

Article

Composition and Spatial Distribution of Benthic Foraminifera from Two Tropical Estuaries (7° S, Brazil)

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Abstract: This study investigates the composition and spatial distribution of benthic foraminiferal assemblages in the estuaries of the Mamanguape and Paraíba rivers in North-east Brazil. Samples were collected from different sectors along both estuaries and analyzed for foraminiferal density, diversity, and species composition in relation to abiotic factors like salinity, temperature, pH, and sediment grain size. Results show that calcareous foraminifera dominate both estuaries, likely influenced by stable pH and salinity gradients. Additionally, the sediment composition of both estuaries varies from typical tropical estuarine patterns, with the presence of coarse and medium sands suggesting significant environmental dynamics. Statistical analyses confirm that foraminiferal assemblages reflect spatial environmental variations within and between the estuaries, underscoring the potential of foraminifera as bioindicators in coastal ecosystem assessments.

Keywords: spatial variation; environmental dynamics estuaries; salinity; change; anthropogenic



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1. Introduction

Benthic foraminifera (kingdom Chromista, phylum Foraminifera) are single-celled organisms that are abundant in all marine environments, from deep-sea settings to transitional areas [1–4]. There are currently approximately 48,000 cataloged species, both fossil and recent, making them the most diverse group of shelled microorganisms in modern seas [5]. They typically have a short life cycle and are considered environmental sentinels, with their tests preserved in sedimentary records after death [6–8]. Globally, foraminifera play significant functional roles in the benthic environment, contributing to bioturbation, seabed ventilation, nutrient cycling, and the global geochemical cycles of carbon and nitrogen [9–16].

Like other benthic organisms, the structure of foraminiferal assemblages is influenced by abiotic and biotic factors. Consequently, the abundance, diversity, and composition of these assemblages are jointly controlled by the physical and chemical parameters of the environment [2,3,17]. Some of these parameters include temperature, salinity, food distribution and availability, energy state at the benthic/pelagic boundary, oxygen availability, substrate type, and bottom morphology [3,18–22]. Additionally, foraminifera possess characteristics that make them ideal for assessing environmental health, such as a short lifespan and the high preservation potential of their tests in sedimentary records [8]. As a result, these assemblages are sensitive to environmental changes, whether natural or anthropogenic [3,7,23–26]. Since variations in environmental parameters create specific

habitats for different species, making some microhabitats suitable for some species but uninhabitable for others, benthic foraminiferal associations can be used as indirect indicators of changes in environmental parameters [27–29].

Estuaries are transitional environments located at the interface between continental and marine waters [30]. Due to exposure to variable physico-chemical parameters and strong environmental gradients, estuaries are naturally stressed by daily exposure to various environmental factors such as ocean currents, hydrology, rainfall, temperature, and dissolved oxygen [31–33]. Furthermore, about 70% of the world's population lives in coastal regions, resulting in significant ecological stress on aquatic systems, particularly estuaries [33,34].

Thus, there is a need for methods to monitor these environments. Strategies can be adopted to characterize, assess, and monitor environmental quality [35]. For approximately 20 years, benthic organisms have been used as bioindicators of environmental quality [36]. The study of foraminiferal assemblages can provide valuable information about marine ecosystems [37]. The use of these organisms as indicators of environmental quality in coastal areas has been increasing [2,38–43].

Therefore, studies on the composition, abundance, and distribution of foraminiferal assemblages in different environments are essential. This study aims to analyze the composition and spatial distribution of benthic foraminifera in the estuaries of the Paraíba and Mamanguape rivers (7° S, Brazil) and relate their distribution to abiotic parameters, recognizing variations in benthic foraminiferal distribution along the salinity gradient and grain size.

2. Materials and Methods

2.1. Study Area

The estuaries of the Mamanguape and Paraíba rivers belong to the Northeast Brazil Marine Ecoregion [44]. According to the Köppen–Geiger climate classification, the climate in both estuaries is of type As, meaning equatorial with a dry summer [45]. The rainy season extends from February to August, with the highest rainfall occurring in June and the lowest in November [46]. The Paraíba River estuary has a wetter climate (with an average annual precipitation of 1717 mm) than the Mamanguape River estuary (with an average annual precipitation of 1392 mm) [47]. The tides are semi-diurnal, with a maximum level of 2.2 m in the Mamanguape River estuary and 2.8 m in the Paraíba River estuary [48,49].

The Paraíba River estuary covers an area of 20,124 km², draining the cities of João Pessoa, Bayeux, and Santa Rita, and near its mouth, the port city of Cabedelo [48,50] (Figure 1A). The region of the Paraíba River estuary houses the Cabedelo Restinga National Forest designated as a Priority Area for Biodiversity Conservation across nine categories, including ecosystems (estuary, restinga, wetlands, and reefs) and zoological groups (elasmobranchs, birds, fish, benthos, and mammals) [51]. Despite this, the estuary lacks a protected area; it suffers from numerous anthropogenic impacts such as domestic and industrial sewage discharge, port activities, sugarcane cultivation, shrimp farming, boating activities, recreation, and tourism [46,52,53].

The Mamanguape River estuary covers an area of 3522 km² and includes an Environmental Protection Area aimed at protecting coastal ecosystems and the population of marine manatees (*Trichechus manatus*) in the region [50,54] (Figure 1B). There is a well-preserved mangrove forest in the area, which grows around the primary channel and extends over 600 hectares, along with remnants of the Atlantic Forest [55]. However, extensive sugarcane fields and aquaculture areas for shrimp production are found beyond the mangrove area [46]. The river mouth forms a 6 km wide bay that is almost closed by a coastal reef line, resulting in calm waters [46].

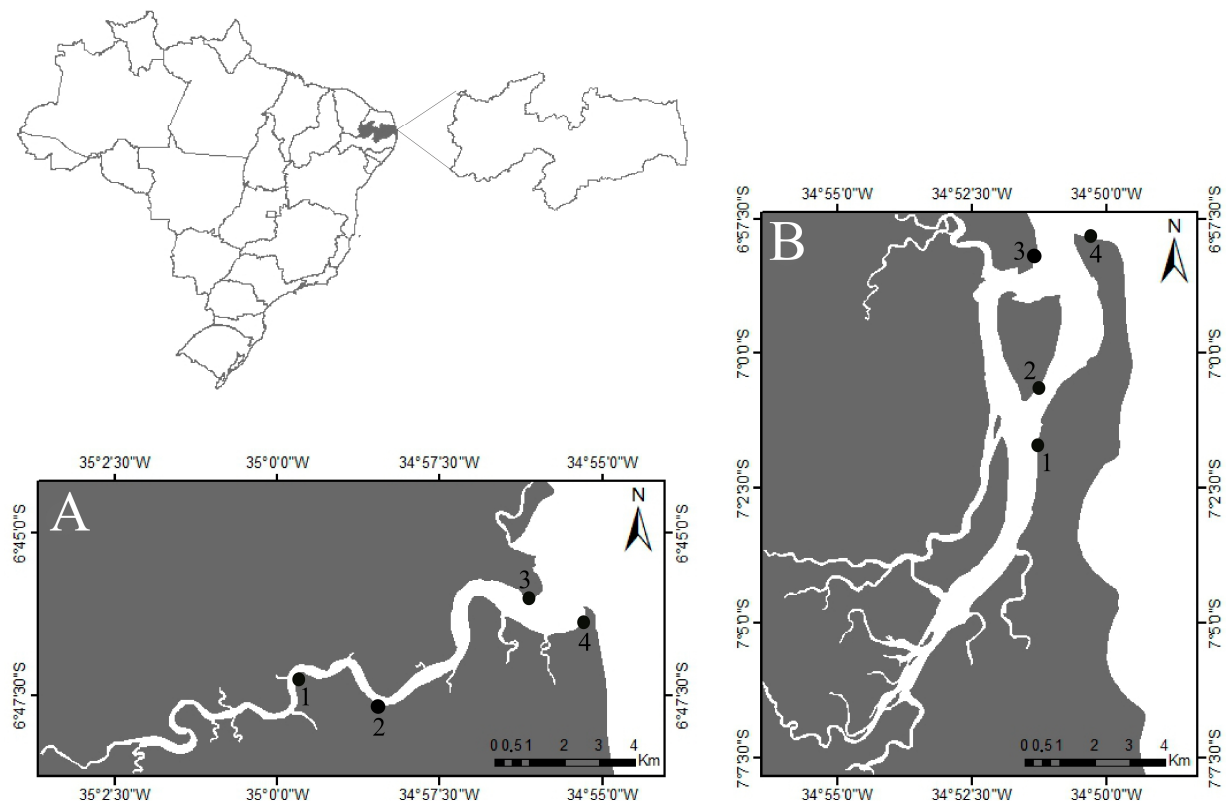


Figure 1. Map of part of the coast of Paraíba showing the two estuaries studied: (A) Mamanguape River estuary and (B) Paraíba River estuary. The circles on the map indicate the points where the samples were collected. Generated in the ocean data view program [56].

2.2. Sampling

Samples were collected on 8 and 10 February 2020, respectively from the Mamanguape and Paraíba river estuaries. Samples were taken randomly from the external, intermediate, and internal sectors, distributed from the mouth to the inner part of the estuary, on the exposed shoreline at low tide (Figure 1). Three replicates were collected at each point. Sampling was conducted using a 15 cm diameter PVC pipe inserted 10 cm into the sediment. For each replicate, 50 mL of surface sediment (top 2 cm) was collected with a spoon. The collected material was fixed in a 70% alcohol solution containing Bengal rose dye (1 g/L) to stain the protoplasm of living specimens. At the time of collection, salinity, dissolved oxygen, temperature, total dissolved solids, and pH were measured using a multiparameter probe (Series U-50-Horiba). Salinity was measured by conductivity and therefore has no unity [57]. Additionally, sediment was collected and kept frozen for grain size analysis.

2.3. Laboratory Procedures

In the laboratory, samples were washed with running water on sieves with mesh sizes of 63 μm and 125 μm . Then, the sediment retained on each sieve was transferred to filter paper and dried in an oven at 50 $^{\circ}\text{C}$ for 48 h. The samples were then examined under a stereomicroscope, and 300 specimens were picked (150 from each size fraction totaling 300 specimens from each replicate) using a fine-tipped brush and placed in a dark plate. Identification was carried out according to Boltovskoy et al. [58], Laut et al. [59,60], Lei & Li [61], Symphonia & Senthil [62], and Damasio et al. [63], with nomenclature standardized according to the online platform WoRMS-World Register of Marine Species [5].

After washing and sorting the 300 benthic foraminifera from each replicate, density calculations were performed. Samples were fractionated between 1/4 and 1/64 so that

small fractions of each replicate could be analyzed. After counting all individuals (alive and dead, the living ones will be pink-colored) in the fraction, the value was multiplied by the denominator to estimate the sample density. The granulometric study was conducted according to Suguio [64] at the Meiofauna Laboratory (Federal University of Campina Grande), by sieving dry sediments (100 g) from each station using a sieve shaker with intermittent tapping (ROTAP). Afterward, each mesh was weighed again to determine the percentage of each grain size fraction present in the samples.

2.4. Data Analysis

The Shannon–Wiener diversity index (H') [65] was applied to calculate diversity, while Pielou's index [66] was used for equitability. A two-way analysis of variance (ANOVA) was performed to compare species number, diversity, and equitability according to estuary and sampling point.

To test whether community structure differed among the factors “Estuary” and “Sampling point” and their interactions, a permutational analysis of variance (PERMANOVA) was conducted. Species abundance data in each replicate were log-transformed ($\log(x + 1)$), and a similarity matrix was generated using Bray–Curtis similarity. The analysis was performed using residual permutation under a reduced model, with p -values calculated from 999 random permutations. Factors used were estuary (Mamanguape and Paraíba) and sampling points (1, 2, 3, and 4) [67]. Additionally, a percentage similarity analysis (SIMPER) was performed to identify the species contributing to the similarity between tested groups [68]. Species abundance data from each replicate were log-transformed ($\log(x + 1)$), and a biological data similarity matrix was constructed using Bray–Curtis, while the Euclidean distance was used for the abiotic data similarity matrix.

In order to relate the foraminifera species that contributed > 1% of the total abundance to the environmental parameters considered (temperature, salinity, dissolved solids, dissolved oxygen, pH, and grain size), we used redundancy analysis (RDA). The longest gradient length for detrended correspondence analysis (DCA) was 2.004, supporting the choice of RDA for the community analysis [69]. DCA was performed using the abiotic and relative species abundance data were log-transformed ($\log(x + 1)$).

Diversity, equitability, PERMANOVA, and SIMPER analyses were carried out using Primer v6 [70] with the PERMANOVA+ expansion [71]. ANOVA was performed using STATISTICA 8 software [72], DCA and RDA were performed using CANOCO for Windows 4.5 [69].

3. Results

The temperature in the Mamanguape River estuary relatively constant, ranging from 30.7 °C to 31.3 °C (Figure 2), while in the Paraíba River estuary, it varied between 30.7 °C and 34.43 °C (Figure 2). Salinity ranged from 26 to 36.6 in the Mamanguape estuary and from 31.4 to 36.6 in the Paraíba estuary, with the highest values observed in the external sectors (Figure 2). Dissolved oxygen varied from 5.2 to 9.6 mg/L in the Mamanguape estuary and from 3.35 to 7.52 mg/L in the Paraíba estuary, with the lowest values found in the internal sectors of both estuaries (Figure 2). Total dissolved solids ranged from 27.3 to 33.1 g/L in the Mamanguape estuary and from 29.4 to 33.2 g/L in the Paraíba estuary, showing a decreasing trend towards the inner sectors (Figure 2). The pH varied between 8.7 and 8.8 in the Mamanguape estuary and from 8.6 to 8.7 in the Paraíba estuary, with a decreasing trend towards the inner sectors of both estuaries (Figure 2).

Both estuaries were dominated by sand fractions at all sampling points. In the Mamanguape estuary, sampling point 1 was dominated by coarse and medium sand fractions (36.6% and 18.64%, respectively; Figure 3A), while sampling point 2 was dominated by

coarse and fine sand fractions (22.06% and 23.56%, respectively; Figure 3A). Sampling point 3 had mostly very coarse and coarse sand fractions (34.8% and 43.6%, respectively; Figure 3A). Sampling point 4 was dominated by medium and fine sand fractions (34.4% and 45.4%, respectively; Figure 3A). In the Paraíba estuary, no clear spatial pattern was observed; sampling point 1 was dominated by coarse and medium sand (52.53% combined), while fine sand dominated the intermediate sector (59.14%), coarse sand dominated sampling point 3 (50.8%; Figure 3B), and fine sand dominated sampling point 4 (39.34%; Figure 3B).

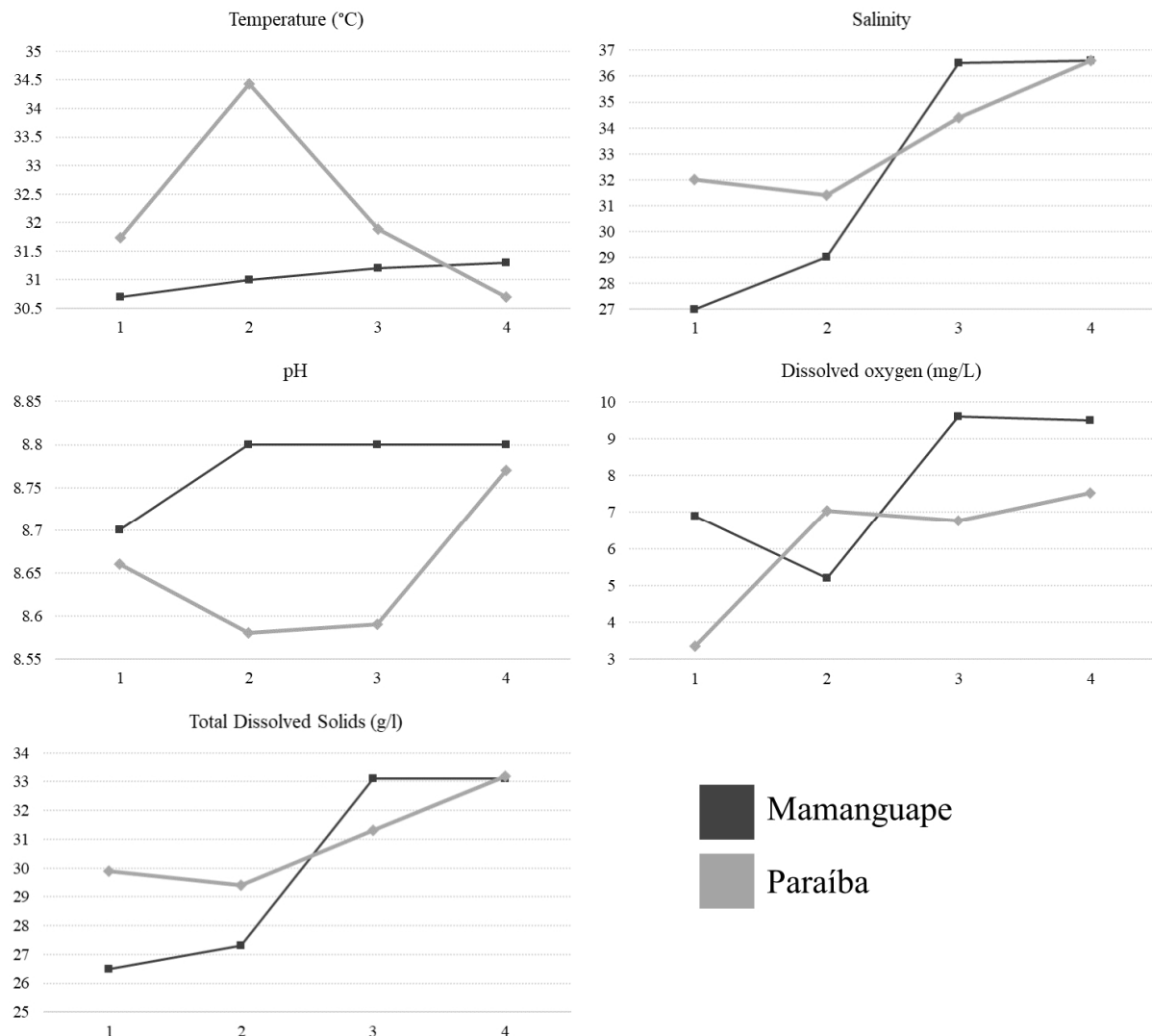


Figure 2. Variation of environmental parameters, measured at the time of collection, in the different sectors of the Mamanguape River and Paraíba River estuaries in February 2020.

Foraminifera densities ranged from 45.2 to 576.9 individuals/cm³, with averages ($\pm$ SD) of 440.4 ± 220.7 ind/cm³ in the Mamanguape estuary and 221.7 ± 292.4 ind/cm³ in the Paraíba estuary (Figure 4). Density increased toward the outer parts of both estuaries, with averages in the outer sector of 558.6 ± 72.9 ind/cm³ in the Mamanguape estuary and 559.3 ± 547.7 ind/cm³ in the Paraíba estuary.

A total of 60 foraminifera species were found, with 50 species in the Mamanguape estuary and 60 in the Paraíba estuary. Eight species were exclusive to the former, and 18 were exclusive to the latter (Table S1).

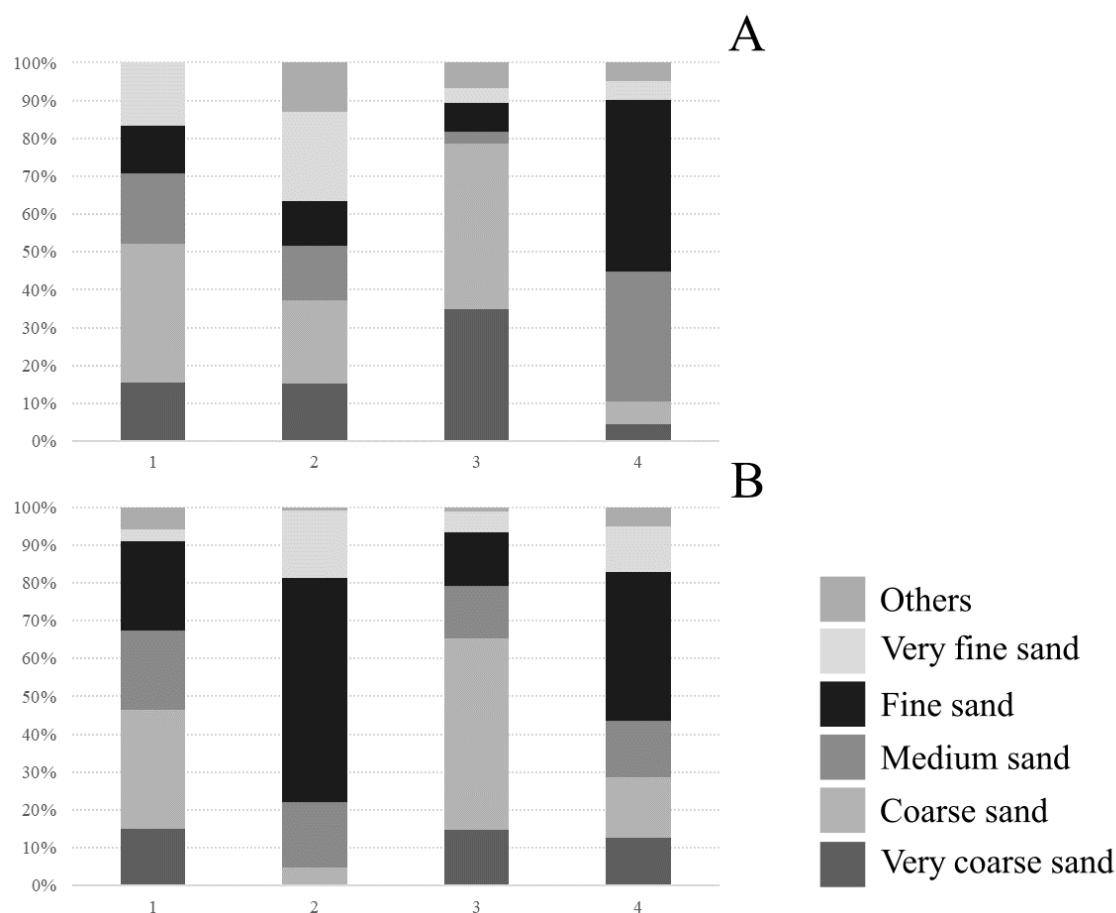


Figure 3. Variation in the percentages of each granulometric fraction in the different sectors of the Mamanguape River (A) and Paraíba River (B) estuaries in February 2020. Others refer to the gravel, silt, and clay fractions combined.

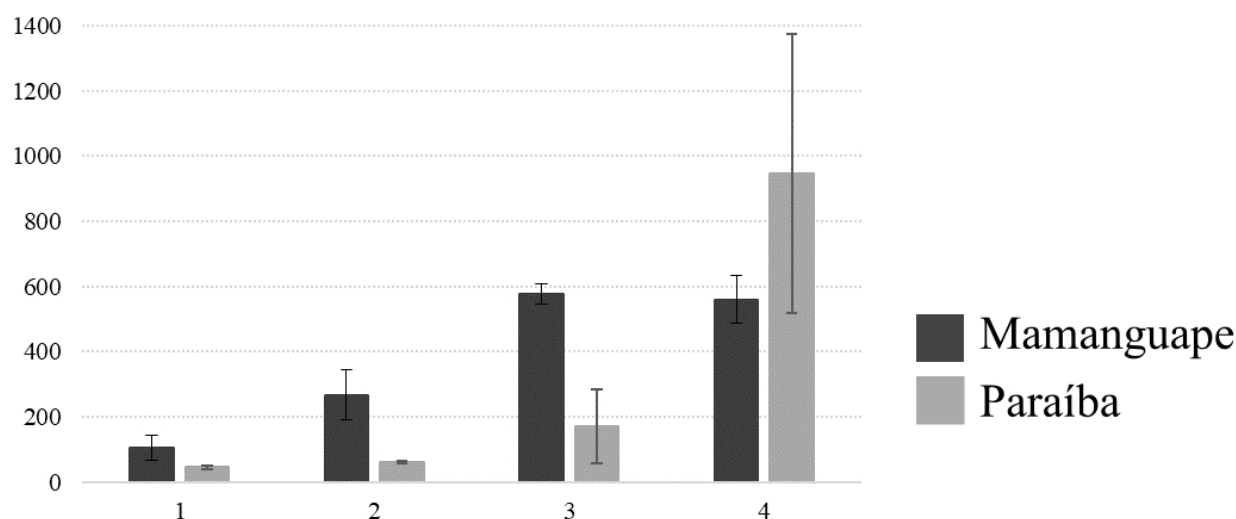


Figure 4. Spatial variation of the mean density (ind/cm³ ± standard deviation) of benthic foraminifera in the Mamanguape and Paraíba river estuaries in February 2020. Error bars are the standard deviation.

The number of species per sample ranged from 9 to 33.6, with averages of 10.4 ± 0.99 in the Mamanguape estuary and 25 ± 8.03 in the Paraíba estuary, showing a significant difference between the estuaries (ANOVA, $p < 0.05$; Table 1). In the Mamanguape estuary, species numbers increased toward the outer parts, the same trend was observed in the Paraíba estuary (Figure 5).

Table 1. Summary of statistical results of two-way ANOVA examining the effect of different estuaries (Mamanguape or Paraíba River estuary) and sampling point on species number (S), diversity (H') and evenness (J').

	DF	MS	F	p	Turkey HSD
S (species number)					
Estuary	1	228.17	23.913	0.000163	See below ^a
Sampling point	3	471.61	49.426	0.000000	See below ^b
Estuary × Sampling point	3	41.39	4.338	0.020364	See below ^c
H' (diversity)					
Estuary	1	0.64383	28.646	0.000065	See below ^d
Sampling point	3	2.15051	95.682	0.000000	See below ^e
Estuary × Sampling point	3	1.17449	52.256	0.000000	See below ^f
J' (evenness)					
Estuary	1	0.034740	20.952	0.000310	See below ^g
Sampling point	3	0.101752	61.368	0.000000	See below ^h
Estuary × Sampling point	3	0.114939	69.321	0.000000	See below ⁱ

^a Mamanguape (A); Paraíba (B). ^b Sampling point 2, sampling point 1 (A); Sampling point 4, sampling point 3 (B). ^c Mamanguape, sampling point 1 (A); Mamanguape, sampling point 2 (A); Paraíba, sampling point 2 (AB); Paraíba, sampling point 1 (B); Mamanguape, sampling point 4 (BC); Paraíba, sampling point 3 (CD); Mamanguape, sampling point 3 (CD); Paraíba, sampling point 4 (D). ^d Mamanguape (A); Paraíba (B). ^e Sampling point 1, sampling point 2 (A); Sampling point 4 (B); Sampling point 3 (C). ^f Paraíba, sampling point 4 (AB), Paraíba, sampling point 1 (AB); Paraíba, sampling point 3 (AC); Mamanguape, sampling point 4 (AC); Paraíba, sampling point 2 (B); Mamanguape, sampling point 3 (C); Mamanguape, sampling point 1 (D); Mamanguape, sampling point 2 (E). ^g Mamanguape (A); Paraíba (B). ^h Sampling point 1(A); Sampling point 2 (B); Sampling point 4 (C); Sampling point 3 (D). ⁱ Paraíba, sampling point 4 (A); Paraíba, sampling point 2 (A); Paraíba, sampling point 1 (AB); Paraíba, sampling point 3 (ABC); Mamanguape, sampling point 4 (BC); Mamanguape, sampling point 3 (C); Mamanguape, sampling point 1 (D); Mamanguape, sampling point 2 (E).

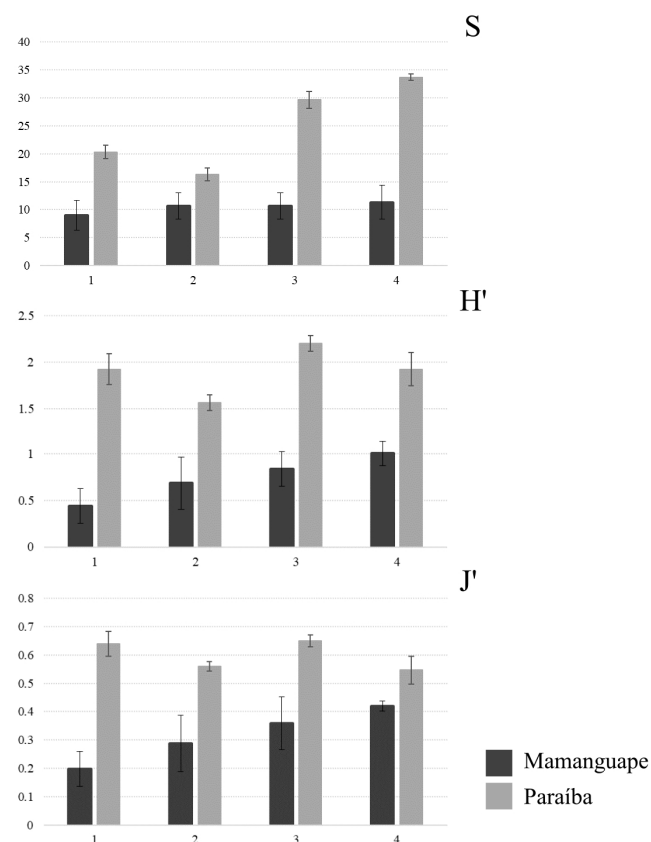


Figure 5. Spatial variation in the mean number of species (S), Shannon–Wiener diversity (H'), and Pielou evenness (J') of benthic foraminifera from the Mamanguape and Paraíba river estuaries in February 2020. Error bars represent standard deviation.

Diversity values ranged from 0.44 to 1.9, averaging 0.74 ± 0.23 in the Mamanguape estuary and 1.90 ± 0.26 in the Paraíba estuary. The Mamanguape estuary showed an increasing trend in diversity towards the outer parts; in the Paraíba estuary this same trend could be observed (Figure 5).

Pielou's evenness values ranged from 0.19 to 0.64, with means of 0.31 ± 0.09 in the Mamanguape estuary and 0.59 ± 0.05 in the Paraíba estuary. There was an increasing trend toward the outer parts of the Mamanguape estuary (Figure 5), while the Paraíba estuary showed little variation, with the highest average in sampling point 3 (0.64 ± 0.02).

Both estuaries were dominated by calcareous species, representing more than 70% of the total, followed by porcelaneous species (6–20%) and agglutinated species (0.2–2%). The most abundant species in both estuaries were *Ammonia tepida*, *Ammonia parkinsoniana*, *Amphistegina gibbosa*, *Criboelphidium excavatum*, *Haynesina germanica*, *Quinqueloculina milletti*, and *Quinqueloculina seminulum* (Table S1; Figure 6).

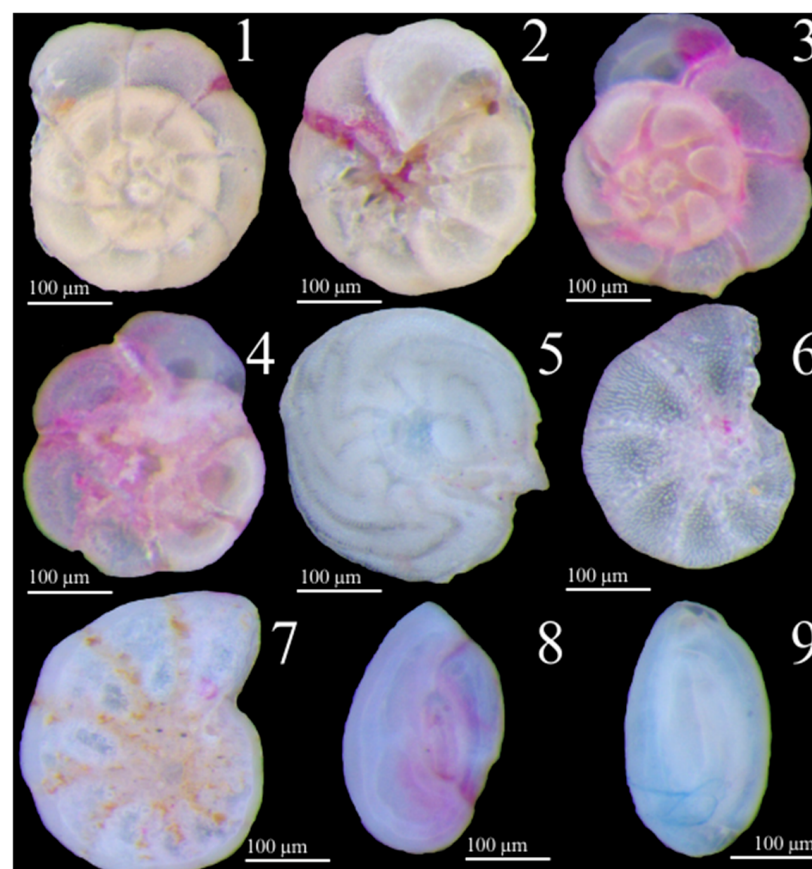
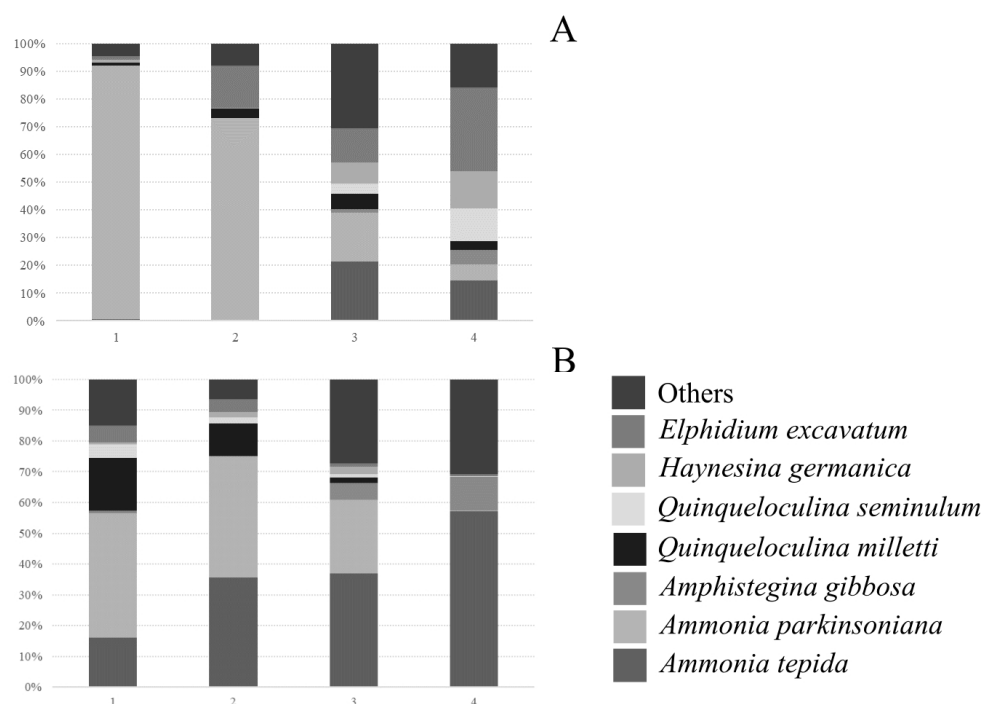


Figure 6. Most abundant species of benthic foraminifera from the Mamanguape and Paraíba River estuaries. *Ammonia parkinsoniana* (1; spiral view), *Ammonia parkinsoniana* (2; umbilical view), *Ammonia tepida* (3; spiral view), *Ammonia tepida* (4; umbilical view), *Amphistegina gibbosa* (5), *Elphidium excavatum* (6), *Haynesina germanica* (7), *Quinqueloculina milletti* (8), and *Quinqueloculina seminulum* (9).

Community structure differed significantly between the factors tested and their interactions (PERMANOVA; $p < 0.05$; Table 2). Sampling points 3 and 4 of the Paraíba estuary were distinct from other sectors, with *A. tepida* accounting for a large portion of the population (37.07% and 57.05%, respectively), followed by *A. parkinsoniana* (23.75% and 0.20%, respectively) and *A. gilatat* (5.50% and 10.97%, respectively; Figure 7).

Table 2. Results of PERMANOVA performed on the structure of the benthic foraminifera community of the Mamanguape and Paraíba river estuaries. DF = Degree of Freedom.

Factor	DF	Pseudo-F	p (Perm)	Exclusive Permutations
Estuary	1	20.8	0.001	999
Sampling point	3	17.9	0.001	999
Estuary × Sampling point	3	8.5	0.001	999

**Figure 7.** Spatial variation in the abundance (%) of the main species of benthic foraminifera, by sector, of the Mamanguape River (A) and Paraíba River (B) estuaries in February 2020.

Species contributing to community differentiation included *A. tepida*, *A. parkinsoniana*, *A. gibbosa*, *B. dilatata*, *B. striatula*, *C. excavatum*, *E. repandus*, *H. germanica*, and *Q. milletti* (Table 3). Sampling point 1 showed 71.7% similarity, with *A. parkinsoniana* and *A. tepida* contributing most to this similarity (>40%; Table 3).

Table 3. SIMPER results comparing the different sampling points (SP) of the estuary and the two estuaries of the present study. In parentheses are the average similarities (%) of each sector and the contribution (%) of the main species.

Species/Contribution	Sampling Points				Estuary	
	SP1 (71.7)	SP2 (79.6)	SP3 (76.9)	SP4 (76.0)	MM (75.5)	PB (76.6)
<i>Ammonia tepida</i>	10.73	10.44	11.29	12.30	7.32	15.0
<i>Ammonia parkinsoniana</i>	33.28	25.02	10.43	3.97	23.79	12.33
<i>Amphistegina gibbosa</i>			5.42	8.43	2.76	4.42
<i>Bolivina dilatata</i>	8.31	4.95	2.44		6.46	1.65
<i>Bolivina striatula</i>		4.61	3.25		5.80	1.10
<i>Elphidium excavatum</i>	6.41	15.07	5.88	7.68	11.58	6.18
<i>Eponides repandus</i>			4.44	4.45	1.42	3.03
<i>Haynesina germanica</i>	5.22	3.39	6.26	5.53	6.50	3.69
<i>Quinqueloculina lamarckiana</i>			3.57	4.54		3.12
<i>Quinqueloculina milletti</i>	7.07	13.07	5.39	3.35	6.68	7.88

Axis 1 represented 47.9% of the total explained variance and was positively correlated with the factors very fine sand, coarse sand, very coarse sand, and others (Figure 8). Axis 2 represented 27.2% of the total explained variance and was positively correlated with very coarse sand, dissolved oxygen, salinity, total dissolved solids, pH, medium sand, very coarse sand, and others. *A. parkinsoniana* was positively correlated with very fine sand and negatively correlated with salinity and total dissolved solids.

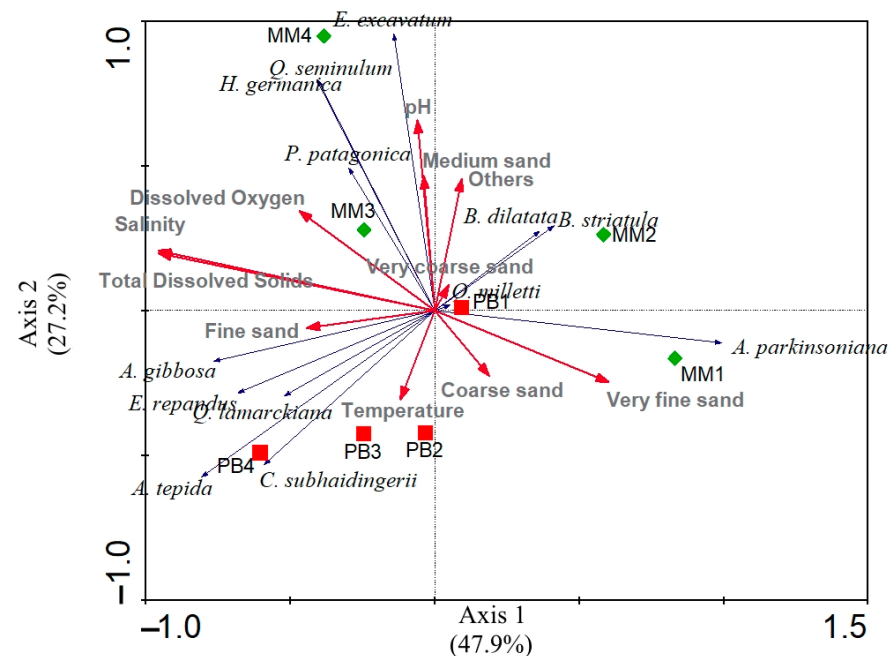


Figure 8. RDA ordination diagrams of benthic foraminiferal fauna with environmental variables (temperature, salinity, dissolved solids, dissolved oxygen, pH, and grain size) from the Mamanguape and Paraíba river estuaries in February 2020.

4. Discussion

Both estuaries were dominated by calcareous species, followed by porcelaneous and agglutinated. Unlike the findings here, a clear transition from a biota dominated by calcareous taxa to one dominated by agglutinated taxa is common in many estuarine systems [73–75]. The dominance of calcareous species throughout the estuary in this study may be due to the absence of a pronounced gradient in salinity and pH as one moves toward the inner sector of both estuaries. Typically, calcareous foraminifera prefer areas closer to seawater, where higher salinities are observed [3,76]. In another study in a temperate region, calcareous species became dominant and expanded into the inner estuarine zones during summer when normal marine conditions prevailed [8]. In general, pH also influences the distribution of foraminifera, as calcareous forms are highly susceptible to dissolution under low pH, while agglutinated tests are more resistant and can dominate in acidic conditions [76,77]. In this study, pH remained constant in both estuaries, which, along with salinity, likely influenced the prevalence of calcareous species across sectors (see above).

The sediment grain size results from this study differed from other tropical and temperate estuaries [8,30,60,78]. In the Mamanguape River estuary, the inner and intermediate sectors were dominated by sand fractions, while the outer sector was dominated by medium and fine sand. No clear spatial pattern was observed in the Paraíba River estuary. The predominance of sandy grain sizes with coarse sediment fractions reveals a highly dynamic environment, unlike what is typically expected for tropical Brazilian estuaries, which are usually composed of fine sand associated with very fine sand and muddy sediments [30,64]. In another study of the Mamanguape River estuary, finer sediment fractions were domi-

nant [79]. However, in a more recent study, coarse and medium sand fractions were found to be dominant [80], consistent with the present study. The observed characteristics suggest that these estuaries may be undergoing sediment distribution processes due to natural or anthropogenic dynamics, thereby altering the expected grain size pattern [81,82].

The number of species found in this study—50 in the Mamanguape River estuary and 60 in the Paraíba River estuary—was higher than that reported in most other tropical estuaries, ranging from 30 to 45 species [63,74,75,83], and temperate estuaries, ranging from 34 to 39 species [59,84]. In another study in the Mamanguape River estuary, 93 species were found [85], which is considerably higher than the present study, emphasizing the significant species richness of this estuary. Although the study was published in 2021, the samples were collected in 2006. There is also a difference in the sampling location. In the study by Sariaslan & Langer [85], the samples were collected in dense parts of mangroves. Therefore, the difference in the number of species may have been due to these two factors. It is worth noting that this estuary is located within an environmental protection area, possibly explaining the higher species count as evidence of its conservation status.

As previously presented, Shannon values increased as they approached the outermost part of the two estuaries. This trend is common in other estuarine environments [59,60,74]. Shannon diversity values in Paraíba estuary were similar to those observed in other tropical estuaries, ranging from 0 to 2.6 [63,83,86]. However, in the Mamanguape estuary, the values were lower than in other tropical estuaries (0.4–1), different from what was expected since this estuary is located in an environmental preservation area. The lowest Shannon diversity values in the Mamanguape estuary were observed at sampling points 1 and 2, where the species *A. parkinsoniana* was more abundant (91.5 and 72.6%, respectively). This species is known to be tolerant to low salinities [30,63,87], and it is believed that this is why it was more predominant in these two sampling points, perhaps for this reason it was more predominant in these 2 sampling points, which caused the diversity values to be lower. This also affects the values of Pielou's evenness, which in the Mamanguape estuary were lower at sampling points 1 and 2 and, overall, were lower than in other tropical estuaries [63,83].

In the innermost sampling points of the present study, we noted the presence of species typical from both tropical [30,63,87] and temperate [88–91] transitional environments. The species were *A. parkinsoniana*, *C. excavatum*, and *A. tepida*, and they are considered resilient to salinity changes. The species found in the outermost part are typically associated with coarser sediment fractions and are adapted to high hydrodynamic environments [92–94]. These species were also noted in the outer sectors of other tropical estuaries [30,75,95].

The species structuring the Mamanguape River estuary community were *A. parkinsoniana*, *C. excavatum*, *A. tepida*, and *H. germanica*, which are typical estuarine species resilient to salinity changes. In the Paraíba River estuary, besides estuarine species, marine species adapted to high hydrodynamics, such as *A. gibbosa*, *E. repandus*, and *Q. lamarckiana*, also contributed to community structuring. The presence of these species indicates more efficient saline water renewal in the Paraíba River estuary compared to the Mamanguape River estuary, suggesting a higher potential for environmental recovery associated with geomorphological characteristics [33].

The genus *Ammonia* was dominant in both estuaries, thriving in natural and polluted environments. *A. parkinsoniana* was more abundant in the Mamanguape River estuary, suggesting less anthropogenic influence, this genus also was positively related with very fine sand and negatively related with salinity. While *A. tepida* dominated in the Paraíba River estuary, potentially indicating a higher degree of impact. Further studies are needed to assess the level of impact on the Paraíba River estuary.

5. Conclusions

This study found a higher abundance of calcareous foraminifera, followed by porcelainous and agglutinated species, primarily due to the consistent salinity and pH levels in both estuaries. Grain size, mostly sandy, also influenced the predominance of calcareous species.

Estuarine species contributed to structuring communities in the inner and intermediate sectors, while marine species did so in the outer sector. The structuring species in the Mamanguape River estuary were typical of estuarine environments, while marine species were also found in the Paraíba River estuary, indicating a higher capacity for marine water renewal.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/d17030142/s1>, Table S1: Relative abundance (%) of species from the Mamanguape and Paraíba river estuaries. Where (A) are agglutinating foraminifera, (C) are calcareous foraminifera and (P) are porcelain foraminifera.

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