Research Article
Open Access
CrossMark

Environmental diagnosis in The Maracajaú Reef area through the foraminifera community

Abstract

Brazilian coral reefs face increasing environmental pressures from global ocean acidification, rising temperatures, and local anthropogenic impacts that threaten their growth and sustainability. This study evaluates reef health in Maracajaú (Rio Grande do Norte, Brazil) by analyzing benthic foraminifera communities, with a particular focus on symbiont-bearing species. Using the FORAM Index (FI)—a bioindicator based on the proportion of foraminifera with symbiotic algae, opportunistic species, and other small taxa—we developed a surrogate measure of water quality relevant to coral reef health.

A total of 40 samples revealed *Quinqueloculina lamarckiana* as the dominant species, followed by *Amphistegina gibbosa*. Correlation analyses identified coarse sediment fractions and sand percentage as the key abiotic factors influencing foraminiferal abundance, while depth had limited impact. Temporal comparisons indicated higher species diversity in 2014 compared to 2013. In reef areas heavily visited by tourists, foraminiferal abundance was notably reduced, while no individuals were found in non-reef zones. Opportunistic species dominated in coastal and high-impact zones, whereas deeper stations were characterized predominantly by *A. gibbosa*. The southern reef region supported *A. gibbosa* alongside other symbiont-bearing species, while *Amphisorus hemprichii* dominated inner reef areas. These findings highlight the FORAM Index's utility in monitoring reef health and underscore the need for sustainable management of Maracajaú's coral reefs.

Volume 14 Issue 1 - 2025

Patricia Pinheiro Beck Eichler-Barker, Helena Araújo de Macêdo, Helenice Vital
Universidade Federal do Rio Grande do Norte (Universidade Federal do Rio Grande do Norte, UFRN), Brazil

Correspondence: Patricia Pinheiro Beck Eichler-Barker, Universidade Federal do Rio Grande do Norte (Universidade Federal do Rio Grande do Norte, UFRN), Brazil, Email helena_macedo_@hotmail.com

Received: January 08, 2025 | **Published:** January 30, 2025

Introduction

Brazil's coral reefs, like others worldwide, face growing environmental stressors, including global ocean acidification and rising temperatures. These factors, combined with localized anthropogenic pressures such as pollution and habitat destruction, threaten the growth and resilience of coral reef systems. This study aims to assess the health of one of Brazil's critical reef environments, the Maracajaú reefs (Rio Grande do Norte), through the lens of benthic foraminiferal communities, particularly those hosting symbiotic algae.

Similar to hermatypic corals, symbiont-bearing foraminifera (SBF), which include relatively large species, thrive in shallow, warm, oligotrophic (nutrient-poor) waters.[1] Expanding on this concept, Hallock et al.,[2] developed the Foram Index (FI), a bioindicator for water quality and coral reef health. The FI is calculated using the proportions of three groups of foraminifera: (1) taxa with symbiotic algae (Ps), (2) opportunistic or stress-tolerant taxa (Po), and (3) other smaller taxa (Ph). This index has been applied successfully in reef health assessments across the globe, including studies in Florida, Puerto Rico, Colombia, Australia, and Kiritimati.[2–6]

However, conflicting results have emerged from regions such as Indonesia[7] and Fiji,[8] where higher FI values did not consistently correlate with coral reef health or lower eutrophication levels. Similarly, in Brazil, FI calculations have yielded variable outcomes, particularly in studies conducted in Bahia and Abrolhos. In these regions, low FI values often coincide with deteriorating water quality, while anomalously high FI values have been observed in areas with low coral cover but high macroalgae prevalence, likely due to reworked sediments.[9–11]

In northern Bahia, Kelmo & Hallock[12] demonstrated the utility of the FI in detecting environmental changes linked to El Niño events, though their work was not specifically focused on coral reef health. These findings underscore the complexity of applying the FI in diverse reef systems and highlight the need for localized investigations to refine its utility.

The present study examines the distribution and composition of foraminiferal communities in Maracajaú's reef ecosystem, aiming to characterize ecological variations across different environments based on salinity, temperature, sedimentological parameters, and pollution levels. By integrating FI analysis with environmental data, this research seeks to provide a comprehensive assessment of reef health and its potential response to natural and anthropogenic stressors.

Background

Coral reefs are among the most biodiverse ecosystems on Earth, supporting a vast array of species that play vital roles in maintaining the ecological balance and resilience of these marine environments. Within these ecosystems, foraminifera—microscopic, single-celled organisms—play an essential role. These organisms construct agglutinating calcareous shells and contribute significantly to the production of calcium carbonate in reef systems, making them key players in the formation of marine sediments. They are abundant in marine environments and play a critical role in ecological and geological studies. Due to their sensitivity to environmental changes, foraminifera are valuable bioindicators, helping researchers assess water quality, pollution levels, and ecosystem health. Their fossilized tests also provide historical insights into past climatic and oceanographic conditions.

Studying foraminiferal communities involves field sampling, laboratory analysis, and advanced imaging techniques. Common methods include sediment core collection and surface scraping to obtain foraminifera from reef substrates. In the laboratory, specimens are separated using sieves, followed by microscopic identification and quantification. Molecular techniques such as DNA sequencing are increasingly used to analyze genetic diversity. Additionally, stable isotope analysis helps evaluate environmental influences on their growth and distribution. Environmental factors such as temperature, salinity, nutrient availability, and water quality significantly influence foraminiferal distribution and community structure. Coral reef-associated foraminifera are particularly sensitive to changes in pH and temperature, making them effective indicators of ocean acidification and climate change. Organic pollution and sedimentation also alter community compositions, often favoring opportunistic species over symbiotic ones. Symbiont-bearing foraminifera, such as those hosting algae, play a critical role in carbon cycling and primary production. They contribute to reef-building processes by secreting calcium carbonate, which supports reef structure. These foraminifera also form an essential part of the marine food web, serving as a food source for higher trophic levels. Symbiont-bearing foraminifera adapt to their environments through mutualistic relationships with photosynthetic algae, which provide energy in nutrient-poor waters. These foraminifera often exhibit selective feeding behaviors and morphological adaptations, such as larger tests with chambers that enhance light penetration. Such adaptations enable them to thrive in diverse and sometimes extreme reef environments. Invasive foraminifera can disrupt native ecosystems by competing with indigenous species for resources. In some cases, they may alter sediment composition or displace native communities, leading to biodiversity loss. Additionally, invasive species can introduce pathogens or shift ecosystem dynamics, underscoring the importance of monitoring and managing their spread in vulnerable reef environments.

Foraminifera are indispensable to environmental assessment and marine ecology, offering critical insights into ecosystem health and climate impacts. Advancing research methods and understanding their ecological roles and adaptations is vital for protecting and managing marine environments.

Foraminiferal species interact intricately with their surrounding environment, responding dynamically to changes in environmental conditions throughout their life cycles. This ability to record environmental shifts positions foraminifera as highly effective bioindicators, particularly in assessing reef health. Sensitive to environmental stressors, these benthic microorganisms are one of the most important constituents of marine sediments, offering valuable insights into both the quantum and qualitative aspects of recent environmental changes. Hallock et al. (2003) highlighted foraminifera as critical bioindicators in coral reef systems, noting their metabolic requirements closely mirror those of corals, making them ideal proxies for assessing the ecological integrity of reef habitats.

According to Sen Gupta,[13] foraminifera are invaluable tools in oceanographic research due to several factors: they are abundant, diverse, and relatively easy to collect, with minimal environmental impact. Their short life cycles also allow for high-resolution environmental assessments. These traits make foraminifera an essential tool for investigating changes in marine environments, particularly in the context of anthropogenic impacts.

In Maracajaú, the growing tourism industry has increased environmental stressors on the local reef system. Inadequate environmental awareness among local populations further exacerbates these impacts. Given this, studies utilizing foraminifera to monitor environmental changes induced by human activity are crucial for the management and preservation of this reef area. Furthermore, foraminifera's role as biological indicators is complemented by the simplicity and cost-effectiveness of data collection and analysis, making them an ideal choice for long-term environmental monitoring.

Environmental alterations, such as changes in sediment acidity, can significantly affect foraminiferal distributions. These shifts may lead to a disproportionate abundance of certain species in areas where environmental conditions are favorable, while less tolerant species may be absent in more stressed regions. Foraminifera's limited mobility renders them particularly vulnerable to environmental changes, and their presence in specific habitats serves as a reliable record of past and present conditions. Consequently, foraminifera not only reflect the health of the environment they inhabit but also offer valuable data for environmental diagnostics.

By combining foraminiferal data with physical, geological, and chemical parameters, this study aims to provide a comprehensive ecological profile of the Maracajaú reef system. This multi-faceted approach will enhance our understanding of the region's environmental health and offer critical insights for sustainable management strategies, ensuring the long-term resilience of this unique marine ecosystem.

Location of the study area

The study of this study was carried out in the coral reefs of Maracajaú, a coastal community with approximately 2,000 inhabitants that is located in the municipality of Maxaranguape, on the north-eastern coast of the state of Rio Grande do Norte, Brazil (See Figures 1 & 2). It is 58 km from the capital Natal and access is through the paved highways BR-406 and RN-160 (Figure 3).

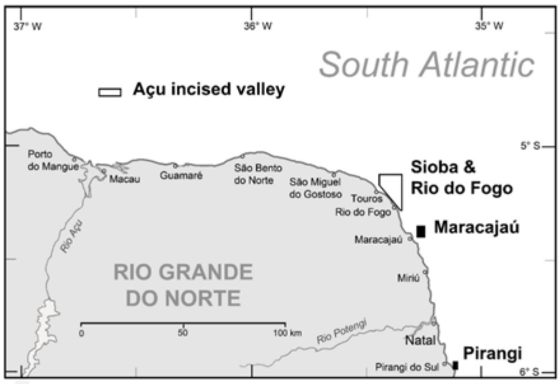

Figure 1 Map of the geographic location of Maracajaú.

Figure 2 Map of the location of the study area with evidence at the sampling points.

Figure 3 Map of the access road from Natal to Maracajaú on the BR-406 and RN-160 highways.

Citation: Eichler-Barker PPB, Macêdo HA, Vital H. Environmental diagnosis in The Maracajaú Reef area through the foraminifera community. *J Aquac Mar Biol.* 2025;14(1):1–12. DOI: 10.15406/jamb.2025.14.00410

The "Parrachos" de Maracajaú (05°38'S, 35°25'W) belong to the Coral Reefs Environmental Protection Area (APARC) which is located on the shallow platform that reaches from Cabo de São Roque to Cabo Calcanhar and in the coastal strip corresponds to the Municipalities of Maxaranguape, Rio do Fogo and Touros.[14]

According to Moura[15] the geographical location of Rio Grande do Norte is quite interesting, because in this place there is a change in the orientation of the Brazilian coast, naturally dividing the coast of Rio Grande do Norte into two sectors: the Eastern that extends from the border with the state of Paraíba to the municipality of Touros, and the North that covers from the municipality of Touros to the border with the state of Ceará.

Characterization of the study area

General characteristics: "Coral reefs or "Parrachos" are marine ecosystems found in regions of warm and clear waters, formed by the deposition of the calcareous skeleton of organisms such as corals, algae and mollusks, constituting the most diverse marine habitat in the world. These reefs are also responsible for protecting the coastline from wave action, reducing the risks of coastal erosion" (IDEMA).

Approximately 7km from Maracajaú Beach we can find the Parracho de Maracajaú (Figure 4). Its reef structure has an oval shape and is composed of several peaks of coralline-algal growth on a sandstone base, with tops between 0 and 3 m deep at low tide.[14,16]

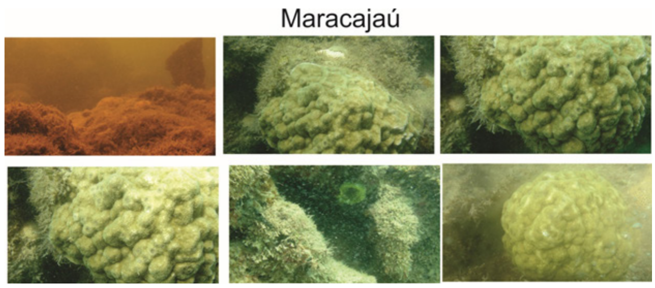

Figure 4 Photographs of the Maracajaú corals, taken in the field, in June 2014.

Despite the undeniable economic importance that the Parracho de Maracajaú represents for the local population of the Municipality of Maxaranguape, we can say that it is a very threatened ecosystem where the organisms present are fragile and little tolerable to environmental factors. For Pastorok & Bilyard[17] this low tolerance of reef organisms, including the corals themselves, has to do with abiotic alterations combined with the vulnerability of interspecific interactions and the high temperatures common in these places, making coral reefs one of the most threatened environments in the world.

Anthropic action: Coral reef habitats cover less than 1% of the seafloor, but are home to more than a million marine species. In Brazil, coral reefs are distributed for about 3,000 km along the northeastern coast, from the south of Bahia to Maranhão, constituting the only reef ecosystems in the South Atlantic.[16]

Anthropogenic interference is triggering the degradation of reefs around the world, which can be an irreversible phenomenon causing changes in the physical-chemical environment and, thus, ends up altering the patterns of the communities that occupy these environments.

"According to a study coordinated by the *Global Coral Reef Monitoring Network* , about 27% of the world's coral reefs have already been destroyed and 58% are threatened, mainly by anthropogenic action and global climate change. Among the human activities that contribute most to the destruction of coral reefs are overfishing, tourism, pollution of coastal waters and the destruction of mangroves."[14] Maritime pollution caused by agricultural activities, aquaculture, unplanned coastal development, excessive production of garbage and sewage, and the destruction of mangroves are also causes damage to reef ecosystems.[18]

Still taking as a reference the work of[14] in which he mentions that corals are sessile animals of the phylum Cnidarians that live in symbiosis with unicellular algae called zooxanthellae, which through photosynthesis synthesize part of the food necessary for the growth of corals, it can be stated that the amount of light that can interact with zooxanthellae is directly linked to their survival and that of corals. Through the function $I_z = I0^{e\text{-}Ez}$ where Iz and I0 are the intensities of photosynthetically active radiation (PAR) at depth z and immediately below the water surface and E is the vertical attenuation coefficient of incident PAR, it is possible to determine the PAR that decreases exponentially with depth. Thus, in the case of the Maracajaú "Parrachos", one of the visually detectable effects of tourism in the region lies in the re-suspension of sediments caused by the movement of the boats' engines and by the very presence of bathers in the water, since the vertical attenuation coefficient of the incident PAR increases and the availability of light for the symbiotic algae of the corals and primary producers of the ecosystem decreases.

It is important to warn that, once the transparency of the water is diminished, the tourist potential is also impaired. One of the reasons that most attract visitors to the "Parrachos" is precisely the visibility that the water has, which allows a better view of the marine species there.

Based on the concern with the conservation of coral reefs, in 2002, the Conscious Conduct in Reef Environments Campaign was prepared by the Secretariat of Biodiversity and Forests of the Ministry of the Environment. The evident beauty of these ecosystems and the growing tourist activity, as well as the increase in popularity of diving practices, drew public attention not only in positive aspects, but in the existence of problems such as: Physical damage to the ecosystem caused by the trampling of tourists and the disorderly traffic of boats; Predatory fishing by amateur divers, which can drastically reduce the stocks of the targeted species; Pollution; and the removal of marine organisms for the making of handicrafts/souvenirs.

The dissemination of the Campaign took place in two stages, in 2001 and 2005, with the support of IBAMA, the National Fish and Wildlife Foundation, technical support from the managers and teams of the conservation units, who voluntarily disseminated the campaign to the surroundings of their areas, as well as diving operators, tourism agents, research projects, teachers, students and other interested parties.

"In 2004, the campaign received an external contribution from the *National Fish and Wildlife Foundation* for the production of a video and the realization of training courses for local agents in five of the areas most visited by tourists and also the most impacted, which are: Maracajaú (Coral Reef Environmental Protection Area/RN), João Pessoa/ Paraíba, Recife de Fora Municipal Park, Porto Seguro/ Bahia and the beaches of Porto de Galinhas and Tamandaré, on the coast of Pernambuco, which were carried out until 2009."

Coral Reef Environmental Protection Area (APARC): APARC covers the coastal strip and the shallow internal continental shelf associated with the municipalities of Maxaranguape, Rio do Fogo and Touros, and the respective offshore reefs: Maracajaú, Rio do Fogo and Cioba, totaling an area of approximately 180,000ha.[14,19] This preservation area was created by state decree No. 15,746, of June 6, 2001. The objectives are to protect marine biodiversity, control and regulate tourism, diving and local fishing, encourage the use of environmentally friendly artisanal fishing equipment and carry out research.

Tourist activity in the "Parrachos" de Maracajaú is much more intense than in the rest of the areas that APARC exerts influence and this has only been increasing over the years, which represents a challenge to the proper planning of the Conservation Unit (UC) since the use of resources and human occupation in this area take place in an ungoverned way.

APARC's management plan divides the area of the Conservation Unit into four zones: Full Protection Zone, Fishing Zone, Recreational Tourism Zone and Scuba Diving Zone. The Integral Protection Zone is formed by areas with rich and fragile ecosystems and is aimed at scientific purposes. The Fishing Zone is intended for fishing and extensive use. Fishing within APARC must follow pre-established rules. The Recreational Tourism Zone is the area with potential for tourism. The zones for recreational tourism were defined in the shallow reefs, closer to the coast and also because they have tourist potential and logistical ease of travel. Finally, the Scuba Diving Zone is formed by areas that have characteristics with potential for diving tourism activities, such as reefs and shipwrecks.[14]

Climate and Hydrography: Coral reefs usually develop in shallow, relatively warm, clear, oligotrophic water sites. They are tropical ecosystems that are distributed around the world, but restricted to ranges of the 20°C isotherms of the Northern and Southern hemispheres.

The Köppen-Geiger climate classification is the most widely used global classification system in geography, climatology, and ecology. It is based on the assumption that the natural vegetation of every major region of the Earth is essentially an expression of the climate prevailing on it. To determine the climatic types, seasonality and the average annual and monthly values of air temperature and precipitation are considered. Therefore, according to the Köppen-Geiger classification system, the climate of the region is classified as humid tropical As, characterized by a rainy season during autumn and winter, and a dry season in spring and summer, which is in agreement with Maida & Ferreira[16] who states that the climate in the Maxaranguape region is marked by dry and rainy seasons. from September to March and April to August, respectively.

The region has warm waters (average temperature of 28ºC) and clear waters for most of the year.[19] The tidal range for the region reaches 2.5 meters. The local wind usually blows from the east quadrant (southeast and northeast) generating waves and currents in the same direction as the wind. Average annual temperatures range from 21.0°C (minimum) to 30.0°C (maximum). Still based on the work of Maida & Ferreira[16] the turbidity of the water is generally high, especially in the rainy season, but with high visibility in the spring and summer seasons (October to March). Turbidity is natural and consequent to the action of winds and/or tidal currents that cause the suspension of particles.

Regional geology: "The municipality of Maxaranguape is geologically inserted in the Borborema Province, consisting of the sediments of the Barreiras Group (ENb), the Colluvioeluvial deposits (NQc), Inactive Dunes (Qd), Coastal deposits (Q2l) and Aluvionar deposits (Q2a)", as can be seen in Figure 5.

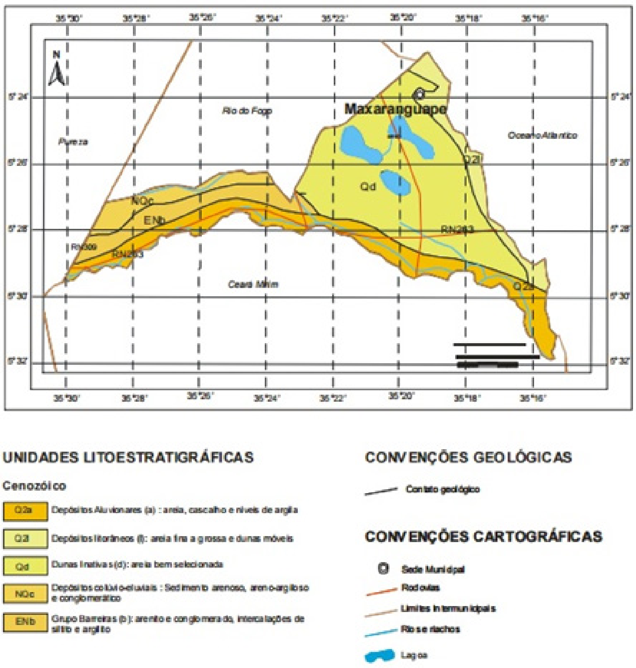

Figure 5 Geological map of the Maxaranguape region where Maracajaú is located.

The coast of Rio Grande do Norte has a coastal strip of sandy beaches approximately 400km long, interspersed with the mouths of rivers with the presence of mangroves, coastal lagoons and cliffs, and has discontinuous sandstone reef cords along the coast, both bordering the beaches and inland at different depths and distances from the coast.[20]

Methods and materials

The preparation of this report consisted of six stages: research and bibliographic survey; data collection in the field; data processing; analytical statistics; integration of data and analytical results and conclusions and preparation of the final report. These steps are represented in the flowchart in Figure 6.

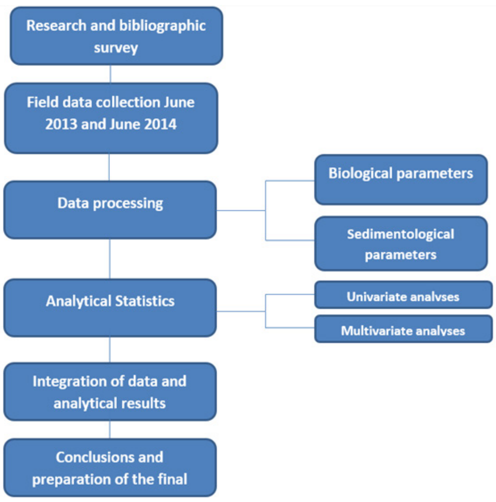

Figure 6 Flowchart of the stages of preparation of the report.

Research and bibliographic surveys

Data collection in the field

Two field samplings were carried out, in total 40samples of bottom sediments from 40 different stations, with 30 samples collected in June 2013 and 10 in June 2014. The locations were provided via GPS. For the collection of surface bottom sediments, we rely on the use of the van veen catcher and the service of professional divers, when necessary. From the sediment that was collected in special bags, only the top layer, about two centimeters, was removed for microfauna analysis. Each sample collected was preserved in bags containing Bengal rose (1g of Bengal rose dissolved in 1 liter of alcohol 70). The Bengal rose acted by staining the protoplasm of the organisms that were alive at the time of collection, distinguishing them from the dead, and the alcohol, in turn, prevented the bacterial attack (Figure 7).

Figure 7 *Van veen* dredger used for sample collection.

To measure the physical data (salinity, conductivity, density, temperature and pressure) the CTD device was used (Figure 8). With the station fixed, this equipment was descended through the water column to the bottom, where the data was collected and downloaded in real time to a portable computer.

Figure 8 CTD device in the process of descent for data collection.

Data processing

Biological parameters: From each sampling point, an average of 50g of sediment was removed for the granulometric analyses that were processed in the Laboratories of Geochemistry and Sedimentology of UFRN. Thus, the laboratory treatment of the samples containing foraminifera that were collected in the field began with washing and sieving in 0.062mm and 0.50mm mesh opening sieves. These samples were soon sent to filter papers and all of them were duly named. Once this stage was completed at the Geochemistry Laboratory, it was time to go to the Sedimentology Laboratory where the samples were dried at a temperature of 60ºC.

After the material dried, the benthic foraminifera and the associated microbiota (mainly ostracods) were screened, i.e., they were carefully transferred to special black-bottomed slides with the aid of brushes and gum adragante, so that they could be properly analyzed and identified with regard to the taxonomy and quantitative analysis of the extracted data. This identification was mainly based on Boltovskoy et al.[21] The microscope used was the reflected light binocular (Figure 9).

Figure 9 Binocular reflected light microscope.

The preparation of the table of total abundance of foraminifera was carried out soon after all species had been properly identified. This table works with the sum of living and dead organisms for the species found in the "Parrachos" de Maracajaú. This sum resulted in the absolute frequency of the species, from which the relative percentage of the species found was calculated.

Sedimentological parameters

Particle Size: The particle size analysis of the samples was carried out based on the method described in Suguio,[22] detailed below, where the classification of the fractions is given according to Wentworth.[23]

First, in order to eliminate salts that could affect the analyses, the material was washed three times in succession. Then it was taken to heating plates, where it remained under a temperature of 60°C until it was dried. Subsequently, all the material was quartered until about 30g of the original sample was obtained, constituting the initial weight, and the rest was kept as a form of archive.

After quartering, the samples were treated with hydrochloric acid (HCl) diluted to 10% to eliminate the calcium carbonate ($CaCO_3$) present and then the material was washed to eliminate the HCl. Then, after complete drying at 60ºC on the heating plates, there was a new weighing to measure how much mass the sample lost, that is, how much mass there was of $CaCO_3$. Then, the samples were treated with hydrogen peroxide (H_2O_2), diluted in distilled water (100ml of H_2O_2 to 900ml of distilled water), in order to eliminate the organic matter. After the attack, the samples were washed to eliminate H_2O_2 and then dried on the heating plates at a temperature of 60ºC.

With all the calcium carbonate and organic matter eliminated, there was a particle size analysis that consisted of an initial sieving using a 2mm sieve to obtain the mass of the fraction higher than this value.

Citation: Eichler-Barker PPB, Macêdo HA, Vital H. Environmental diagnosis in The Maracajaú Reef area through the foraminifera community. *J Aquac Mar Biol.* 2025;14(1):1–12. DOI: 10.15406/jamb.2025.14.00410

The fraction obtained less than 2mm was taken to the Cilas 1180 laser granulometer (Figure 10) with a range of 2mm to 2microns, using the *laser* as an instrument for analyzing sediment samples. The equipment aims to process the data and determine the particle size fraction of the material to be analyzed.

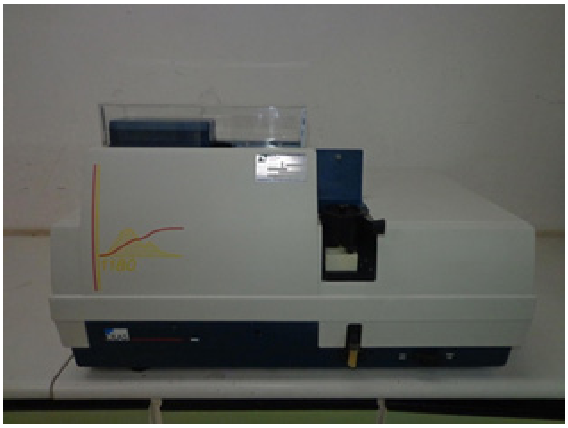

Figure 10 Cilas *1180* laser granulometer.

The sample is placed in a cylinder of the equipment where it will be subjected to 60 seconds of ultrasound in order to effectively disaggregate any and all grains. Automatically, all the rest of the activities will be commanded through the computer, when the peristaltic pump will be activated, which will conduct the sample to the quartz cell. Then, the sample will undergo constant laser bombardment, displaying data such as concentrations and measurements of laser variations, referring to the sediment at the time of analysis. The measurements of variations serve to inform if there is an excess or a lack of material (sample), or even if the quartz cell is impurities. All processing will be displayed in tables with concentrations, sieves, diameters and graphs or histograms so that the user of the granulometer can have a greater perception of the processing.

Analytical statistics

The foraminifera that have symbiosis with algae found in the "Parrachos" of Maracajaú (RN) are 7 species: *Amphisorus hemprichii, Amphistegina gibbosa, Archaias angulatus, Borelis schlumbergeri, Heterostegina antillarum, Laevipeneroplis proteus, Peneroplis carinatus.* Opportunists, on the other hand, are represented by 4 species: *Ammonia* sp, *Elphidium* sp and *Bolivina* sp.

Therefore, we have: FI = (10 x Ps + Po + (2 x Ph), in which a result higher than 4 is indicative of an environment that leads to reef growth; values between 2 and 4 represent an environment that is not very suitable for coral reef growth after a stress event; values lower than 2 represent stressful conditions for coral reef growth.

Univariate analyses: In this work, univariate techniques were used, which are characterized by encompassing the indices of dominance, diversity and equitativeness and show good effectiveness when used together to evaluate changes in the community structure. The indices calculated were the Shannon-Wiener diversity index in base 10,[24] the Simpson dominance index and the Shannon equitivity index (base 10) and were obtained from the relative frequency table of foraminifera species for each season.

Multivariate analyses: Other methods used in this work were multivariate, which allow considering changes related to several properties simultaneously. The data used in these multivariate analyses were the depth, salinity, conductivity, density, temperature, $CaCO_3$ content, and particle size distribution of the sediment.

To corroborate the data obtained in the descriptive statistical analyses, the PCA, CLUSTER and MDS analyses were applied through the PRIMER program of the University of Plymouth and are described in Clarke & Warwick.[25]

The BEST method of analysis[26] was implemented using the PRIMER v6 program (Plymouth Routines in Multivariate Ecological Research PRIMER-E Ltd., Plymouth). This procedure allows combining a set of data in order to find the best combination between the multivariate parameters of the assemblies.

The similarity matrix was constructed using the Bray-Curtis index with logarithmized biological and abiotic data. Dendrograms were performed for the seasons (Q mode) and species (R mode). The data were then sorted using correlation based on non metric Multi Dimensional Scaling (MDS).[26]

Results and discussions

Grain size

In view of the data in Tables 1 & 2, it can be seen that the depth ranged from 2.1m (sample 14) to 5.4m (sample 22). The highest percentage of coarser fraction was found at stations 17 and 24, followed by stations 20 and 22. The lowest value of the coarse fraction was found at stations 2, 4, 5 and 11. The highest percentage of sand was found at stations 1, 2, 8, 12, 13, 19 and 22. The lowest value for sand was found at 5, 7, 17 and 27. The percentage of silt and clay was highest at stations 5, 7, 17, 23 and 27 and the lowest percentage was found at 1, 2, 12, 13, 19, 20, 21, 22, and 24. Total organic matter (TOM) was highest in stations 7 and 22, and its lowest value was recorded in station number 12. Higher $CaCO_3$ values were found in 17 and 18, near the tourist area, and in 27 and 28 in areas further away from the "Parrachos".

Based on the data presented in Tables 1 and 2, the depth varied between 2.1m (sample 14) and 5.4m (sample 22). The stations with the highest percentages of the coarser fraction were 17 and 24, followed by stations 20 and 22, while the lowest coarse fraction values were observed at stations 2, 4, 5, and 11. Sand content was highest at stations 1, 2, 8, 12, 13, 19, and 22, whereas the lowest sand percentages were found at stations 5, 7, 17, and 27. The silt and clay content peaked at stations 5, 7, 17, 23, and 27, with the lowest values recorded at stations 1, 2, 12, 13, 19, 20, 21, 22, and 24. Total organic matter (TOM) was highest at stations 7 and 22, with the lowest value noted at station 12. Elevated CaCO3 levels were identified at stations 17 and 18, near the tourist area, as well as at stations 27 and 28 in locations farther from the "Parrachos" (Figures 11&12).

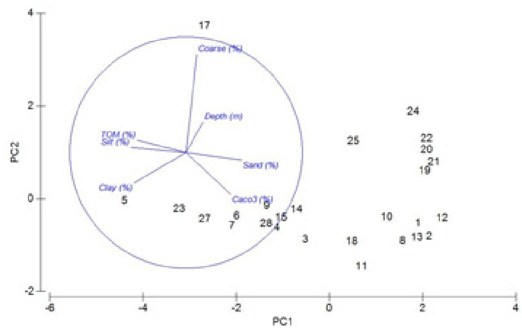

Figure 11 Graph with the groupings of the stations according to the values of PC1 and PC2, in addition to the arrangement of the abiotic parameters in relation to each quadrant.

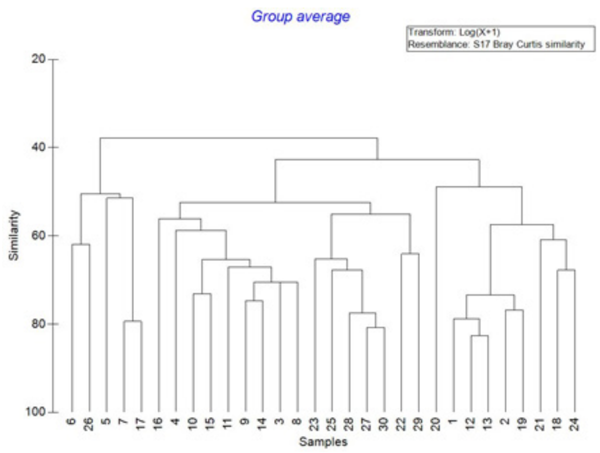

Figure 12 Dendrogram from Maracajaú 2013 showing the grouping of the stations according to the similarity of the foraminifera species found between them.

Multivariate analyses

The principal component analysis (PCA) applied to the abiotic data showed that the stations tend to differ into basically 4 distinct groupings (Tables 3-5), which took into account the values of PC1 and PC2 because they are the most relevant for this analysis (Tables 6&7).

Table 3 PCA generated table, with emphasis on the good cumulative variation found in PC2

PC	Eigenvalue	% Change	% Cumulative Change
1	4,12	58,8	58,8
2	1,24	17,7	76,5
3	0,936	13,4	89,8
4	0,34	4,9	94,7
5	0,296	4,2	98,9

Table 4 PC1 and PC2 values for the abiotic parameters used in PCA

Variables	PC1	PC2
Coarse fraction	0,094	0,846
Sand	0,477	-0,065
Silt	-0,472	0,043
Clay	-0,445	-0,261
Total Organic Matter (TOM)	-0,417	0,106
CaCO3	0,385	-0,360
Depth	0,146	0,261

Table 6 Foraminifera species of Maracajaú (2013 and 2014)

Maracajaú 2014	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**
Split	**32**	**32**	**16**	**4**	**16**	**16**	**32**	**32**	**32**
Ammonia tepida	1	4	0	0	1	1	0	0	0
Amphisorus hemprichii *	3	3	0	0	7	1	0	0	0
Amphistegina gibbosa *	9	2	0	20	19	11	21	40	37
Bolivina brevior	1	4	0	0	0	0	0	0	0
Bolivina variabilis	0	0	0	0	0	0	0	0	0
Borelis schlumbergeri *	0	0	0	2	0	2	3	3	1
Cancris auriculus	0	0	0	0	0	0	0	0	0
Cibicides sp.	0	0	0	0	0	0	0	0	0
Cornuspira involvens	1	0	0	0	0	0	0	0	0
Cornuspira planorbis	0	0	0	0	0	0	0	0	0
Discorbinella floridensis	0	0	0	0	0	0	0	0	0
Elphidium excavatum	0	2	0	0	0	0	0	0	0
Elphidium poeyanum	0	0	0	0	0	0	0	0	0
Elphidium sagrum	0	0	0	0	0	0	0	0	0
Eponides antillarum	0	0	0	0	0	0	0	0	0
Fissurina laevigata	0	0	0	0	0	0	0	0	0
Glabratella globigeriniformis	0	0	0	0	0	0	0	0	0
Hauerina atlantica	0	0	0	0	0	0	0	0	0
*Heterostegina antillarum**	0	2	0	0	0	0	0	0	0
Laevipeneroplis proteus *	0	0	0	0	2	2	0	0	0
Miliolinella subrotunda	0	0	0	0	0	0	0	0	0
Miliolinella webbiana	0	0	0	0	0	0	0	0	0
Neoconorbina terquemi	0	0	0	0	0	0	0	0	0
Nonionella atlantica	0	0	0	0	0	0	0	0	0
Nonionoides grateloupii	0	0	0	0	0	0	0	0	0
Patellina corrugata	0	0	0	0	0	1	0	0	0
Peneroplis carinatus *	1	3	0	4	2	7	10	7	9
Planispirillina sp.	0	0	0	0	0	0	0	0	0
Poroeponides lateralis	3	5	0	0	1	2	0	5	2
Pyrgo comata	0	0	0	0	0	0	0	2	0
Pyrgo ringens	1	2	0	0	10	7	19	10	2

Table 6 Continued.....

Pyrgo subsphaerica	0	0	0	0	0	0	0	0	0
Pseudononion atlanticum	2	0	0	0	0	0	0	0	0
Quinqueloculina agglutinans	0	0	0	0	0	0	0	0	0
Quinqueloculina crassicarinata	4	0	0	0	0	0	0	0	0
Quinqueloculina laevigata	2	0	0	0	0	0	0	0	0
Quinqueloculina lamarckiana	66	28	56	31	12	32	29	45	46
Quinqueloculina microstata	0	0	0	0	0	0	0	0	0
Quinqueloculina patagonica	4	7	0	0	18	7	3	0	0
Quinqueloculina philippinensis	2	0	0	0	0	12	1	0	0
Quinqueloculina poeyana	0	0	0	0	0	0	0	0	0
Quinqueloculina polygona	3	10	0	6	5	7	7	0	0
Quinqueloculina samoaensis	0	0	0	0	0	0	0	0	0
Quinqueloculina seminula	0	0	0	0	0	0	0	0	2
Siphogenerina rophana	0	1	0	0	0	0	0	0	0
Siphonina retiulata	0	0	0	0	0	2	0	0	0
Spiroloculina antillarum	0	0	0	0	0	0	0	0	0
Tiphotrocha comprimata	0	0	0	0	0	0	0	0	0
Triloculina trigonula	0	15	0	0	16	12	4	0	4
Triloculina bertheliana	0	0	0	0	0	0	0	0	0
Wiesnerella auriculata	0	0	0	0	0	0	0	0	0
TOTAL COUNTED	103	88	56	63	93	106	97	112	103

Tables 7 Number of species (S), number of individuals (N), Equitivity (J'), diversity (H'loge) and dominance (1- lambda) for foraminifera species found in Maracajaú (2013 and 2014)

Maracajau 2013	**S**	**N**	**J'**	**H'(loge)**	**1-Lambda'**
1	12	212	0.683128	1.697509	0.754225
2	12	202	0.645867	1.604919	0.740801
3	19	162	0.684986	2.0169	0.784832
4	9	106	0.7287	1.601116	0.7531
5	7	22	0.843052	1.640503	0.792208
6	10	30	0.80622	1.856389	0.793103
7	10	36	0.771522	1.776496	0.757143
8	19	178	0.655141	1.929024	0.76322
9	19	190	0.686743	2.022073	0.7824
10	19	160	0.704437	2.074172	0.742217
11	19	94	0.687248	2.023561	0.743079
12	9	350	0.699722	1.537446	0.725518
13	10	260	0.667476	1.536921	0.743778
14	18	170	0.713388	2.061957	0.787957
15	19	142	0.666443	1.962302	0.738088
16	12	50	0.72602	1.804092	0.74449
17	10	36	0.768258	1.76898	0.757143
18	17	228	0.638236	1.808258	0.75141
19	11	252	0.640806	1.536586	0.708847
20	10	60	0.634849	1.461794	0.684746
21	21	294	0.512758	1.561102	0.663788
22	13	80	0.73032	1.873234	0.740823
23	30	408	0.647708	2.202983	0.764838
24	25	258	0.602022	1.937834	0.755769
25	22	194	0.649633	2.008042	0.735805
26	10	22	0.815219	1.877111	0.813853
27	22	168	0.671939	2.076993	0.741517
28	21	182	0.666936	2.030501	0.739785
29	14	70	0.734346	1.93798	0.757764
30	19	172	0.67	1.98	0.74

The BEST analysis revealed the coarse fraction as the variable that best correlates with the abundance of foraminifera followed by the sand fraction. The variable with the least responsibility for the variability of the species is the depth in the Maracajaú "Parrachos" (Figure 13).

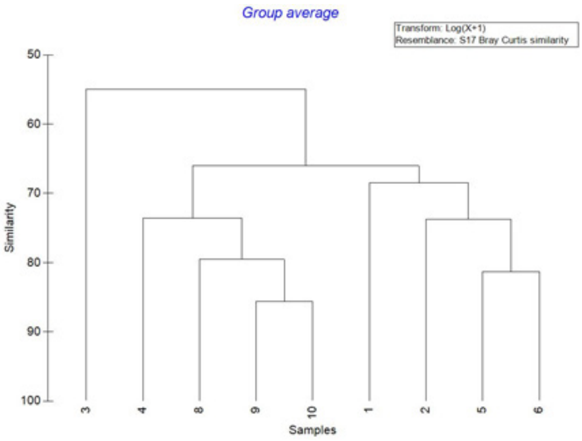

Figure 13 Dendrogram from Maracajaú 2014 showing the grouping of the seasons according to the similarity of the foraminifera species found between them.

Analysis of biotic parameters

Our study showed through the ecological indices of equitivity, diversity and dominance, that in general, the samples from Maracajaú 2014 are more diverse than 2013. The dominant species in Maracajaú is *Quinqueloculina lamarckiana* followed by *Amphistegina gibbosa*.

In Maracajaú 2013, five groups were formed: Group I: 6, 26; where, IF is between 2 and 4 (environment with low recovery of coral reef growth after a stressful event). Group II; 5, 7, 17, (also with an IF between 2 and 4) and some stations where the IF is lower than 2, being an area under stressful conditions for growth for coral reefs. Both groups have only *Amphisorus hemprichii* as the dominant species. Group III: 16, 4, 10, 15, 11, 9, 14, 3, 8, with stations (also with IF between 2 and 4) and some stations where the IF is lower than 2, also being an area under stressful conditions for growth for coral reef with stations with no individuals or very few individuals; and Group IV: 23, 25, 28, 27, 30, 22, 29 with the most diverse seasons and IF between 2 and 4 (also being an area under stressful conditions for growth for coral reef) with *Amphisorus hemprichii* dominating and Group V: 4, 18, 9, 10, 20, 1, 12, 13, 2, 19, 21, 18, 24 with the most diverse seasons and occurrence of *Amphistegina gibbosa* and IF higher than 4 indicating an environment that conduces to growth of the coral reef.

In Maracajaú 2014, two groups were formed: Group I: 1, 2, 5, 6 with the most diverse seasons and the presence of *Amphisorus hemprichii* and Group II: 4, 8, 9, 10 with less diverse seasons and the dominance of *Amphistegine*, most of which have an IF greater than 4, indicating an environment that leads to coral reef growth and *Amphistegine* dominance.) living in this area, with an IF lower than 2 with few conditions for coral reef growth.

The SDM analysis applied to biotic data (Figure 14) generated three distinct groups that differ in terms of ecological indices. Maracajaú 2013 Group I (1, 2, 12, 13, 19) are the most diverse stations, while Group II (3, 4, 9, 14, 23, 8, 18, 21, 24) and Group III (27, 30, 28, 25, 5, 6, 7, 17, 16, 22, 29, 10, 15, 11) are the least diverse stations.

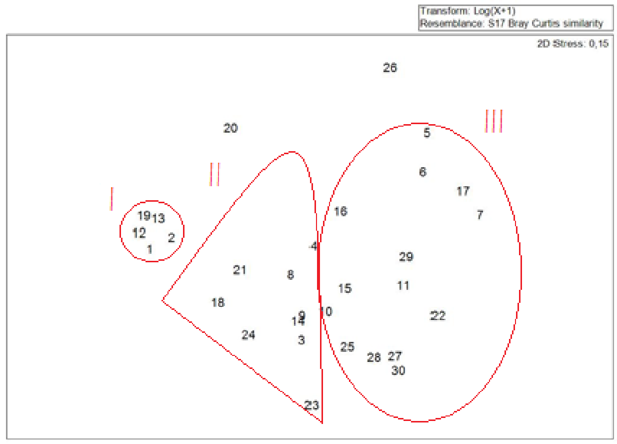

Figure 14 Groups formed from the application of MDS to biotic data.

The 2014 Maracajaú SDM revealed the formation of 2 groups with less diverse stations, with group I formed by the stations: 4, 8, 9, 10; and Group II with stations 1, 2, 5, 6, more diverse and station 3 with only a single species (Table 8).

Tables 8 Number of species (S), number of individuals (N), Equitivity (J'), diversity (H'loge) and dominance (1- lambda) for foraminifera species found in Maracajaú (2013 and 2014)

Maracajau 2014	S	N	J'	H'(loge)	1-Lambda'
1	17	238	0.582364	1.649961	0.717973
2	16	208	0.699594	1.939686	0.772157
3	3	128	0.895015	0.983274	0.606299
4	7	130	0.720116	1.401281	0.685629
5	13	202	0.727165	1.865141	0.754396
6	17	228	0.684636	1.939719	0.750522
8	11	226	0.745631	1.787944	0.763343
9	9	256	0.732384	1.609213	0.737684
10	10	238	0.68	1.58	0.73

As can be seen in Figure 15, the data obtained revealed the reef environment of Maracajaú as having mainly three geohabitats that differ. The group composed of opportunistic species is mainly concentrated in the northernmost part of the region under study. The central part shows the main occurrence of the genus *Amphisorus*. Further south, the occurrence of the genus is observed *Amphistegine* with symbiont algae-like foraminifera species (Figure 16).

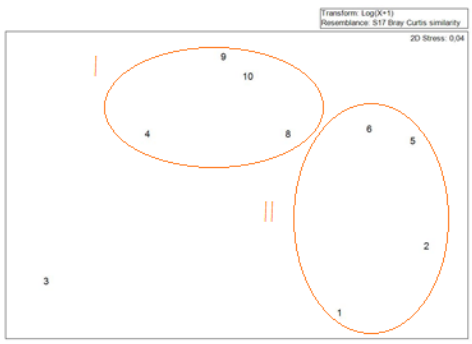

Figure 15 Groups formed from the application of MDS in biotic data.

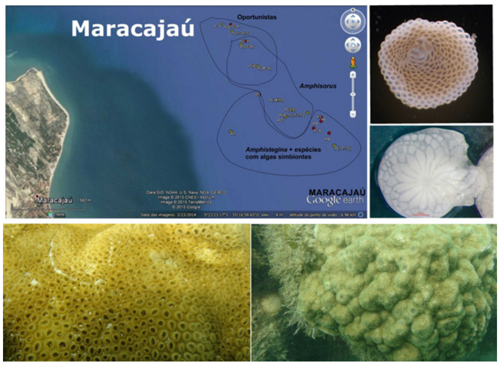

Figure 16

The *Quinqueloculin* and *Pneroplis* in Figure 17 show a yellowish and black coloration, respectively, which indicate depositional environments with low levels of oxygen, accumulated organic matter. Taphonomic processes may also be acting on the carapaces after the death of the organism (Table 9).

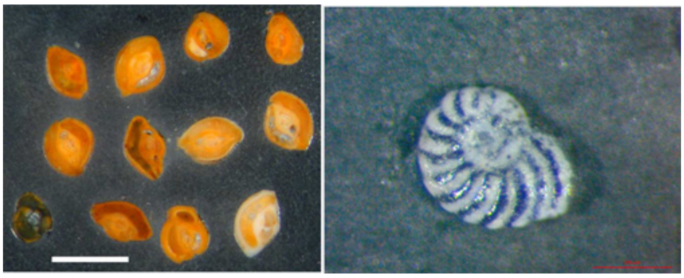

Figure 17 Photomicrograph of *Quinqueloculin sp* and Pneroplis.com yellow and black coloration.

Discussion

The reef environment of Maracajaú supports a diverse assemblage of benthic foraminifera, including opportunistic species, symbiont-bearing taxa, and small-sized genera. Dominated by *Quinqueloculina lamarckiana* and *Amphistegina gibbosa*, this fauna represents a suitable system for applying the Foram Index (FI) proposed by Hallock et al.[2] The observed foraminiferal tests exhibit yellowish and black coloration, possibly originating from depositional environments or taphonomic processes, as radiocarbon dating revealed ancient material aged between 3,000 and 6,000years.

Ecological indices derived from univariate analyses (evenness, diversity, and dominance) revealed notable temporal differences. Samples collected in 2014 exhibited higher diversity and stability, with a reduced dominance of opportunistic species compared to 2013. This shift likely reflects targeted sampling in 2014 in areas previously identified as biodiverse.

Multivariate analyses (PCA, Cluster, MDS, and BEST) identified coarse sediment fractions as the primary environmental variable influencing foraminiferal distributions, followed by sand content, while depth had minimal impact. These findings align with prior studies demonstrating strong correlations between foraminiferal assemblages and environmental factors.[28]

In 2013, cluster analyses revealed environments with FI values ranging from less than 2 to 4, indicating stressed conditions for coral reef recovery. Zones dominated by *Amphisorus hemprichii* were particularly vulnerable, while other environments, characterized by the co-occurrence of *A. hemprichii* and *A. gibbosa*, demonstrated FI values exceeding 4, suggesting conditions conducive to coral reef growth. By 2014, two distinct groups emerged: one with higher diversity and the presence of *A. hemprichii*, and another dominated by *A. gibbosa*, with most stations exhibiting FI values greater than 4. However, Station 3 remained an outlier, with only *Q. lamarckiana* present and an FI below 2, indicative of poor conditions for reef growth.

The application of the FI proved effective, demonstrating that water quality in most studied environments supports calcified benthic symbionts. However, the persistence of areas incapable of coral recovery after stress events is alarming. While the underlying causes remain unclear—whether natural variability or anthropogenic impacts—Maracajaú appears to maintain a non-eutrophic system.[29] According to Kennish's classification, non-eutrophic systems are characterized by healthy, productive biological communities with desired biodiversity patterns, in contrast to eutrophic or hypertrophic systems that exhibit undesirable conditions and community structures.

The findings underscore the critical need for further investigations into the tolerance limits of benthic species to environmental factors. Laboratory-based experiments testing the response of foraminifera to controlled variables could greatly enhance our understanding of reef ecosystem dynamics. Such research is essential to refine the use of FI as a tool for environmental assessment and to support effective coastal management strategies.

Maracajaú's reef ecosystems present a unique opportunity to study the interplay between environmental stressors and benthic communities. The observed variability highlights the importance of ongoing monitoring and targeted conservation efforts to ensure the long-term health and resilience of these vital marine habitats.[30-37]

Conclusion

This study assessed the benthic foraminiferal assemblages in Brazilian coral reef environments to evaluate whether the Foram Index (FI) indicates water quality that supports calcified symbiont communities. The findings highlight the influence of both natural and anthropogenic stressors on foraminiferal distribution and reef health.

In reef areas subject to heavy tourism, such as those near trampling zones, the abundance of foraminifera was significantly reduced. Opportunistic species dominated in coastal stations and heavily impacted regions, reflecting environmental stress and potential degradation. Conversely, areas devoid of reef colonies were entirely devoid of foraminifera, indicating unsuitable conditions for these organisms.

In deeper stations, *Amphistegina gibbosa* was the predominant species, reflecting its tolerance to environmental variability. The southern reef zones displayed a richer assemblage, with *A. gibbosa* coexisting alongside other symbiont-bearing species, suggesting relatively favorable conditions for benthic communities.

Amphisorus hemprichii was most abundant in the innermost reef areas, where environmental conditions may favor its growth and symbiotic relationships. These spatial variations underscore the sensitivity of foraminiferal assemblages to environmental gradients and anthropogenic impacts.

The application of the FI proved effective in detecting water quality variations across different reef zones, reinforcing its utility as a bioindicator tool for monitoring coral reef health. These findings provide critical insights into the vulnerability and resilience of Maracajaú's reefs, emphasizing the need for conservation strategies to mitigate human impact and promote ecosystem recovery.

Acknowledgements

We extend our gratitude to CAPES (Coordination for the Improvement of Higher Education Personnel) for their support through the project "Oceanographic processes in the breakdown of the continental shelf of the Brazilian Northeast: scientific foundations for marine spatial planning" (Edital Marine Science 2 43/2013, 23038.004320/2014-11). This funding facilitated the research and postdoctoral fellowship for P.P.B. Eichler at the Federal University of Rio Grande do Norte (UFRN-Brazil), Moss Landing Marine Laboratories, San Jose State University (MLML/SJSU), and the Ocean Sciences Department of the University of California at Santa Cruz (UCSC) (grants Nº88887.305531/2018-00, Nº88881.188496/201801). Furthermore, this work was conducted under the auspices of the INCT AmbTropic phase II (CNPq process 465634/2014-1), for which we are grateful.

Conflict of interest

The authors declare that there are no conflicts of interest.

References

1. Hallock P. *Larger foraminifera as indicators of coral–reef vitality*. In: Martin RE, editor. *Environmental Micropaleontology*. Kluwer Academic/Plenum Publishers, New York. 2000;121–150.
2. Hallock PB, Lidz H, Cockey–Burkhard EM, et al. Foraminifera as bioindicators *In* Coral reef assessment and monitoring: The FORAM Index. *Environmental Monitoring and Assessment*. 2003;81:221–238.
3. Carnahan EA, Hoare MM, Hallock P, et al. Foraminiferal assemblages in Biscayne Bay, Florida, USA: responses to urban and agricultural influence in a subtropical estuary. *Marine Pollution Bulletin*. 2009;59:221–233.
4. Velásquez JJ, López–Angarita, Sánchez. Evaluation of the FORAM index in a case of conservation. Benthic foraminifera as indicators of ecosystem resilience in protected and non–protected coral reefs of the Southern Caribbean. *Biodiversity Conservation*. 2011;20:3591–3603.
5. Uthicke SA, Thompson, Schaffelke. Effectiveness of benthic foraminiferal and coral assemblages as water quality indicators on inshore reefs of the Great Barrier Reef, Australia. *Coral Reefs*. 2010;29:209–225.
6. Carilli1 J, Walsh S. Benthic foraminiferal assemblages from Kiritimati (Christmas) Island indicate human–mediated nutrification has occurred over the scale of decades. *Marine Ecology Progress Series*. 2012;456:87–99.
7. Natsir SM, Subkhan M. The distribution of benthic foraminifera in coral reefs community and seagrass bed of Belitung Islands based on FORAM Index. *Journal of Coastal Development*. 2011;15:51–58.
8. Strotz LC, Brock GA. Holocene foraminifera from the reefs surrounding Viti Levu, Fiji Islands: A test of the FORAM Index, Forams 2006 Abstract, Yearbook of the Institute of Geosciences–Federal University of Rio de Janeiro. 2006;29:305–306.
9. Barbosa CF, Prazeres MF, Ferreira BP, et al. Foraminiferal assemblage and reef check census in coral reef health monitoring of East Brazilian margin. *Marine Micropaleontology*. 2009;73:62–69.
10. Barbosa CF, Ferreira BP, Seoane JCS, et al. Foraminifer–based coral reef health assessment for southwestern Atlantic offshore archipelagos, Brazil. *Journal of Foraminiferal Research*. 2012;42(2):169–183.
11. Oliveira–Silva P, Barbosa CF, Machado de Almeida C, et al. Sedimentary geochemistry and foraminiferal assemblages in coral reef assessment of Abrolhos, Southwest Atlantic. *Marine Micropaleontology*. 2012(94–95):14–24.
12. Kelmo F, Hallock P. Responses of foraminiferal assemblages to ENSO climate patterns on bank reefs of northern Bahia, Brazil: A 17–year record. *Ecological Indicators*. 2013;30:148–157.
13. Sen Gupta BK. *Modern Foraminifera*. Kluwer Academic Publishers. 1999.
14. Amaral RF, Feitoza BM, Attayde JL, et al. Environmental Diagnosis of the Area of Intensive Tourist Use (AUTI) in Parracho de Maracajaú. IDEMA–RN. *Internal Report*. 2005;128.
15. Moura CWN. Coralline with geniculum (Corallinales, Rhodophyta) from the eastern coast of the state of Rio Grande do Norte – Brazil. *Master's thesis, Federal Rural University of Pernambuco*. 1992;254.
16. Maida M, Ferreira BP. *Coral Reefs of Brazil: an overview*. Proceedings of the 8th International Coral Reef Symposium. 1997;1:263–274.
17. Pastorok RA, Bilyard GR. Effect of sewage polution on coral–reef communities. *Marine Ecology Progress Series.* 1985;21:175–189.
18. Leão ZMAN. The coral reefs of Bahia: morphology, distribution and the major environmental impacts. *Annals of the Brazilian Academy of Sciences*. 1996;68(3):339–452.
19. Marcelino A, Amaral R. *Coral Reefs state environmental protection area*. In: Prates APL, editor. *Atlas of coral reefs in Brazilian conservation units: MMA/SBF*. 2003;180.
20. Santos CLA, Vital H, Amaro VE, et al, Mapping submerged reefs off the coast of Rio Grande do Norte, NE Brazil: Macau to Maracajau. *Revista Brasileira de Geofísica*. 2007;25(Supl. 1):27–36.
21. Boltovskoy E, Giussani G De K, Watanabe S, et al. *Atlas of benthic shelf foraminifera of southwest atlantic.* Netherlands, Dr. W. Junk. 1980;174.
22. Suguio K. *Introduction to sedimentology*. Edgard Blucher/EDUSP, São Paulo. 1973;317.
23. Wentworth CK. A scale of grade and class terms for clastic sediments. *JJ Geol*. 1922;30(1):377–392.
24. Newman MC. Quantitative methods in Aquatic ecotoxicology. *Lewis publisher*. 1995.
25. Clarke KR, Warwick RM. Changes in marine communities: an approach to statistical analyses and interpretation. *Natural Environment Research Council*, *Plymouth*. 1994;144.
26. Clarke KR. Non pararmetric multivariate analyses of changes in community structure. *Aust J Ecol* 2019;18:117–143.
27. Folk RL. Petrology of Sedimentary Rocks. *Hemphill Publishing Company*. Austin, Texas, USA. 1974;181.
28. Hayward BW, Grenfell H, Cairns G, et al. Environmental controls on benthic foraminiferal and thecamoebian associations in a New Zealand tidal inlet. *Journal of Foraminiferal Research*. 1996;26(2):150–171.
29. KENNISH MJ. Practical Handbook of Estuarine and Marine Pollution. *Marine Science Series. Boca Raton*. 1997.
30. Araújo HAB, Machado AJ. Benthic foraminifera associated with the south Bahia coral reefs, Brazil. *Journal of Foraminiferal Research*. 2008;38:23–38.
31. CPRM – Geological Service of Brazil Registration project of sources of groundwater supply. Diagnosis of the municipality of Maxaranguape, state of Rio Grande do Norte / Organized [by] João de Castro Mascarenhas, Breno Augusto Beltrão, Luiz Carlos de Souza Junior, Saulo de Tarso Monteiro Pires, Dunaldson Eliezer Guedes Alcoforado da Rocha, Valdecílio Galvão Duarte de Carvalho. Recife: CPRM/PRODEEM, 2005;11.
32. Hallock P. *Symbiont–bearing foraminifera*. In: Sen Gupta BK, editor. *Modern Foraminifera*. Kluwer Academic Publishers, Dordrecht. 1999;123–139.
33. Hallock P. *The FORAM Index revisited: Uses, challenges, and limitations*. Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia. 2012;9–13.

34. Koukousioura O, Dimiza MD, Triantaphyllou MV, et al. Living benthic foraminifera as an environmental proxy in coastal ecosystems: A case study from the Aegean Sea (Greece, NE Mediterranean). *Journal of Marine Systems*. 2011;88:489–501.
35. Narayan YR, Pandolfi JM. Benthic foraminiferal assemblages from Moreton Bay, South–East Queensland, Australia: Applications in monitoring water and substrate quality in subtropical estuarine environments. *Marine Pollution Bulletin*. 2010;60:2062–78.
36. Schueth JD, Frank TD. Reef foraminifera as bioindicators of coral reef health: low isles reef, northern Great Barrier Reef, Australia. *Journal of Foraminiferal Research*. 2008;38:11–22.
37. Uthicke S, Nobes K. Benthic Foraminifera as ecological indicators for water quality on the Great Barrier Reef. *Estuarine, Coastal and Shelf Science*. 2008;78:763–773.

Citation: Eichler-Barker PPB, Macêdo HA, Vital H. Environmental diagnosis in The Maracajaú Reef area through the foraminifera community. *J Aquac Mar Biol.* 2025;14(1):1–12. DOI: 10.15406/jamb.2025.14.00410