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AN INTEGRATED APPROACH TO ENVIRONMENTAL HEALTH ASSESSMENT OF A CORAL REEF ECOSYSTEM BASED UPON FORAMINIFERA

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ABSTRACT

The reef system is the main feature of the Recife de Fora Marine Park (RFMP) on the East Brazilian coast. High hydrodynamics introduce nutrients, sediment, and contaminants from rivers while promoting reef flat erosion. To identify threats to reef ecosystems, we employed a foraminifera-based assessment using the FoRAM Index and the FORAM Stress Index, combined with analyses of environmental variables. Results revealed instability/stress in part of the western backreef stations, near the Buranhém river output, and a general estuarine influence. Reef flat and backreef surroundings data are marked by health decline and instability/stress, while forereef data indicated equilibrium/stability. Active offshore processes partially compensated for coastal negative influences, helping the system to remain healthy by the active "cleansing" of waves and tides. The results established a baseline of ecosystem quality for low-cost biodiversity queries, representing an advance in assessment using foraminifera important in long-term monitoring programs.

INTRODUCTION

Coastal coral-reef ecosystems face natural and anthropogenic impacts, emphasizing the importance of assessing their health status and integrity. In the western South Atlantic, these ecosystems host a low diversity of reef-building corals of which six are endemic species, remnants of Tertiary and Caribbean taxa (Leão et al., 2010; Pereira et al., 2023). Therefore, the study of these environments is essential for biodiversity queries and assessment of these populations. Coral-reef ecosystems in the western South Atlantic, as in other tropical areas, play a crucial role in food provision, habitat maintenance, shoreline protection, and recreation (Elliff & Kikuchi, 2017).

Despite such ecological and societal significance, reefs encounter various pressures, as western Atlantic live coral cover has decreased over the last 50 years (Kuffner & Toth, 2016) and reefs are under increasing thermal threats (Pereira et al., 2022; Araujo et al., 2023). Stress events triggered by El Niño–Southern Oscillation (ENSO) have led to intense bleaching episodes in thepast few decades (Leão et al., 2010; Ferreira et al., 2013; Pereira-Filho et al., 2021). On regional scales, Brazilian coastal reefs are also located where most of the population is concentrated and tourism occurs (Costa et al., 2008; Leão et al., 2010). Anthropogenic influences date back to European colonization (Leão, 1996; Addad & Martins-Neto, 2000) and include increasing input of sediments and contaminants as consequences of minimally regulated urban development, land cleaning, and inadequate sewage systems (Marques et al., 2019; Costa et al., 2000).

Policy makers are strongly advised to implement short- and long-term monitoring programs using bioindicators. This approach not only standardizes the assessments, but also creates a basis for comparison, while enabling measurements of restoration progress without sampling impact (Cooper et al., 2009; Schönfeld et al., 2012; Alve et al., 2016; Sousa et al., 2020; O'Malley et al., 2021; Lutzenkirchen et al., 2024).

Foraminifera are single-celled, calcifying organisms that are major producers of reef sediments (Debenay et al., 1999) with large benthic foraminifera (LBF, diameter >1 mm) relying physiologically on algal endosymbiosis, as do reef-building corals. Consequently, in both groups, distribution and community structure can change based on similar environmental requirements, as they are highly sensitive to changes in water transparency, oxygen, and nutrient input (Hallock et al., 2003; Prazeres et al., 2016; Marques et al., 2019; Martins et al., 2019). Foraminifera also possess high preservation potential, making them excellent bioindicators for temporal variations in all marine environments (Nigam et al., 2006). They are effective tools for quantifying and qualifying the environmental diagnosis of coastal and coral-reef areas (Yanko et al., 1994; Armynot du Châtelet et al., 2009; Cooper et al., 2009; Bouchet et al., 2012, 2021; Schönfeld et al., 2012; Prazeres et al., 2016; Jorissen et al., 2018; O'Malley et al., 2021). Therefore, they are highly recommended for long-term monitoring (Cooper et al., 2009).

To improve and standardize the application of foraminifera in monitoring, Hallock et al. (2003) developed the FoRAM index (FI: Foraminifera in Reef Assessment and Monitoring), and Dimiza et al. (2016) developed the FORAM Stress Index (FSI), both to diagnose water quality in coastal ecosystems using benthic foraminifera as bioindicators, with the latter developed for areas of muddy sediment. Both indices are based upon functional groups: the FI uses symbiont-bearing, small heterotrophic, and stress-tolerant categories, while the FSI assesses sensitive (including symbiont-bearing foraminifers, small epiphytic rotaliids, and miliolids) and stress-tolerant taxa (opportunists adapted to high organic matter and metal enrichment). Both indices have the objective to quantify the environment's potential to support the prolific development of calcifying organisms harboring endosymbionts.

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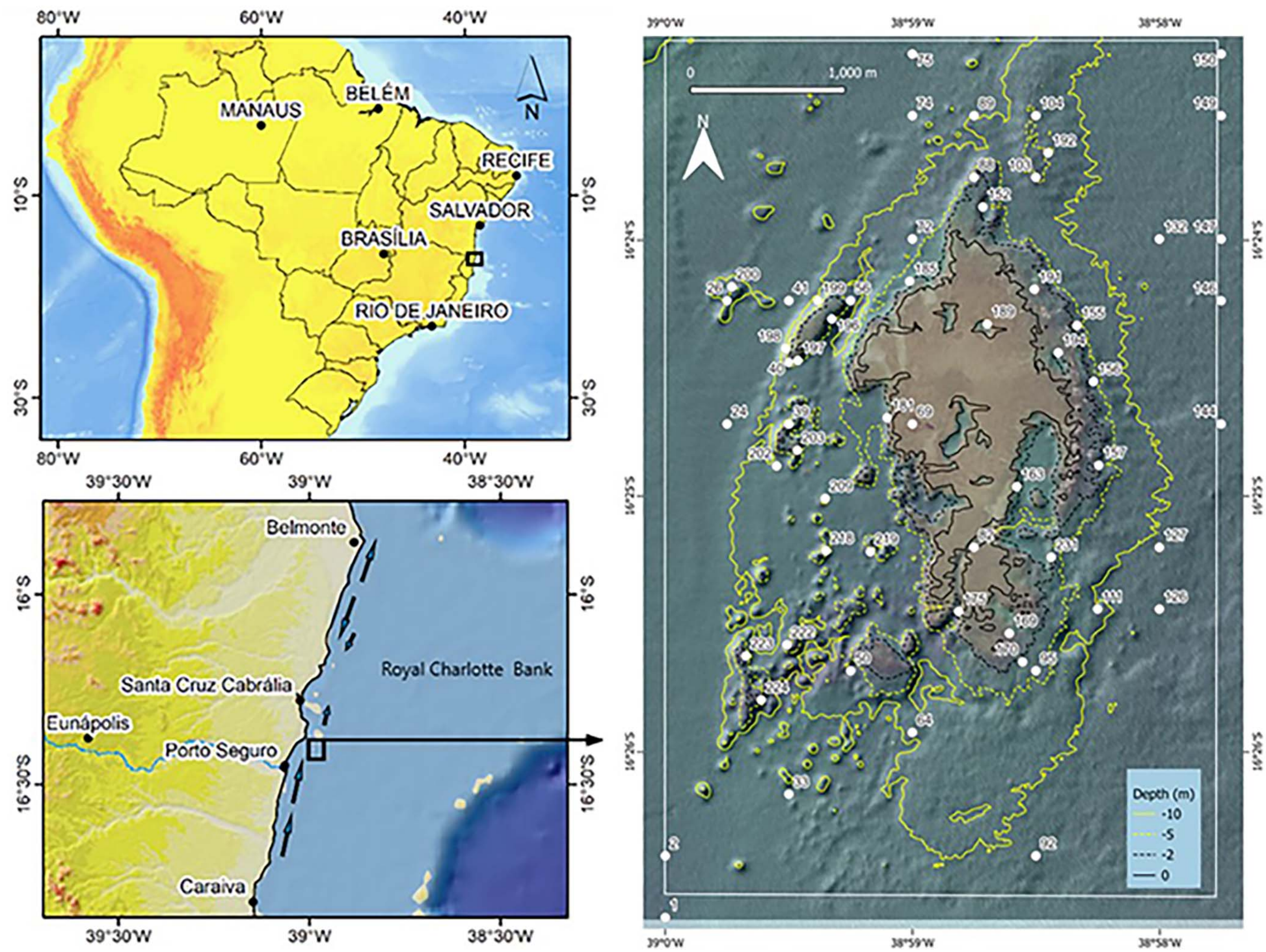

FIGURE 1. Upper left: study site location (black box). Lower left: the Recife de Fora Marine Park (RFMP) is part of the coastal reef complex of the Royal Charlotte Bank, a network protected area, recognized by UNESCO as a World Natural Heritage Area. Arrows show longshore drift currents along the coast, predominantly to north in the RFMP influence zone (modified from Silva, 2008). Right: RFMP (white box) and the 59 sampling stations, with isobaths for the reef flat and contiguity, east of the Porto Seguro city, eastern Brazil. Digital bathymetry model, isobaths, hillshade and Quickbird satellite imagery from Arantes & Seoane (2017).

To assess and monitor coral communities, reef-dwelling foraminiferal assemblages have been used as bioindicators of environmental stress using these indices. These methods have been applied elsewhere, in Corumbau, Abrolhos, Fernando de Noronha, and Tamandaré (Barbosa et al., 2009, 2012, 2016; Oliveira-Silva et al., 2012), showing specific areas of coral ecosystem decline. In Maracajaú and Pirangi reefs, Eichler & de Moura (2020), using only living specimens for FI calculation, came to the same conclusion.

The aim of this work is to assess the most threat-susceptible sites of Recife de Fora Marine Park (RFMP), which hosts a diversity of reef-building corals, including five out of six Brazilian endemic species, as well as octocorals and hydrozoans that are also endemic. Assessment is made through foraminiferal-assemblage distributions, ecological descriptors, and application of environmental-based indices mapped and compared with environmental variables. As this work involves the area of influence of an erosional carbonate reef flat (Braz et al., 2022) where palimpsest and fine sediment is also found, we combined analysis using both FI and FSI indices.

STUDY SITE

The Recife de Fora Marine Park (RFMP) is a Marine Protected Area of 20 km^2 (i.e., analogous to category II of the IUCN – International Union for Conservation of Nature), located about 5 km from Porto Seguro city, in the State of Bahia between coordinates 16°23′–16°25′S and 38°58′–39°00′W (Fig. 1). The most imposing structure is the Recife de Fora, an isolated, energy-dissipation remnant reef flat composed of mixed carbonate-siliciclastic lithology ~2.5 km long and 1.5 km wide. The RFMP is divided into forereef, reef flat and backreef (Arantes & Seoane, 2017; Kennedy et al., 2020). The water depth around this reef flat does not exceed 20 m (Leão, 1996) and is influenced by sea-level changes.

The site is affected by trade winds originating from the subtropical NE anticyclones. The region is under the influence of the Intertropical Convergence Zone (ITCZ) oscillations and southwesterly winds, generating a tropical humid climate, with mean rainfall of 1300 – 2000 mm/year. Sea-surface temperatures vary from 30°C (February–May) to

27°C (July–August). During winter, temperature can drop to 21°C (https://earthdata.nasa.gov/worldview). El Nino-Southern Oscillation (ENSO) variability has been shown to have a regional influence on the timing and longevity of reef growth through the Holocene (Pereira-Filho et al., 2021), mainly related to its warm phase.

Neogene sediments of the Barreiras Formation and Quaternary sediments containing beachrocks, dunes, estuaries, and mangroves dominate the continental coastal area. The shelf is relatively wide and influenced by northward-flowing longshore coastal currents with an average annual velocity of about 0.36 m/sec (DHN, 2012), and by the offshore Brazil Current (CB), which is a south arm of the South Equatorial Current (SEC) flowing north-south and transporting Tropical Water highly influenced by the Brazil-Malvinas Confluence (BMC).

Longshore currents along the coast of Porto Seguro are defined by wave and net sediment transport direction (Silva, 2008, arrows in Fig. 1). Water motion is a prominent aspect of the RFMP, where the forereef is influenced by waves coming from the southeast throughout the year. Active tidal circulation is driven by the up to 2.5-m amplitude (DHN, 2012), resulting in a daily half-cycle of complete immersion during the high tides and emersion of reef pinnacles during low tides (~2 hours each cycle, Seoane et al., 2012). In the backreef, low energy tidal action, riverine water, and sediment output from the Buranhém River modifies the environment at the southwestern area of the reef by transporting and reworking sediments, causing turbidity, and allowing organic-rich fine sediments to accumulate in the backreef, influencing water quality that reaches the reef (Arantes & Seoane, 2017).

The spatial sampling carried out in this work allowed the analysis of the variability of the assemblages linked to the different reef habitats to test the spatial patterns found. Other work on the variability and mapping of existing benthic habitats and species in the RFMP were used for comparisons with our analysis and interpretations (Bruno et al., 2009; Arantes & Seoane, 2017; Tedesco et al., 2018; Marques et al., 2019, 2020; Braz et al., 2022).

MATERIAL AND METHODS

Sampling

For sedimentological and foraminiferal analysis, 59 surficial sediment samples (Fig. 1) were collected by SCUBA diving in several campaigns in 2008, by scraping 200 g of sediment at a depth 0–1 cm inside a jar.

On the boat, only the foraminiferal samples were fixed with 4% formaldehyde solution buffered with borax to maintain marine alkalinity, along with 2 g of rose Bengal stain for distinguishing living and dead foraminifera during picking (Boltovskoy & Wright, 1976; Scott et al., 2001). On the sunny side of the boat, the depth of disappearance of the Secchi disk was used to estimate water transparency. Surface-water temperature and depth were measured by the equipment attached to the divers' vests and ecobathymetry on board (Table 1).

Laboratory Activities

Sediment Analyses: Organic Matter, Carbonate, and Texture

For organic matter (OM) determination, ceramic crucibles were weighed, and a portion of 5 g of bulk wet sediment sample was added (algal pieces included), followed by oven drying at 60°C for 72 hours. After drying, samples were weighed and subjected to 450°C muffle heating for 10 hours to gravimetrically determine organic matter (Table 1; Müller, 1967). Calcium carbonate determination involved the weight difference of 5 g bulk wet sediment before and after acid attack using 1M HCl (Loring & Rantala, 1992).

To determine grain-size distribution of the siliciclastic portion of the sediment samples, 50 grams of each sample were washed through a 0.5 mm–0.002 mm mesh series of sieves to separate oversized particles. Subsequently, samples with finer sand and mud (<0.5 mm) were analyzed using a laser particle analyzer (Cilas® model 1064). Grain size was defined using the Gradistat v. 4.0 (Blott & Pye, 2001), and the grain-size parameters of mean (Mz), standard deviation (σI), asymmetry (SkI) and normalized kurtosis (K′G) were interpreted according to Folk & Ward (1957; Fig. 2, Table 1).

Foraminiferal Analysis

Fifty-nine normalized 10 g samples were washed over a 0.063-mm mesh sieve to remove silt and clay fractions and then dried in an oven at 50°C overnight. The dried sample was then split twice to produce a quarter sample, from which a minimum of 150 individuals (living and dead) were picked (Hallock et al., 2003). Additional splits were examined, if necessary, and results standardized to 10 g of sediment. Foraminiferal picking was done under a Zeiss STEMI 2000 stereomicroscope.

To minimize possible taphonomic bias in the interpretation of the results, only individuals with full, white or clear, and pristine tests were considered according to moderate and good preservation classes of Hohenegger & Yardanova (2001). Taxonomic classification was based on Cushman (1929), Boltovskoy et al. (1980), Loeblich & Tappan (1988), Hottinger et al. (1993), Jones (1994) and the World Register of Marine Species (WoRMS, 2023). All micropaleontological slides with species analyzed in this study can be found in the author collection deposited in the Micron Laboratory at the University Federal Fluminense, Rio de Janeiro, Brazil.

Biotic Indices

Biotic indices were determined to interpret ecological descriptors of foraminiferal assemblages. Density data (N), species richness (S, used here as number of genera per sample), Shannon Index (H′; Shannon, 1948), and Pielou's evenness (J′; Pielou, 1975) were determined using PAST software. These taxonomic and community structure metrics were calculated as follows. The Shannon Index was calculated with the equation:

$$H' = -\Sigma p_i * \ln(1/p_i)$$

where p_i is the proportion of individuals per species. Pielou's evenness, which indicates the homogeneity of the distribution

TABLE 1. Environmental data of depth (m), temperature (°C), visibility (in meters below water surface), carbonate (%), organic matter (mg g^{-1}) and mean phi sediment size for 59 sampling sites of RFMP.

Stations	Depth (m)	T°C surface	Visibility (m)	$CaCO_3$ (%)	Organic Matter (mg g-1)	Mean (Φ)
1	17.5	28	2	79.42	6.37	1.408
2	15.5	28	10	80.30	9.43	6.091
24	13.6	30	13	73.08	11.87	6.000
26	10.5	30	8	93.97	7.43	6.669
33	14.2	30	2	83.45	5.42	7.294
39	6	28	5	94.03	3.64	4.419
40	2.5	29	2	98.71	4.45	6.502
41	14.5	29	5	60.87	6.41	6.756
50	7	27	7	85.13	17.37	4.198
56	12	26	2	83.95	12.39	4.000
64	11	26	5	85.04	16.21	3.869
69	0	32		98.80	7.24	2.414
72	6.8	30	5	98.54	6.95	3.233
74	0.4	28	0.4	79.87	7.03	1.076
75	15.8	29	15	63.05	6.34	4.432
82	1.4	28	1	96.85	4.26	4.669
88	4	28	4	98.53	2.30	1.076
89	9	28	4	87.14	12.84	6.334
92	14	30	5	95.57	5.74	1.193
95	5	29	4	98.38	3.18	1.076
103	4.7	28	6	89.30	15.23	6.442
104	5	28	5	96.22	2.45	4.419
111	9.9	26	5	93.86	4.23	1.408
126	13.5	28	6	92.24	2.80	1.076
127	12	27	5	94.91	3.82	1.076
132	12.7	33.5	4	86.59	7.64	4.068
144	15	29	15	96.63	3.66	1.076
146	12.42	28	10	89.79	5.22	3.651
147	13.4	30	6	86.41	5.89	3.651
149	13.3	28	6	95.05	5.98	1.193
150	12	28	10	94.36	7.46	1.076
152	9.9	28	7	99.27	3.03	1.076
155	4.3	27	4	91.05	4.36	7.197
156	5	28	1.5	99.10	3.80	1.076
157	3	28	3	96.31	2.73	1.076
163	3	27.8	3	99.10	3.67	1.076
169	1.9	28	1.5	97.37	5.87	3.321
170	2.1	28	2	96.88	4.01	4.419
175	1.5	28	1.5	87.29	5.33	6.076
181	4.3		1	93.91	7.60	4.246
185	6.5	27	6	96.31	7.78	4.072
189	1.4	30	1.5	96.77	4.75	1.000
191	2.4	27	2	99.28	4.79	2.150
192	6.3	28	6	94.54	7.43	4.537
194	4.4	28	2	91.13	16.21	6.199
196	3.5	28	2	96.32	4.14	4.419
197	3.9	28	4	95.01	12.60	5.979
198	4.8	28	5	97.70	2.34	3.233
199	4.9	26	5	88.83	10.12	7.294
200	9.1	26	7	97.03	6.99	4.419
202	5.2	28	4.5	84.19	15.01	7.299
203	3.5	28	3.5	90.06	6.07	7.299
209	16	28	2	95.47	3.03	4.198
218	3	29	3	96.77	4.56	2.890
219	1.5	31	1.5	98.17	3.45	1.076
222	7.3	25	1.5	83.49	17.94	7.303
223	1.5	28	1.5	89.25	11.87	7.294
224	2.4	29	2.4	89.62	11.59	3.515
231	2.3	26	2	98.14	3.54	1.408

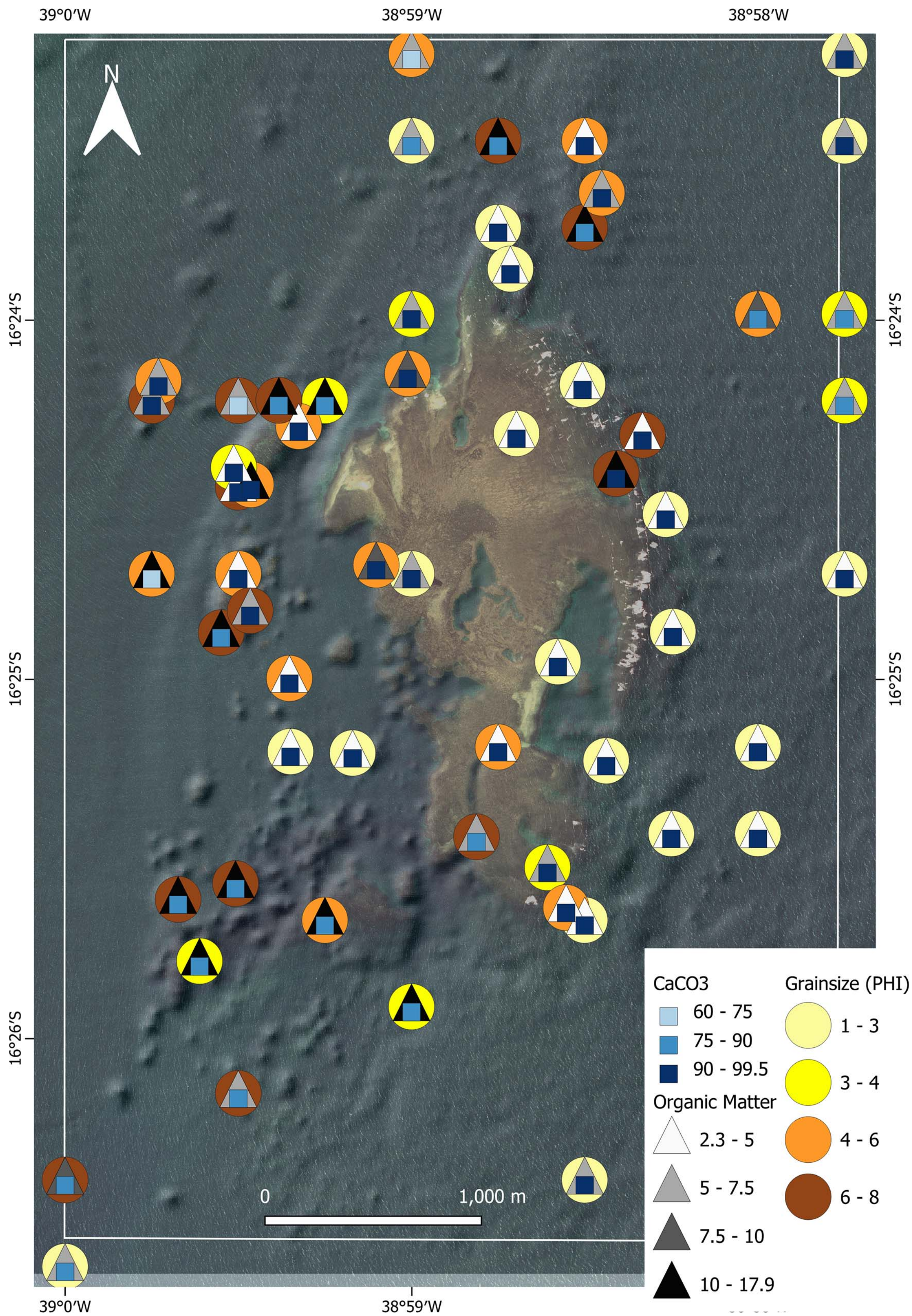

FIGURE 2. Distribution of sedimentological parameters of grain size of siliciclastic components (mean phi – Φ: 1–3, coarse to medium sand; 3–4, medium to fine sand; 4–6, coarse to medium silt; 6–8, fine silt to clay), calcium carbonate (%), and organic matter (mg g^{-1}) for the 59 sampling stations of Recife de Fora Marine Park, Porto Seguro, Bahia, Brazil. Data from Arantes & Seoane (2017).

of individuals in the sample, was calculated using the equation:

$$J' = H'/\ln(S)$$

The evenness value of J′ varies from 0 to 1, where 1 and values close to it represent a higher degree of sample homogeneity, while values approaching 0 indicate greater heterogeneity. These indices are highly relevant for ecological analyses of fauna because they numerically represent the community trends and behavior patterns over time.

The FORAM Index (Hallock et al., 2003) was calculated after quantifying and assigning the foraminiferal assemblage at a generic level, differentiating within predefined functional groups, initially defined as foraminifera that host endosymbionts (s), opportunists (o), and small heterotrophics (h). Further, the basis for this index was revisited by Prazeres et al. (2020) who also revised the abbreviations used in the FI formula:

$$\mathrm{FI} = (10 \bullet P_s) + (P_o) + (2 \bullet P_h)$$

where the proportion (P) of individuals from each functional group is calculated by summing the individuals of each genus of that group (N) divided by the total number of individuals counted (T). Results where $\mathrm{FI} < 2$ indicate instability/stress, with minimal capacity to accrete warm-water carbonates. Values of FI of 2–4 indicate conditions marginal for accretion of warm-water carbonates. In both cases, investigation of the causes is essential. Water quality conditions that support accretion of warm-water carbonates are indicated by $\mathrm{FI} > 4$.

Dimiza et al. (2016) proposed the Foram Stress Index (FSI) for soft-bottom sediments in the Mediterranean waters, based on the proportion of sensitive (*Sen*) and stress tolerant (*Str*) foraminifera to characterize the ecological stress conditions using the equation:

$$\mathrm{FSI} = (10\,Sen) + (Str)$$

The numerical classification results of FSI are highly focused on polluted environments, varying from zero to ten. A value of zero indicates azoic conditions, 1–2 heavily polluted environments, 2–5.5 moderately polluted, 5.5–9.0 slightly polluted/transitional, and > 9.0 normal/pristine conditions. Classification of genera into functional groups was based on Dimiza et al. (2016), Barbosa et al. (2016), Jorissen et al. (2018), and Minhat et al. (2020). The interpretation of the results of FI and FSI followed those indicated by original authors (Hallock et al., 2003; Dimiza et al., 2016, respectively).

GIS Mapping

Geographic Information System (GIS) base maps from Seoane et al. (2012) and Arantes & Seoane (2017) are based on publicly available cartography base data, field survey, bathymetry modeling, and the 3D geomorphology model, over which micropaleontological assemblages are superimposed. The mapping of the different habitats in the RFMP was defined according to Mumby & Harbone (1999) classes, considering substrate, underwater geomorphology, and macrofauna and flora of the benthic community (Arantes & Seoane, 2017).

Statistical Analysis

We utilized the exploratory cluster analysis of group averages performed using a similarity matrix (Bray-Curtis) of fourth-root transformed abundances of foraminifera (≥4%) with a second permutation procedure, the similarity profile (SIMPROF) routine (Clarke & Gorley, 2006) on PRIMER software. The matrix was also used to perform the similarity percentages analysis (SIMPER) to define which species contributed most to the assemblages considering a 90% cut. Nonmetric multidimensional scaling (nMDS) was used to visualize the similarity in foraminiferal assemblages. The same matrix of faunal density was used to evaluate the level of similarity (dissimilarity) between groups of samples within each compartment (backreef, reef flat, and forereef) using the ANOSIM in PRIMER software.

A Principal Component Analysis (PCA) was applied to summarize the statistical correlations among environmental and biotic variables, with a minimal loss of the original information using RStudio version 4.1.0. Before the analysis, a Kaiser-Meyer-Olkin (KMO) test was used to determine the sampling adequacy for PCA (average value of 0.6), followed by Bartlett's test of sphericity to test whether the correlation matrix was an identity matrix (p-value <0.01).

RESULTS

Environmental Samples

Of the 59 samples analyzed, 58 were analyzed for siliciclastic grain size, with one of pure carbonate. From this total, 28 stations (47%) exhibited a dominance of sand, while (53%) were dominated by silt, with up to 10% sand content in their composition (Fig. 2, Table 1).

The prevalence of silt (mean $\Phi > 4.0$–8.0), with an average grain size of 5.9Φ was observed for 18 of the 23 stations (78%) in the backreef with only five sandy stations (22%). Sandy samples (mean Φ size between 0–4) were found on 13 of the 24 stations (54%) on the reef flat with an average grain size of 1.8Φ, and on 10 of 12 forereef samples (83%, average grain size of 1.6Φ). In general, the sediment was fine, polymodal, poorly sorted, with platykurtic to mesokurtic kurtosis and with positive to very positive asymmetry (Arantes & Seoane, 2017).

Organic matter (OM) was analyzed for the 59 stations, and values are generally lower around the reef flat, with higher values primarily concentrated in its southwest portion, especially in sheltered stations. The OM values were >6.0 mg g^{-1} in 49% of stations, while values <6.0 mg g^{-1} were found at 51% of stations, predominantly on reef flat and forereef. For OM determination, algal pieces were included in the samples, resulting in anomalously high values. The method used also could increase the weight, during the calcination of OM transforming Fe^{2+} to Fe^{3+} and other minor transition metals. Carbonate content was notably high ($61-99\%$) across most stations (Fig. 2, Table 1).

At 30 stations (50%), water transparency was <5 m, indicating permanently turbid water at the base of the water column, with a large amount of suspended sediment. These stations are under the influence of the prevailing NE-SW winds and the permanent inflow of the Buranhém River into the Porto Seguro Bay area.

Foraminiferal Analysis

Univariate Analysis and Community Structure

Univariate analyses (Table 2) were used to evaluate communities independently of the species that compose them, generating single values that were used to compare among stations and to assess assemblage diversity. Here, assemblages were considered communities, consistent with Buzas et al. (2007).

A total of 98 genera, spanning 58 families from the orders Rotaliida, Miliolida, and Textulariida, were identified. Rotaliida included 63 genera from 41 families, Miliolida had 30 genera from 13 families, and Textulariida featured five genera across four families. Rotaliida and Miliolida comprised 64% and 30% of the total assemblage, respectively, while Textulariida contributed 5%.

Regarding community indices, metrics varied considerably among stations, with H' ranging from 1.7–3.2, S from 12–51, and foraminiferal density from 43–128,876 ind/10 g. Evenness ($J' = 0.53 \pm 0.07$) remained consistent among reef areas. The highest diversity (2.88 ± 0.31), richness (35 ± 7), and densities ($29{,}991 \pm 42{,}578$) were found in the protected back reef area, followed by the reef flat and forereef areas.

Foraminiferal Indices

Through the analyses of foraminiferal community structure using functional groups (Fig. 3, FoRAM Index (FI), and FORAM Stress Index (FSI; Table 2), we evaluated the status of the benthic ecosystem for carbonate bioconstruction. Overall, both indices indicate favorable to slightly polluted-transitional conditions for the Recife de Fora reef flat and its surrounding areas, with symbiont-bearing and sensitive species being more abundant at stations characterized by sandier sediments with higher $CaCO_3$ content and less organic matter. However, stressed areas were identified in the longshore current-dominated northwest back reef and in the Buranhén riverine input in the southwest backreef, as indicated by both indices (Fig. 3).

Multivariate Analysis of Environmental Parameters and Community Structure

In the backreef area (23 stations), 89 genera were identified, with the miliolid *Quinqueloculina* being the most prevalent (>10%). The reef flat (24 stations) produced 88 genera, with three samples having >10% miliolida and >26% *Amphistegina* and LBF. The forereef (12 stations) produced 69 genera, with *Amphistegina* representing >18%. ANOSIM analysis within each area showed significant similarities within sites: Backreef (Global $R = 0.898$), reef flat (Global $R = 0.941$), and forereef (Global $R = 0.957$). In all stations, most species occurrences were considered rare (55 – 66 genera), contributing less than 4% in at least one station, collectively representing 70 – 79% of the assemblage.

Nonmetric Multidimensional Scaling

Nonmetric multidimensional scaling (nMDS) was preceded by an initial exploratory analysis on the data to simplify comparisons among samples using *post hoc* methods such as cluster analysis and principal components analysis. Spatially, such differences were revealed by cluster analysis based on foraminiferal community (Figs. 4A–B). At a similarity level of 60, four main clusters are apparent, which correspond to increasing values of FI and FSI (Fig. 4A, left to right on the diagram), from backreef to reef flat and forereef (Fig. 4B). The nMDS ordination in two dimensions, with a 2D stress level of 0.08, was used to visualize these relationships.

The first cluster ($FSI = 7.8 \pm 0.28$; $FI = 2.37 \pm 0.18$) consisted mainly of stations from the backreef, primarily comprising miliolids forming two groups labeled "*d*" and "*e*". Group "*d*" included *Quinqueloculina* and *Spiroloculina* (78% similarity), while group "*e*" consisted of *Quinqueloculina* and *Elphidium* (76% similarity). Assemblage "*d*" had the highest density (89,164 individuals per 10g), while assemblage "*e*" had the highest richness (37) and diversity (3.04). The first cluster also included backreef stations with moderately higher values of FSI (8.13 ± 0.13) and FI (2.60 ± 0.08) and reef flat, which also included miliolids forming assemblages "*f*" and "*g*." Assemblage "*f*" includes *Sigmamiliolinella* and *Quinqueloculina* (80% similarity), while assemblage "*g*" consists of *Quinqueloculina* and *Elphidium* (73% similarity).

The second cluster comprised stations from the outer reef flat and forereef areas with higher values of FSI (8.91 ± 0.21) and FI (3.91 ± 0.61). These assemblages "*a*," "*b*," and "*c*" were dominated by *Quinqueloculina* and *Amphistegina*, *Amphistegina* and *Quinqueloculina*, and *Amphistegina* and *Neoeponides*, with similarities of 77%, 78%, and 76%, respectively, as revealed by SIMPER analysis.

The third cluster, assemblage "*i*," of two samples from the outer reef flat, included *Amphistegina* (15%) and *Archaias* (12%) as dominants, with 73% similarity and high values of both FSI (9.65) and FI (6.49). The fourth cluster, assemblage "*k*," consisted of *Amphistegina* (14%) and *Quinqueloculina* (10%) as dominant, with 80% similarity, and positioned either in the forereef or on backreef pinnacles; some stations in the backreef presented a FSI of 9.20 and FI of 5.56. Samples at site 40 ("*h*") and site 170 ("*j*") did not form assemblages due to their extremely low numbers of individuals, likely due to intense currents and erosion.

Principal Component Analysis

A principal component analysis (PCA) was performed to capture the most important community patterns and environmental drivers influencing the species that contributed to the applied indices (FI and FSI), indicating statistical significance (Figs. 5A–B). The PC1 (Dim. 1) explained 58% of the overall variance. The strongest correlations were FI (0.93) and FSI (0.87), *Amphistegina* (0.92), *Neoeponides* (0.87), and dominance (D at 0.81) with additional positive correlations with $CaCO_3$ (0.58), and negative correlations with species richness and diversity (both H' and S at -0.88), phi size (-0.64), total abundances (N at -0.59) and organic matter

TABLE 2. Univariate data of foraminiferal faunal density of Recife de Fora.

Samples #	Taxa_S	Individuals N	Dominance D	Diversity Shannon_H′	Evenness e^H/S	Equitability J′	FSI	FI
1	32	21529	0.09	2.89	0.56	0.83	7.45	2.21
2	34	114487	0.08	2.89	0.53	0.82	7.79	2.68
24	37	95841	0.06	3.11	0.60	0.86	6.32	2.35
26	42	4987	0.06	3.14	0.55	0.84	7.56	3.15
33	37	112581	0.07	3.09	0.59	0.86	6.38	2.37
39	36	760	0.06	3.12	0.63	0.87	8.45	3.60
40	33	2373	0.12	2.76	0.48	0.79	6.66	2.36
41	42	26514	0.07	3.21	0.59	0.86	6.58	2.23
50	38	16741	0.11	2.85	0.45	0.78	8.25	2.28
56	43	128876	0.08	2.99	0.46	0.79	7.20	2.00
64	35	114284	0.10	2.95	0.54	0.83	7.56	2.12
69	31	3010	0.11	2.74	0.50	0.80	8.83	2.47
72	39	4975	0.07	3.08	0.56	0.84	8.19	2.97
74	37	31792	0.07	3.06	0.57	0.85	8.08	2.83
75	31	14363	0.07	2.98	0.64	0.87	7.79	2.32
82	35	10202	0.10	2.89	0.51	0.81	8.02	2.33
88	14	53	0.18	2.14	0.61	0.81	9.10	5.15
89	37	98676	0.08	3.05	0.57	0.84	7.94	2.55
92	29	5131	0.11	2.66	0.49	0.79	9.03	4.07
95	25	1455	0.11	2.57	0.52	0.80	9.06	3.83
103	34	584	0.06	3.10	0.65	0.88	8.62	2.49
104	36	1228	0.17	2.57	0.36	0.72	8.97	2.86
111	15	57	0.17	2.20	0.60	0.81	9.06	5.34
126	32	3291	0.08	2.87	0.55	0.83	8.75	3.89
127	22	1477	0.17	2.23	0.42	0.72	9.43	4.95
132	36	7592	0.06	3.17	0.66	0.88	7.92	3.16
144	28	3210	0.10	2.65	0.51	0.80	8.66	4.86
146	41	3881	0.07	3.13	0.56	0.84	8.03	3.92
147	35	19469	0.07	3.09	0.63	0.87	8.41	3.50
149	33	5983	0.10	2.80	0.50	0.80	8.75	4.73
150	28	3178	0.12	2.58	0.47	0.77	8.86	4.36
152	30	449	0.09	2.83	0.56	0.83	8.88	2.85
155	28	437	0.13	2.56	0.46	0.77	9.56	5.90
156	14	656	0.19	1.99	0.52	0.75	9.95	6.40
157	17	43	0.14	2.37	0.63	0.84	9.35	5.42
163	26	1403	0.11	2.60	0.52	0.80	9.48	4.52
169	35	45947	0.08	2.99	0.57	0.84	7.67	2.17
170	14	140	0.27	1.71	0.40	0.65	9.76	6.47
175	33	36351	0.08	2.92	0.56	0.83	7.16	2.11
181	31	73551	0.10	2.72	0.49	0.79	7.09	2.00
185	30	5898	0.09	2.81	0.55	0.83	8.58	2.55
189	34	23486	0.09	2.92	0.55	0.83	7.96	2.60
191	21	335	0.14	2.40	0.52	0.79	9.34	6.58
192	45	33733	0.06	3.21	0.55	0.84	7.94	2.73
194	33	13672	0.13	2.65	0.43	0.76	8.67	2.70
196	32	315	0.08	2.96	0.61	0.86	8.90	3.66
197	35	71048	0.09	2.95	0.55	0.83	7.61	2.05
198	33	933	0.10	2.84	0.52	0.81	9.49	3.88
199	33	1825	0.11	2.85	0.52	0.81	7.64	2.15
200	35	5548	0.06	3.14	0.66	0.88	8.37	3.19
202	33	5017	0.08	2.82	0.51	0.81	7.29	1.88
203	35	13268	0.07	3.00	0.57	0.84	6.89	1.84
209	30	1561	0.12	2.69	0.49	0.79	8.46	2.92
218	12	52	0.29	1.75	0.48	0.71	9.45	6.36
219	28	85	0.14	2.60	0.48	0.78	9.04	5.23
222	36	40521	0.07	3.04	0.58	0.85	6.84	1.89
223	42	3000	0.07	3.09	0.52	0.83	8.17	2.77
224	25	104	0.19	2.36	0.43	0.73	9.22	5.85
231	29	2827	0.12	2.70	0.51	0.80	8.50	2.92

(OM at −0.56). The variables depth, temperature, water transparency, and *Triloculina* did not significantly influence results and were removed by the analysis providing the best signal-to-noise ratio (Skalski et al., 2018).

The PC2 (Dim 2) explained 11% of the variance relating positively with high organic matter (0.50) and fine grain sizes (>4Φ, 0.37), and negatively with $CaCO_3$ (−0.53), which reflected in an increase in the number of individuals (0.40) and

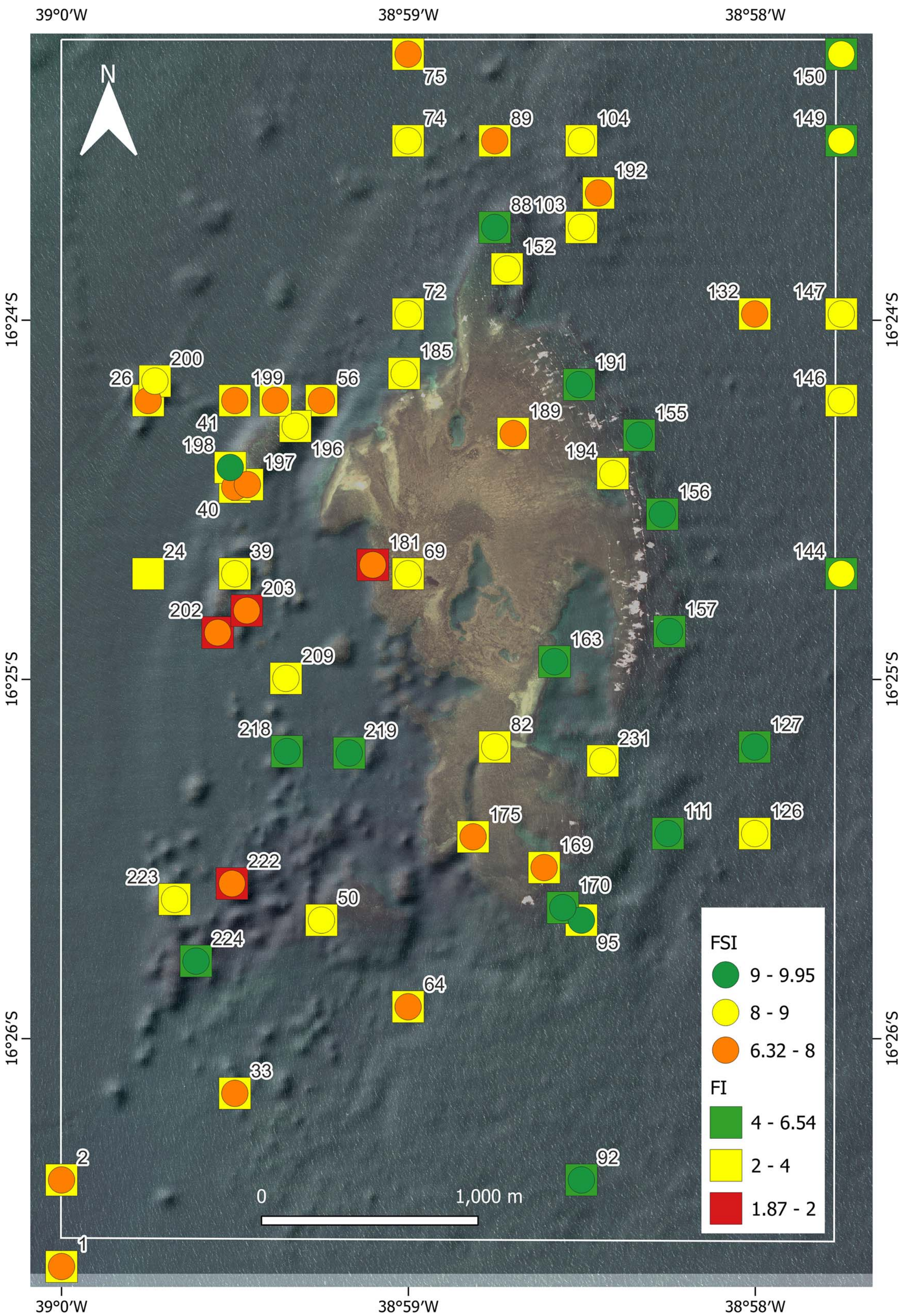

FIGURE 3. Foraminiferal environmental-quality indices: FoRAM Index (FI) and FORAM STRESS Index (FSI) for the Recife de Fora Marine Park, Porto Seguro, Bahia, Brazil. FI: results <2 indicate instability/stress; between 2 – 4 indicate conditions marginal for the carbonate factory; an index >4 indicates conditions favorable for the carbonate accretion of equilibrium/stability. FSI: 5.5 – 9.0, slightly polluted/transitional, >9.0 normal/pristine conditions.

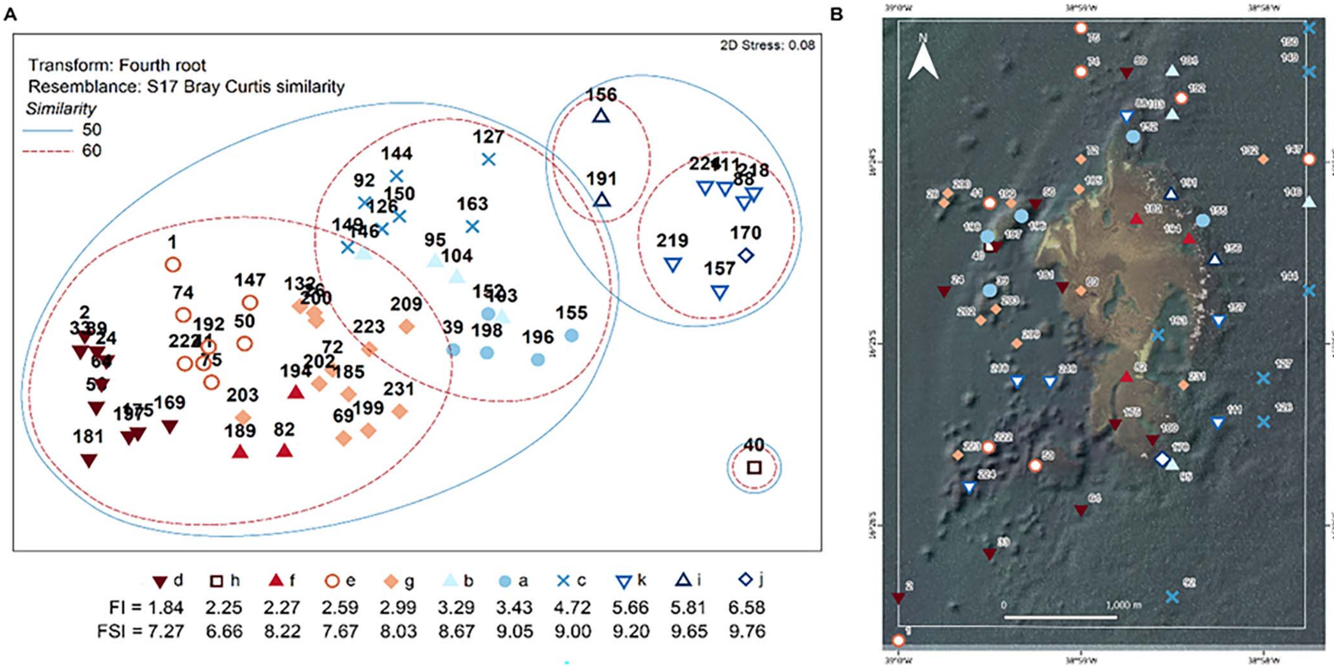

FIGURE 4. Cluster analysis based on foraminiferal community density and foraminiferal based indices. Symbols and letters depict the assemblages defined by SIMPER. FI: results <2 indicate instability/stress; between 2 – 4 marginal conditions to the carbonate factory; and >4 indicates equilibrium/stability. FSI: 5.5 – 9.0 slightly polluted/transitional, >9.0 normal/pristine conditions.

dominance (0.25) of heterotrophic/sensitive taxa, decreasing FSI correlations (−0.19). Interestingly, *Quinqueloculina* was by far the strongest influence on Dim. 3, at 0.75.

DISCUSSION

In general, environmental assessment is related to the activities of human societies and their impacts on local conditions. In virtually all scenarios, the detrimental effects of humans depend upon both such activities and the ability of the environment to mitigate their effects. The gradient of possible impacts depends both on the nature and intensity of the human activities and the local to regional environmental processes. Monitoring and assessment of environmental quality are essential in determining the trajectories of natural ecosystems under threat. The health of the marine environment and the well-being of humans are found to be related (Fleming et al., 2023). Therefore, the development and maintenance of effective monitoring systems depends on recognition of the local physical, chemical, geological, and biological conditions that the unique local system requires. Then program can be created to periodically assess the condition of the natural system and determine how much change (impact) that ecosystem can tolerate without experiencing irreversible decline. This is where environmental indicators, whether physical, chemical, geological or biological, are crucial.

The RFMP environment currently hosts a diversity of reef-building corals, including five out of six Brazilian endemic species, as well as endemic octocorals and hydrozoans. The ecosystem has sustained these unique characteristics, despite

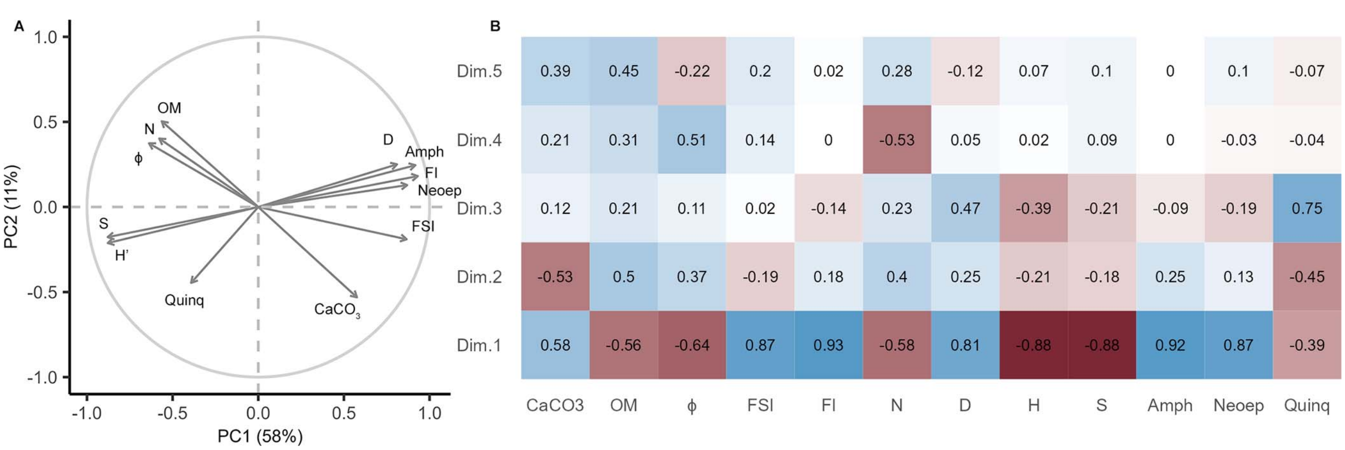

FIGURE 5. Principal Components Analysis (PCA): (A) the RFMP foraminiferal relative percentages and environmental variables; (B) The correlation of environmental and faunal variables and the principal components. Blue tones indicate positive correlations, while red tones indicate negative correlations. Amph = *Amphistegina*, Neoep = *Neoeponides*, Quinq = *Quinqueloculina*.

more than two centuries of human actions and development of the adjacent terrestrial watershed and coastal zone. Understanding the ecosystem setting is essential to maintaining the best conditions for sustainability.

Benthic indicators of coral-reef condition can only be useful, according to some studies (e.g., Smith et al., 2008 and references therein), in long-term monitoring (decadal) programs that track trajectories of reef accretion and attempt to discover the processes that influence these trajectories. In this sense, foraminifera can provide information on the facies-temporal synthesis on different scales, useful in long-term monitoring.

While some authors have worked with foraminiferal assemblage data from RFMP (Bruno et al., 2009; Oliveira-Silva et al., 2012; Marques et al., 2019), none have focused on assessment of environmental stress, despite recent observations by Marques et al. (2019), Ferreira et al., 2020, and Braz et al. (2022) indicating that the coral reefs are declining in the RFMP. The foraminiferal genera identified are common in the tropical Atlantic Ocean (Machado et al., 2006; Araújo & Machado, 2008a), and the environmental quality can be considered relatively high when compared to studies carried out on other reefs in the state of Bahia (Machado, 1995, 2000; Araújo & Machado, 2008a,b; Eichler et al., 2015). However, our approach revealed stressed areas inside the RFMP by sampling a substantial number of sampling stations under different hydrodynamic and habitat conditions. By integrating data of water transparency, depth, temperature, sediment composition, with metrics based on benthic foraminiferal assemblages, we were able to assess the most threat-susceptible sites in RFMP and the environmental drivers determinant to the species that define the two applied numerical indices. The results demonstrated that environmental bioindicators based upon benthic foraminiferal assemblages have the potential to assess current condition, but also show how they can be used for longer term monitoring.

Foraminiferal Total Assemblages of the RFMP

Reef and shelf foraminifera commonly live on coral fragments, sponges, algae, and seagrass, with their dead tests accumulating in sediments. Most of the algal symbiont-bearing and sensitive species live on these solid substrata or live epiphytically (e.g., Stephenson et al., 2015), while taxa more tolerant of intermittent hypoxia, especially *Ammonia* spp., can thrive in organic-rich, muddy sediments (e.g., Yanko-Hombach et al., 2017). These different substrata are determined by reef morphology and local hydrodynamics, with small differences in the composition of these substrates determining local foraminiferal assemblages (Cockey et al., 1996; Renema, 2006; Araújo & Machado, 2008b).

Since the number of living (stained) foraminifers was negligible, a result consistent with previous studies in reef environments (Brasier, 1975; Cockey et al., 1996; Peebles et al., 1997; Stephenson et al., 2015; François et al., 2022), and many samples could be excluded from the comparative approach of the indices in the RFMP, the total number (living + dead) was considered, as in Hallock et al. (2003), Langer & Lipps (2003), and Fajemila et al., (2015). Moreover, the total assemblages are highly influenced by local sedimentation rates and taphonomic processes (e.g., Scott & Medioli, 1980; Armynot du Châtelet et al., 2004; Debenay et al., 2005), and these could be possible biases in the results, although live fauna may also represent a bias in the results, unless they are monitored for a year or more (Debenay et al., 2001). Accordingly, total assemblages are time-averaged successive generations (Dimiza et al., 2019). This approach is useful here because the original FI was designated based on the total fauna (Hallock et al., 2003), and the FSI (Dimiza et al., 2016) was elaborated based on the living fauna. Analyses that have used live foraminiferal assemblages when applying the FI show equally poor values in areas under anthropogenic pressure in northeast reefs of the Brazilian coast (Eichler & de Moura, 2020).

Dead assemblages of foraminifera dominated the sediments because of their palimpsestic character and hydrodynamics. To minimize taphonomic bias in the interpretation, moderate and good preservation classes of Hohenegger & Yordanova (2001) were considered during counting; estuarine species were included. Relict fauna included specimens with rusty appearance and blackened miliolids; these were excluded from our count, although they further indicate an erosional continental shelf. If included in counting, relict fauna could bias the results of predicted indices for the RFMP.

A hypothesis-testing framework analysis of differences in resemblances among groups of samples (ANOSIM - analysis of similarities) was applied in our community data to detect possible differences in the assemblages of the backreef (Global $R = 0.898$ – slope of the linear regression of ranked resemblances), reef flat (Global $R = 0.941$), and forereef (Global $R = 0.957$), showing significant similarities in the samples, based on total counts, under these three ecological conditions.

Foraminiferal-based Indices and Assemblages for the RFMP

The FI and FSI provide numerical indicators of the ability of an environment to support the prolific growth of calcifying organisms that host symbiotic algae (zooxanthellate corals and LBF; Carnahan et al., 2009; Dimiza et al., 2016). The LBF depend on photosynthetic symbionts for their development and test calcification, similar to the requirements of reef-building corals, which is why the LBF are used as bioindicators of water quality (Hallock et al., 2003; Schueth & Frank, 2008; Uthicke & Nobes, 2008; Fujita et al., 2009, O'Malley et al., 2021) and biological conditions in coral-reef environments (Nobes et al., 2008).

Endosymbiosis limits the occurrence of LBF and corals to the photic zone and to relatively clear, nutrient-poor waters (Hallock et al., 2003). Relatively abundant LBF were found at the south and northeast reef fronts, areas with clear waters, while fewer specimens were observed in parts of the backreef portions either influenced by longshore currents or river discharge, as confirmed by a recent survey (Marques et al., 2019). When environmental conditions include lower water transparency, more organic matter, and accumulation of muddy sediments, the foraminiferal assemblage will likely be dominated by small, heterotrophic species (Hallock et al., 2003). In areas of reduced salinity or hypoxia and abundant phytoplankton production, stress-tolerant taxa such as *Ammonia* can dominate (e.g., Yanko-Hombach et al., 2017).

While LBF are essential for higher FI and FSI results, dominance by small heterotrophic foraminifera will reduce the FI to <4 and the FSI to <6; the prevalence of opportunistic species that tolerate environmental stresses, chemical pollution, and organic enrichment (Carnahan et al., 2009, Dimiza et al., 2016) will reduce the FI in extreme cases to <2, while the FSI can reach zero for azoic conditions. The FI is based on the premise that favorable environments for reef growth contain at least about 25–30% of LBF (Hallock et al., 2003). However, the FI is not directly applicable to detecting bleaching and other effects of climate change on corals (Schueth & Frank, 2008), which is why Stainbank et al. (2020) proposed the *Amphistegina* bleaching index.

The foraminiferal-based indices reflect the environmental status of the RFMP, reef flat, and its surroundings. In the 12 forereef stations, the foraminiferal assemblages were quite diverse, with 69 genera recorded; the LBF *Amphistegina* represented >18% specimens. However, the FI for these samples was mostly between 4 and 6, which indicates that smaller heterotrophic taxa are thriving and their shells are accumulating in forereef sediments. This was supported by cluster analysis that showed *Quinqueloculina* and *Eponides* as dominant in assemblages positioned both in the forereef and on backreef pinnacles, (e.g., assemblage *b*, Fig. 4). In reef-flat sediments, 88 genera were identified in 24 stations, with Miliolida representing >10% and *Amphistegina* abundant (>26%) in some stations. The indices and their spatial distribution, in general, show the highest values at the forereef and at pinnacles in the backreef (Fig. 3). *Amphistegina* are representative in assemblages in these stations. The tests of *Amphistegina*, along with other LBF, such as *Archaias* and *Peneroplis*, can reach up to 50% of the assemblage in forereef sediments (Castignetti & Manley, 1998; Fujita et al., 2009), with larger tests accumulating in sandy sediments.

The smaller heterotrophic foraminifera, especially miliolids, are grazers and feed on organic matter, bacteria and benthic microalgae. Thus, they commonly accumulate in sediments with higher levels of organic matter found in the backreef muddy sediment (Araújo & Machado, 2008a). They also can live epiphytically on seagrass, as well as on algae and sponges associated with *Halophila decipiens* seagrass (Tedesco, et al., 2018), which dominate the backreef, pinnacles, and part of the reef flat (Kennedy et al., 2020), contributing to the high species richness. Not surprisingly, the distribution of heterotrophic taxa followed their ecological preferences, being more abundant in the backreef area where higher OM was found. Consequently, the backreef FI values were commonly in the 2–4 range, which comprised the assemblages *d*, *e*, and *g* dominated by *Quinqueloculina* spp. and *Elphidium* spp. (Fig. 4). Many miliolids, such as *Triloculina*, *Sigmamiliolinella*, *Spiroloculina*, *Cycloforina*, and *Pyrgo*, are included as sensitive taxa in the FSI equation, contributing to high index values at stations where smaller miliolids dominated. Stations on the reef flat (Table 3) were also dominated by the miliolids *Quinqueloculina, Spiroloculina*, and *Sigmamiliolinella,* except stations comprising the assemblage *f*, dominated by LBF like *Archaias* and *Amphistegina*. Tests of these taxa often concentrate in hydrodynamic areas influenced by waves and tides, which partly explains why miliolids reach their maximum frequency in the protected area of the reef (Langer & Lipps, 2003) and over the reef flat.

Most miliolid genera do not host algal symbionts and are considered sensitive in the FSI, contributing to high values of FSI, even where the FI remains <4. The FI indicated a range of scenarios from critical conditions to potential for recovery, whereas FSI indicates slightly polluted/transitional to normal/pristine conditions of high environmental quality (Fig. 4). These differences are not surprising because the FI was developed for reef environments and was not designed to differentiate among stressed environments (Hallock et al., 2024). The FSI, in contrast, was not developed for reef environments, but for the Mediterranean, which has diverse foraminiferal assemblages that include LBF, but does not host coral reefs (Dimiza et al., 2016). Assessing both for sediments from the RFMP is highly appropriate, because the "reef" status is inherently somewhere between prolific coral reefs and foraminiferal dominated sediment production of the Mediterranean (e.g., Hallock et al., 2024).

The assignment of some hyaline foraminifera also contributes to challenges in environmental evaluation. A major example is *Elphidium*, which is classified as sensitive in the FSI but opportunistic for FI. This genus ranked second most important in assemblages *e* and *g*, which exhibited low FI values (2.59 and 2.99, respectively), indicating an environment marginal for reef growth, but regular FSI scores (7.67 and 8.03) indicate slightly polluted/transitional conditions. Actually, this apparent discrepancy is quite common because *Elphidum* includes numerous species, some of which are able to sequester the chloroplasts from their algal food sources, allowing them to survive in quite variable conditions. That is, when food is readily available and water transparency is low, they can thrive completely by feeding, but when seasonal conditions change, water transparency improves and organic matter becomes scarcer, they can continue to thrive mixotrophically, with their energy supplies enhanced by photosynthesis and production of carbohydrates by their sequestered chloroplasts (Jauffrais et al., 2019; Jesus et al., 2022).

Elphidium tests were found in all stations except 181 (Appendix), which presented the worst conditions in the backreef stations (extreme west at Fig. 4A), possibly demonstrating the diverse capacities of the live specimens (Lintner et al., 2023). *Elphidium* tests were recorded southwest of the reef system and across the whole backreef area, as expected, indicating their tolerance for salinity oscillations (Capotondi et al., 2022). Stress-tolerant foraminifera can survive organic-rich sediments, trace metals, and chemical effluents (Alve, 1995; Carnahan et al., 2009) as well as a high-load of contaminants from the Buranhém river, as found by Marques et al. (2019).

In the backreef samples, higher H′, test density, and generic richness, driven by greater abundance of rare species, was observed. This seems to be a common feature of northern backreef conditions, where longshore currents dominate, bringing rare species to this portion of the RFMP. Both indices indicated marginal conditions in southwest areas under the influence of Buranhém River discharge, where contamination of heavy metals in large benthic foraminifera (LBF) was previously observed (Marques et al., 2019). Based on the results, Buranhém River influence over foraminiferal distribution seems coupled to the input of muddy sediments and OM. This agrees with the PCA, showing that the decrease in water quality indices and heterotrophic foraminiferal abundances follow the decrease in $CaCO_3$ and sediment size, along with increased OM.

TABLE 3. Similarity Percentage (SIMPER) of Foraminiferal genera of Recife de Fora assemblages. Only groups with average similarity above 70% are included. Groups *h* and *j* had less than 2 samples in the group.

Species	Av.Abund	Av.Sim	Contrib%	Cum.%	Group	Average Similarity
Quinqueloculina	7.77	6.87	8.95	8.95	***e***	**76.79**
Elphidium	6.92	6.15	8.01	16.96		
Triloculina	6.41	5.24	6.82	23.78		
Miliolinella	5.51	4.81	6.26	30.04		
Spiroloculina	5.57	4.76	6.2	36.24		
Peneroplis	5.38	4.71	6.14	42.38		
Nonion	4.99	4.26	5.55	47.93		
Pyrgo	4.75	4.19	5.45	53.38		
Rosalina	4.79	4.16	5.42	58.8		
Quinqueloculina	11.18	7.84	10.07	10.07	***d***	**77.93**
Spiroloculina	8.67	6.01	7.72	17.78		
Miliolinella	8.22	5.8	7.45	25.23		
Bolivina	8.12	5.65	7.25	32.48		
Cycloforina	7.78	5.53	7.09	39.57		
Sigmamiliolinella	7.35	5.1	6.54	46.11		
Triloculina	7.49	4.82	6.19	52.3		
Peneroplis	7.57	4.76	6.11	58.4		
Quinqueloculina	5.29	7.32	9.97	9.97	***g***	**73.38**
Elphidium	4.01	5.04	6.87	16.83		
Sigmamiliolinella	4.01	5	6.81	23.65		
Miliolinella	3.85	4.99	6.8	30.45		
Cycloforina	3.64	4.61	6.29	36.74		
Spiroloculina	3.67	4.29	5.85	42.59		
Rosalina	3.13	4.09	5.58	48.16		
Pyrgo	3.13	3.88	5.29	53.45		
Bolivina	3.11	3.56	4.84	58.3		
Quinqueloculina	3.03	6.25	8.13	8.13	***a***	**76.96**
Amphistegina	2.84	6.11	7.94	16.07		
Sigmamiliolinella	2.56	5.15	6.69	22.76		
Neoeponides	2.32	4.83	6.28	29.03		
Triloculina	2.23	4.79	6.23	35.26		
Elphidium	2.05	4.44	5.77	41.03		
Eponides	1.97	4.41	5.73	46.76		
Spiroloculina	1.98	4.24	5.51	52.27		
Miliolinella	2.01	4.08	5.3	57.57		
Sigmamiliolinella	7.58	8.54	10.68	10.68	***f***	**79.98**
Quinqueloculina	7.26	8.29	10.37	21.04		
Cycloforina	5.31	6.35	7.94	28.98		
Cibicides	5.26	5.49	6.86	35.84		
Miliolinella	4.88	5.35	6.7	42.54		
Bolivina	4.62	5.12	6.4	48.93		
Elphidium	4.67	5.01	6.27	55.2		
Amphistegina	2.2	11.24	13.95	13.95	***k***	**80.51**
Quinqueloculina	1.61	8.26	10.25	24.21		
Neoeponides	1.56	7.98	9.91	34.12		
Elphidium	1.48	7.39	9.18	43.3		
Triloculina	1.38	7.1	8.82	52.12		
Eponides	1.18	5.88	7.3	59.42		
Amphistegina	5.13	8.91	11.7	11.7	***c***	**76.22**
Neoeponides	4.37	7.71	10.12	21.82		
Elphidium	4.33	7.61	9.98	31.79		
Quinqueloculina	4.35	7.58	9.94	41.73		
Peneroplis	3.63	6.14	8.06	49.79		
Reusella	2.98	4.76	6.24	56.04		
Amphistegina	3.86	6.42	8.28	8.28	***b***	**77.54**
Quinqueloculina	3.6	6.35	8.18	16.47		
Triloculina	3.27	5.68	7.33	23.79		
Elphidium	3.17	5.46	7.04	30.83		
Neoeponides	3.06	5.21	6.72	37.55		
Miliolinella	2.49	4.82	6.22	43.76		
Pyrgo	2.45	4.74	6.12	49.88		
Reusella	2.43	4.11	5.3	55.19		
Sigmamiliolinella	2.2	4.09	5.27	60.46		

TABLE 3. Continued.

Species	Av.Abund	Av.Sim	Contrib%	Cum.%	Group	Average Similarity
Amphistegina	3.45	11.17	15.38	15.38	***i***	**72.64**
Archaias	2.74	8.76	12.06	27.44		
Neoeponides	3	8.49	11.69	39.12		
Quinqueloculina	2.66	8.49	11.69	50.81		
Borelis	2.34	7.67	10.56	61.37		

The LBF species like *Peneroplis* and *Archaias* were less common in the more turbid southwest reef area, although water transparency was not indicated as a major driver in foraminiferal distribution (Fig. 5). Low water transparency decreases photosynthetic efficiency by endosymbionts, and abundant organic matter favors smaller heterotrophic taxa (Hald & Steinsund, 1992; Tarasova, 2006; Araújo & Machado, 2008a; Romano et al., 2008; Barbosa et al., 2009).

Stress-tolerant genera such as *Bolivina*, *Ammonia*, and *Nonion* showed the highest frequencies in the backreef, but only reduced the FI to <2 in four backreef stations. Some genera, including *Quinqueloculina*, *Miliolinella*, *Rosalina*, and *Gavelinopsis*, are not considered tolerant to stress, but can occur under estuarine influence inside the RFMP. The back reef of RFMP hosts coral species (Arantes & Seoane, 2017) on reef pinnacles of the leeward side of the reef flat, where indices indicated intermediate conditions, likely associated with very shallow depths and active water motion. Thus, the low results obtained using FI do not reflect the reality of reef health in very shallow water, as observed for Tamandaré Bay (Barbosa et al., 2016), where FSI showed better values than FI. This relation with water quality, more than sediment, was also found for coral reef health in southern South China Sea (A'ziz et al., 2021). However, Hallock et al. (2003) and Prazeres et al. (2020) both advised caution when working in depths <5 m, because reef-building corals are more influenced by conditions in the water column, allowing them to live in such conditions, whereas LBF numbers may be overwhelmed by smaller heterotrophic taxa in shallow waters.

The PCA analysis (Fig. 5) revealed that high FI and FSI values were found in samples with lower OM, higher $CaCO_3$, and sandy sediments, while heterotrophic and stress-tolerant taxa prevailed in muddy sediments with higher OM. However, the predominance of "sensitive" species in all except four samples (i.e., FI > 2, FSI always >6, see Fig. 3) indicates that hypoxia is not a major stressor, despite the exceptionally high organic matter in the sediment.

Overall, the application of the FI must consider a calibration that includes the environmental preferences of the genera present in the assemblage, as suggested by Renema (2008), the addition of a factor based on the diversity of large foraminifera in the assemblage, as suggested by Uthicke & Nobes (2008), or even a modified interpretation of the index (Carnahan et al., 2009). In our analysis, both environmental indices produced consistent results, indicating anthropogenic influences in the backreef. The higher sensitivity of the FSI compared to the FI can be attributed to the inclusion of heterotrophic and stress-tolerant genera as sensitive indicators. Consequently, elevated FSI values may not always correspond to high water quality in the RFMP. Nevertheless, despite variations in sensitivity, the results oscillate positively and negatively together, showing a general consistency. While more comparative studies are needed, differences between indices might be more semantic than reflective of the actual values, whether a "slightly polluted" result in the FSI matches "instability/stress" in the FI, or if "normal/pristine" in the FSI corresponds to "potential for recovery" or "stability" in the FI.

Since shallow reef environments are generally located in areas that receive coastal influences and pollutants, for the interpretation of both indices in a combined manner, not only a modified interpretation of the original FI is necessary, as suggested by Carnahan et al. (2009), but also an interpretation that integrates the results of both indices. Thus, we suggest, when using both indices, the following interpretation: Results <1 indicate heavily polluted to azoic conditions, impeditive of coral growth; between 1–2 indicate polluted conditions with low potential for the development of the carbonate fabric; between 2–4 indicate transitional benthic conditions that limit potential for accumulation of carbonate fabric or recovery; between 4–6 indicate generally suitable conditions for carbonate accretion, but can indicate decline if earlier indices >6; greater than 6 indicate suitable conditions for carbonate accretion, i.e., relatively pristine.

CONCLUSIONS

The possibility of assessing ecological traits over space and time is an exciting new frontier. Both univariate and multivariate analyses can and should play an important role in the study of taxonomic abundances applicable to environmental assessment. Geochemical studies and assessments using faunal indices can reveal areas requiring attention due to loss of environmental quality from contaminants and erosion predominating over carbonate deposition. Given the importance of RFMP as a location of endemic coral biodiversity in the south Atlantic, we demonstrated the value of an integrated approach to environmental assessment combining physical-chemical measurements and the responses of benthic bioindicators.

Abundant genera such as *Quinqueloculina* and *Elphidium* in the southwest, *Amphistegina* spp. on the reef pinnacles of backreef and forereef, and miliolids on reef flat reflected the sedimentation patterns and water quality inside the RFMP. In general, the faunal patterns agree with indices indicating equilibrium/stability for the forereef; a marginally stressed reef flat; and the backreef presenting areas where the community is under stress and experiencing instability associated with freshwater input from the Buranhém River. However, good FSI and FI values were able to show that the entire backreef is not negatively influenced by low water quality and heavy metal contamination from the river and coastal zone, likely because longshore currents, wave fronts, and tidal conditions provide exchange with offshore waters.

Further research using foraminifera will allow such temporal comparison and the compartmentalization of areas under different impacts in long-term monitoring. And future studies of foraminiferal assemblages from RFMP likely can indicate if the environment continues to sustain the coral and LBF assemblages, or if the terrestrial input continues to cause decline in their habitats and abundances.

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APPENDIX

Foraminiferal genera density per 10 grams of sediment of Recife de Fora sample stations.

The Appendix can be found linked to the online version of this article.

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