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Foraminiferal assemblage structure from Brazilian tropical urbanized beaches (~7° S)

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Abstract: Foraminifera are diversified protists with high ecological and bioindicator importance. Physical-chemical parameters of the environment can be evaluated through the taphonomic analysis of the test coloring, because once they settle in the sediment their tests begin to behave as sedimentary particles. Five urbanized tropical Brazilian beaches were sampled in this study in order to characterize the diversity, abundance, taxonomic and taphonomic structure of Foraminifera assemblages. General environmental characterization such as granulometric analysis, temperature and salinity was also performed. A total of 69 foraminiferan species were found, dominated by *Quinqueloculina lamarckiana*, *Archaias angulatus*, *Amphistegina lessonii*, *Ammonia tepida* and *Eponides repandus*. A large predominance of dead tests (>90%) was found, and only them were considered in further analyses. The cluster based on the taxonomic composition formed two groups, separating Miramar from the other beaches. Miramar was dominated by *Ammonia tepida* (18.9%), *Sorites marginalis* (16.8%), *Quinqueloculina lamarckiana* (13.9%) and *Textularia agglutinans* (10.2%), and had the highest density, number of species and diversity, what may be related with the sheltered nature of this beach and the dominance of fine sand. The other four beaches have high oceanic influence and the medium and coarse sand predominated. In these beaches *Quinqueloculina lamarckiana* dominated, representing between 30.9 and 38.7% of total foraminiferans. The taphonomic analysis indicates that Miramar presents a high deposition of tests and a low hydrodynamic energy, since the majority of tests were white. In Bessa, Manaíra and Seixas most of the tests were brownish, which is characteristic of beaches with high hydrodynamic energy, which causes the tests to be constantly brought to the oxidation zone.

Key words: sandy beaches, foraminiferans, taphonomy, abundance, tropical waters, South Atlantic.

INTRODUCTION

Foraminifera is a diversified taxon, with more than 60.000 described species, and with high ecological and bioindicator importance of both current and past conditions (Horne et al. 2002, Gupta et al. 2019). Once dead, their tests settle in the sediment and begin to behave like sedimentary particles indicating or paleoindicating the environmental conditions during their deposition (Debenay et al. 1996, Gupta et al. 2019). Physical-chemical parameters of the environment can be evaluated through the taphonomic analysis of the test coloring and abrasion. Thus, beyond the diversity abundance and taxonomic composition, important features of Foraminifera assemblages are proportion of living and dead organisms and their taphonomic characteristics. The study of total community of Foraminifera (alive and dead) allows a deeper and longer-term view, since the changes in community composition due to taphonomic processes are also incorporated (Goldstein & Watkins 1999, Walker & Goldstein 1999, Gupta et al. 2019).

Foraminifera rarely lives on beaches (Murray 1973) and their occurrence in these environments is typically due to post-mortem transport (Haslett et al. 2000). Yet, several species of larger Foraminifera are found along the eastern Mediterranean coast, associated with high water energy and temperature, deep light penetration, coarse substrate and presence of sea grasses (Samir et al. 2003, Yokes & Meriç 2004). Most studies are from temperate regions (e.g. Boltovskoy & Totah 1985, Alperin et al. 2011, Kirci-Elmas 2018, Bernasconi et al. 2018, Ferraro et al. 2018, Romano et al. 2018), while among the relatively few studies on the tropics (Licari et al. 2003, Mojtahid et al. 2006, Debenay & Fernandez 2009) those from the intertidal zone are mostly concentrated at Indian shorelines (Devi & Rajashekhar 2009, Hussain & Casey 2016, Hussain et al. 2016, Rao et al. 2018). Particularly at the Brazilian coast, foraminiferological studies are concentrated at subtropical latitudes (e.g. Zaninetti et al. 1977, Debenay et al. 1998, Eichler et al. 2001) close to the historically consolidated research groups on marine biology (e.g. Boltovskoy & Valentin 2018). There are few studies from tropical Brazil (e.g. Anjos-Zerfass et al. 2006, Batista et al. 2007, Quadros et al. 2015, De Moraes & Machado 2016), and, at the best of our knowledge, none characterized sandy beaches assemblages. Studies on the patterns of Foraminifera associations allow a deeper understanding of the sedimentary dynamics of various types of environments and may provide tips on the impact status of the environments (Lançone et al. 2005).

The present study aims to characterize the diversity, abundance, taxonomic and taphonomic structure of the recent benthic Foraminifera assemblages from different beaches from João Pessoa metropolitan area. This is an important city of the tropical Northeast Brazil that has been growing considerably in the past decades. As consequence, the associated anthropic impacts on its beaches such as domestic sewage, tourism and real estate speculation are also increasing.

MATERIALS AND METHODS

Five beaches from the Metropolitan region of João Pessoa, Paraíba, Brazil (Figure 1) were sampled once between February and March of 2017. These beaches were chosen because they have different characteristics and anthropic interventions. Lucena is the northern most

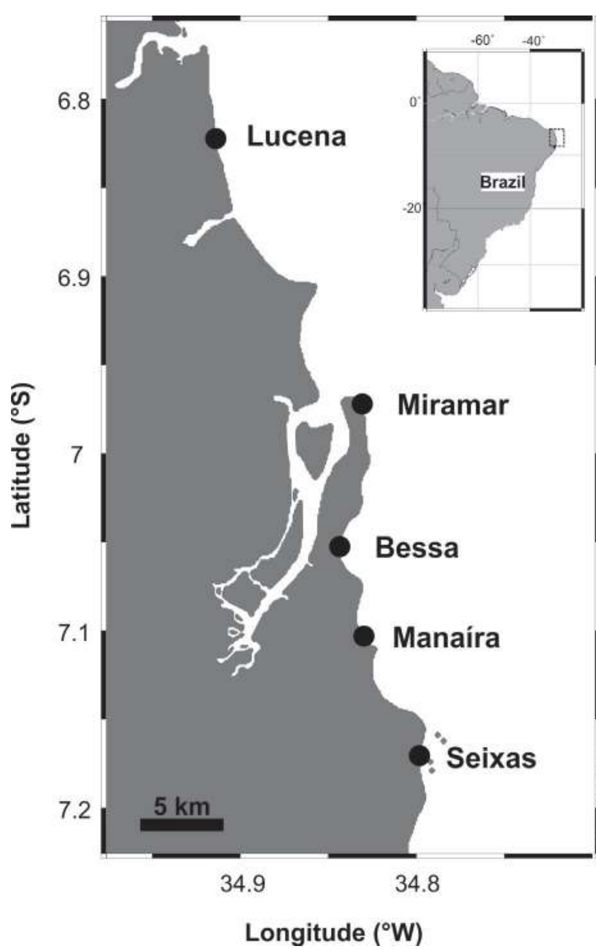

Figure 1. Map of Brazil showing the location of the beaches sampled. Generated using Ocean Data View software (Schlitzer 2019).

beach and the most distant from the capital. Miramar is a sheltered beach with a low energy of waves, with human occupation and moderate presence of tourists. Seixas is a little closer to the capital, being affected by the great energy of waves and by tourists mostly during weekends. Bessa and Manaíra are urban beaches that suffer daily with anthropic actions. Most of the beaches studied are of the dissipative type, however Manaíra is intermediary and Seixas is more reflexive (following Calliari et al. 2003). There is a major source of freshwater nearby, the Paraíba River estuary (Figure 1), however its plume typically flows northwards and thus is not expected to directly influence the conditions of the study area even in the close Miramar beach (Dominguez et al. 2016). This is particularly true since we performed the sampling during the summer which is the dry season.

Three replicate samples were taken in each beach in the intertidal zone using a corer with 5 cm long PVC tube and 5 cm of diameter. To each replica 50 ml of the sediment from the first 2 cm were collected. The samples were fixed in 70% alcohol solution containing rose bengal (1g/L) to stain the protoplasm of the living specimens. Temperature and salinity were also measured with a thermometer and a manual refractometer respectively. On each beach, sediment for granulometric analysis was also taken, and treated following standard procedures (Suguio 1973).

In the laboratory, the samples were washed through one sieve (0.063 mm) under a stream of fresh water, to remove the fine sand. Among the replicates of the samples, the sieve was washed with a solution of methylene blue to avoid contamination. The sediment retained in the 0.063 mm fraction was oven-dried (50°C) through 24 hours. Then the sediment was sifted through two sieves (0.125 mm and 0.5 mm). The samples were analyzed under a stereomicroscope and 300 specimens (dead + live) from each sieve were removed with the aid of a fine-tipped brush and deposited on a dark plate. These individuals were identified following mostly Boltovskoy et al. (1980), Debenay (2012) and Hanagata & Nobuhara (2015). To estimate density, quarter samples were analyzed and all individuals (dead + live) counted from both sieves. Taphonomic analyses were performed on dead specimens of one replicate from each beach, adopting the traditional color pattern (e.g. Leão & Machado 1989, Duleba 1994, Teodoro et al. 2009, Supplementary Material - Figure S1)

Due to the general rarity of living specimens (see below in the results), all data presented and analyses performed were based only on dead specimens. Community indexes such as Pielou's evenness (J) and Shannon–Wiener diversity (H') were calculated for each sample. One-way ANOVA were used to test the hypothesis that the beaches differ regarding the number of species, Shannon diversity, evenness and abundance. In case of significant differences ($p<0.05$) pairwise comparisons were performed using the Tukey test, after applying the Bonferroni correction (Zar 1999). Both taxonomic and taphonomic data (dead tests only) were transformed by log (x+1), and a similarity matrix was generated for each data-set using the Bray-Curtis similarity measure. With each matrix we generated a cluster using the group average mode. A similarity percentual analysis (SIMPER) was performed in order to discriminate the contribution of each species/color to the groups formed in the cluster (Clarke & Warwick 2001). Univariate analyses were performed using GraphPad Prism version 5.01 and multivariate analyses performed using PRIMER 6.

RESULTS AND DISCUSSION

Environmental parameters

Fine and very fine sediments predominated at Miramar, Bessa and Manaíra beaches. These fractions were also representative at Lucena, however at this beach larger fractions summed >60% (Figure 2). At Seixas, differently, fine sand very fine sand represented <25%, and sediment was dominated by larger particles, particularly medium (~45%) and coarse (~25%) sands (Figure 2). Salinity reached a maximum of 39 in Miramar, with values between 36-37 on the other beaches, while the temperature was between 29 and 31°C in all stations (Table I). These values are typical of this tropical area where the continental shelf is narrow and there is a high influence of the warm, salty and oligotrophic Tropical Water of the Brazil Current over the coast (Boltovskoy et al. 1999). Moreover, during the dry season sampled here continental runoff influence is minimum and the coastal waters heat up and evaporate (Dominguez et al. 2016), particularly at Miramar that is partially sheltered by a dam and thus has low energy and high salinity (Table I).

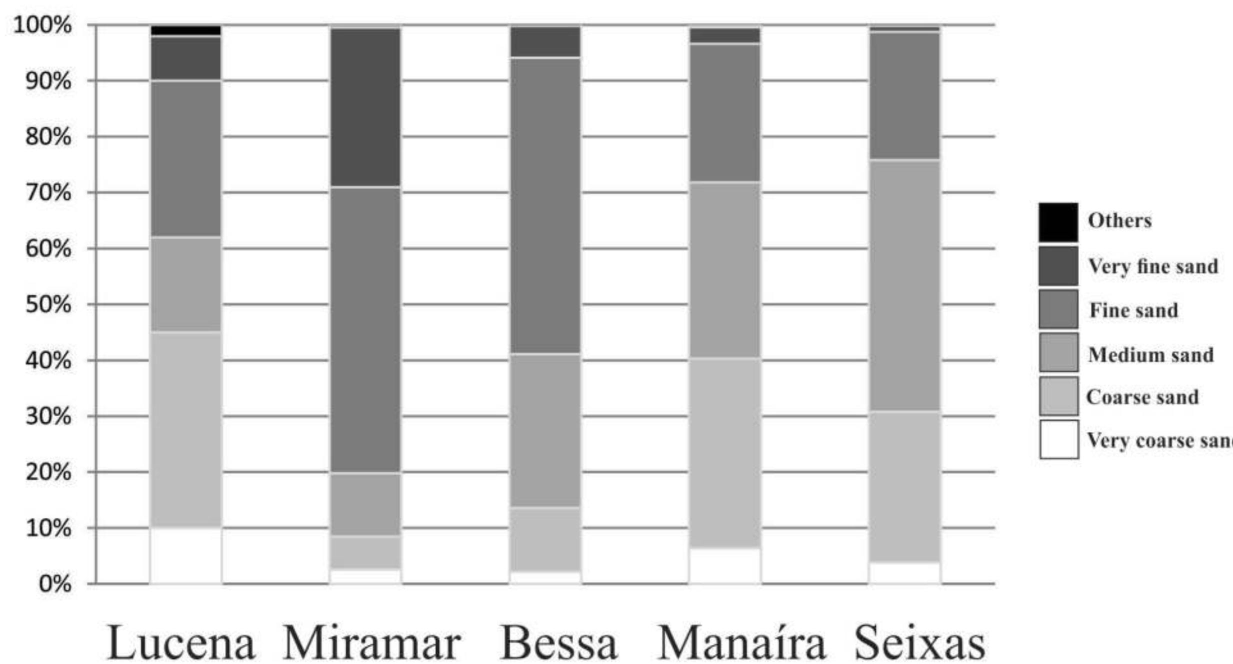

Figure 2. Relative contribution (%) of each granulometric fraction at different beaches from João Pessoa metropolitan area.

Table I. Temperature and salinity of the studied beaches.

Beach	Salinity	Temperature (°C)
Lucena	36	29
Miramar	39	30
Bessa	37	31
Manaíra	36	31
Seixas	36	31

Foraminifera - Taxonomic structure

A total of 4,594 foraminiferans was analyzed, belonging to 69 species from 36 genus, referring to 25 families (Supplementary Material - Table SI, Figure S2). Dead Foraminifera largely dominated the community, representing between 90.0 and 98.3% of all foraminiferans at Miramar and Lucena, respectively. Only 13 species had live representatives and dead individuals largely predominated in all cases, except for *Poroeponides lateralis* and *Cymbaloporetta bradyi* which were represented only by a single live individual each. Due to the large absence of live individuals, all further analyses have been performed with dead individuals only. The ecological indexes and the abundance varied significantly between the beaches (ANOVA; $p<0.05$), with higher values at Miramar in all cases and tending to be lower at Seixas (Figure 3a). The average number of species varied between 30.6 and 17.6 and the density between 1273 and 263 ind./cm^3, with the lowest and the highest values always at Seixas and Miramar respectively (Figures 3a-c, 4a).

Unfortunately, there are no previous data on Foraminifera from Northeastern Brazilian sandy beaches, emphasizing the importance of field studies on these poorly known ecosystems. The number of species found in this study (69 spp.) is within the range usually observed in other comparable studies on tropical coastal environments, where number of Foraminifera species lies within 60 and 102 (Samir & El-Din 2001, Gandhi et al. 2002, Samir et al. 2003), depending on the sampling effort and extent of the study site. Yet, studies from Indian sandy beaches with sample size similar to the present study retrieved considerably less species (24-34 spp., Hussain et al. 2016, Hussain & Casey 2016). The values of Shannon diversity were also relatively high in the present study, particularly at Miramar with a mean of 2.6, compared to the maximum of 2.8 from Guanabara bay, Brazil (Donnici et al. 2012), 1.8 from the Mediterranean coast of Egypt (Samir et al. 2003) and 0.95 from Chilika Lagoon, India (Gupta et al. 2019).

Only 61 individuals were alive in the moment of the collection. The high proportion of dead Foraminifera is common in most Brazilian coastal environments (e.g. Debenay et al. 2001, Vilela et al. 2004) and in several places around

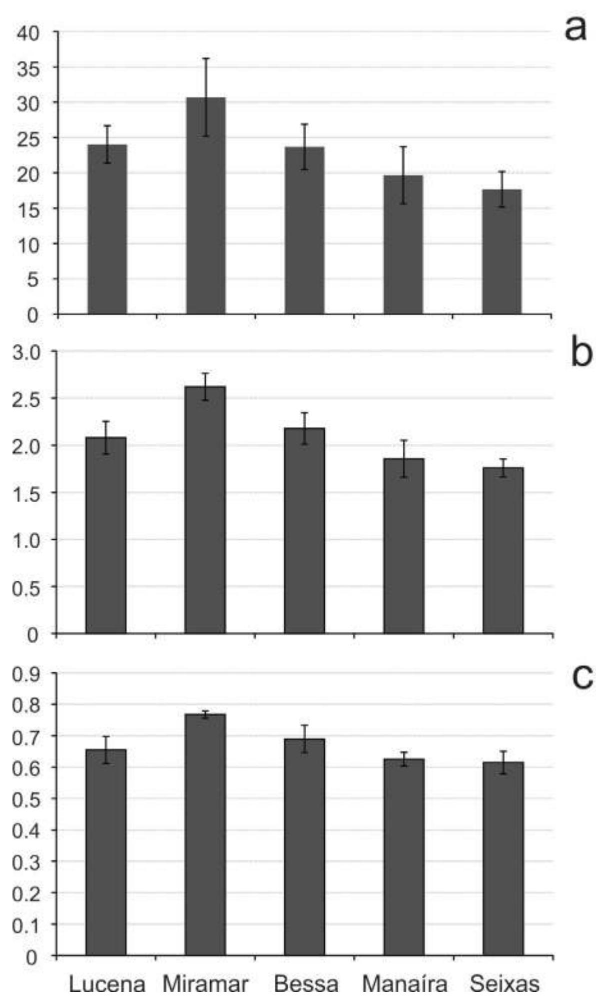

Figure 3. **Spatial variation of the mean number of species (a), diversity of Shannon-Winner (b) and Pielou's equitability (c) of dead foraminiferan assemblages from João Pessoa metropolitan area. Lowercase letters indicate the result of the Tukey a posteriori test; beaches sharing at least one letter do not differ significantly (p>0.05) from each other. Error bars represent the standard deviation.**

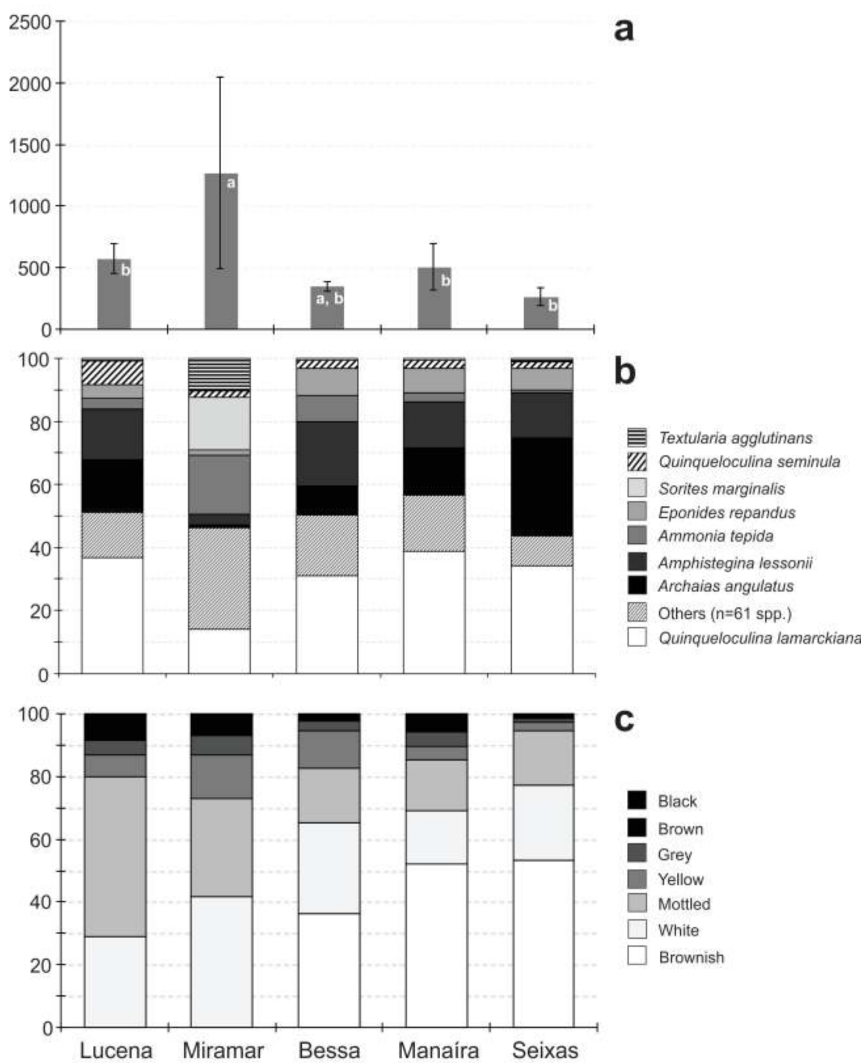

Figure 4. Mean density (a; ind./cm^3), relative abundance of dominant species (b; %) and colors (c; %) of dead foraminiferans from João Pessoa metropolitan area. Error bars in a represent the standard deviation and the lowercase letters indicate the result of the Tukey's posterior test; beaches sharing at least one letter do not differ (p>0.05) from each other.

the world (e.g. Samir & El-Din 2001, Gupta et al. 2019), being typical of sandy beaches where the presence of most species commonly is due to post-mortem transport (Murray 1973, Haslett et al. 2000). Previous comparisons of fauna of dead and alive Foraminifera demonstrated various degrees of correspondence between the two assemblages (Debenay et al. 2005). Most of the discrepancies were attributed to the transport of dead tests (Douglas et al. 1980, Duros et al. 2012), population dynamics (Gooday & Hughes 2002), occupation of microhabitats (Loubere & Rayray 2016) or an interaction between multiple factors (Mackensen & Douglas 1989, Duros et al. 2014).

Staining with rose bengal, used here, is the most common method used to differentiate among living and dead individuals (e.g. De Stigter et al. 1998, Bernhard 2000, Eichler et al. 2001, Tapia et al. 2008, Gupta et al. 2019). There are, however, a number of negative aspects regarding its use (Bernhard et al. 2006): it can stain bacteria attached to or located inside the test (Martin & Steinker 1973); staining is difficult to visualize in opaque specimens such as certain agglutinant or miliolid foraminiferans (Bernhard 2000), likewise *Quinqueloculina lamarckiana*, *Sorites marginalis* and *Textularia agglutinans*, abundant in the present study (see below). All of the few stained tests found in the present study had a lighter shade of pink compared to the coloration of the alive Foraminifera seen elsewhere (e.g. Sadri et al. 2011, Ishimura et al. 2012, Lejzerowicz et al. 2013). This may be related to the presence of bacteria and/or opaque species.

The cluster analysis based in the taxonomic structure formed two groups (Figure 5a), separating Miramar from the other beaches. At Miramar, 49 species were found (Table SI) with the dominance of *Ammonia tepida* representing 18.9%, followed by *S. marginalis* (16.8%), *Q. lamarckiana* (13.9%) and *Textularia agglutinans* (10.2%). In addition, several less abundant species (<3% each) summed slightly more than 30% (Figures 4b, 5a). At the other beaches, between 30 and 41 species were found and *Q. lamarckiana* dominated widely, representing between 30.9 and 38.7% of total foraminiferans, followed by *Amphistegina lessonii* (14.4-20.5%) and *Archaias angulatus* (9.0-31.1%). Besides these, *Eponides repandus* represented between 7-8.8% at Seixas, Manaíra and Bessa, and *Q. seminula* represented 7.5% at Lucena (Figures 4b, 5a). The average dissimilarity between the two groups (Figure 5a) was 54.0% and the species which contributed with more than 3% for the differences were: *S. marginalis*, *A. angulatus*, *T. agglutinans*, *A. tepida*, *Cribroelphidium excavatum*, *A. lessonii*, *Pyrgo subsphaerica* and *Quinqueloculina laevigata* (Table II).

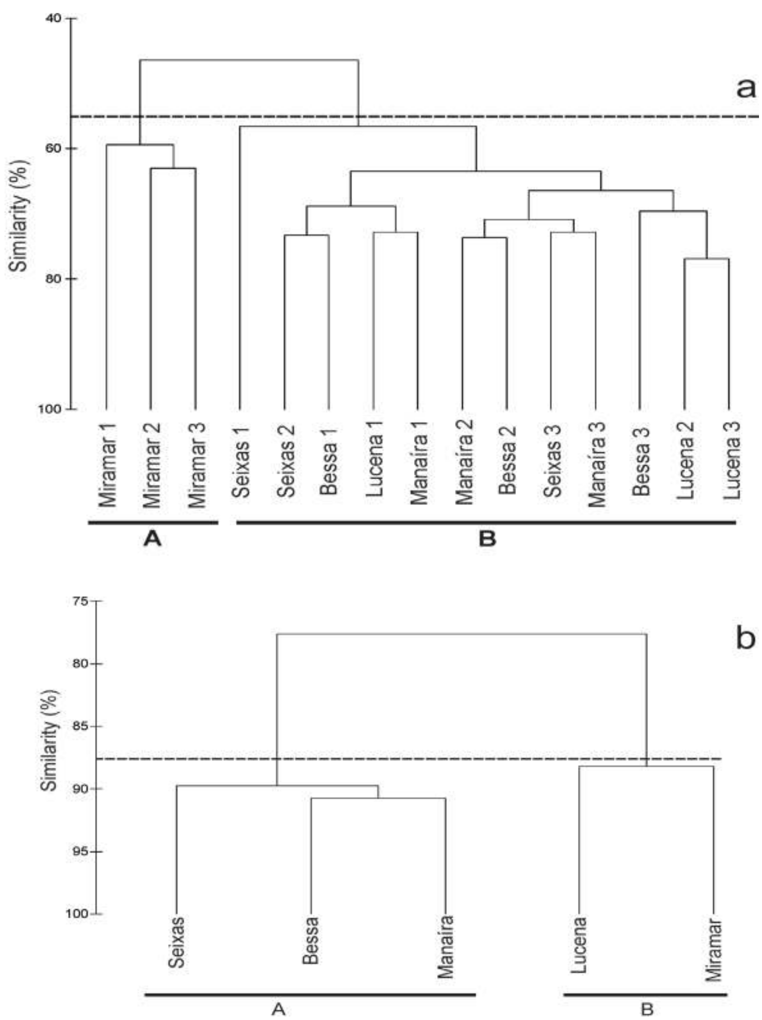

Figure 5. **Cluster analysis (a) based on taxonomic composition of dead foraminiferans from João Pessoa metropolitan area, each number represent one replicate sample of each sampling site, and (b) based on taphonomic composition of Foraminifera from João Pessoa metropolitan area.**

The highest ecological indexes, abundance and amount of living Foraminifera (32 individuals) were found at Miramar. The community structure on this beach differed from the others (Figure 4b; Table II), with broad dominance of *A. tepida* and *S. marginalis*, besides several other species individually little abundant, but which contributed to the increase of the ecological indexes in this area. *A. tepida* is considered typical of paralic environments, found in both hypersaline and low salinity regions, commonly found among the dominant species in these environments (Debenay et al. 2001, Debenay & Guillou 2002). This is particularly true in polluted regions or under high anthropic stress (e.g. Vilela et al. 2004, 2011, Gupta et al. 2019), since it is tolerant to thermic and chemist pollution like fertilizers, heavy metals and hydrocarbons (e.g. Seiglie 1975, Setty 1976, Setty & Nigam 1984, Yanko & Flexer 1991). Indeed, *A. tepida* has been used as a heavy metal pollution indicator (Du Chatelet et al. 2004) and its massive presence in the region may suggest the need to evaluate the local quantities of heavy metals and/or other

Table II. Results of the SIMPER analysis, indicating the average dissimilarity between the groups formed by the cluster according to the taxonomic and taphonomic composition and the species/colors that mostly contributed to the differences.

Variable	Overall average dissimilarity (group A x B)	Taxa or color	Average dissimilarity	Contribution (%)	Cum. (%)	Average abundance (±SD)	
						A	B
Taxonomic composition	53.6	*Sorites marginalis*	4.16	7.77	7.77	5217.34	0.16 0.38
		Archaias angulatus	3.3	6.16	13.93	2.332.51	60.4127.26
		Textularia agglutinans	2.49	4.64	18.57	31.6620.40	21.64
		Ammonia tepida	2.19	4.08	22.65	58.3318.14	11.58 12.12
		Cribroelphidium excavatum	1.96	3.66	26.31	89.64	0
		Amphistegina lessonii	1.7	3.17	29.48	10.336.02	50.3315.68
		Pyrgo subsphaerica	1.63	3.04	32.52	135.29	2.52.23
		Quinqueloculina laevigata	1.61	3.01	35.54	73	1.412.10
Taphonomic composition	22.4	Brownish	10.8	48.1	48.1	142 27.07	0
		Black	2.4	10.9	59.0	2.663.05	77.07
		Brown	1.7	7.8	75.0	6.66 3.78	154.24
		Mottled	1.7	7.6	82.6	51.663.21	117.538.89
		Yellow	1.7	7.6	90.2	1915.71	3014.14
		Gray	1.3	6.0	96.3	95	15.5 3.5
		White	0.8	3.7	100	70.66 19.03	101.5 26.16

water pollutants. No detailed information is available on the levels of water pollution in the studied region, but the proximity of the estuary of the Paraíba River may have contributed. The level of nutrients was considered high in this estuary, suggesting anthropic disturbance (e.g. Alves et al. 2016, Dolbeth et al. 2016). Besides that, this estuary shelters the Cabedelo harbor which can further contribute with the pollution.

Sorites marginalis is indicator of saline to hypersaline environment of tropical waters, with substrate of algal carbonate sand (Machado & Souza 1994) and is also characteristic of environments of low hydrodynamic energy (Mohamed et al. 2013). Miramar presented the highest salinity value of this study, possibly related to the low hydrodynamic energy and evaporation what also is in accordance to the taphonomic analysis (see below). These conditions also favor the preservation of some arenaceous shallow forms in the foraminiferal assemblages such as *Textularia* spp. (Mohamed et al. 2013), represented by *T. agglutinans* in this study, which is commonly found in tropical regions of low energy (e.g. Levy et al. 1995, Solai et al. 2013, Anbuselvan & Senthil Nathan 2019).

The other beaches are oceanic, considered habitats physically rigorous in which benthic community has been correlated with physical factors of the beach morphodynamic such as size of the grain, beach slope and coastal process connected to the action of the waves (Defeo et al. 2003). On these beaches dominant species were mainly *Q. lamarckiana*, but also *A. lessonii* and *A. angulatus*. Indeed, these three genera commonly are dominant on sandy sediments, particularly under higher energy conditions from shelf environments and deposits of reef influence on the shelf (Moraes 2006, Figueiredo et al. 2011). Moreover, *Amphistegina*, *Archaias* and *Quinqueloculina* have resistant tests (Moberly 1968, Martin 1986, Gualancañay 2007) what might confer them adaptative advantages in environments with high hydrodynamic energy such as these beaches (see below). *Q. lamarckiana* is commonly found in beach sediments (Phleger 1960) and the genus *Quinqueloculina* has a wide distribution in marine environments (Sanches et al. 1995, Leipnitz et al. 1995), although some species may also appear in mixohaline environments, in small numbers (Zaninetti 1979). *Amphistegina* is normally associated with *A. angulatus* and others miliolids such as *Quinqueloculina* in carbonate sediments ranging from coarse to medium sand (Leipnitz et al. 1999). *Amphistegina* is also common and abundant in the sediments of the continental shelf of Northeast Brazil (Tinoco 1972, 1980). In addition, *A. lessonii* and *A. angulatus* are macro foraminiferans, with complex internal morphology that harbors symbiotic algae that complement their nutrition and thus, important elements of the benthic community in shallow, warm, well-lit, and nutrient-poor tropical seas (Hallock 1985, Hohenegger et al. 1999, Lee 2006, Murray 2006).

Foraminifera - Taphonomic structure

The white, mottled and brownish tests were dominant depending on the beach. The white and mottled were highly representative at all beaches, dominating at Miramar and Lucena respectively, while brownish tests were dominant at Bessa, Manaíra and Seixas representing 35 and 52% (Figure 4c). The cluster analysis based in the taphonomic structure also grouped the samples into two groups: the first one with Lucena and Miramar, and the second group with the other beaches (Figure 5b). The colors which contributed more to the differences were brownish (48.1%) and black (10.9%), with the others representing <9% (Table II).

The white tests suggest a high deposition rate and low hydrodynamic energy (Leão &

Machado 1989), what explain their dominance at Miramar (see above). Most of the tests from Lucena were mottled, with a large variation of colors. This indicates that these tests were relics, i.e. were previously deposited, and are for some time undergoing many alterations that the different colors indicate (Batista et al. 2007). If the tests are deposited in oxidant environment or if those containing sulfides are relocated to the oxidation zone, by erosion or by the action of excavating organisms, the sulfides present in the tests are reoxidized to hydroxides and/or iron oxides, and the tests gain a brownish color (Maiklem 1967, Duleba 1994, Silva & Duleba 2013), for example.

The taxonomic and the taphonomic cluster, both based on dead specimens, did not provide exactly the same results, emphasizing the use of both complimentary approaches which provide different information. The taphonomic cluster followed a geographic pattern, since Lucena and Miramar were close to each other in the north and reflects their deposition and abrasion dynamics. For the taxonomic cluster the characteristic of the type of the sediment of each beach was preponderant; while medium and coarse gains predominated in most sampled beaches, at Miramar fine and very fine sand predominated (~80%), what usually is associated to higher organic content (Moore 1958, Ferreira 1977, 1978, Tilbert et al. 2019). In addition, Miramar seems to be becoming a lagoon, with very low hydrodynamic energy and high salinity.

This study provides novel data about benthic foraminifera from beaches of the João Pessoa metropolitan area. We found 69 species dominated by *Quinqueloculina lamarckiana*, *Archaias angulatus*, *Amphistegina lessonii*, *Ammonia tepida* and *Eponides repandus*. Highest abundance and species richness occurred in the sheltered and fine-grained Miramar where most tests were white associated to the high deposition rate and low hydrodynamic energy. In the other beaches lower abundances and diversity were found, associated to larger-sized grains, and most of the tests were brownish, indicative that they are constantly carried to the oxidation zone and thus of high hydrodynamic energy environments Lastly, we highlight the importance of more studies in the region, especially in Miramar and the Paraíba River Estuary, taking account the results obtained in the present study and the importance of Foraminifera as bioindicators.

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SUPPLEMENTARY MATERIAL

Table SI. List of foraminiferan species and their relative abundance (%) at the different beaches from João Pessoa metropolitan area, in bold are the dominant species of each place.

Figure S1. *Quinqueloculina lamarckiana* tests illustrating the different colors used in the taphonomic analysis. White (a), black (b), brown (c), gray (d), brownish (e), yellow (f), mottled (g).

Figure S2. Main Foraminifera species of João Pessoa metropolitan sandy beaches. (a) *Sorites marginalis*, (b) *Textularia agglutinans*, (c) *Archaias angulatus*, (d) *Amphistegina lessonii*, (e) *Quinqueloculina lamarckiana*, (f) *Quinqueloculina seminula*, (g) *Ammonia tepida* and (h) *Eponides repandus.*

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