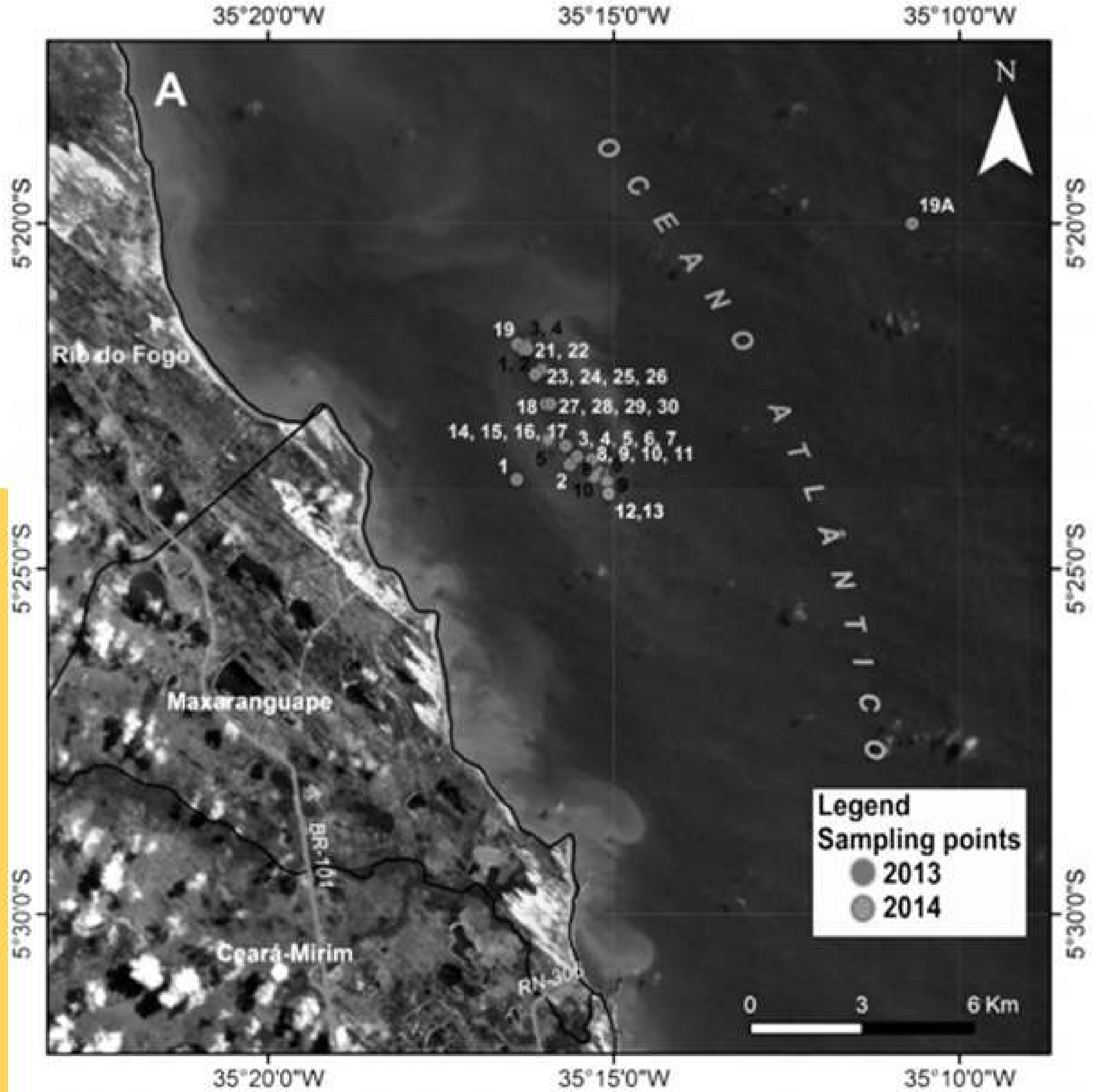


# "Large benthic symbiotic foraminifera biodiversity as means of propagules emission BIODIVERSITY AS CLIMAX INDICATORS"


**Patricia Beck Eichler-Barker**



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# Large benthic symbiotic foraminifera biodiversity as means of propagules distribution


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## Contents

## Abstract

The study indicates that both multivariate analyses and the FORAM index (FI) are dependable tools for evaluating water quality and reef health on coral reefs. The occurrence of foraminifera in reef areas is influenced by factors such as hydrodynamics and reworking processes. The abundance of smaller and stress-tolerant foraminifera, and the absence of symbiont-bearing taxa, suggesting unfavorable conditions for foraminifera in both the Pirangi and Maracajaú reef areas. Cluster analysis reveals distinct patterns of grouping sites among stations, which could be related to differences in ecological indices. Sites are categorized based on their potential for reef growth after a stress event. The presence of sand availability, $CaCO_3$, silt, and clay are key factors affecting the occurrence of heterotrophic and stress-tolerant foraminifera. In Maracajau, total organic matter also contributes to the occurrence of these genera. The FORAM index indicates that the water quality in Pirangi is unsuitable for coral reef growth, while Maracajau has sites that are conducive to reef growth. However, some individual sites in Maracajau are unsuitable for coral survival after a stressful event. The number of foraminifera individuals is low in areas close to tourist sites, while non-reef areas have no individuals. Opportunistic species are dominant in coastal stations where people walk on reefs. Based on an analysis of past, present, and future biodiversity, the study proposes the establishment of permanent conservation areas to manage the Pirangi Marine National Park in Brazil. The Pirangi area has the lowest indices of diversity and environmental stability, with opportunistic species dominating and a dearth of symbiotic foraminifera with algae. Coarse and sand fractions are the critical factors controlling the environment, while depositional energy plays a crucial role in sediment and foraminifera transport and deposition. The establishment of a conservation area is necessary to rehabilitate and preserve the marine environment of the reefs as a source of propagules.

**Keywords:** sedimentary reef, diversity, propagules, ecology, succession, community, stable, quantitative, spatial

## Introduction

The concept of diversity is crucial in ecology and is often used to describe the range of different species and characteristics within an ecological community. In marine environments, the sediment-water interface properties attract specific indicator organisms that dominate the area. However, diverse environments can be colonized by differing species with differing characteristics.

A climax community is an ecological community in which populations of plants or animals remain stable and exist in balance with each other and their environment. This community has the maximum diversity and is in the final stage of succession. However, in the Anthropocene, human activities have destroyed many climax ecosystems through acute accidents or chronic human interference.

The larger Benthic Foraminiferal association with symbiotic organisms is sensitive to changes in abiotic parameters of surrounding water and sediment, and its presence in climax ecosystems can propagate diversity by increasing adjacent and near areas' biodiversity through the movement of currents and bioturbation. Quantitative assessment of how spatial and environmental variables shape the biodiversity of Larger Forams with their symbiotic organisms in three sedimentary reef areas can help identify areas that can be preserved to improve neighboring areas' diversity through propagule emission.

Preservation areas should be implemented in each of the three sedimentary reef areas to improve neighboring areas' diversity through propagule emission. If one very biodiverse part of the whole is preserved during all times, it can benefit the whole by increasing the total diversity of these three differentiated ecosystems. Quantitative assessments of spatial and environmental variables can aid in identifying and protecting critical areas for biodiversity conservation.

Large benthic symbiotic foraminifera are a group of single-celled organisms that live on the ocean floor and form symbiotic relationships with algae. These foraminifera are important members of marine ecosystems, and they play a crucial role in the cycling of carbon and other nutrients.

One of the ways in which large benthic symbiotic foraminifera can propagate is by emitting propagules, which are small, reproductive structures that can develop into new individuals. The higher the biodiversity of these foraminifera, the greater the number of different propagules that can be emitted. This, in turn, can increase the chances of successful reproduction and the survival of the species.

In addition to propagule emission, higher biodiversity of large benthic symbiotic foraminifera can also have other ecological benefits. For example, it can increase the overall resilience and stability of marine ecosystems by providing redundancy in ecological functions. This means that if one species is lost, another species can take its place and maintain the same ecological function.

Furthermore, large benthic symbiotic foraminifera are important indicators of environmental health, as they are sensitive to changes in water quality, temperature, and other environmental factors. Therefore, maintaining and increasing the biodiversity of these foraminifera can help to monitor and preserve the health of marine ecosystems. Higher biodiversity of large benthic symbiotic foraminifera can have multiple benefits, including increased propagule emission, greater ecological resilience, and improved environmental monitoring.

A comprehensive survey was conducted using a quantitative assessment of how spatial and environmental variables shape the biodiversity of Larger Forams with their symbiotic organisms in three sedimentary reef areas. The survey included measuring environmental variables such as water and sediment quality, temperature, salinity, and light availability. These environmental variables were measured at different depths and locations within each reef area to capture spatial variability. To measure biodiversity, samples of sediment and water were collected from different locations within each reef area. The samples were analyzed to identify the species of Larger Forams present, as well as their abundance and distribution within each reef area. The symbiotic organisms associated with the Larger Forams were also identified and analyzed.

The data collected was analyzed using statistical techniques to identify relationships between environmental variables and biodiversity. Multiple regression analysis was used to identify which environmental variables are most strongly correlated with biodiversity.

Based on the results of the quantitative assessment, preservation areas should be implemented in each of the three sedimentary reef areas. These preservation areas should be located in areas where propagule emission is capable of reaching neighboring marine sites and improving diversity. Overall, the quantitative assessment of how spatial and environmental variables shape the biodiversity of Larger Forams with their symbiotic organisms provided valuable information for conservation efforts and the development of preservation areas in sedimentary reef areas.

We have recommended implementing preservation areas in each high biodiversity spot where propagules emissions are capable to reach out to other adjacent marine sites and can actually improve the diversity of neighboring areas.

## Sedimentary reefs

Coral reefs and sedimentary algae-dominated reefs are both under threat due to a combination of climate change and local water quality issues. Coral reefs are particularly vulnerable to environmental stressors such as warming sea temperatures, ocean acidification, and pollution. These stressors can cause coral bleaching, a phenomenon in which corals expel their symbiotic algae, leading to the death of the coral colony if the stress persists for too long. In addition to coral bleaching, other threats to coral reefs include overfishing, destructive fishing practices, coastal development, and ocean acidification.

Sedimentary algae-dominated reefs, also known as macroalgae-dominated reefs, are also under threat from climate change and local water quality issues. Macroalgae thrive in nutrient-rich waters, and excess nutrients from human activities such as agriculture and sewage can lead to an overgrowth of macroalgae, which can smother and kill coral colonies. In addition, climate change is causing shifts in the balance of reef ecosystems, favoring macroalgae over corals in some regions.

Both coral reefs and macroalgae-dominated reefs are declining globally due to a combination of environmental stressors. To protect these important marine ecosystems, it is crucial to address both climate change and local water quality issues through measures such as reducing greenhouse gas emissions, protecting marine habitats, and implementing sustainable fishing and agricultural practices.

The high diversity of climax ecosystems like marine reef areas can make them more resistant to biological invasions, but if the biodiversity has been lost, it can be more susceptible to invasion by exotic species. Additionally, the relationship between benthic foraminifera with and without symbionts can be used to understand the resilience of reef ecosystems and has potential applications in various fields related to climate change.

Foraminifera symbiont community diversity metrics can be used is in climate change adaptation. As ocean temperatures rise, coral reefs are becoming more stressed, which can lead to the loss of symbiotic algae and the death of the coral colony. However, some species of foraminifera are able to tolerate higher temperatures by hosting different types of symbiotic algae. By studying the diversity of symbiotic algae in foraminifera communities, researchers can identify which species are better able to adapt to warming waters and potentially use them as a basis for interventions to help protect coral reefs from the impacts of climate change.

Another example is in mitigation efforts, such as reducing pollution and improving water quality. Benthic foraminifera are highly sensitive to changes in water quality, and changes in their community composition can indicate changes in the health of reef ecosystems. By monitoring foraminifera communities and identifying which species are more sensitive to pollution, researchers can develop targeted interventions to improve water quality and mitigate the impacts of human activities on reef ecosystems.

Finally, the use of symbiont community diversity metrics can also be applied to remediation efforts, such as the restoration of degraded reef ecosystems. By understanding the relationships between foraminifera with and without symbionts, researchers can identify which species are more likely to survive in degraded ecosystems and use them as a basis for restoration efforts. Additionally, by monitoring the diversity of symbiotic algae in foraminifera communities, researchers can track the success of restoration efforts over time.

Overall, the study of benthic foraminifera with and without symbionts can provide valuable insights into the resilience of reef ecosystems and has potential applications in a range of fields related to climate change. High species diversity in small protected areas can enhance invasion resistance by increasing crowding and species richness in localized marine neighborhoods. This can reduce the establishment and success of invading species, ultimately helping to protect the existing biodiversity in the area.

When a diverse community of species is present in a given area, the limited space and resources available can become crowded, making it more difficult for invading species to establish themselves. Additionally, the presence of a variety of native species can create a complex web of interactions and ecological niches, which can make it more difficult for invading species to find a suitable place to fit in.

Furthermore, the success of invading species can also be reduced in diverse communities. In ecosystems with high diversity, there are typically many species that are well-adapted to the local conditions and have already filled the available ecological niches. As a result, invading species may struggle to compete with the existing native species, reducing their chances of becoming successful invaders.

Overall, local biodiversity represents an important line of defense against the spread of invaders and the loss of precious biodiversity. By protecting and promoting diversity in marine ecosystems, we can help to reduce the establishment and success of invading species, ultimately protecting the existing biodiversity and preventing fauna replacement.

## Symbiont-bearing species

Certain species of benthic foraminifera, particularly those in the genus *Amphistegina*, are known to thrive in coral reef habitats and are affected by global and local environmental stresses in ways similar to hermatypic corals. These foraminiferal species host diverse algal endosymbionts that provide them with several potential advantages, including energy from photosynthesis, enhancement of calcification, and uptake of host metabolites by symbiotic algae.[1]

Like corals, these foraminiferal species host algal endosymbionts, which provide them with energy from photosynthesis. This energy can be used by the foraminifera to support growth and reproduction, as well as other metabolic processes. Additionally, the presence of symbiotic algae can enhance calcification in foraminifera, allowing them to build their calcium carbonate shells more efficiently.

Finally, symbiotic algae can also uptake host metabolites from the foraminifera, which can help to regulate the internal environment of the host and provide additional nutrients. These benefits of algal symbiosis have allowed foraminifera to thrive in a wide range of marine environments, including coral reefs, and have made them an important component of these ecosystems.

However, like corals, benthic foraminifera with algal endosymbionts are also vulnerable to environmental stresses, such as changes in water temperature, pollution, and ocean acidification. When stressed, the symbiotic relationship between the foraminifera and their algal endosymbionts can break down, leading to a loss of energy and other benefits provided by the algae. This can ultimately lead to declines in the abundance and diversity of benthic foraminifera and other associated reef organisms.

Overall, the presence of algal endosymbionts in benthic foraminifera can provide important benefits, including energy from photosynthesis, enhancement of calcification, and uptake of host metabolites. However, these species are also vulnerable to environmental stresses and are impacted by changes in their surrounding marine environment, highlighting the importance of conservation and protection efforts for these important reef organisms.

The FORAM Index (FI) is a proxy measure of water quality relevant to coral-reef health, developed by Hallock et al.,[2] based on the composition of the entire community of benthic foraminifera. It is computed based on the proportions of three species groups: symbiont-bearing foraminifera (SBF), “opportunistic” or “stress-tolerant” foraminifera, and other small taxa.

The SBF group includes several relatively large species of foraminifera that have a mutualistic relationship with photosynthetic algae (zooxanthellae). These foraminifera prefer nutrient-poor, shallow, warm-water environments, similar to hermatypic corals.

The "opportunistic" or "stress-tolerant" foraminifera group includes species that can tolerate a wide range of environmental conditions and are often found in disturbed or polluted habitats. The other small taxa group includes various species of foraminifera that do not fit into the other two groups.

The FI provides a measure of the relative health of coral reefs, with higher values indicating better water quality and healthier coral communities. A high proportion of SBF in the foraminifera community suggests that the environment is nutrient-poor and that corals are likely to be healthy. In contrast, a high proportion of opportunistic or stress-tolerant foraminifera suggests that the environment is disturbed or polluted and that coral health may be compromised.

The FORAM Index has been widely used in coral-reef environmental studies to assess water quality and its relation to coral health. Studies in diverse regions, such as off the coasts of Florida,[2,3] Puerto Rico,[2] Colombia,[4] Australia,[5–8] and Kiritimati/Christmas Island[9] have successfully shown a correlation between higher FI values and healthier coral communities, indicating lower nitrification and better water quality.

However, two studies from Indonesia and Fiji[10] and Fiji[11] have reported conflicting results. In the case of Indonesia, the trend between higher FI values and coral growth and lower nitrification is unclear, and in Fiji, the relationship is negative, indicating that higher FI values are associated with poorer water quality and lower coral health.

Studies of reef foraminifera off the state of Bahia in Brazil have shown that the FI values do not fit the model established by Hallock et al.[2] in the southern Gulf of Mexico and the northern Caribbean Sea. In both nearshore and offshore reefal areas of Bahia (Corumbau and Abrolhos), low FI values are everywhere, suggesting deterioration of water quality, although coral communities may be thriving at many sampling sites. In contrast, Barbosa et al.[12] show high FI values at some sites with a low coral cover but a high macroalgal cover, indicating that the FI may not always be a reliable indicator of coral-reef health in this region.

Further studies of Abrolhos reefs by Oliveira-Silva et al.[13] and Barbosa et al.[14] found anomalies in the FI values, which they attributed to the presence of palimpsest sediment, which can disguise the FI and prevent it from correlating with coral cover. Despite these anomalies, the FI remains a useful tool for tracking environmental changes related to ENSO events, as demonstrated by Kelmo and Hallock[15] in their investigation of historical FI trends in northern Bahia.

Overall, the studies conducted in Brazil highlight the need for caution when interpreting FI values in regions with unique environmental conditions and diverse coral communities. While the FI can provide valuable information about water quality and its impact on coral-reef health, it should be used in conjunction with other measures and interpreted in the context of local environmental conditions.

## Field and laboratory procedures

### Sampling sites

In June 2013 and July 2014, scuba divers scooped surface sediment in 55 stations in Pirangi and 40 stations in Maracajaú Reef areas (Figure 1 & 2). The sampling covered reef areas, sandy sediments, and macroalgae substratum. Although the same areas were sampled twice, the exact station locations differed between 2013 and 2014. Therefore, two separate data sets (Tables 1 & 2, Figure 3) were obtained for each area.

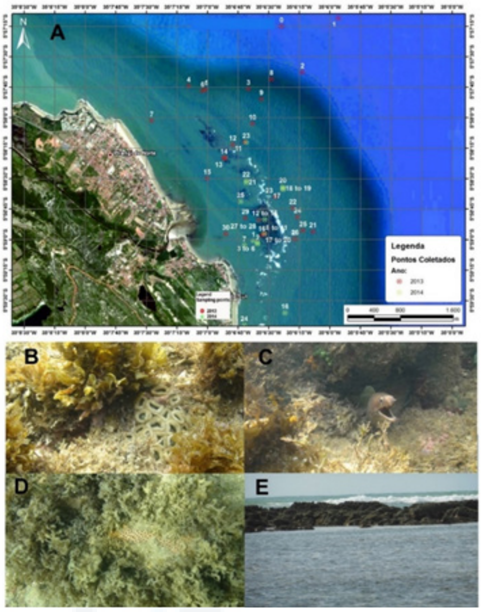



**Figure 1** A) a map displaying the sampling sites at Pirangi Reefs in 2013 and 2014; B), C), and D) submerse images of coral reefs; and E) a view of the Pirangi Reefal area.

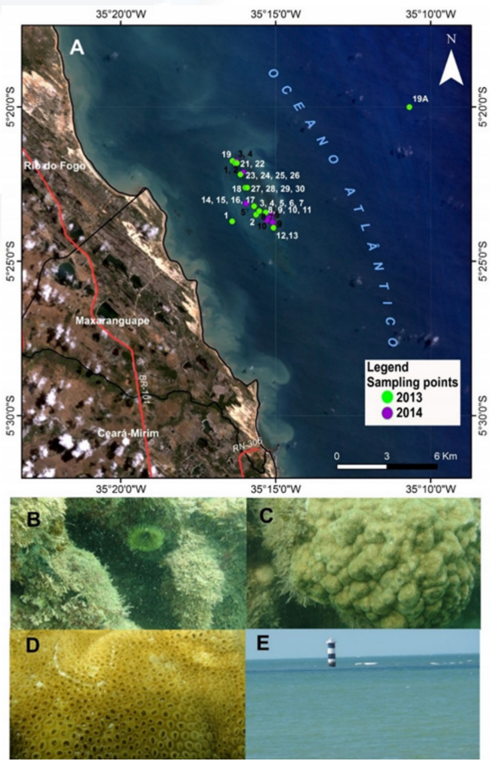



**Figure 2** A) a map showing the sampling sites at Maracajaú Reefs in both 2013 and 2014; B), C), and D) submerse images of coral reefs; and E) a view of the Maracajaú Reefal area.


**Figure 3** displays the cores that were collected in Pirangi and Maracajau in 2013.

**Table 1** Contains abiotic data collected from Pirangi in both 2013 and 2014

| Pirangi 2013 | Latitude | Longitude | Depth | Pirangi 2014 | Latitude | Longitude | Depth |
|---|---|---|---|---|---|---|---|
| **0** | 5-57-15 | 35-0623.8 | 10 | **1** | 5°59'05.5" | 35°06'37.5" | 12 |
| **1** | 5-57-11 | 35-05-55.8 | 12 | **2** | 5-59-02.1 | 35-06-35.5 | 3 |
| **2** | 5-57-37.6 | 35-06-13.5 | 9.5 | **3** | 5-59-01.3 | 35-06-35.5 | 4 |
| **3** | 5-57-45.8 | 35-06-40 | 12 | **4** | SAME | SAME | |
| **4** | 5-57-44.4 | 35-07-09.3 | 7 | **5** | SAME | SAME | |
| **5** | 5-57-46 | 35-07-00.9 | 1.5 | **6** | SAME | SAME | |
| **6** | 5-57-46.8 | 35-07-02.5 | 5 | **7** | 5-59-02.8 | 35-06-42.0 | - |
| **7** | 5-58-01.5 | 35-07-27.5 | 5.4 | **8** | 5-58-57.2 | 35-06-32.1 | 1 |
| **8** | 5-57-41 | 35-06-28.7 | 13 | **9** | SAME | SAME | |
| **9** | 5-57-50.8 | 35-06-33.6 | 13.5 | **10** | SAME | SAME | |
| **10** | 5-58-02.9 | 35-06-37.9 | 10 | 11 | SAME | SAME | |
| **11** | 5-58-11.9 | 35-06-41.8 | 11 | **12** | 5-58-50.1 | 35-06-32.0 | 2 |
| **12** | 5-58-13.2 | 35-06-47.6 | 8 | **13** | SAME | SAME | |
| **13** | 5-58-19.9 | 35-06-51.4 | 1.5 | **14** | SAME | SAME | |
| **14** | 5-58-19.8 | 35-06-51.9 | 1.5 | **15** | SAME | SAME | |
| **15** | 5-58-29.8 | 35-07-00.2 | 4.6 | **16** | 05° 5936 | 35° 0622 | 1 |
| **16** | 5-58-57.7 | 35-06-33.3 | 0.7 | **17** | 05° 5835.3 | 35° 0622,8 | 1 |
| **17** | SAME | SAME | | **18** | 05° 5834.8 | 35° 0623.1 | 1 |
| **18** | 5-58-57.0 | 35-06-32.0 | 1 | **19** | SAME | SAME | |
| **19** | SAME | SAME | | **20** | SAME | SAME | |
| **20** | SAME | SAME | | **21** | 05° 5832 | 35° 0641 | 1 |
| **21** | 5-58-56.0 | 35-06-08.2 | 9 | **22** | 05°5831 | 35°0641 | 4 |
| **22** | 5-58-44.5 | 35-06-18.1 | 11 | **23** | 05° 5812 | 35° 0641 | 1 |
| **23** | 5-58-39.0 | 35-06-26.7 | 8 | **24** | 05° 5942 | 35° 0642 | 3 |
| **24** | 5-58-48.8 | 35-06-15.9 | 7 | **25** | 05°5841.2 | 35°0643.8 | 2 |
| **25** | 5-58-55.5 | 35-06-13.1 | 6 | | | | |
| **26** | 5-58-59.6 | 35-06-17.1 | 4 | | | | |
| **27** | 5-58-50.3 | 35-06-34.9 | 2.5 | | | | |
| **28** | SAME | SAME | | | | | |
| **29** | 5-58-49.4 | 35-06-41.4 | 3.5 | | | | |
| **30** | 5-58-57.2 | 35-06-51.0 | 3.5 | | | | |

**Table 2** presents abiotic data collected from Maracajaú in both 2013 and 2014. In both areas, eight cores were collected, with lengths varying from 22 to 25 cm (as shown in Figure 3)

| Maracajaú 2013 | Latitude | Longitude | Depth | Maracajaú 2014 | Latitude | Longitude | Depth |
|---|---|---|---|---|---|---|---|
| **1** | 05° 23' 42,4" | 35° 16' 24,1" | 3.5 | 1 | 05º22'07.2" | 35º16'02.8" | 4.2 |
| **2** | 05° 23' 29,2" | 35° 15' 37,7" | 4 | 2 | same | same | |
| **3** | 05° 23' 22,5" | 35° 15' 31,6" | 2.5 | 3 | 05-21-45.2 | 35-16-15.7 | 3.4 |
| **4** | 05° 23' 22,5" | 35° 15' 31,6" | 3.5 | 4 | same | same | |
| **5** | 05° 23' 22,5" | 35° 15' 31,6" | 3.5 | 5 | 05-23-07.6 | 35-15-56.9 | 3 |
| **6** | 05° 23' 22,5" | 35° 15' 31,6" | 3.5 | 6 | 05°23'29.5" | 035°15'08.9" | 2.5 |
| **7** | 05° 23' 22,5" | 35° 15' 31,6" | 3.5 | 7 | 05°23'29.4" | 035°15'09.0" | 2.4 |
| **8** | 05° 23' 25,2" | 35° 15' 19,0" | 2.5 | 8 | 05°23'33.2" | 035°15'09.7" | 1 |
| **9** | 05° 23' 25,2" | 35° 15' 19,0" | 2.5 | 9 | 05°23'44.0" | 035°15'05.6" | 2.1 |
| **10** | 05° 23' 25,2" | 35° 15' 19,0" | 2.5 | 10 | 05°23'39.6" | 035°15'17.0" | 2.2 |
| **11** | 05° 23' 25,2" | 35° 15' 19,0" | 2.5 | | | | |
| **12** | 05° 23' 54,8" | 35° 15' 03,9" | 4 | | | | |
| **13** | 05° 23' 54,8" | 35° 15' 03,9" | 3.2 | | | | |
| **14** | 05° 23' 13,0" | 35° 15' 41,6" | 2.1 | | | | |
| **15** | 05° 23' 13,0" | 35° 15' 41,6" | 3.7 | | | | |
| **16** | 05° 23' 13,0" | 35° 15' 41,6" | 2.5 | | | | |
| **17** | 05° 23' 13,0" | 35° 15' 41,6" | 2.5 | | | | |
| **18** | 05° 22' 36,7" | 35° 15' 58,7" | 2.5 | | | | |
| **19A** | 05° 20' 00,1" | 35° 10' 40,8 | 4 | | | | |
| **19** | 05° 21' 44,9" | 35° 16' 23,5" | 4 | | | | |
| **20** | 05° 21' 48,9" | 35° 16 18,2" | 4 | | | | |
| **21** | 05° 21' 54,2" | 35° 16' 15,0" | 5 | | | | |
| **22** | 05° 21' 54,2" | 35° 16' 15,0" | 5.4 | | | | |
| **23** | 05° 22' 11,2" | 35° 16' 8,2" | 3.9 | | | | |
| **24** | 05° 22' 11,2" | 35° 16' 8,2" | 3.9 | | | | |
| **25** | 05° 22' 11,2" | 35° 16' 8,2" | 3.9 | | | | |
| **26** | 05° 22' 11,2" | 35° 16' 8,2" | 3.9 | | | | |
| **27** | 05° 22' 36,8" | 35° 15' 55,1" | 3.5 | | | | |
| **28** | 05° 22' 36,8" | 35° 15' 55,1" | 3.5 | | | | |
| **29** | 05° 22' 36,8" | 35° 15' 55,1" | 3.5 | | | | |
| **30** | 05° 22' 36,8" | 35° 15' 55,1" | 3.5 | | | | |
| **T1** | 11 | | 2.5 | | | | |
| **T2** | 11A | | 2.5 | | | | |
| **T3** | 21 | | 5 | | | | |
| **T4** | 27 | | 3.5 | | | | |

## Laboratory methods

Recent sediment samples were obtained using a van Veen grab sampler, and the uppermost 1 cm was subsampled for foraminiferal analysis. To identify live specimens, the samples were stored in a mixture of 1 g rose Bengal in distilled water. The sediments were processed following standard procedures,[16] which involved washing a fixed volume of 50 $cm^3$ of sediment through a 0.063-mm sieve. After drying, the samples were split using a microsplitter into subsamples of 100 living specimens, which were then counted. When the number of foraminifers in a sample was less than 100, all specimens were counted. Species identification and counting of dry specimens were conducted under an optical microscope. Although only a few tests were stained by rose Bengal, all of the data were based on total foraminifera counts, and scanning electron micrographs were obtained to clarify ambiguous identifications. Field recording of water temperature, salinity, and oxygen were performed, but they did not reveal any noticeable variations or trends within either area. Additionally, granulometry of sediments was conducted and compared with foraminiferal fauna.

Cores were manually extracted and dried for several weeks. After drying, they were cut in half, and pictures were taken. Subsequently, foraminiferal fauna was sub-sampled every 2 cm. The length of the cores varied from 20 to 25 cm. Based on the sedimentation rate for inner continental shelves,[17] we can estimate that 1 cm represents one year in the past.

## Numerical analyses

To assess changes in community structure, diversity and dominance indices were used in conjunction. Specifically, Pielou evenness, Shannon-Wiener diversity, and Simpson dominance indices[18] were computed. The Primer program developed at the University of Plymouth[19] was used to perform these calculations.

Multivariate analyses were used to analyze both the environmental and foraminiferal data. Principal components analysis (PCA) was performed on the environmental data to identify patterns and correlations among variables. Cluster analysis and non-metric multidimensional scaling (MDS) were used to analyze the foraminiferal data and create a "map" of sample similarity based on biological communities and environmental patterns, rather than just geographical location. The BIOENV or BEST analysis was used to match the biotic data sets with the best match between multivariate patterns of the assemblages. The diversity, dominance, evenness, PCA, cluster, MDS, and BIOENV/BEST analyses were all carried out using the PRIMER v6 program developed at the University of Plymouth, which is described in various publications by Clarke and Warwick,[19] Clarke and Ainsworth,[20] and Clarke.[21] The BEST analysis or Biota and Environment (BIOENV) matching was performed using the Spearman Rank correlation method and resemblance measure with Euclidean distance.

The FORAM Index (FI) is a method used to assess the potential for reef growth based on the proportions of three groups of foraminiferal species: symbiont-bearing, opportunistic or stress-tolerant, and other small taxa.[2,22] The index heavily weights symbiont-bearing species, which are important for reef growth. The FI is calculated using the proportions of these three groups (Ps, Po, and Ph) according to the formula $(10 \times Ps) + Po + (2 \times Ph)$. A value of >4 indicates an environment conducive to reef growth. In RN reefs, there are seven species of symbiont-bearing foraminifera: 1. *Amphistegina gibbosa, 2. Amphisorus hemprichii, 3. Archaias angulatus, 4. Borelis schlumbergeri, 5. Heterostegina depressa, H. antillarum, 6. Peneroplis carinatus 7. Laevipeneroplis proteus* (Figure 4). To have an FI >2, there must be some symbiont-bearing taxa, and for an FI >4, symbiont-bearing taxa must make up at least 25% of the assemblage (Figure 4).


**Figure 4** Symbiont-bearing foraminifera in RN reefs: 1. *Amphistegina gibbosa*, 2. *Amphisorus hemprichii*, 3. *Archaias angulatus*, 4. *Borelis schlumbergeri*, 5. *Heterostegina depressa*, *H. antillarum*, 6. *Peneroplis carinatus* 7. *Laevipeneroplis proteus*.

Based on Table 3 and Figure 5, it seems that the sediment characteristics and chemical composition vary across the different stations sampled. Stations 17 and 27 had a higher percentage of coarse fraction and $CaCO_3$, while stations 1, 3, 7, 10, 15, 22, and 30 had lower values of coarse fraction and/or sand. Higher $CaCO_3$ at 17 and 18 close to the area of tourism and 27 and 28 from outer reef. Stations 3, 7, and 29 had higher silt and clay content, and stations 7 and 22 had higher total organic matter. The depth also varied across the stations, ranging from 0.7 to 13.5m, and most stations were located in the outer reef, except for coastal station 30. These differences in sediment characteristics and depth may contribute to the observed differences in the foraminiferal communities across the different stations.

**Table 3** Granulometry of sediment from Pirangi 2013

| Pirangi 2013 | Depth (m) | Coarse (%) | Sand (%) | Silt (%) | Clay (%) | TOM (%) | Caco3 (%) |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 27.84 | 70.82 | 1.07 | 0.27 | 0.03 | 32.80 |
| 2 | 9.5 | 2.08 | 97.75 | 0.13 | 0.03 | 0.83 | 3.70 |
| 3 | 12 | 23.62 | 56.65 | 10.99 | 8.75 | 3.23 | 58.70 |
| 7 | 5.4 | 0.00 | 65.16 | 16.96 | 17.88 | 9.10 | 39.40 |
| 8 | 13 | 3.84 | 96.16 | 0.00 | 0.00 | 1.03 | 19.40 |
| 9 | 13.5 | 16.92 | 82.91 | 0.17 | 0.00 | 2.07 | 44.80 |
| 10 | 10 | 0.57 | 99.43 | 0.00 | 0.00 | 1.27 | 73.90 |
| 11 | 11 | 11.62 | 88.21 | 0.17 | 0.00 | 1.63 | 81.00 |
| 15 | 4.6 | 0.00 | 98.73 | 1.27 | 0.00 | 4.93 | 56.10 |
| 17 | 0.7 | 44.54 | 54.95 | 0.51 | 0.00 | 2.70 | 81.10 |
| 18 | 1 | 17.70 | 81.65 | 0.65 | 0.00 | 2.80 | 84.00 |
| 22 | 11 | 0.08 | 99.41 | 0.51 | 0.00 | 14.67 | 45.20 |
| 26 | 4 | 9.93 | 89.14 | 0.93 | 0.00 | 3.00 | 32.30 |
| 27 | 2.5 | 40.50 | 57.61 | 1.90 | 0.00 | 3.37 | 88.10 |
| 28 | 2.5 | 15.99 | 84.01 | 0.00 | 0.00 | 2.87 | 98.40 |
| 29 | 3.5 | 4.41 | 60.43 | 14.58 | 20.57 | 4.67 | 50.60 |
| 30 | 3.5 | 0.00 | 99.05 | 0.95 | 0.00 | 2.07 | 23.60 |

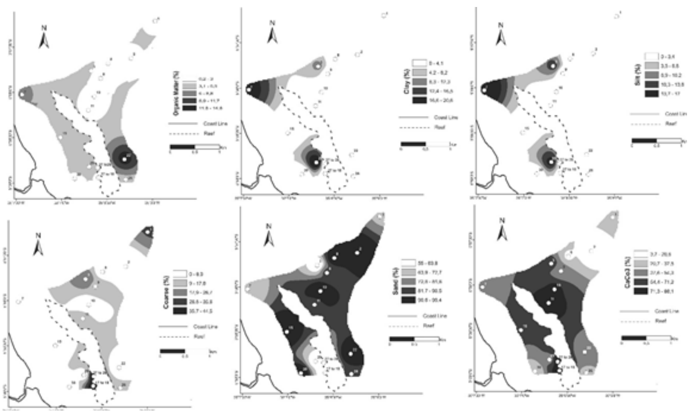


**Figure 5** Percentage of organic matter, clay, silt, coarse, sand and CaCO3 in Pirangi for 2013.

## PCA (principal component analysis)

Principal Component Analysis (PCA) is a multivariate statistical technique used to identify patterns and relationships among different variables. In this case, PCA was used to analyze the correlation among different environmental variables measured at different stations in Pirangi reef in 2013.

The results of PCA showed that the first two principal components (PC1 and PC2) explained 67.7% of the total variance among the variables (Table 4). This indicates that these two components are the most important for explaining the correlations among the variables.

**Table 4** Cumulative variation of abiotic variables that explain the foraminiferal fauna

| PC | Eigenvalues | %Variation | Cum. %Variation |
|---|---|---|---|
| 1 | 2.6 | 37.1 | 37.1 |
| 2 | 2.14 | 30.6 | **67.7** |
| 3 | 1.11 | 15.8 | 83.5 |
| 4 | 0.723 | 10.3 | 93.8 |
| 5 | 0.41 | 5.9 | 99.7 |

According to the loading plot (Figure 6), stations 17 and 27 had the highest loading of coarse fraction, which is consistent with the previous findings. Additionally, stations 18, 27, 28, and 17 had the highest percentage of CaCO3, indicating that these stations are located in areas with higher reef development potential.

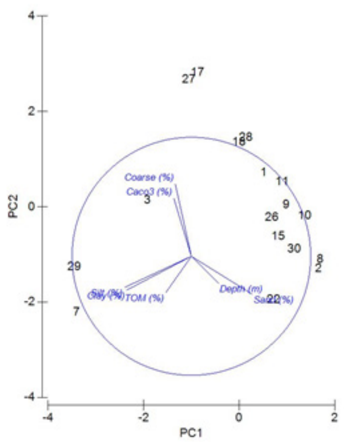



**Figure 6** Plot representing PCA analysis for Pirangi 2013.

Station 22, which is the deepest station, had the highest percentage of sand. Stations 7 and 29 had the highest percentage of silt, clay, and total organic matter (TOM), suggesting that these stations are located in areas with higher sedimentation rates and higher organic matter content.

According to the PCA analysis, the first two principal components explain up to 60.7% of the total variance (Table 5). PC1 is characterized by high positive values for the percentage of sand and depth, as seen in both Table 5 and Figure 6. Conversely, PC1 has high negative values for the percentage of silt and clay, which are associated with the presence of other types of foraminifera such as heterotrophic and stress-tolerant species. PC2, on the other hand, is characterized by high positive values for coarse fraction and calcium carbonate content.

**Table 5** PCA axes values for abiotic variables

| Variable | PC1 | PC2 | PC3 | PC4 | PC5 |
|---|---|---|---|---|---|
| Coarse (%) | **-0.135** | **0.607** | -0.254 | -0.23 | -0.364 |
| Sand (%) | **0.506** | **-0.317** | 0.295 | 0.108 | 0.183 |
| Silt (%) | **-0.559** | **-0.261** | -0.126 | 0.082 | 0.136 |
| Clay (%) | **-0.544** | **-0.285** | -0.102 | 0.155 | 0.207 |
| TOM (%) | **-0.212** | **-0.303** | 0.51 | -0.698 | -0.337 |
| Caco3 (%) | **-0.147** | **0.489** | 0.405 | -0.222 | 0.725 |
| Depth (m) | **0.225** | **-0.226** | -0.63 | -0.606 | 0.365 |

The depth of the stations in the area varied from 2.1 to 5.4 meters. Stations 17, 24, 20, and 22 had a higher percentage of coarser fractions, while stations 2, 4, 5, and 11 had the lowest values of the coarser fractions. The highest percentage of sand was found at stations 1, 2, 8, 12, 13, 19, and 22, whereas the lowest value for sand was found at stations 5, 7, 17, and 27. Stations 5, 7, 17, 23, and 27 had the highest average of silt and clay, whereas stations 1, 2, 12, 13, 19, 20, 21, 22, and 24 had the lowest percentage of silt and clay. The stations with the highest total organic matter (TOM) were 7 and 22, while station 12 had the lowest. Higher levels of $CaCO_3$ were found at stations 17 and 18, which are close to the touristic area, and at stations 27 and 28, which are from the outer reef. These findings are presented in Table 6 and Figure 7.

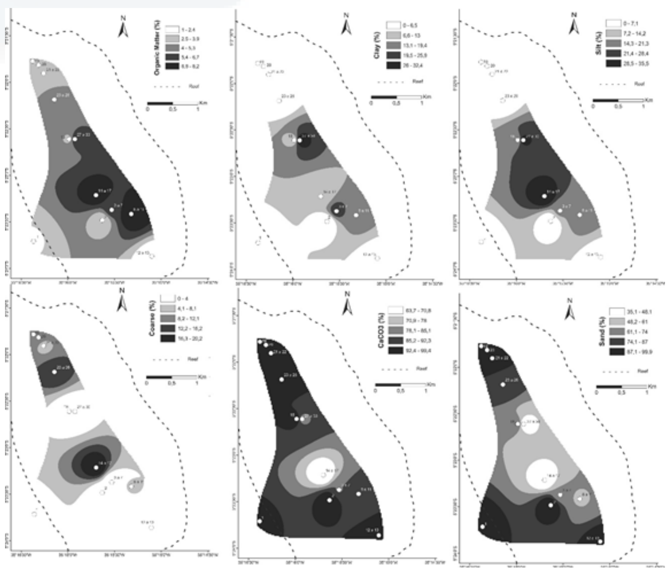


**Figure 7** Percentage of organic matter, clay, silt, coarse, sand and CaCO3 in Maracajau for 2013.

**Table 6** Granulometry of sediment from Maracajau 2013

| Maracajaú 2013 | Depth (m) | Coarse (%) | Sand (%) | Silt (%) | Clay (%) | TOM (%) | Caco3 (%) |
|---|---|---|---|---|---|---|---|
| 1 | 3.5 | 1.70 | 97.72 | 0.48 | 0.10 | 2.30 | 93.90 |
| 2 | 4 | 0.00 | 99.93 | 0.07 | 0.00 | 2.70 | 98.60 |
| 3 | 2.5 | 0.43 | 70.26 | 15.08 | 14.23 | 4.83 | 87.30 |
| 4 | 3.5 | 0.08 | 61.56 | 15.78 | 22.59 | 6.13 | 85.00 |
| 5 | 3.5 | 0.00 | 32.76 | 34.02 | 33.22 | 15.03 | 76.40 |
| 6 | 3.5 | 2.06 | 44.60 | 22.66 | 30.67 | 6.40 | 84.90 |
| 7 | 3.5 | 1.06 | 37.59 | 32.98 | 28.37 | 4.57 | 86.60 |
| 8 | 2.5 | 1.61 | 96.14 | 1.95 | 0.31 | 3.23 | 96.20 |
| 9 | 2.5 | 4.16 | 60.24 | 19.39 | 16.21 | 8.18 | 88.00 |
| 10 | 2.5 | 4.84 | 87.11 | 6.50 | 1.56 | 3.83 | 97.90 |
| 11 | 2.5 | 0.14 | 79.07 | 5.48 | 15.31 | 2.63 | 97.10 |
| 12 | 4 | 2.86 | 96.80 | 0.27 | 0.07 | 0.97 | 99.10 |
| 13 | 3.2 | 1.05 | 98.95 | 0.00 | 0.00 | 3.30 | 97.70 |
| 14 | 2.1 | 2.73 | 72.83 | 10.93 | 13.50 | 4.53 | 76.60 |
| 15 | 3.7 | 1.93 | 51.24 | 29.57 | 17.26 | 4.70 | 92.50 |
| 17 | 2.5 | 20.24 | 36.86 | 35.66 | 7.24 | 7.67 | 63.67 |
| 18 | 2.5 | 1.96 | 75.72 | 15.06 | 7.26 | 3.47 | 97.20 |
| 19 | 4 | 8.39 | 91.10 | 0.41 | 0.10 | 3.40 | 99.40 |
| 20 | 4 | 10.92 | 88.02 | 0.85 | 0.20 | 2.40 | 97.70 |
| 21 | 5 | 7.31 | 92.70 | 0.00 | 0.00 | 2.93 | 97.50 |
| 22 | 5.4 | 8.12 | 91.17 | 0.58 | 0.14 | 2.37 | 90.80 |
| 23 | 3.9 | 0.66 | 28.86 | 35.77 | 34.71 | 7.27 | 79.10 |
| 24 | 3.9 | 15.76 | 82.99 | 1.08 | 0.17 | 4.27 | 98.50 |
| 25 | 3.9 | 6.82 | 84.34 | 7.10 | 1.73 | 3.93 | 75.60 |
| 27 | 3.5 | 0.99 | 35.04 | 31.53 | 32.44 | 6.40 | 82.40 |
| 28 | 3.5 | 1.82 | 49.67 | 22.20 | 26.31 | 4.87 | 88.40 |

According to the results of the PCA analysis, the first two principal components account for up to 76.5% of the total variance (Table 7).

**Table 7** Cumulative variation of abiotic variables that explain the foraminifera fauna

| PC | Eigenvalues | %Variation | Cum. %Variation |
|---|---|---|---|
| 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 |

The results of the PCA analysis revealed that the two primary components accounted for up to 76.5% of the total variance (Table 7). The highest positive values for PC1 indicated that the availability of sand and $CaCO_3$, as well as depth, were the most influential factors in the foraminiferal fauna at those stations (Table 8 and Figure 8). On the other hand, the highest negative values demonstrated that the percentage of silt, clay, and total organic matter (TOM) contributed to the occurrence of other heterotrophic foraminifera (*Bolivina, Elphidium, Nonion*) and stress-tolerant foraminifera (*Cibicides, Discorbis, Miliolinella, Pyrgo, Quinqueloculina, Rosalina,* and *Triloculina*).

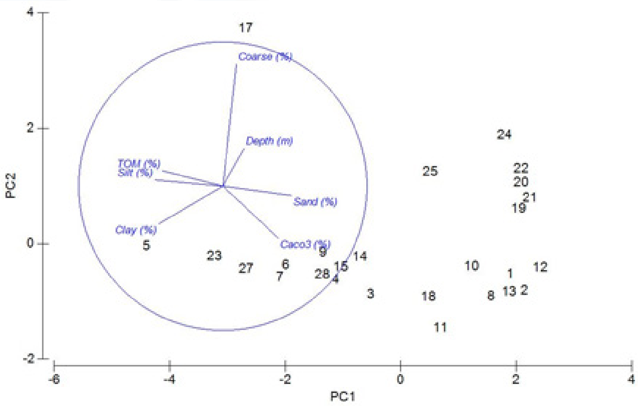



**Figure 8** Plot representing PCA analysis for Maracajau 2013.

## BEST

According to the BEST analyses or Biota and Environment (BIOENV), in both Pirangi and Maracajau reefs in 2013, the coarse fraction was found to be the variable with the strongest correlation with foraminifera abundance, followed by sand.

The best-correlated variables from BIOENV for both Pirangi and Maracajau reefs in 2013 are: Pirangi Reef: Coarse fraction and sand; Maracajau Reef: Coarse fraction, sand, and total organic matter (TOM); *Variables:* 1 Coarse (%); 2 Sand (%); 3 Silt (%); 4 Clay (%); 5 TOM (%); 6 Caco3 (%); 7 Depth (m).

The ecological index of evenness, diversity, and dominance revealed that the samples collected from Maracajaú were more diverse than those from Pirangi in both years of the study. In both reef areas, the dominant species was *Quinqueloculina lamarckiana*, followed by *Amphistegina gibbosa* (Figure 9 & Table 9).

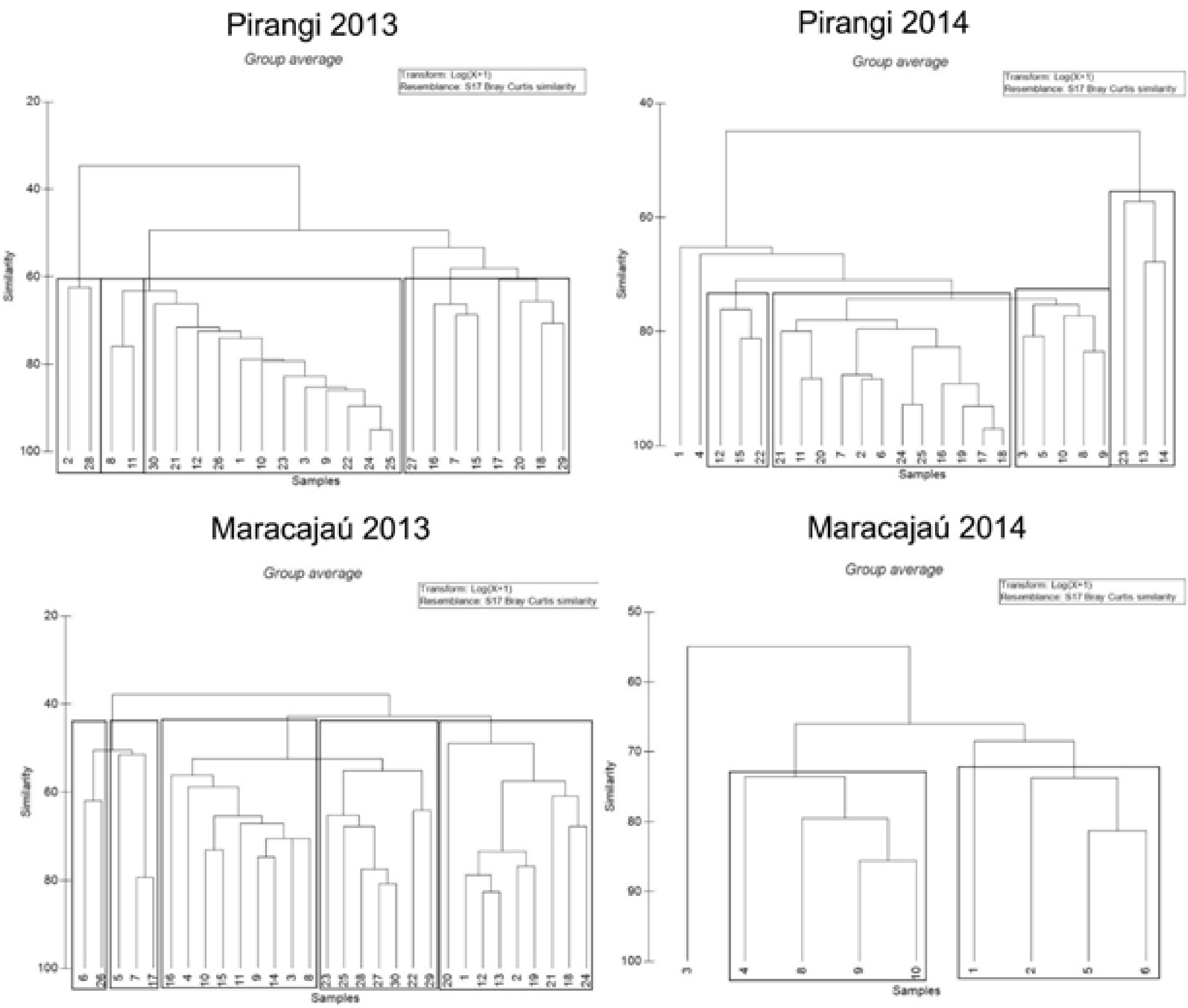



**Figure 9** Cluster analysis plots of Pirangi and Maracajau for 2013 and 2014 sampling.

According to cluster analysis results, the stations in Pirangi 2013 were divided into four groups. Group I included stations 2 and 28, which had fewer individuals and no SBS. Group II was composed of stations 8 and 11 with a low number of individuals and no SBS. Group III was formed by coastal stations 30, 21, 12, 26, 1, 10, 23, 3, 9, 22, 24, and 25, with medium diversity and a greater proportion of SBS. Group IV included deeper stations 27, 16, 7, 15, 17, 20, 18, and 29, with a higher number of species, including *Amphisorus hemprichii* in stations 17 and 18 (Table 10 & 11).

In Pirangi 2014, the stations were grouped into four clusters. Group I included stations 12, 15, and 22. Group II was formed by stations 21, 11, 20, 7, 2, 6, 24, 25, 16, 19, 17, and 18. Group III included stations 3, 5, 8, 9, and 10. Group IV consisted of stations 13, 14, and 23, while stations 1 and 4 did not belong to any group.

For Maracajau 2013, cluster analysis resulted in five groups. Group I included stations 6 and 26, with only *Amphisorus hemprichii* present. Group II was formed by stations 5, 7, and 17 with only *Amphisorus hemprichii.* Group III included stations 16, 4, 10, 15, 11, 9, 14, and 3, with no or very few individuals. Group IV was formed by stations 23, 25, 28, 27, 30, 22, and 29, with higher diversity and most of them with *Amphisorus hemprichii*. Group V included stations 4, 18, 9, 10, 20, 1, 12, 13, 2, 19, 21, 18, and 24, with *Amphistegina* dominating less diverse stations (Table 12–15).

**Table 13** Absolute density of foraminifera species from 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 | | | 1 | 1 | | | |
| *Amphisorus hemprichii** | 3 | 3 | | | 7 | 1 | | | |
| *Amphistegina gibbosa** | 9 | 2 | | 20 | 19 | 11 | 21 | 40 | 37 |
| *Bolivina brevior* | 1 | 4 | | | | | | | |
| *Bolivina variabilis* | | | | | | | | | |
| *Borelis schlumbergeri** | | | | 2 | | 2 | 3 | 3 | 1 |
| *Cancris auriculus* | | | | | | | | | |
| *Cibicides sp.* | | | | | | | | | |
| *Cornuspira involvens* | 1 | | | | | | | | |
| *Cornuspira planorbis* | | | | | | | | | |
| *Discorbinella floridensis* | | | | | | | | | |
| *Elphidium excavatum* | | 2 | | | | | | | |
| *Elphidium poeyanum* | | | | | | | | | |
| *Elphidium sagrum* | | | | | | | | | |
| *Eponides antillarum* | | | | | | | | | |
| *Fissurina laevigata* | | | | | | | | | |
| *Glabratella globigeriniformis* | | | | | | | | | |
| *Hauerina atlantica* | | | | | | | | | |
| *Heterostegina antillarum** | | 2 | | | | | | | |
| *Laevipeneroplis proteus** | | | | | 2 | 2 | | | |
| *Miliolinella subrotunda* | | | | | | | | | |
| *Miliolinella webbiana* | | | | | | | | | |
| *Neoconorbina terquemi* | | | | | | | | | |
| *Nonionella atlantica* | | | | | | | | | |
| *Nonionoides grateloupii* | | | | | | | | | |
| *Patellina corrugata* | | | | | | 1 | | | |
| *Peneroplis carinatus** | 1 | 3 | | 4 | 2 | 7 | 10 | 7 | 9 |
| *Planispirillina sp.* | | | | | | | | | |
| *Poroeponides lateralis* | 3 | 5 | | | 1 | 2 | | 5 | 2 |
| *Pyrgo comata* | | | | | | | | 2 | |
| *Pyrgo ringens* | 1 | 2 | | | 10 | 7 | 19 | 10 | 2 |
| *Pyrgo subsphaerica* | | | | | | | | | |
| *Pseudononion atlanticum* | 2 | | | | | | | | |
| *Quinqueloculina agglutinans* | | | | | | | | | |
| *Quinqueloculina crassicarinata* | 4 | | | | | | | | |
| *Quinqueloculina laevigata* | 2 | | | | | | | | |
| *Quinqueloculina lamarckiana* | 66 | 28 | 56 | 31 | 12 | 32 | 29 | 45 | 46 |
| *Quinqueloculina microstata* | | | | | | | | | |
| *Quinqueloculina patagonica* | 4 | 7 | | | 18 | 7 | 3 | | |
| *Quinqueloculina philippinensis* | 2 | | | | | 12 | 1 | | |
| *Quinqueloculina poeyana* | | | | | | | | | |
| *Quinqueloculina polygona* | 3 | 10 | | 6 | 5 | 7 | 7 | | |
| *Quinqueloculina samoaensis* | | | | | | | | | |
| *Quinqueloculina seminula* | | | | | | | | | 2 |
| *Siphogenerina rophana* | | 1 | | | | | | | |
| *Siphonina retiulata* | | | | | | 2 | | | |
| *Spiroloculina antillarum* | | | | | | | | | |
| *Tiphotrocha comprimata* | | | | | | | | | |
| *Triloculina trigonula* | | 15 | | | 16 | 12 | 4 | | 4 |
| *Triloculina bertheliana* | | | | | | | | | |
| *Wiesnerella auriculata* | | | | | | | | | |
| **Total counted** | 103 | 88 | 56 | 63 | 93 | 106 | 97 | 112 | 103 |

**Table 14** Evenness, diversity and dominance of foraminifera species from Pirangi and Maracajaú (2013 and 2014)

| Pirangi 2013 | S | N | J' | H'(loge) | 1-Lambda' | Pirangi 2014 | S | N | J' | H'(loge) | 1-Lambda' |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8 | 212 | 0.52 | 1.08 | 0.59 | 1 | 9 | 158 | 0.55 | 1.20 | 0.61 |
| 2 | 2 | 8 | 1.00 | 0.69 | 0.57 | 2 | 9 | 176 | 0.61 | 1.34 | 0.65 |
| 3 | 8 | 294 | 0.48 | 1.01 | 0.57 | 3 | 12 | 274 | 0.59 | 1.48 | 0.68 |
| 7 | 15 | 270 | 0.60 | 1.63 | 0.69 | 4 | 14 | 142 | 0.64 | 1.69 | 0.70 |
| 8 | 2 | 228 | 1.00 | 0.69 | 0.50 | 5 | 10 | 204 | 0.61 | 1.40 | 0.67 |
| 9 | 6 | 228 | 0.50 | 0.90 | 0.55 | 6 | 9 | 196 | 0.61 | 1.35 | 0.65 |
| 10 | 6 | 194 | 0.53 | 0.94 | 0.56 | 7 | 7 | 248 | 0.60 | 1.16 | 0.61 |
| 11 | 3 | 62 | 0.81 | 0.89 | 0.57 | 8 | 13 | 216 | 0.55 | 1.42 | 0.66 |
| 12 | 8 | 94 | 0.65 | 1.35 | 0.66 | 9 | 11 | 158 | 0.60 | 1.43 | 0.66 |
| 15 | 15 | 208 | 0.58 | 1.56 | 0.67 | 10 | 10 | 150 | 0.60 | 1.38 | 0.67 |
| 16 | 16 | 162 | 0.66 | 1.83 | 0.72 | 11 | 7 | 114 | 0.64 | 1.24 | 0.64 |
| 17 | 7 | 118 | 0.73 | 1.43 | 0.68 | 12 | 6 | 94 | 0.69 | 1.24 | 0.65 |
| 18 | 13 | 132 | 0.68 | 1.75 | 0.72 | 13 | 5 | 18 | 0.79 | 1.27 | 0.69 |
| 20 | 12 | 72 | 0.71 | 1.75 | 0.72 | 14 | 3 | 18 | 0.87 | 0.96 | 0.62 |
| 21 | 8 | 176 | 0.63 | 1.31 | 0.64 | 15 | 9 | 146 | 0.68 | 1.50 | 0.68 |
| 22 | 5 | 216 | 0.63 | 1.01 | 0.59 | 16 | 6 | 236 | 0.59 | 1.06 | 0.60 |
| 23 | 6 | 438 | 0.55 | 0.98 | 0.58 | 17 | 5 | 254 | 0.64 | 1.04 | 0.59 |
| 24 | 5 | 244 | 0.65 | 1.05 | 0.60 | 18 | 5 | 252 | 0.65 | 1.04 | 0.59 |
| 25 | 5 | 208 | 0.63 | 1.02 | 0.58 | 19 | 7 | 276 | 0.57 | 1.10 | 0.61 |
| 26 | 10 | 440 | 0.48 | 1.11 | 0.59 | 20 | 8 | 182 | 0.52 | 1.09 | 0.59 |
| 27 | 13 | 58 | 0.69 | 1.76 | 0.72 | 21 | 9 | 114 | 0.59 | 1.30 | 0.64 |
| 28 | 5 | 16 | 0.82 | 1.32 | 0.72 | 22 | 12 | 160 | 0.62 | 1.54 | 0.68 |
| 29 | 13 | 110 | 0.67 | 1.72 | 0.71 | 23 | 5 | 60 | 0.76 | 1.23 | 0.66 |
| 30 | 11 | 244 | 0.44 | 1.06 | 0.58 | 24 | 6 | 194 | 0.62 | 1.11 | 0.63 |
| | | | | | | 25 | 5 | 126 | 0.69 | 1.11 | 0.63 |

**Table 15** Evenness, diversity and dominance of foraminifera species from Pirangi and Maracajaú (2013 and 2014)

| Maracajau 2013 | S | N | J' | H'(loge) | 1-Lambda' | Maracajau 2014 | S | N | J' | H'(loge) | 1- Lambda' |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 212 | 0.68 | 1.70 | 0.75 | 1 | 17 | 238 | 0.58 | 1.65 | 0.72 |
| 2 | 12 | 202 | 0.65 | 1.60 | 0.74 | 2 | 16 | 208 | 0.70 | 1.94 | 0.77 |
| 3 | 19 | 162 | 0.68 | 2.02 | 0.78 | 3 | 3 | 128 | 0.90 | 0.98 | 0.61 |
| 4 | 9 | 106 | 0.73 | 1.60 | 0.75 | 4 | 7 | 130 | 0.72 | 1.40 | 0.69 |
| 5 | 7 | 22 | 0.84 | 1.64 | 0.79 | 5 | 13 | 202 | 0.73 | 1.87 | 0.75 |
| 6 | 10 | 30 | 0.81 | 1.86 | 0.79 | 6 | 17 | 228 | 0.68 | 1.94 | 0.75 |
| 7 | 10 | 36 | 0.77 | 1.78 | 0.76 | 8 | 11 | 226 | 0.75 | 1.79 | 0.76 |
| 8 | 19 | 178 | 0.66 | 1.93 | 0.76 | 9 | 9 | 256 | 0.73 | 1.61 | 0.74 |
| 9 | 19 | 190 | 0.69 | 2.02 | 0.78 | 10 | 10 | 238 | 0.68 | 1.58 | 0.73 |
| 10 | 19 | 160 | 0.70 | 2.07 | 0.74 | | | | | | |
| 11 | 19 | 94 | 0.69 | 2.02 | 0.74 | | | | | | |
| 12 | 9 | 350 | 0.70 | 1.54 | 0.73 | | | | | | |
| 13 | 10 | 260 | 0.67 | 1.54 | 0.74 | | | | | | |
| 14 | 18 | 170 | 0.71 | 2.06 | 0.79 | | | | | | |
| 15 | 19 | 142 | 0.67 | 1.96 | 0.74 | | | | | | |
| 16 | 12 | 50 | 0.73 | 1.80 | 0.74 | | | | | | |
| 17 | 10 | 36 | 0.77 | 1.77 | 0.76 | | | | | | |
| 18 | 17 | 228 | 0.64 | 1.81 | 0.75 | | | | | | |
| 19 | 11 | 252 | 0.64 | 1.54 | 0.71 | | | | | | |
| 20 | 10 | 60 | 0.63 | 1.46 | 0.68 | | | | | | |
| 21 | 21 | 294 | 0.51 | 1.56 | 0.66 | | | | | | |
| 22 | 13 | 80 | 0.73 | 1.87 | 0.74 | | | | | | |
| 23 | 30 | 408 | 0.65 | 2.20 | 0.76 | | | | | | |
| 24 | 25 | 258 | 0.60 | 1.94 | 0.76 | | | | | | |
| 25 | 22 | 194 | 0.65 | 2.01 | 0.74 | | | | | | |
| 26 | 10 | 22 | 0.82 | 1.88 | 0.81 | | | | | | |
| 27 | 22 | 168 | 0.67 | 2.08 | 0.74 | | | | | | |
| 28 | 21 | 182 | 0.67 | 2.03 | 0.74 | | | | | | |
| 29 | 14 | 70 | 0.73 | 1.94 | 0.76 | | | | | | |
| 30 | 19 | 172 | 0.67 | 1.98 | 0.74 | | | | | | |

In Maracajau 2014, two groups were formed. Group I included stations 1, 2, 5, and 6, with more diverse stations and the presence of *Amphisorus hemprichii*. Group II consisted of stations 4, 8, 9, and 10, with less diverse stations and the dominance of *Amphistegina*. Station 3 stood alone because only one species, *Quinqueloculina lamarckiana*, was found in this area (Figure 10).

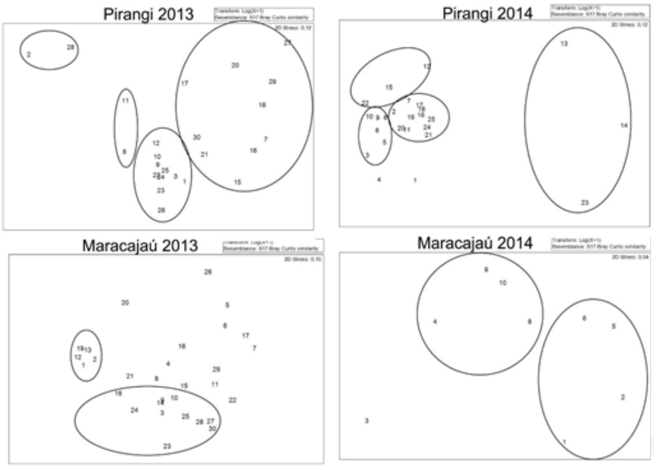



**Figure 10** MDS plots of Pirangi and Maracajau for 2013 and 2014 sampling.

MDS analysis revealed that stations were differentiated by their ecological index.

In Pirangi, 2013, MDS analysis revealed 4 groups. Group I includes stations 28, 2, and 11, while Group II includes stations 1, 10, 9, 3, 21, 26, 23, 25, 24, 22, and 12. Group I and II have deeper stations with less diversity and more dominance of one or two species. Group III includes stations 20, 16, 17, 18, 7, 29, and 27, which are from reef formations, while Group IV includes stations 7, 15, 29, and 30 from coastal stations with higher diversity.

Pirangi 2014 showed that Group I has higher diversity and includes stations 1, 3, 4, 5, 8, 20, 22, 10, 11, 15, 21, 24, 2, 6, 9, 7, 19, 7, 16, 17, 18, 25, 16, and 12. Stations 13, 14, and 23 are outliers with low diversity.

In Maracajau 2013, Group I includes stations 1, 2, 12, 13, and 19, which are more diverse. Group II includes stations 3, 4, 9, 14, 23, 8, 18, 21, and 24, while Group III includes stations 27, 30, 28, 25, 5, 6, 7, 17, 16, 22, 29, 10, 15, and 11. Group II and III have less diverse stations.

Maracajau 2014 shows that Group I includes less diverse stations 4, 8, 9, and 10, while Group II includes more diverse stations 1, 2, 5, and 6. Station 3 has only one species.

## Core results

In Table 16, the number of species ranges from 16 to 29, while the number of specimens ranges from 68 to 430. Station 3 has the lowest evenness value of 0.660, while station 9 has the highest evenness value of 0.791. Station 1 has the lowest diversity value of 1.831, while station 6 has the highest diversity value of 2.430. The dominance value is lowest in station 9 with a value of 0.128, while station 1 has the highest dominance value of 0.287.

**Table 16** Species and specimens number, evenness, diversity and dominance

| Stations | Species number | Specimens number | Evenness | Diversity | Dominance |
|---|---|---|---|---|---|
| 1 | 16 | 68 | 0,660623 | 1,831,637 | 0,287197 |
| 2 | 17 | 92 | 0,727518 | 2,061,213 | 0,184074 |
| 3 | 22 | 162 | 0,675165 | 2,086,965 | 0,203246 |
| 4 | 20 | 204 | 0,757521 | 226,933 | 0,152682 |
| 5 | 24 | 234 | 0,669553 | 2,127,874 | 0,203046 |
| 6 | 28 | 307 | 0,729419 | 2,430,575 | 0,137943 |
| 7 | 26 | 318 | 0,688104 | 2,241,908 | 0,176041 |
| 8 | 26 | 235 | 0,731908 | 2,384,626 | 0,15234 |
| 9 | 20 | 142 | 0,79145 | 2,370,972 | 0,128843 |
| 10 | 18 | 165 | 0,714209 | 2,064,328 | 0,183177 |
| 11 | 29 | 430 | 0,682146 | 2,296,986 | 0,148967 |
| 12 | 22 | 231 | 0,76364 | 2,360,445 | 0,139356 |

Stations 4 and 9 demonstrate high evenness with low dominance values, indicating that no species dominate over others, while station 10 has the lowest diversity and higher dominance, and station 6 shows the highest diversity of core 1, as shown in Figure 11 &12.

Number of species show stations that are more diverse are 6 and 11, and station 1 exhibits the lowest diversity.

*Ammonia tepida, Bolivina striatula, Discorbis peruvianus, Elphidium discoidale, Quinqueloculina lamarckiana, Q. patagonica,* and *Textularia earlandi* were found in all periods from the most recent to the most ancient (last 25 years), indicating an increase in diversity towards the past in every analyzed core (Figure 9). Although only data from Core 1 is shown, every other core exhibited the same trend.

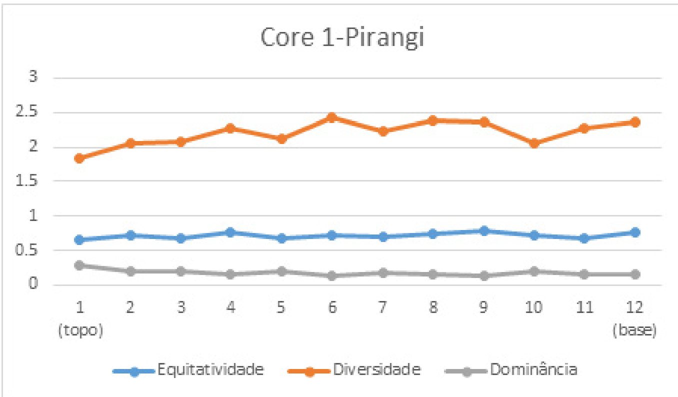



**Figure 11** **Evenness,** diversity and dominance in Core 1.

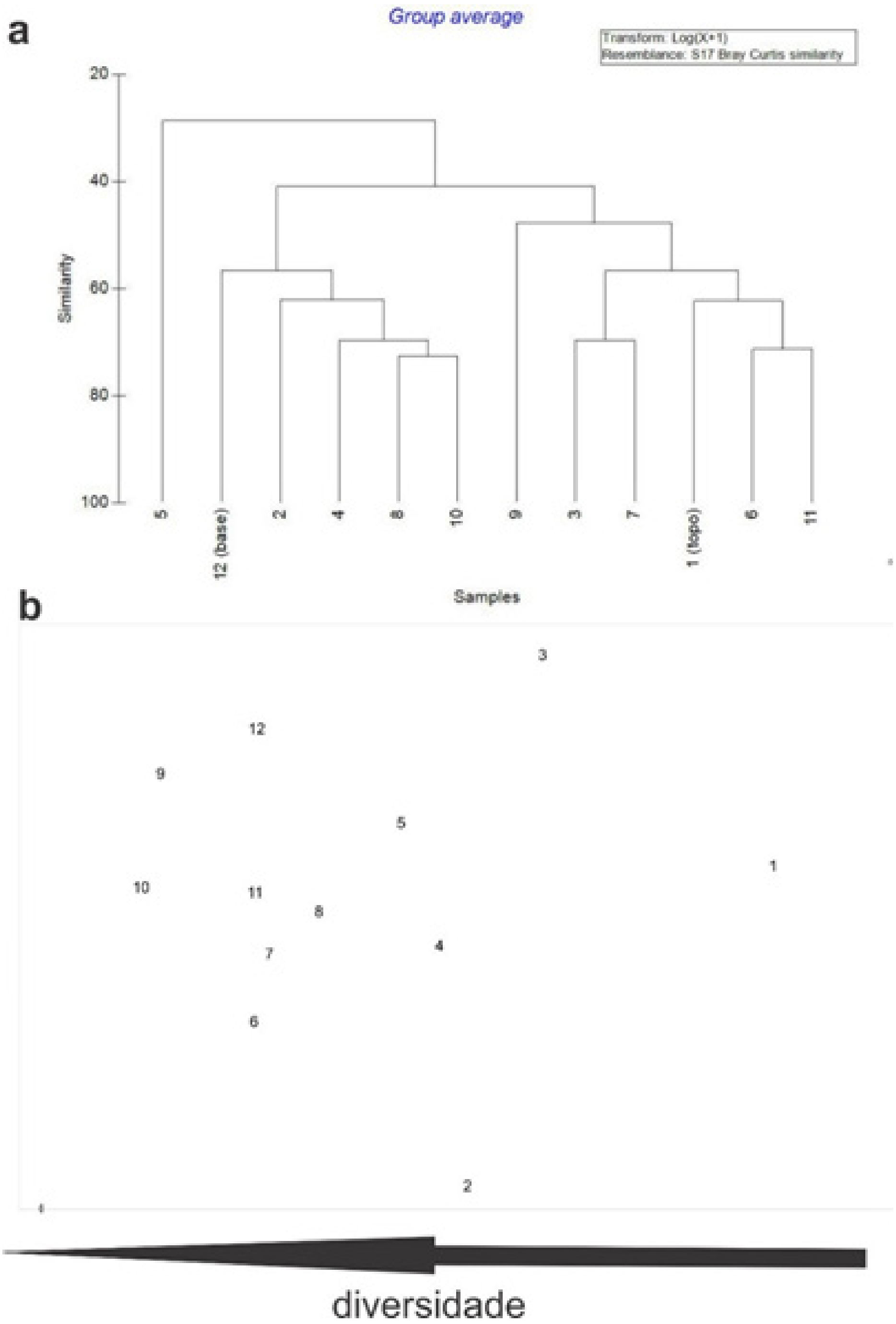



**Figure 12a shows the** cluster analysis and Figure 12b shows the MDS analysis, both performed on the foraminifera species. The MDS analysis in Figure 12b reveals that station 1 had the lowest diversity, followed by stations 3 and 2.

Using the sedimentation rate of inner continental shelves,[17] it is estimated that 1 cm is equivalent to one year in the past. Approximately 24 years ago (when Core 1 was at a depth of 24 cm), the environment had higher diversity and evenness, and lower dominance. While inter-annual oscillations can be observed, there is a trend towards decreasing diversity and evenness, with a higher dominance of fewer species in the eight analyzed cores in the present.

## FORAM index (FI)

For Figures 13 to 16, the illustrative legend explains that an FI value higher than 4, represented by orange color, indicates an environment "conductive to reef growth," while an FI between 2 and 4 suggests the presence of some symbiont-bearing taxa, and an FI higher than 4 requires symbiont-bearing taxa to make up at least 25% of the assemblage.

| LEGEND | FI values |
|---|---|
| higher than 4 | Indicative of an environment conducive to reef growth |
| between 2 and 4 | Marginal environment for reef growth that is unsuitable for recovery after stress events |
| lower than 2 | Stressed conditions for reef growth |

| Pirangi 2013 | 1 | Proportions | FI | 2 | Proportions | FI | 3 | Proportions | FI | 7 | Proportions | FI | 8 | Proportions | FI | 9 | Proportions | FI | 10 | Proportions | FI | 11 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SBS | 7 | 0,07 | 0,66 | 0 | 0,00 | 0,00 | 12 | 0,08 | 0,82 | 10 | 0,07 | 0,74 | 0 | 0,00 | 0,00 | 7 | 0,06 | 0,61 | 1 | 0,01 | 0,10 | 0 | 0,00 | 0,00 |
| Oportunists | 3 | 0,03 | 0,03 | 0 | 0,00 | 0,00 | 3 | 0,02 | 0,02 | 10 | 0,07 | 0,07 | 0 | 0,00 | 0,00 | 1 | 0,01 | 0,01 | 1 | 0,01 | 0,01 | 0 | 0,00 | 0,00 |
| small taxa | 96 | 0,91 | 1,81 | 4 | 1,00 | 2,00 | 132 | 0,90 | 1,80 | 115 | 0,85 | 1,70 | 114 | 1,00 | 2,00 | 106 | 0,93 | 1,86 | 95 | 0,98 | 1,96 | 31 | 1,00 | 2,00 |
| Total | 106 | 1,00 | 2,50 | 4 | 1,00 | 2,00 | 147 | 1,00 | 2,63 | 135 | 1,00 | 2,52 | 114 | 1,00 | 2,00 | 114 | 1,00 | 2,48 | 97 | 1,00 | 2,07 | 31 | 1,00 | 2,00 |

| 12 | Proportions | FI | 14 | Proportions | FI | 15 | Proportions | FI | 16 | Proportions | FI | 17 | Proportions | FI | 18 | Proportions | FI | 20 | Proportions | FI | 21 | Proportions | FI | 22 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 0,09 | 0,89 | 0 | 0,00 | | 10 | 0,10 | 0,96 | 8 | 0,10 | 0,99 | 12 | 0,22 | 2,18 | 8 | 0,12 | 1,21 | 3 | 0,08 | 0,83 | 3 | 0,03 | 0,34 | 17 | 0,16 | 1,57 |
| 3 | 0,07 | 0,07 | 0 | 0,00 | | 6 | 0,06 | 0,06 | 9 | 0,11 | 0,11 | 0 | 0,00 | 0,00 | 1 | 0,02 | 0,02 | 4 | 0,11 | 0,11 | 5 | 0,06 | 0,06 | 0 | 0,00 | 0,00 |
| 38 | 0,84 | 1,69 | 0 | 0,00 | | 88 | 0,85 | 1,69 | 64 | 0,79 | 1,58 | 43 | 0,78 | 1,56 | 57 | 0,86 | 1,73 | 29 | 0,81 | 1,61 | 80 | 0,91 | 1,82 | 91 | 0,84 | 1,69 |
| 45 | 1,00 | 2,64 | 0 | 0,00 | | 104 | 1,00 | 2,71 | 81 | 1,00 | 2,68 | 55 | 1,00 | 3,75 | 66 | 1,00 | 2,95 | 36 | 1,00 | 2,56 | 88 | 1,00 | 2,22 | 108 | 1,00 | 3,26 |

| 23 | Proportions | FI | 24 | Proportions | FI | 25 | Proportions | FI | 26 | Proportions | FI | 27 | Proportions | FI | 28 | Proportions | FI | 29 | Proportions | FI | 30 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | 0,14 | 1,42 | 12 | 0,10 | 0,98 | 9 | 0,09 | 0,87 | 22 | 0,10 | 1,00 | 1 | 0,03 | 0,34 | 0 | 0,00 | 0,00 | 1 | 0,02 | 0,18 | 1 | 0,01 | 0,08 |
| 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 1 | 0,00 | 0,00 | 3 | 0,10 | 0,10 | 0 | 0,00 | 0,00 | 2 | 0,04 | 0,04 | 4 | 0,03 | 0,03 |
| 188 | 0,86 | 1,72 | 110 | 0,90 | 1,80 | 95 | 0,91 | 1,83 | 196 | 0,89 | 1,79 | 25 | 0,86 | 1,72 | 5 | 1,00 | 2,00 | 52 | 0,95 | 1,89 | 117 | 0,96 | 1,92 |
| 219 | 1,00 | 3,13 | 122 | 100,00 | 2,79 | 104 | 1,00 | 2,69 | 219 | 1,00 | 2,80 | 29 | 1,00 | 2,17 | 5 | 1,00 | 2,00 | 55 | 1,00 | 2,11 | 122 | 1,00 | 2,03 |

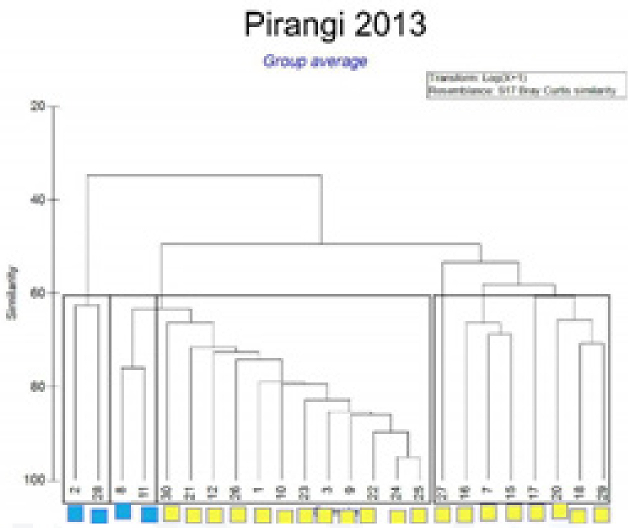



**Figure 13** Cluster analyses and illustrate data from FI for Pirangi 2013.

| Pirangi 2014 | 1 | Proportions | FI | 2 | Proportions | FI | 3 | Proportions | FI | 4 | Proportions | FI | 5 | Proportions | FI | 6 | Proportions | FI | 7 | Proportions | FI | 8 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SBS | 5 | 0,07 | 0,72 | 29 | 0,35 | 3,49 | 54 | 0,43 | 4,29 | 29 | 0,42 | 4,20 | 29 | 0,33 | 3,33 | 30 | 0,32 | 3,19 | 31 | 0,26 | 2,56 | 36 | 0,35 | 3,50 |
| Oportunists | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 4 | 0,06 | 0,06 | 1 | 0,01 | 0,01 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 2 | 0,02 | 0,02 |
| small taxa | 64 | 0,93 | 1,86 | 54 | 0,65 | 1,30 | 72 | 0,57 | 1,14 | 36 | 0,52 | 1,04 | 57 | 0,66 | 1,31 | 64 | 0,68 | 1,36 | 90 | 0,74 | 1,49 | 65 | 0,63 | 1,26 |
| Total | 69 | 1,00 | 2,58 | 83 | 1,00 | 4,80 | 126 | 1,00 | 5,43 | 69 | 1,00 | 5,30 | 87 | 1,00 | 4,66 | 94 | 1,00 | 4,55 | 121 | 1,00 | 4,05 | 103 | 1,00 | 4,78 |

| 9 | Proportions | FI | 10 | Proportions | FI | 11 | Proportions | FI | 12 | Proportions | FI | 13 | Proportions | FI | 14 | Proportions | FI | 15 | Proportions | FI | 16 | Proportions | FI | 17 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 0,32 | 3,20 | 32 | 0,43 | 4,27 | 19 | 0,35 | 3,45 | 18 | 0,38 | 3,83 | 4 | 0,44 | 4,44 | 0 | 0,00 | 0,00 | 23 | 0,36 | 3,59 | 23 | 0,20 | 2,02 | 17 | 0,14 | 1,44 |
| 3 | 0,04 | 0,04 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 1 | 0,02 | 0,02 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 3 | 0,05 | 0,05 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 |
| 48 | 0,64 | 1,28 | 43 | 0,57 | 1,15 | 36 | 0,48 | 0,96 | 28 | 0,60 | 1,19 | 5 | 0,56 | 1,11 | 9 | 1,00 | 2,00 | 38 | 0,59 | 1,19 | 91 | 0,80 | 1,60 | 101 | 0,86 | 1,71 |
| 75 | 1,00 | 4,52 | 75 | 1,00 | 5,41 | 55 | 0,00 | 4,41 | 47 | 1,00 | 5,04 | 9 | 1,00 | 5,56 | 9 | 1,00 | 2,00 | 64 | 1,00 | 4,83 | 114 | 1,00 | 3,61 | 118 | 1,00 | 3,15 |

| 18 | Proportions | FI | 19 | Proportions | FI | 20 | Proportions | FI | 21 | Proportions | FI | 22 | Proportions | FI | 23 | Proportions | FI | 24 | Proportions | FI | 25 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 0,12 | 1,24 | 16 | 0,13 | 1,33 | 14 | 0,16 | 1,57 | 12 | 0,23 | 2,26 | 27 | 0,36 | 3,60 | 0 | 0,00 | 0,00 | 33 | 0,35 | 3,47 | 22 | 0,36 | 3,61 |
| 0 | 0,00 | 0,00 | 1 | 0,01 | 0,01 | 1 | 0,01 | 0,01 | 0 | 0,00 | 0,00 | 4 | 0,05 | 0,05 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 |
| 99 | 0,88 | 1,75 | 103 | 0,86 | 1,72 | 74 | 0,83 | 1,66 | 41 | 0,77 | 1,55 | 44 | 0,59 | 1,17 | 30 | 1,00 | 2,00 | 62 | 0,65 | 1,31 | 39 | 0,64 | 1,28 |
| 113 | 1,00 | 2,99 | 120 | 1,00 | 3,06 | 89 | 1,00 | 3,25 | 53 | 1,00 | 3,81 | 75 | 1,00 | 4,83 | 30 | 1,00 | 2,00 | 95 | 1,00 | 4,78 | 61 | 1,00 | 4,89 |

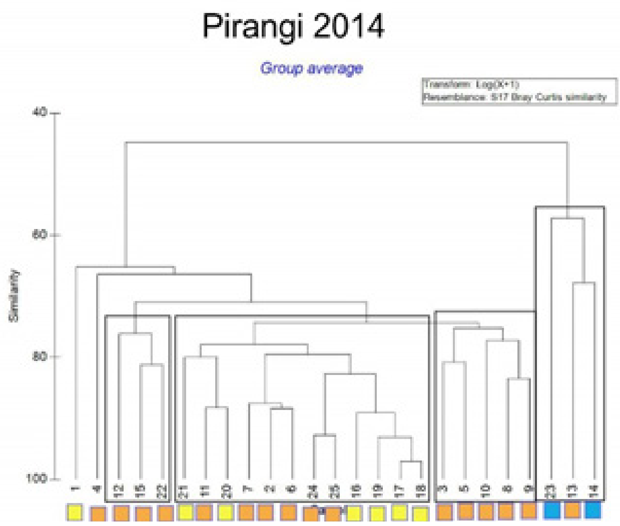
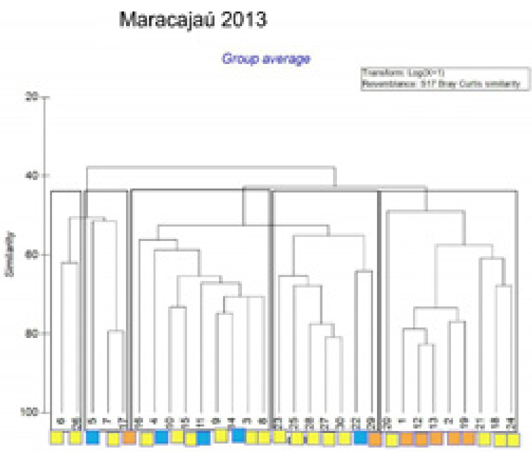



**Figure 14** Cluster analyses and illustrate data from FI for Pirangi 2014.



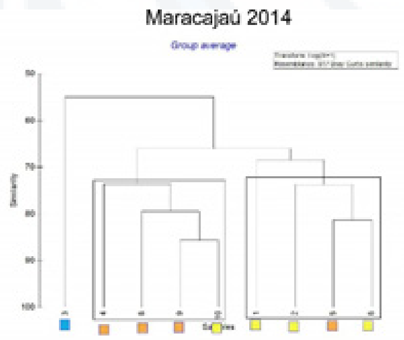

| Maracajaú 2013 | 1 | Proportions | FI | 2 | Proportions | FI | 3 | Proportions | FI | 4 | Proportions | FI | 5 | Proportions | FI | 6 | Proportions | FI | 7 | Proportions | FI | 8 | Proportions | FI | 9 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SBS | 48 | 0,53 | 5,33 | 47 | 0,55 | 5,53 | 1 | 0,02 | 0,15 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 3 | 0,23 | 2,31 | 3 | 0,18 | 1,76 | 2 | 0,04 | 0,35 | 5 | 0,06 | 0,61 |
| Oportunists | 2 | 0,02 | 0,02 | 0 | 0,00 | 0,00 | 1 | 0,02 | 0,02 | 1 | 0,03 | 0,03 | 0 | 0,00 | 0,00 | 1 | 0,08 | 0,08 | 0 | 0,00 | 0,00 | 2 | 0,04 | 0,04 | 2 | 0,03 | 0,03 |
| small taxa | 40 | 0,44 | 0,89 | 38 | 0,45 | 0,89 | 63 | 0,97 | 1,94 | 36 | 0,97 | 1,95 | 9 | 1,00 | 2,00 | 9 | 0,69 | 1,38 | 14 | 0,82 | 1,65 | 53 | 0,93 | 1,86 | 72 | 0,91 | 1,82 |
| Total | 90 | 100,00 | 6,24 | 85 | 1,00 | 6,42 | 65 | 1,00 | 2,11 | 37 | 1,00 | 1,97 | 9 | 100,00 | 2,00 | 13 | 1,00 | 3,77 | 17 | 1,00 | 3,41 | 57 | 1,00 | 2,25 | 79 | 1,00 | 2,48 |

| 10 | Proportions | FI | 11 | Proportions | FI | 12 | Proportions | FI | 13 | Proportions | FI | 14 | Proportions | FI | 15 | Proportions | FI | 16 | Proportions | FI | 17 | Proportions | FI | 18 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 0,15 | 1,52 | 0 | 0,00 | 0,00 | 96 | 0,60 | 6,04 | 58 | 0,57 | 5,69 | 0 | 0,00 | 0,00 | 7 | 0,10 | 1,01 | 2 | 0,08 | 0,83 | 6 | 0,35 | 3,53 | 6 | 0,06 | 0,61 |
| 2 | 0,03 | 0,03 | 2 | 0,04 | 0,04 | 1 | 0,01 | 0,01 | 1 | 0,01 | 0,01 | 1 | 0,01 | 0,01 | 1 | 0,01 | 0,01 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 3 | 0,03 | 0,03 |
| 65 | 0,82 | 1,65 | 44 | 0,59 | 1,17 | 62 | 0,39 | 0,78 | 43 | 0,42 | 0,84 | 68 | 0,99 | 1,97 | 61 | 0,88 | 1,77 | 22 | 0,92 | 1,83 | 11 | 0,65 | 1,29 | 89 | 0,91 | 1,82 |
| 79 | 1,00 | 3,19 | 0 | 0,62 | 1,21 | 159 | 1,00 | 6,82 | 102 | 1,00 | 6,54 | 69 | 1,00 | 1,99 | 69 | 1,00 | 2,80 | 24 | 1,00 | 2,67 | 17 | 1,00 | 4,82 | 98 | 1,00 | 2,46 |

| 19 | Proportions | FI | 20 | Proportions | FI | 21 | Proportions | FI | 22 | Proportions | FI | 23 | Proportions | FI | 24 | Proportions | FI | 25 | Proportions | FI | 26 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 47 | 0,40 | 3,98 | 7 | 0,24 | 2,41 | 16 | 0,11 | 1,12 | 0 | 0,00 | 0,00 | 7 | 0,04 | 0,37 | 5 | 0,04 | 0,44 | 4 | 0,04 | 0,42 | 1 | 0,11 | 1,11 |
| 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 9 | 0,23 | 0,23 | 13 | 0,07 | 0,07 | 3 | 0,03 | 0,03 | 10 | 0,11 | 0,11 | 1 | 0,11 | 0,11 |
| 71 | 0,60 | 1,20 | 22 | 0,76 | 1,52 | 127 | 0,89 | 1,78 | 30 | 0,77 | 1,54 | 168 | 0,89 | 1,79 | 105 | 0,93 | 1,86 | 81 | 0,85 | 1,71 | 7 | 0,78 | 1,56 |
| 118 | 1,00 | 0,00 | 29 | 1,00 | 3,93 | 143 | 1,00 | 2,90 | 39 | 1,00 | 1,77 | 188 | 1,00 | 2,23 | 113 | 1,00 | 2,33 | 95 | 1,00 | 2,23 | 9 | 1,00 | 2,78 |

| 27 | Proportions | FI | 28 | Proportions | FI | 29 | Proportions | FI | 30 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 0,06 | 0,61 | 9 | 0,10 | 1,01 | 1 | 0,30 | 3,03 | 2 | 0,02 | 0,24 |
| 10 | 0,12 | 0,12 | 13 | 0,15 | 0,15 | 3 | 0,09 | 0,09 | 13 | 0,15 | 0,15 |
| 67 | 0,82 | 1,63 | 67 | 0,75 | 1,51 | 29 | 0,88 | 1,76 | 69 | 0,82 | 1,64 |
| 82 | 1,00 | 2,37 | 89 | 1,00 | 2,66 | 33 | 1,00 | 4,88 | 84 | 1,00 | 2,04 |

**Figure 15** Cluster analyses and illustrate data from FI for Maracajau 2013.




| Maracajaú 2014 | 1 | Proportions | FI | 2 | Proportions | FI | 3 | Proportions | FI | 4 | Proportions | FI | 5 | Proportions | FI | 6 | Proportions | FI | 8 | Proportions | FI | 9 | Proportions | FI | 10 | Proportions | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SBS | 13 | 0,13 | 1,26 | 10 | 0,11 | 1,14 | 0 | 0,00 | 0,00 | 26 | 0,41 | 4,13 | 30 | 0,32 | 3,23 | 23 | 0,22 | 2,17 | 34 | 0,35 | 3,51 | 50 | 0,45 | 4,46 | 47 | 0,46 | 4,56 |
| Oportunists | 2 | 0,02 | 0,02 | 10 | 0,11 | 0,11 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 1 | 0,01 | 0,01 | 1 | 0,01 | 0,01 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 | 0 | 0,00 | 0,00 |
| small taxa | 88 | 0,85 | 1,71 | 68 | 0,77 | 1,55 | 56 | 1,00 | 2,00 | 37 | 0,59 | 1,17 | 62 | 0,67 | 1,33 | 82 | 0,77 | 1,55 | 63 | 0,65 | 1,30 | 62 | 0,55 | 1,11 | 56 | 0,54 | 1,09 |
| Total | 103 | 1,00 | 2,99 | 88 | 1,00 | 2,80 | 56 | 1,00 | 2,00 | 63 | 1,00 | 5,30 | 93 | 1,00 | 4,57 | 106 | 1,00 | 3,73 | 97 | 1,00 | 4,80 | 112 | 1,00 | 5,57 | 103 | 1,00 | 5,65 |

**Figure 16** Cluster analyses and illustrate data from FI for Maracajau 2014.

Figure 13 displays the results of the Cluster analysis and data from FI obtained from Pirangi in 2013. The stations are divided into four groups based on their characteristics. Group I consists of stations 2, 8, 11, and 28, which have a low number of individuals, no SBS, and FI values lower than 2. These conditions suggest stress for reef growth, and stations in this group are represented in blue in Figure 13. Group II comprises stations 30, 21, 12, 26, 1, 10, 23, 3, 9, 22, 24, and 25. These are coastal stations with medium diversity, a greater proportion of SBS, and FI values between 2 and 4. Group III includes stations 27, 16, 7, 15, 17, 20, 18, and 29, which are deeper stations with a higher number of species. These stations are represented in yellow in Figure 13. Notably, stations 17 and 18 have a higher proportion of *Amphisorus hemprichii*. Both groups have FI values between 2 and 4, indicating that the marginal environment for reef growth is unsuitable for recovery after stress events. The dominant species in the blue group is *Quinqueloculina lamarckiana*, while *Amphistegina gibbosa* dominates in the yellow group.

In Pirangi 2014, the stations were divided into four groups based on their FI values, as shown in Figure 14. Group I consisted of stations 12, 15, and 22, which had FI values higher than 4, indicating an environment conducive to reef growth, and were represented in orange. Group III included stations 3, 5, 8, 9, and 10, which also had FI values higher than 4 and were indicative of an environment conductive to reef growth, represented in orange (Figure 14). Group II included stations 2, 6, 7, 11, 16, 17, 18, 19, 20, 21, 24, and 25, with FI values between 2 and 4, indicating a marginal environment for reef growth that is unsuitable for recovery after stress events. These stations were represented in orange and yellow in the figure. Group IV was composed of stations 13, 14, and 23, with a mixture of FI values higher than 4 and lower than 2, suggesting stressed conditions for reef growth.

Stations 1 and 4 did not form any groups and stood by themselves. The researchers observed a higher FI in 2014 than in 2013 and dominance of *Quinqueloculina lamarckiana* in blue sites, *Homotrema rubra* in yellow, and the presence of *Amphistegina gibbosa* and *Borelis schumberger* in orange. They also observed that the FI was lower in the touristic area where people could swim, dive, and walk in the reefs.

In Maracajau 2013, the stations were grouped based on their FI values. Group I included stations 6 and 26, while Group II consisted of stations 5, 7, and 17. These groups had FI values between 2 and 4, which suggest a marginal environment for reef growth that is unsuitable for recovery after stress events. Both groups were characterized by the presence of only *Amphisorus hemprichii*, with this species appearing in yellow and blue in the corresponding figure.

Group III was made up of stations 16, 4, 10, 15, 11, 9, 14, 3, and 8. These stations had FI values between 2 and 4, indicating a marginal environment for reef growth that is unsuitable for recovery after stress events. Moreover, some of these stations exhibited stressed conditions for reef growth, as they had few specimens.

Group IV included stations 23, 25, 28, 27, 30, 22, and 29. These stations had FI values between 2 and 4, but they were more diverse than those in Group II. *Amphisorus hemprichii* was present in yellow and some events occurred.

Group V was the most diverse group, comprising stations 4, 18, 9, 10, 20, 1, 12, 13, 2, 19, 21, 18, and 24. These stations had FI values higher than 4, and between 2 and 4, which indicates an environment conductive to reef growth and a marginal environment for reef growth that is unsuitable for recovery after stress events. *Amphistegina* was the dominant species in this group.

In Maracajau 2014, two groups were identified: Group I composed of stations 1, 2, 5, and 6 with FI values between 2 and 4, indicating a marginal environment for reef growth that is unsuitable for recovery after stress events. These stations were more diverse and had *Amphisorus hemprichii* present in yellow. Group II included stations 4, 8, 9, and 10, with mostly FI values higher than 4, indicating an environment conductive to reef growth in orange. These stations were less diverse with *Amphistegina* as the dominant species. Station 3 had an FI lower than 2, indicating stressed conditions for reef growth, and was unique in that it contained only one species, *Quinqueloculina lamarckiana.*

The FI data represented in Illustrative Figure 17 indicates that the samples collected in Pirangi were taken from areas outside of the reef, as much of the reefal area in Pirangi is exposed and emerges from the water, and was therefore not included in this study. In 2014, higher FI values were found mainly in the southern part of the area in the backreef zones, which are less exposed to wave energy as shown in Figure 17.

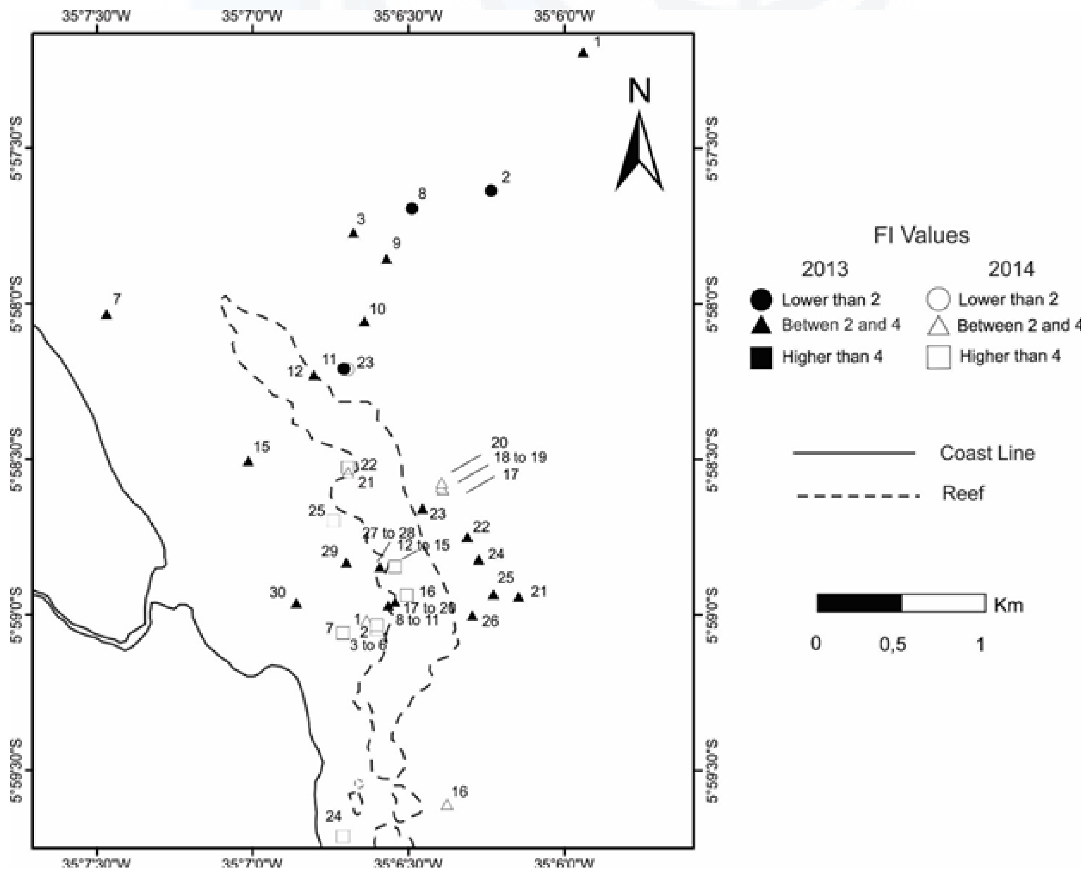



**Figure 17** FI values for Pirangi reefal area.

Figure 18 illustrates the FI data for Maracajau, which reveals higher values for the southern part in both years. It is worth noting that Maracajau's reefal area is mostly submerged, and only one station was sampled in the back reef.

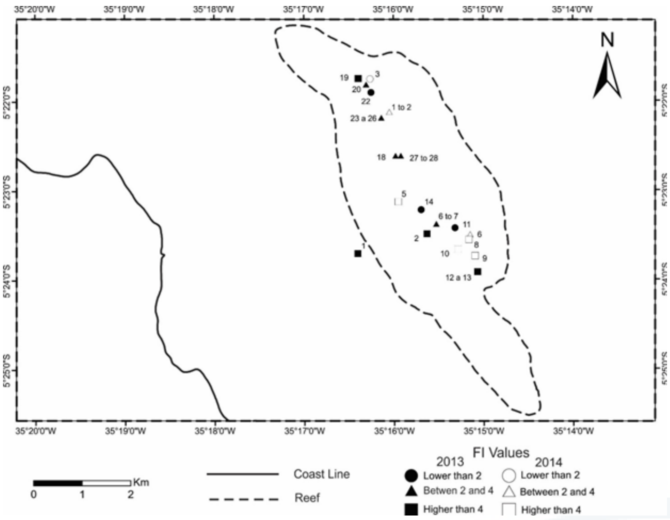



**Figure 18** FI values for Maracajau reefal area.

## Discussion

The occurrence of foraminifers in this area of the shelf may be influenced by local factors such as high hydrodynamics and other reworking processes, which could affect the interpretation of the FI index. Therefore, caution should be exercised when applying this index because a high abundance of symbiont-bearing foraminifers may lead to a misinterpretation of good water quality, which is not necessarily the case, as demonstrated by Barbosa et al.[12] in a study comparing coral reef coverage in various sites along the Brazilian coast. Similarly, low FI values may be related to silt in the sediment, which is unsuitable for symbiont-bearing foraminifera, and not necessarily low water quality for coral survival in the Abrolhos area, which has some of the highest coral cover in the world (30-32%) and is considered one of the best reefs globally.[12,23] Silva et al.[13] found that foraminiferal assemblages were most strongly influenced by sediment texture, algae, and coral cover, which affect the proportion of functional groups. The relative frequencies of hard coral and algal cover in the Abrolhos and Corumbau sites demonstrate that coral communities are well-developed in these regions. However, despite this, FI values suggest that water quality may be deteriorating. Silva et al. (op. cit) also demonstrated that sediment texture can strongly influence the FI index and should be taken into account when interpreting the results.

Our study indicates that Pirangi and Maracajaú have unsuitable conditions for important calcifiers, as indicated by the dominance of smaller and stress-tolerant taxa and minimal representation of symbiont-bearing taxa. We found that the foraminiferal fauna correlates well with coarse and sand fractions, with depth being the least influential variable. It is important to exercise caution when applying a bioindicator developed in one region to a new region, as there are regional differences in the adaptability of coral communities and even in sampling methodology. While the FORAM Index (FI) provided a reliable proxy for water quality and reef health at RN, it may not be suitable for atypical sedimentary sites. Barbosa et al.[14] found the lowest FI values in areas with sparse coral populations, such as the harbor area, which is also the case in Pirangi and Maracajau where boats dock and tourists often disturb coral reefs. Additionally, our study found the absence of living Amphistegina specimens, and the taphonomy study suggests that coral communities in these areas may be at risk.

Araújo and Machado[24] observed that the low diversity and evenness index at Abrolhos resulted in the dominance of Quinqueloculina, Amphistegina, and Archaias in shallow, low-energy areas, which increased the FI. In contrast to Schueth and Frank's[5] findings in Australia, the results from Brazil suggest that the distribution of large symbiont-bearing foraminifers is controlled by depositional energy as well as depth. Our study confirms these findings, as we found higher diversity among smaller and opportunistic taxa rather than symbiont-bearing species. Low evenness values in our results may be due to bottom currents preventing foraminifer settlement and the transport and selection of tests. The FI values were generally high in sandy sediment and low in muddy sediment, which is consistent with Barbosa et al.[12] findings. Sanches et al.[25] noted that Archaias was the most abundant and frequent genus in the foraminifer community at Abrolhos,[26] but this has since changed, with Quinqueloculina becoming dominant. A similar change from symbiont-bearing to heterotrophic foraminifers, like Quinqueloculina, was observed by Cockey et al.[27] in Florida reef systems. Amphistegina was mostly found at depths of 10–25 m, which agrees with Baker et al.[28] findings in Florida reefs. In our study, Quinqueloculina, Amphistegina, and Archaias dominated shallow reef areas in Pirangi and Maracajaú. Our Pirangi samples were a mixture of recent and relict tests, with the latter being eroded and broken, indicating they may be relict sediment. This is consistent with previous observations by Moraes and Machado[29] on the carbonate shelf of Bahia state and by Machado and Souza[30] at Rocas atoll (Rio Grande do Norte State.

Cluster analysis is a statistical method that groups data points into clusters based on their similarity to one another. In this case, cluster analysis was used to group the foraminifer samples from different stations based on their ecological indices. The fact that the samples were not grouped by depth suggests that other factors, such as wave energy and exchange with open marine waters, played a more significant role in determining the foraminifer distribution via water and sediment quality. This is similar to the findings of Narayan and Pandolfi[7] in a subtropical estuarine environment.

The best-correlated variable in this study was the coarse fraction, indicating that sediment quality played a significant role in determining the distribution of foraminifers. The cluster analysis identified clear separation within the data where sites were grouped based on their indication of conduciveness to reef growth or not after an event of stress. This suggests that the foraminifer community can be used as an indicator of reef health and recovery after a disturbance. Overall, cluster analysis is a powerful tool for identifying patterns and grouping data points based on their similarities, and can be used to gain insights into complex ecological systems.

Principal component analysis (PCA) is a statistical method that reduces the dimensionality of data by identifying patterns and correlations among variables. In this study, PCA was used to analyze the relationships among foraminifer taxa and sediment variables in Pirangi and Maracajau reefal areas.

The results of the PCA analysis showed that the two first principal components (PC1 and PC2) explained up to 67.7% of the total variance in Pirangi 2013 and 76.5% in Maracajau 2013. The highest positive values of PC1 in both reefal areas were explained by the percentage of sand availability. In Maracajau, the variability of samples was also explained by the percentage of $CaCO_3$. The highest negative values of PC1 in both reefal areas were explained by silt and clay, which contributed to the occurrence of other heterotrophic foraminifera genera such as *Bolivina, Elphidium,* and *Nonion,* as well as stress-tolerant foraminifera genera such as *Cibicides, Discorbis, Miliolinella, Pyrgo, Quinqueloculina, Rosalina,* and *Triloculina*.

In Maracajau, the total organic matter (TOM) also contributed to the occurrence of heterotrophic and stress-tolerant foraminifera genera. The results suggest that sediment characteristics, such as grain size and composition, can influence the distribution and abundance of foraminifer taxa in reefal areas.

These factors can indeed explain the low frequency of stained foraminifera in both reefal areas. Empty tests are commonly found in reef areas due to the high predation pressure, competition for space, and other stressors that may affect the survival of living foraminifera. Additionally, foraminifera that live attached to reefs, stalks, and macroalgae may not leave behind a complete test after a reproductive event, leading to a low frequency of stained specimens in the sediment. The sediment assemblage, therefore, represents an averaged mosaic of communities that are spatially and temporally variable, as demonstrated by Wilson and Ramsook[31] in the West Indies. These findings are consistent with the results of this study, particularly in Pirangi.

The study's findings show that Pirangi has a low mean FI value, ranging from less than 2 to 4 at most stations, indicating that it is a marginal environment for reef growth and may not be suitable for recovery after stress events, as proposed by Hallock et al.[32] While these results agree with Hallock's interpretation, Barbosa et al.[12] disagree, arguing that the low FI values at some sites do not accurately reflect the conditions of the Abrolhos region's eastern Parcel area, which boasts a remarkable coral coverage of around 32% and high reef fish diversity. By applying knowledge of the foraminiferal assemblage and organic matter distribution patterns in the sediment across depths, this study's results could help contribute to the management plan of the Pirangi and Maracajaú National Marine Parks (ANNEX 1) by aiding in the diagnosis of the environmental health of the region.[33–40]

Based on our analysis of foraminifer composition in association with geochemical data, we have identified that the coarse and sand fraction are the controlling parameters. We also found that depositional energy plays an important role in the transportation and deposition of sediments and foraminifera. The dominance of Quinqueloculina, a heterotrophic foraminifer, suggests that changes are occurring in the area, which needs to be taken into consideration in future studies. Our evaluation of the environmental health using the FI results indicates that the water quality in Pirangi is unsuitable for coral reef growth, while Maracajau has sites suitable for coral reef growth, although some sites may not support coral survival after a stress event. We avoided heavily reworked individuals to ensure that the majority of foraminifer assemblages in this area reflected a relict character of the sediments and did not negatively influence the index. Long-term assessments are needed to improve our understanding of the distribution and ecological importance of Brazilian reef-dwelling foraminifers and to extend the application of the FI to large-scale monitoring of reef ecosystems in the Southwestern Atlantic.[40–44]

Additionally, we conducted a taxonomic study at the University of California Museum of Paleontology (UCMP) in 2015 to confirm the true reefal foraminiferal species and to ensure we had the correct identification for all genera. For instance, we illustrate the Amphistegina study in Figure 19.

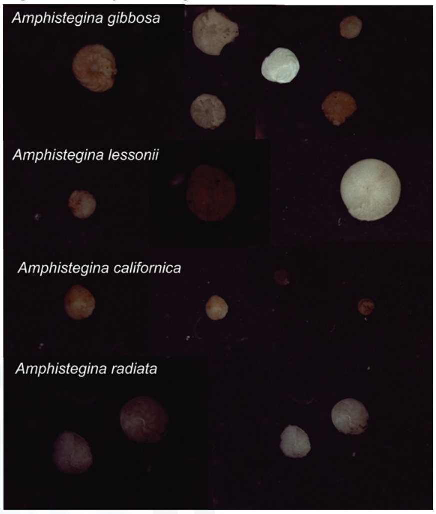



**Figure 19** Different species of *Amphistegina*.

The study of *Amphistegina* conducted in Rio Grande do Norte State confirmed that the specimens from the coral reef are indeed *Amphistegina gibbosa*.[45] This study also found that A. gibbosa is common in the Bahamas, Philippines, and Tonga islands, and is similar to the specimens found in the reefal areas of Rio Grande do Norte that was the subject of our study, as shown in Figure 20.[46,47]


**Figure 20** *Amphistegina* and other genera from different localities.

Figures 21 & 22 illustrate the genera and species of larger foraminifera found in various locations such as the Marshall Islands, Philippines, Bahamas, Australia, Tonga Islands, Samoa, Hawaii, Ifaluk, and the East Indies.

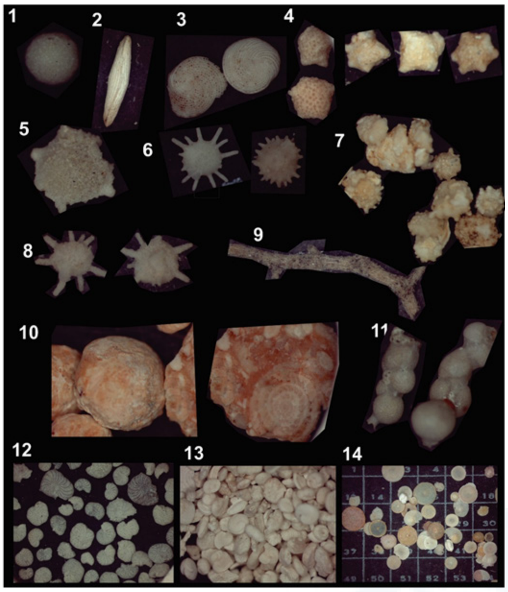


**Figure 21** Larger foraminifera genera from all over the world. 1. *Acervulinidae,* Marshall Islands 2. *Alveolinella boscii,* Philippines 3. *Archaias angulatus,* Bahamas 4. *Baculagypsina sphaerulatus,* Australia and Tonga Islands 5. *Calcarina hispida,* Philippines 6. *Calcarina mayoni,* Samoa 7. *Calcarina spengleri,* Tonga Islands 8. *Calcarinidae,* Marshall_islands 9. *Dendrophyra attenuate,* Philippines 10. *Camerina*, Tonga Islands 11. *Carpenteria proteiformis,* Philippines 12. Slide from Bahamas 13. Slide from Australia 14. Slide from Hawaii.

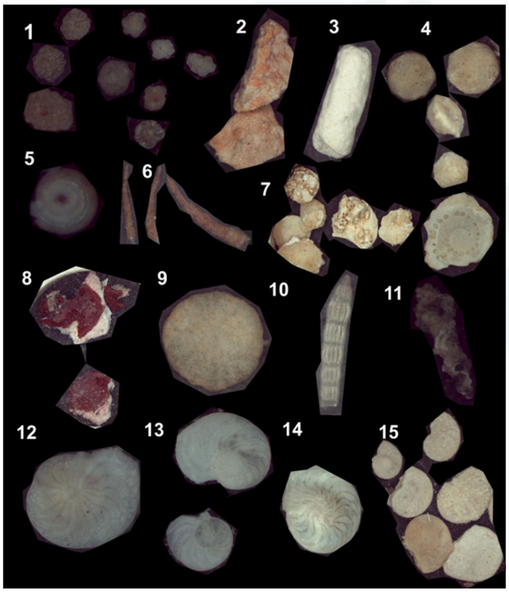


**Figure 22** Larger foraminifera genera from all over the world. 1. *Cymbalopora bradyi,* Samoa 2. *Discocyclina*, Tonga Islands 3. *Eleuthera*, Bahamas 4. *Gypsina_vermicularis*, Tonga Islands 5. *Fishcherinidae*, Marshall Islands 6. *Haliphysema catenulate*, Philippines 7. *Heterostegina_depressa*, Tonga Islands, 8. *Homotrematidae*, Marshall islands 9. *Marginopora*, Ifaluk 10. *Nodosaria_vertebrata*, pacifico, 11. *Nubeculina divaricata Variation advena*, Samoa 12. *Numulitidae*, Marshall Islands 13. *Operculina bartsehi*, Philippines 14. *Operculina cumingii*, East Indies 15. *Operculina philippensis*, Philippines.

A comprehensive examination of the Ifaluk region was conducted, and it was discovered that there were similarities with the microfauna from the RN reefs. A. gibbosa, Peneroplis carinatus, and Bolivina sp. were discovered. However, some species of Calcarina and Sorites that are present in Ifaluk are absent in the RN reefs, as depicted in Figure 23.

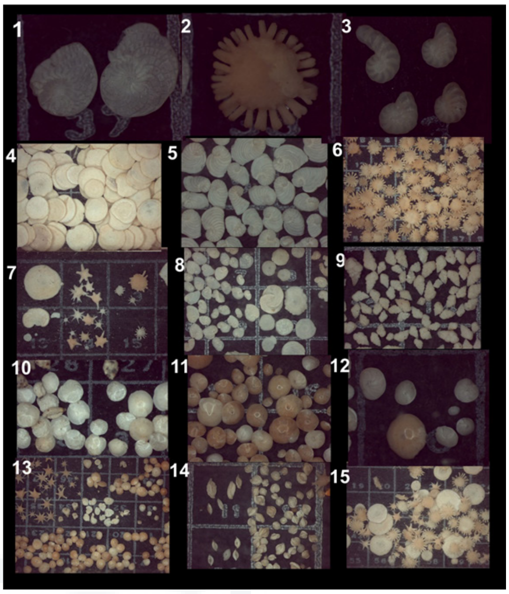


**Figure 23** Larger foraminifera genera from IFaluk island. 1. *Heterostegina depressa*, 2. Calcarina sp., 3. Peneroplis pertussis (1 specimen) and P. carinatus (3 specimens), 4. Soritidae, 5. Peneroplis planatus, P. pertussis, 6. Calcarina sp., 7. Soritidae and Calcarina sp, 8. Peneroplis planatus, Sorites sp. 9. Bulimina sp.10. 11. 12. Amphistegina gibbosa, 13. Calcarina sp., Amphistegina gibbosa, Bulimina, Peneroplis. 14. Quinqueloculina sp. 15. Calcarina sp and Sorites sp.

Reefal areas in Honolulu Hawaii, Java, Indonesia New Guinea Philippines are illustrated in Figure 24.

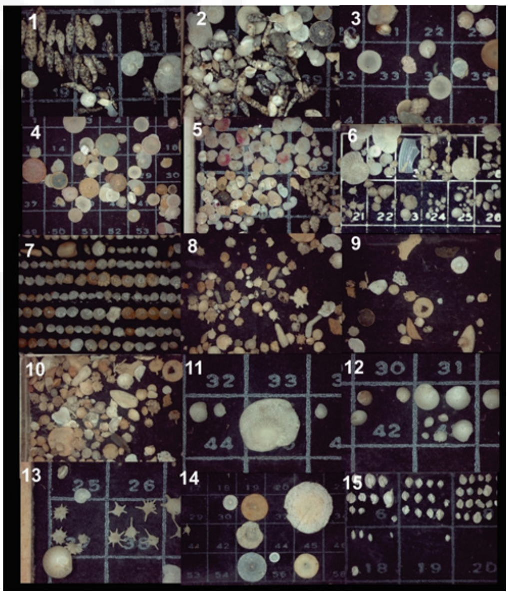


**Figure 24** Foraminifera genera from Reefal areas in Honolulu (Hawaii), Java, (Indonesia), New Guinea and Philippines. 1. Lituola (agglutinated) and *Operculina* sp. (Hawaii), 2. Soritidae, Lituola and *Operculina* sp. (Hawaii), 3. Soritidae and *Amphistegina gibbosa* (Hawaii), 4. Soritidae (Hawaii), 5. *Peneroplis* and *Lituola* (Hawaii), 6. *Operculina* sp (Indonesia), 7. Indonesia (mixed fauna), 8, 9, 10 New Guinea (mixed fauna), 11 *Heterostegina depressa*, 12. *Amphistegina gibbosa,* 13 *Calcarina* sp. and Amphistegina (Philippines), 14 Soritidae, 15 Quinqueloculina (Philippines).

Reefal areas in Philippines, East Indies, Bahamas, Australia, and Marshall Islands are illustrated in Figure 25.

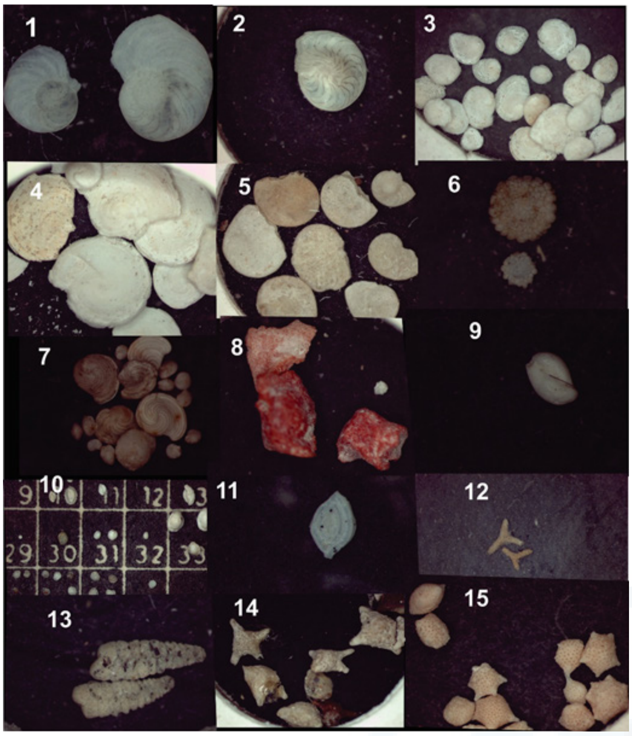



**Figure 25** 1. *Operculina bartsehi* (Philippines), 2. *Operculina cumingii* (East Indies), 3. 4. *Orbiculina adunca* (Bahamas), 5. *Operculina philippensis* (Philippines), 6. *Planorbulina larvata* (Philippines), 7. *Orbiculina achemea* (Bahamas), 8. *Polytrema mimeaceum* (Murray island, Australia), 9. 10. *Quinqueloculina costata* (Bahamas), 11. *Spiroloculina* (Marshall Islands), 12. *Saccorkiza ramose* (Philippines), 13. *Textularia goesii* Philippines, 14. *Siderolites tetraedra* (Philippines). 15. *Tinoporus baculatus* (Murray island, Australia).

## Summary and conclusion

Both numerical analysis and the FORAM index (FI) produced similar results regarding the health of coral reefs in Rio Grande do Norte (RN).

High hydrodynamics and reworking processes may affect the occurrence of foraminiferal fauna in this area and therefore affect the interpretation of the FI index.

The dominance of smaller and stress-tolerant species and minimal representation of symbiont-bearing taxa indicate unsuitable conditions for foraminifera in Pirangi and Maracajaú.

The study shows that foraminiferal fauna is closely related to coarse and sand fractions, with depth being the least influencing variable.

While the FI provides a reliable proxy for water quality and reef health in RN, it may not be suitable for atypical sedimentary sites.

The genus *Amphistegina* is most commonly found in the ($10\leq x\leq 15$ m) and ($15\leq x\leq 25$ m) domains.

Cluster analysis shows clear patterns of grouping sites among stations, which could be linked to differences in ecological indices. Sites are grouped based on their indication of conduciveness to reef growth or not after stress events.

The percentage of sand availability and $CaCO_3$, as well as the percentage of silt and clay, contributed to the occurrence of other heterotrophic and stress-tolerant foraminiferal genera in both reefal areas. In Maracajau, TOM also contributed to their occurrence.

The low frequency of stained foraminifers in both reefal areas, especially in Pirangi, might be due to empty tests common in reef areas, and most reef-dwelling foraminifers living attached to reefs, stalks, and macroalgae.

The mean FI values at Pirangi indicate that it is a marginal environment for reef growth and unsuitable for recovery after stress events, particularly in areas with tourist activities.

Coarse and sand fractions are controlling parameters, and depositional energy plays an important role in the transportation and deposition of sediments and foraminifera. The dominance of *Quinqueloculina* indicates unidentified changes are occurring in the area and must be considered in future studies.

The FI results show that Pirangi's water quality is not suitable for coral reef growth, and Maracajau has sites suitable for coral reef growth, although some individual sites may not support coral after stress events.

Long-term assessments are needed to improve our knowledge regarding the distribution and ecological importance of Brazilian reef-dwelling foraminifers and to extend the application of the FI to large-scale monitoring of this and other reef ecosystems in the Southwestern Atlantic.

The number of individuals is small in the reef area close to touristic sites, while there are no individuals in non-reef areas. Opportunistic species dominate in coastal stations where people step on reefs. Coastal and deeper stations generally have *Amphistegina gibbosa* with symbiont-bearing foraminiferal species. *Amphistegina gibbosa* with SBS dominates the south of the reef area, while *Amphisorus* is dominant in the internal reef areas.

We propose establishing permanent conservation areas to increase biodiversity management in the Pirangi Marine National Park (RN, Brazil). Our study aimed to evaluate local anthropic stresses in three little-known ecosystems on the Brazilian coast (Maracajaú, Pirangi, and Açu do Rio Grande do Norte) by examining the structure of benthic foraminifera associations present on the surface of sediments near corals. Our hypothesis was to determine whether foraminifera can serve as "health bioindicators of reef areas." Our findings revealed that the Pirangi area had the worst diversity and stability indices of the three reef areas, with a prevalence of opportunistic species and a scarcity of symbiotic foraminifera with algae. The absence of these species indicates a decline in fauna, as they indicate environments of excellent ecological health. In particular, diversity and equitability levels near the commercial exploration area drastically declined, indicating a sharp decline in the trampling of algae and the benthic community as a whole, which tends to spread to areas near the exploration area. Our data highlights the urgent need to establish a delimited area for permanent conservation to restore and preserve the marine area of the reefs as a source of propagules. The recommended area covers the most productive regions in terms of diversity and stability of the environment. Figure 26 depicts the collection stations in the Pirangi area and suggests a delimited isolation area.


**Figure 26** displays the collection points that were examined for foraminifera in 2013 and 2014. The red area indicates the proposed delimitation for permanent conservation areas.

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## Conflicts of interest

The authors declare there are no conflicts of interest.

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