.5 – 14.2%, and *A. exiguus* (35.2% of stations) with relative abundance between 2.3 – 8.2% (Table 3). The species *A. mexicana* was present only in the Maricá Lagoon (MC04, MC087 and MC29), *E. macrescens* (MC24), *M. fusca* (MC24), *P. ipohalina* (MC19), Q. seminulum (MC19, MC20, MC25 and MC26), and T. salsa (MC20) were present only in Guarapina Lagoon. *T. inflata* (MC12) was present only in Barra Lagoon (Table 3).

4.3 Statistical analysis

The DCA using environmental parameters and foraminiferal relative abundance indicated a variance coefficient of 46% for axis 1 and of 5% for axis 2 (Fig. 6). The first DCA axis displayed a positive covariance of *A. mexicana*, *Q. seminulum*, *T. earlandi*, *T. salsa* and

W. palustris with pH and temperature (Fig. 6). Most species (*A. cassis, A. exiguus, A. dilatatus, A. morenoi, C. gunteri, E. macrescens, M. fusca, M. subrotunda* and *T. inflata*) presented a positive relationship with clay in axis 1 (Fig. 6). *A. tepida* and *A. parkinsoniana* were positively related to sand in axis 2 (Fig. 6). The species *C. excavatum*, *C. exilis*, *P. guaratibaensis*, *P. japonicum* and *P. oblonga* were positively related to salinity and silt in axis 2 (Fig. 6).

The R-mode CA revealed the presence of six assemblages considering a similarity level of 53% (Fig. 7): Assemblage A - composed mainly by *A. cassis*, *A. morenoi* and *A. dilatatus*; Assemblage B – composed mainly by *A. exiguus* followed by *C. gunteri*, *M. fusca*, *M. subrotunda* and *T. inflata*; Assemblage C – composed mainly by *A. parkinsoniana* and *T. earlandi* followed by *A. mexicana*, *C. exilis*, *E. macrescens*, *Q. seminulum*, *T. salsa* and *W. palustris*; Assemblage D – composed mainly by *E. excavatum* followed by *P. japonicum* and *P oblonga*; Assemblage E - composed only by *P. guaratibaensis*; and Assemblage F composed by only *A. tepida*.

The Q-mode CA generated six station groups at a 75% level of similarity (Fig. 7): Group I was composed only of stations from 2019 (MC04. MC08 and MC27); Group II including the stations from 2013 MC14, MC17 and MC21 and stations from 2019 MC09, MC20, MC22, MC23 and MC24; Group III containing the MC20 from 2013 and stations from 2019 MC12, MC29 and MC30; Group IV composed by only MC22 from 2013; Group V containing the stations MC18 and MC19 from 2013 and stations MC17, MC19 and MC26; and Group VI composed by stations MC04, MC11, MC12, MC15 and MC16 from 2013 and stations MC17 and MC18 from 2019 (Fig. 7). Based on the combination of Q-mode and R-mode from CA we can observe that: Group I was formed by assemblages A and B; group II was formed by Assemblage D; groups III and IV were formed by Assemblage C; Group V was formed by Assemblage E; and Group VI formed by Assemblage F (Fig. 7).

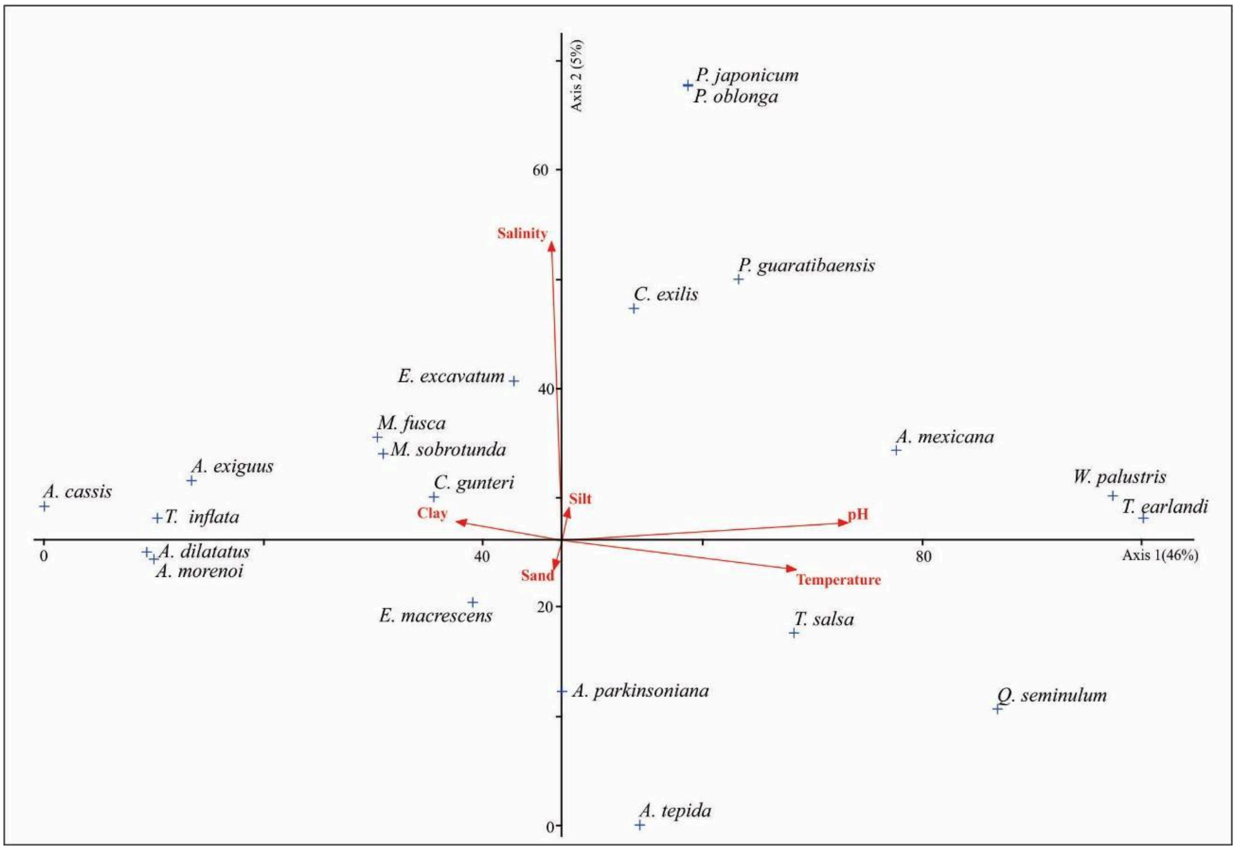

Figure 6. DCA with abiotic variables and relative abundance of living foraminifera in 2013 and 2019 in the Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil.

5. Discussion

5.1 Environmental changes

The physicochemical parameters measured in July/2019 were significantly divergent from the record obtained in March/2013 by Laut et al. (2019). The environmental parameters analysed indicated an increase in marine influence in the lagoons in 2019, compared to 2013. The higher salinity values in the vicinity of Ponta Negra Channel reinforce that it represents the main connectivity with the sea (Kjerfve and Knoppers 1999; Guerra et al. 2011) and its important role in renewing the waters of the MGLS. In the sampling performed in 2012, Franco et al. (2019) identified seasonal variations in some parameters of MGLS; among them, the salinity showed values of 34 in summer (mean 20) and 25 in winter (mean 15). In the present study, the highest salinity values were registered in the winter month and the lowest in the summer, which is expected since the highest rainfall means in the region occur between December and March. The mean rainfall for the sampling time was 58 mm in 2019, while in 2013 it was 130 mm (INMET, 2022). Historically, the Maricá Lagoon presents itself as a freshwater environment with short periods of brackish water intrusion (Kjerfve and Knoppers 1999; Bomfim et al. 2010; Guerra et al. 2011; Laut et al. 2019 and 2021). The lowest salinity values were recorded at stations near the Ubatiba River (MC01 and MC02 in 2013 and MC01 and MC29) in Maricá Lagoon in both periods, but the results suggested a reduced riverine input in 2019. The higher salinity values in 2019 may also be the result of the opening of Barra's artificial channel and the dredging of Itaipuaçu channel that contributed to the increase of marine influence in the system. The Guarapina Lagoon with a mean salinity of 17.2 in 2013 also underwent a major transformation between the periods from being a mesohaline system to a polyhaline system with a mean salinity of 25.2 according to the Venice Classification System (1958).

The higher water mean temperature in 2013 may also be the result of the influence of higher summer air temperature. According to Franco et al (2019), the mean temperature of MGLS in summer is approximately 28.1°C and in winter 23.7°C. The maximum values of temperature were related to silty areas in the mouth of the Ubatiba River (2013) and Barra Lagoon (2019). These results demonstrate that in silted areas rich in organic matter the sediment can present temperature values above the means measured in the region (Chapman and Kimstach. 1996). Similar results were recorded in the shallowest region with peat deposits at Saquarema Lagoonal System located 11 km east of the MGLS (Belart et al. 2018). The study of Azevedo et al. (2010) in Saquarema Lagoonal System recorded the homogenization of water parameters in which the temperature decreased after the stabilization of the tidal channel increased interactions with the sea. Similar results were obtained after the channel interventions in MGLS in 2019 where temperature values were lower and more homogeneous than in 2013. This result may be an indication of the increase in circulation and exchanges with the ocean.

In 2013, the pH measure characterised the MGLS as an alkaline environment (Laut et al. 2019). In 2019, the pH presented lower values, tending towards more neutrality, mainly in the Barra Lagoon. However, this still showed alkaline characteristics, especially in the Guarapina Lagoon, which had a higher marine influence. The pH values in 2019 were close to the parameters established as ideal for brackish waters (6.5 to 8.5), according to the environmental agencies of Brazil (CONAMA, 2005).

The contribution of the sandy barrier as a source of sand for the lagoonal system at both sampling times is highlighted by the grain size analysis. As described by Silvestre et al. (2017), Laut et al. (2019, 2021) and Silva et al. (2014), the dominance of sand at the southern margin of MGLS is a result of wind carrying sand from the barriers. In the same way, the dominance of sand at stations near the Ponta Negra channel was a result of wind transport and the combined action of tidal currents and waves, mainly associated with storm conditions. The largest differences in grain size distribution between sampling times were concentrated in the northern regions of Maricá and Guarapina lagoons, near to the river mouths. In 2019, these areas were covered by silt and clay, indicating a decrease in fluvial transport contribution. Cruz (2010) reports that the hydrodynamics in MGLS is mainly driven by flooding during rainy periods. Therefore, the decrease in precipitation in 2019 may have affected the hydrodynamics and transport capacity of the river to the lagoonal system.

The lagoon sediments, classified based on Sheppard (1954), presented a more homogeneous distribution in 2013, when compared to 2019. Silt sediment was dominant throughout the MGLS in 2013, with the exception of the southern and northern margins of Maricá Lagoon. Teodoro et al (2010) suggest that the silty fractions may represent low current velocities and confined areas. Therefore, the central region of Maricá and Barra lagoons and the Cordeirinho channel connecting Padre and Guarapina lagoons were the most confined regions of the system in 2013. The increase in circulation conditions could be verified in 2019, as the sandy-silty sediment class predominated in most of the system. On the other hand, the predominance of clayey-silt sediments observed in 2019 suggests a decrease in the hydrodynamic conditions in the Padre lagoon.

5.2 Foraminifera community response to environmental changes

Laut et al. (2021) showed that the living foraminifera community in 2013 was composed of values of abundance, richness and diversity lower than those recorded in other lagoons in southeastern Brazil (Raposo et al. 2016. 2018; Belart et al. 2019). In the present study, the total number of species found was practically the same between the two periods (S=17 in 2013 and S=19 in 2019). However, the value of S per station was significantly higher in 2019, which also reflected in the increase in the values of H' and J'. Density was also higher in 2019, with the highest values in the Guarapina Lagoon, showing that it is the least confined environment in the system. The ecological index data indicate a positive effect on foraminifera as a result of the dredging and opening of the Barra channel.

Belart et al. (2019) evaluated the effect of seasonality on the composition of benthic foraminifera assemblages in the Saquarema Lagoonal System, identifying a trend towards greater density and richness in the austral summer. However, the present study did not reproduce similar results, as the sampling carried out in the winter of 2019 in MGLS showed values higher than those found in the summer sampling in 2013. This leads to the assumption that seasonality was not the main factor that contributed to the changes in the foraminiferal community in MGLS but the anthropic interventions in the channels of the system.

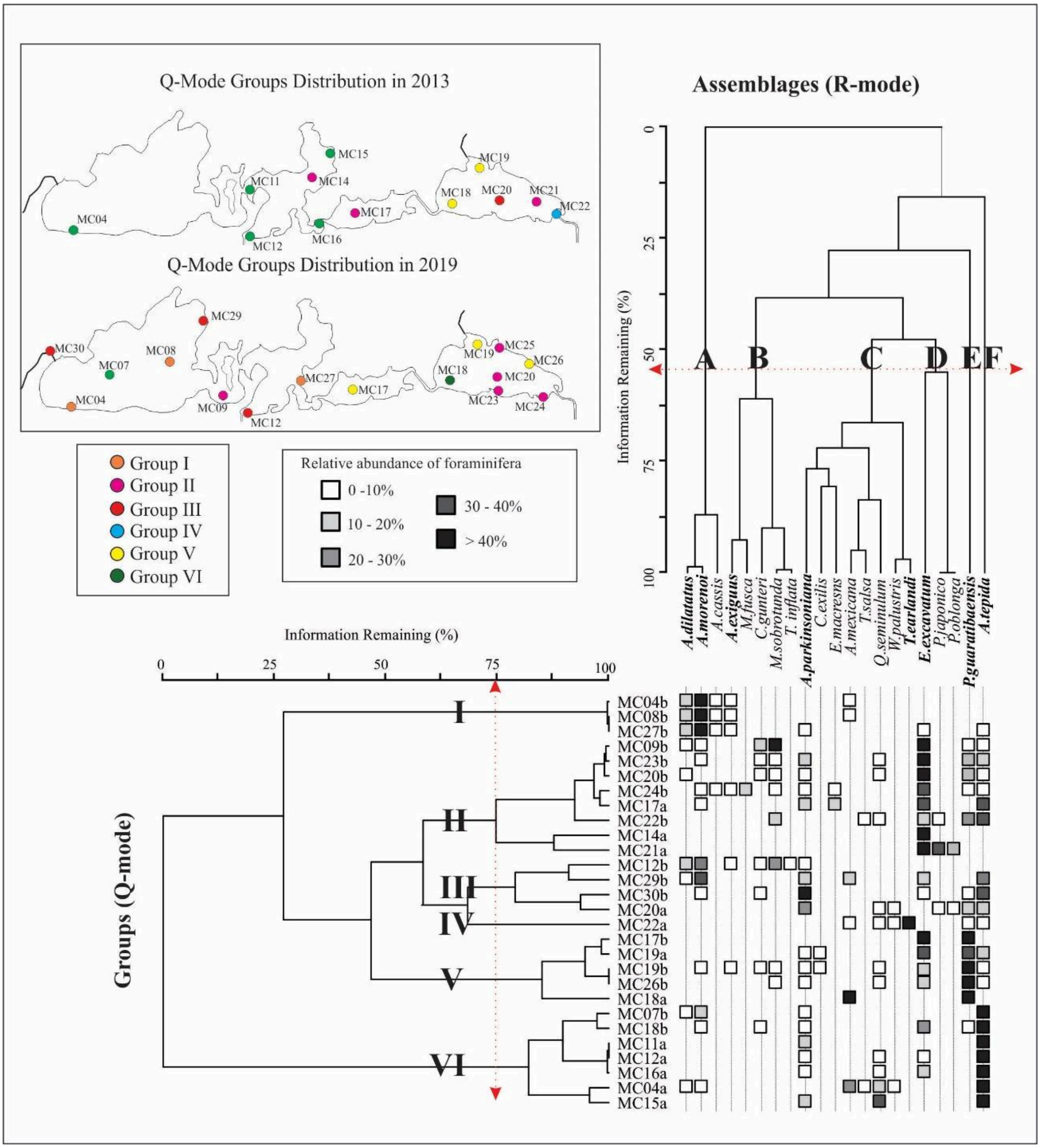

Figure 7. Cluster analysis in R (A to F) and Q (I to VI) modes based on the relative abundance of foraminifera from Maricá-Guarapina Lagoonal System, Rio de Janeiro, Brazil, sampled in 2013 (a) and 2019 (b). In R-mode CA, the principal species of each assemblage are signed in bold. The resulting groups from Q-mode CA are displayed in the upper map.

The most constant foraminifera found in MGLS in 2013 (*A. tepida, A. parkinsoniana, E. excavatum* and *Q. seminulum*) were calcareous cosmopolitan species, described in the literature as tolerant to significant abiotic variations, commonly recorded in environments under natural stress or anthropogenic interference (Clemente et al. 2015; Martins et al. 2016; Laut et al. 2016; Raposo et al. 2018; Belart et al. 2019). In the DCA analysis, the species of the genus *Ammonia* did not show strong correspondences with any of the analysed parameters, while *E. excavatum* was correlated with the sandy sediment. Laut et al. (2021) correlated these species with high concentrations of organic matter components in the sediment associated with low confinement conditions. Similar behaviour has been reported in other studies (Frontalini et al. 2013; Clemente et al. 2015; Martins et al. 2016, 2020). In several transitional ecosystems, the presence of *Q. seminulum* has been associated with sandy sediments and basic/neutral pH. However, it has also been found to be dominant in restricted areas with high water temperature and OM concentrations (Eichler et al. 2003; Laut et al. 2016. 2021; Martins et al. 2015. 2016). Also, in the DCA analysis, *Q. seminulum* was associated with higher pH and temperature values in 2013, being distributed in shallower areas covered by sandy sediments in Maricá and Barra lagoons. In 2019, this species was replaced by *A. morenoi*, and it was restricted to Guarapina lagoon with low values of abundance. Is possible that *Q. seminulum* responded to changes in temperature and grain size that occurred throughout the lagoon system. This change may be related to seasonal issues, as the 2019 sampling was carried out during the winter, which in this region is characterised by mild temperatures and less precipitation.

The wide distribution of *A. morenoi* in the 2019 sampling may be related to the ability of this species to adapt to changes in salinity, as pointed out by Murray (1991), and its tolerance to sediments enriched with organic matter, both of natural and anthropogenic origin (Laut et al. 2016; Raposo et al. 2016; Martins et al. 2020, 2021; Eichler et al. 2021). Similar to this study, Belart et al. (2019) also recorded the highest density and richness of agglutinated foraminifera in the Saquareama Lagoonal System during the winter period. The agglutinated species *A. cassis*, *A. morenoi*, *A. dilatatus* and *A. exiguus*, which were dominant in the MGLS, are commonly associated with mangroves and the areas of highest organic matter accumulation in regions with fluvial sediment deposition (Debenay et al. 2004; Laut et al. 2012. 2017; Belart et al. 2019; Raposo et al. 2019; Semensatto. 2020). In the DCA analysis, these species and other agglutinated responded positively to higher concentrations of clayey sediment. The occurrence of these species in 2019 appears to be linked to the increase of muddy sediments in the lagoon system.

Laut et al. (2021) considered *P. guaratibaensis*, *P. japonicum* and *P. oblonga* bioindicators of higher marine influence and stronger hydrodynamics in MGLS. The DCA analysis showed these species responding positively to higher salinity levels. The species *P. guaratibaensis* was only present in the Guarapina lagoon in 2013, and in 2019 it was distributed throughout the system up to the Maricá lagoon, indicating an increase in hydrodynamics and marine influence in the system. *P. japonicum* and *P. oblonga* were present only in Guarapina Lagoon in 2013 with low abundance values and are common species in adjacent coastal regions of Rio de Janeiro such as Guanabara Bay (Clemente et al. 2015). These organisms are typical of the inner continental shelf and usually occur in the coastal lagoons from Rio de Janeiro during the austral summer, always in the channel zone (Raposo et al. 2018; Belart et al. 2019).

The six groups obtained from the CA analysis showed a strong change in circulation and marine influence in the system. Group I occurred only in 2019 in Maricá and Barra lagoons. These areas were characterised by the concentration of clayey fractions and were dominated by Assemblage A (*A. dilatatus* and *A. morenoi*). The absence of this group in 2013 showed the increase of muddy sediment input transported by rivers in the innermost part of the system. Group II was composed by Assemblage D (*E. excavatum*), indicating higher salinity levels in the system, located in the central region of the Guarapina lagoon and extending to the communication channel between the Barra and Maricá lagoons in 2019. Group III was characterised by *A. parkinsoniana*, which was restricted to the MC20 station in the Guarapina lagoon and moved to more inner regions of the SLMG in 2019, including stations near the Barra and Itaipuaçu channels (MC12 and MC30) and the Ubatiba River (MC29). Group IV isolated the station MC 22 from 2013, which unfortunately could not be reproduced in 2019. This group was characterised by Assemblage C (*A. parkinsoniana* and *T. earlandi*) considered bioindicators of sandy sediments with organic matter (Laut et al. 2021). Group V was formed by stations concentrated in the Guarapina lagoons in 2013 and is also present in the Padre lagoon in 2019 (MC17). The stations in this group were characterised by the distribution of *P. guaratibaensis*, which was related in the DCA analysis to the highest salinity values, indicating an increase in the transport of Guarapina to the innermost region of the lagoon in 2019. The advance to the innermost regions of the system by groups II, III and V in 2019 reinforces the increase in circulation between the lagoons. Group VI was represented by stations with greater abundance of *A. tepida*, which was widely distributed between the Maricá and Barra lagoons in 2013 and corresponded to the regions most impacted by high organic matter in the lagoonal system (Laut et al. 2021). This group occurred only in the central region of the Maricá Lagoon and the innermost region of the Guarapina Lagoon in 2019, which indicates a reduction in the areas most impacted by organic matter after the canal interventions.

6. Conclusions

The Maricá-Guarapina Lagonal System showed significant changes between 2013 and 2019 due to anthropic interventions in the tidal channels. The effects of seasonal variations were overcome by dredging and the opening of the Barra lagoon channel. However, a lower transport of sand into the system was observed, which may be related to the lower intensity of winds and rainfall in 2019.

The anthropic interventions in the system are reflected in a better circulation with a substantial attenuation of the confinement gradient identified in 2013, in which the Guarapina Lagoon was the one that had an effective exchange with the ocean and the Maricá Lagoon was the most confined of the system. The better connectivity of the Maricá Lagoon can be verified by the significant increase in salinity values, which were 0-1 in 2013 and increased to 12.5-16.3 in 2019. The redistribution of silt and clay fractions and the greater textural heterogeneity according to the granulometric classification proposed by Shepard also indicate that the circulation between the lagoons was more efficient in 2019.

Changes in the abiotic environment were reflected directly in the foraminifera, where there was a significant increase in the ecological indexes of density, richness, diversity and evenness. The possibility of changes in community data being the answer to seasonal issues was also overcome because the behaviour of foraminifera in MGLS was utterly different from other lagoons in Rio de Janeiro. In the 2019 samples, seven species (*Ammobaculites exiguus, Ammotium cassis, Cribrolphidium gunteri, Miliammina fusca, Miliolinella subrotunda, Polysaccammina hipohalina* and *Trochammina inflata*) were identified that had not been previously found in the region. The species *Ammotium morenoi*, which was not abundant in 2013, has expanded in the lagoons, occupying areas previously dominated by *Quinqueloculina seminulum*. The species expansion and other agglutinated foraminifera was associated with increased silt and muddy sediments. This assemblage was only identified in 2019, occupying the Maricá lagoon. Other species that in 2013 were associated with regions of higher marine influence also advanced into the inner areas of the system, such as *Ammonia parkinsoniana, Paratrochammina guaratibaensis*, and *Elphidium excavatum*.

The regions considered to have the most anthropogenic impact were related to the Assemblage *Ammonia tepida* VI, the dominant one in the system in 2013, mainly in the Marica and Barra lagoons. In 2019, this assemblage was limited to the central region of Maricá Lagoon and the innermost region of the Guarapina Lagoon, indicating a recovery in the environmental conditions of the sediments. The results showed that the interventions, although temporary in the system, were effective in increasing circulation and marine influence, as reflected in the improvement of the benthic environment for mixohaline organisms. Foraminifera effectively detect positive and negative changes in the MGLS and have great potential for biomonitoring the region.

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