Chapter 1
Playing in the Mud: Benthic Foraminiferal Communities—Dynamic Environmental Impact Indicators

Abstract  We show the applicability of the use of foraminifera communities dynamics correlated with abiotic parameters to provide data in environmental quality and coastal management plans. In this sense, we pinpoint sites most subjected to pollution and contamination and we identify differentiate effluents even when salinity and temperature values form gradient. Foraminiferal assemblages show increase in abundance of tolerant species to specific abiotic parameters. Density and diversity negatively correlated with heavy metal and PAHs. Increase in percentages of deformed or abnormal organisms and reduced size of the organism when they are exposed to heavy pollution mainly due to Hg, PAHs, and PCBs. It was observed that tolerant opportunistic species (*Ammonia tepida* and *Buliminella elegantissima*) benefit directly from organic contamination increasing their relative abundance. The other type of benefit may be indirect, as has occurred for *Elphidium* spp., which greatly increases its dominance due to the absence of other species that have had their shells dissolved first, resulting primarily from the impact of the oil spills. On the sedimentary and coral reef areas, *Amphistegina gibbosa* tests were not found at sites where reefs are walked upon. The presence of hard substrates and coarse sediment, rather than water depth, seems to be controlling the distribution of the tests. The results to date reaffirm the use of foraminiferal species in studies of oil spills, contamination by sewage, and industrial pollution even where the dissolution of carbonate is active due to low pH values. We then conclude that pollution or contamination of an environment overlaps the “natural” zonation and gradient of environmental factors, therefore limiting the establishment of species that are strategists and not opportunists.

Keywords  Pollution · Contamination · Foraminifera · Thecamoebian · Opportunists · Strategists · Abiotic environments · Interface sediment-water
Introduction

Our goal is to provide readable reliable accurate information, for anyone to understand, about environmental factors that influence patterns of benthic foraminiferal distribution in transitional and marine ecosystems. In addition, we intend to identify patterns or potential problems now or that may arise in the near future, and to make sound recommendations toward sustainable ‘eco-stewardship’ for people to act upon, adapt, and make necessary mitigation and remediation changes.

Benthic foraminifera are environmental bio-indicators, especially in polluted and contaminated environments where their sensitivity to stressors are expressed by their assemblages, to alterations of the communities’ dynamics. Their distribution patterns in ecological bio indicator pathway studies show up as early as 1959, with Zalesny studying the Santa Monica Bay in California, USA. He stated that ‘environmental factors such as currents activity, nutrients, salinity, characteristics of bottom sediments, and especially temperature should control the distribution patterns of the living benthic species in that bay. Since then several works have focused on the effects of various types and sources of pollution in different marginal habitats (Setty and Nigam 1982; Sharifi et al. 1991, Alve 1991, 1995). The number of these kind of studies has significantly increased according to an extensive review of research over the last decade about Foraminifera as bio-indicators of pollution (Suokhrie et al. 2017).

What “the Hell on Earth” Is Going On?

The problem is human; more accurately, the attenuating western colonization lifestyle model, where greed trumps reason and accountability, and our ‘anthropic’ activity has caused negative impact effects worldwide, for the post-industrial age, and also for the millennia!

Industrialization contaminants and pollutants increase from domestic or industrial sources are discharged daily, into our air, land, coastal areas and oceans. This measurable increase has accelerated greatly since the early 1960s. Humans in mass are out of touch with ‘living as caretakers gently integrated with nature’. Global pollution from industries and domestic contaminations negatively affect everything that sustains life—water, air and soil.

The planet earth, our mother-earth-nature, literally provides everything we need to thrive. The pursuit for “more stuff”, power, and of course money, while polluting our life-source is illogical and unsustainable. The effects not only pose human health threats, but also initiate eventual mass extinction of many other species, including our own. Our eco-stewardship is to protect the source of life, not abuse it. Otherwise, we will leave our children and the following generations cesspools of toxic and acidic wastewater—or worse. At some point, somewhere, we all came from “indigenous people”. Indigenous people have always sustainably protected
natural resources, looking ahead for seven generations into perpetuity. The reason why we are all here now, it is because indigenous people have always done this.

Persistent pollutants like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, heavy metals and others have a particularly deleterious effect everywhere, including to aquatic life. Organic matter contamination and accumulation from domestic runoff is another problem. Large amounts of untreated sewage also flow directly into lakes, rivers, bays, estuaries, mangroves and oceans worldwide. Untreated sewage carries virus and bacteria, which transmit deadly diseases such as cholera, hepatitis and the new deadly coronaviruses. Unfortunately, the sewage effluents often will deposit closer to our houses, and yet we may only experience the damaging effects much later on. Large amounts of organic matter dumped in coastal areas also cause algae ‘blooms’ proliferating and releasing toxins that kill aquatic life. The environment suffers from oxygen depletion from fast algae blooms, and saline and fresh water mass density differences with high stratification can also enhance stagnation, preventing mixing of water of different densities, worsening effects. Pollutants and contaminants enter the food chain as well, and the effect on the “first responders and consumers” shows up reaching the highest trophic levels.

What Are We Going to Do?

The solution, in part, is to identify natural from anthropogenic patterns, and reverse the effects of environmentally negative human activity. This sounds easy but it is not. This profoundly complex problem can, however, literally be solved with a very simple approach.

We need to use the conditioning and programming effects that education, media, and religion already provide, to use these media channels, to reconnect humanity with Mother Nature the source of our life, and with our eco-stewardship. It is that simple! From home to kindergarten, all the way through higher education and beyond, we can use curriculum, theocracy, and multimedia to influence everyone.

Through the cooperation of international private and intergovernmental multimedia and religious-leadership, we can influence each other to create a better narrative. One that provides solutions oriented messages, and to promote awareness, self response-ability, volunteerism, accountability, and actions that sustain, preserve and maintain our ecology.

In the meantime, at least some definitive answers and solutions for coastal and marine environments are found right now through researching simple microorganisms in mud. After all, they are the first consumers at the lowest level of the food chain, and the first to respond showing positive or negative effects in the ecological chain of “natural” or “disturbed” environments!!
How Are We Going to Do It?

Good question… Well, we are doing our best to inspire everyone to do their best. This includes creating resources and services that optimize our EcoLogicProject message, encourage participation, and influence positive outcomes.

Foraminifera are inexpensive easy-to-handle environmental indicator solutions. They help us identify contamination and pollution sources. They help us rapidly summarize environmental characteristics on and offshore. They highlight environmental variations over short periods, with sensitive reactions to seasonal changes and ‘anthropogenic’ effects. In addition, another great advantage is their abundance and our ability to easily collect them.

Some Forams species respond favorably to pollution and become dominant in contaminated areas, while others react negatively, decreasing in size, or becoming absent. In polluted areas, benthic Forams usually decrease in diversity until only one single opportunistic species remains.

Globally foraminifera establish themselves in natural, polluted and contaminated conditions, giving us the ‘clues to the scene of the crime’, ‘who done it’, and ‘how to solve the case’.

Brazil is a prime example for at-risk environmental ‘crimes-against-nature’ conditions with mounting crisis looming. Our studies here show areas experiencing hazardous pollution or contamination. Forams clearly show us these problems, and target the offending sources, which allows us to highlight solutions.

Here in this first chapter, our intensive case study focus has stretched over 2400 miles (3870 km) along the coast from Laguna in the south, north up past Rio de Janeiro and Bahia, ending at Natal. We are looking specifically in semi-enclosed lagoons, bays, estuarine channel systems, and coral reefs where Forams unravel the environmental issues these coastal areas have.

Below we see first responses that foraminiferal associations have to different ecosystems. We show problems and information about geomorphology and indicator species, and provide recommendations to dissuade the persistent “collective march” toward mass extinction in this our Anthropocene era within these wet systems.

Laguna, Santa Catarina: A Semi Enclosed Coastal Lagoon
(with the World’s Only Wild Dolphins That Cooperatively Help Humans Catch Fish!)

Located 130 km south of Florianópolis (capital of Santa Catarina state) are three interconnected lagoons: Santo Antônio, Imaruí and Mirim, which are about 40 km long. We started with 25 biological and geological samples at the entrance of the lagoons near Laguna city, followed by sampling inside these lagoons, until reaching the entrance of D’Una River (Imbituba city) (Fig. 1.1).
This lagoonal system is characterized by elliptical cells connected to the adjacent ocean by a single narrow channel, which allows classifying it as suffocated. They are mesotidal lagoons with high-energy gravity waves. The channel acts as a dynamic filter, and consequently effects of tidal and current oscillation are attenuated inside the lagoon.

This type of lagoon has large fluvial discharge times, dominant wind effect, and intermittent variation of vertical stratification due to solar heating and freshwater discharge (Miranda et al. 2002). There are marsh grasses on the lagoons’ margins, and this area is the southern limit of mangrove occurrence in Brazil. The risk potential in this area deals with the chemical industry to the north of the lagoon close to D’Una River, the use of illegal mesh in nets for fishing, and site constructions to the south close to Tubarão River. Close to urban areas of Imbituba and Laguna, there are untreated domestic sewage and contaminating aquaculture dumping practices in places where Bottlenose Dolphins (Tursiops truncatus) live and have an interspecies cooperative interaction with fishermen. However these amazing dolphins are slowly going extinct in part because of illegal mesh fishing net (‘ghost nets’) practices that are threatening their populations.

Our salinity and temperature study in these lagoons revealed colder temperatures in the bottom waters when values are compared to the surface waters, and salinity variation is intense in winter (Fig. 1.2a, b).

Descriptive univariate data show decrease of biodiversity revealed by the total number of benthic foraminiferal species toward inner parts of the lagoons. Moreover, in a clear type of zonation, their shells features are a response to the “natural” salinity and temperature gradient in the environment provided by the interface sediment-water where they live. Forams shells can be calcareous (made of CaCO₃) occurring in the entrance of the lagoon, and agglutinated (attaching sediment grains to its shell) occurring towards middle and inner part of the lagoons (Fig. 1.3a, b).

**Fig. 1.1** (a) Study area. (b) Marine sediment samples and measurements of hydrographic properties with samples collected in summer and winter and fixed samples (F1) in summer
Besides descriptive univariate analysis in biological data to verify biodiversity, we also applied a multivariate approach in abiotic data using Principal Component Analysis (PCA) and a Multi-Dimensional Scaling (MDS) in the biological data. PCA was applied to the abiotic data matrix in winter and summer to explain the variability of lagoons’ samples. PCA (Fig. 1.4a, b) shows that summer (AV, CV, DV, BV) and winter groups (AI, BI, CI, DI) are similar and respond to similar abiotic parameters (depth, CaCO₃, temperature, salinity, oxygen, surface pH, granules, sand, silt, clay, and organic matter).

MDS in matrix of summer biological data show formation of four groups (Fig. 1.5a), and winter biological data shows samples presenting two groups.
This setting also show similar samples in relation to salinity and temperature zonation.

This salinity and temperature gradient is remarkable and foraminiferal communities derived from it can be observed in Fig. 1.6 where a zonation map with main dominant foraminiferal and thecamoebians (microorganisms indicative of higher freshwater input) species are distributed along a salinity/temperature gradient.

Foraminiferal associations present well-defined spatial distribution and zonation resulting from environmental conditions established due to seasonality and tidal influence of continental input and marine waters. Near the ocean, succession of marine influence and mixohaline environments present calcareous species *(Quinqueloculina* spp. 19–21; *Saccamina sphaera* 18; *Cassidulina subglobosa* 17; *Pseudononion atlanticum* 16; *Buliminella elegantissima* 15; *Bolivina striatula* 14;
Buccella peruviana 13; Ammonia spp. 12; 11; Elphidium poeyanum 10). Mixohaline environments with calcareous and agglutinated species (Gaudryina exillis 9; Ammotium salsum 8; Ammobaculites exigus 7) in the central part. In the northern part of the lagoons, where fresh water input is more intense, the agglutinated Miliammina fusca (1) and thecamoebians: Pontigulasia compressa (6), Diffugia capreolata (5), Centropyxis aculeate (4), and Diffugia oblonga (3, 2) are indicative of higher freshwater input.

This significant horizontal gradient observed along the lagoons is the result of balance between the periodic intrusions of saline waters into the system by tide and fresh water input from Tubarão and D’Una rivers. Those two rivers are important because of the urbanization of the cities of Tubarão, Laguna and Imbituba in the state of Santa Catarina, Brazil. Tubarão River banks have coal and thermal power plants, and D’Una River waters contain waste from rice monoculture entering the water flow daily. Tubarão River is located closer to the entrance and is more subject to the renewal of its waters by the ocean. The D’Una River is located very far from the ocean and its waters are not benefited with the renewal of ocean waters. Moreover, due to the higher depth of this river (5 and 7 m) in relation to the lagoon
complex (less than 3.6 m), the circulation and oxygenation of the deeper waters is highly compromised.

This data indicates decrease in dissolved oxygen content in the water showing less mixing and therefore the sediment of the north region of the lagoon tends to be seriously impacted from human activity and resulting acidification.

Low oxygenation and salinities in the innermost parts of the Mirim lagoon, close to entrances of D’Una and Tubarão rivers are habitat for fauna, and patterns are related to the double influence of continental input and saline water intake, as indicated by salinity and distance from the ocean. This double influence has been described in many parts of the world and is the most prominent feature found in Brazilian coastal areas.

Forams population density patterns reflect environmental conditions and the groups representing north of Imaruí lagoon and south of Mirim lagoon have foraminifera and thecamoebians due to accumulation of silt, clay, and organic matter evidenced in the analyses of PCA. At the entrance, the samples most influenced by marine waters exhibit the highest diversities, while north of Santo Antônio Lagoon, and in southern part of Imaruí lagoon, agglutinated species dominate. Groups formed by samples collected in the D’Una and Tubarão rivers, and Mirim lagoon are similar with agglutinated *Miliammina fusca* and thecamoebians species, considered indicators of inefficient water renewal.

The low species establishment in inner sites of lagoons are related to contents of organic matter, silt, clay, and salinity, since most of these species do not tolerate low salinity levels. Closer to the ocean, species diversity and individuals’ numbers increases, indicating that salinity controls species distributions. In winter, temperature decreases more than 10 °C in some samples, and it is responsible for decrease in number of foraminifera and thecamoebians, limiting distribution of these organisms. No evidence of eutrophication of the environment or even any type of degradation or other forms of pollution is observed. The tendency of accumulation of organic matter, silt and clay in the narrowing of lagoons does not yet present an alarming situation, but the little renewal capacity of waters is decisive in accumulation of pollutant or contaminant materials.

Pollution dumped in D’Una River tends to accumulate in inner parts and it is not flushed out of the system. Tubarão and D’Una rivers are subjected daily to deleterious pollutant products, and foraminiferal distribution shows possibility of serious problems in the near future, even though it is located closer to the ocean.

The faunal distribution pattern showed above is characteristic of the environment, showing early signs of human activities of pollution or contamination from coal plants, thermoelectric plants, and rice monoculture acidifying the sediment. Harmful effects to the environment from urban development are noticed in northern areas close to D’Una River, in central parts where renewal of waters is inefficient, and at Tubarão River entrance. Since the concentration of pollutants is high in this river, if no coastal management plans for sewage and industrial effluents and environmental monitoring are implemented in the near future, the environment will move towards degradation and collapse. This threat will surely affect the already threatened bottlenose dolphin who cooperatively assist fishermen to catch fish from

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shore at this specific site, a phenomenon only found in two places globally; here and a few kilometers to the south.

**Bertioga Estuarine Channel Is a Tide-Dominated Estuarine Channel in Sao Paulo**

Moving northward, the Bertioga Estuarine Channel is located within the complex called Baixada Santista, on the south coast of São Paulo, and includes the municipalities of São Vicente, Santos, Cubatão, Guarujá, and Praia Grande (Fig. 1.7). It is divided into bodies of water, mountains, mangroves, sandbanks, Atlantic forest, beaches, rivers, estuarine and urbanized areas. Bertioga Channel, a secondary connection from the ocean to the Santos estuarine complex has two entrances. The northern entrance is located close to Bertioga city, and the southern entrance is close to Santos Channel, which flows into Santos Bay, a very polluted and contaminated site. Bertioga Channel is 25 km long, and among the rivers flowing into this channel are the Itapanhaí, Caiubura, Iriuí, Tia Maria, Cabuçu and Trindade. Bertioga Channel is a low energy region and a mixing zone between marine and fresh water with relatively high temperatures allowing for the development of mangroves. Such environments are subject to variations in the abiotic parameters, where fluctuations of salinity and temperature are associated with tides.

Results from 88 samples collected from six distinct monitored stations monthly from April of 1999 to March of 2000 indicate differentiation of environments related to balance of fresh and marine water influence. These environments have conditions for the establishment of specific dominant species, from each different environment: brackish, mixohaline and euhaline. Figure 1.8 shows a differentiation map

![Fig. 1.8](image-url)
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Fig. 1.7 Tide-dominated estuarine Channel (Bertioga, SP) and its monitoring stations
with main foraminiferal species and its response to the hydrographic condition, its relation to transport of pollutants and contaminants, and sites prone to develop worse scenarios.

Monitoring direct impacts of pollutants and contamination on foraminiferal fauna are based on living assemblages where its abundance and species diversity are related to water circulation and sedimentation patterns. *Ammonia tepida* and *Elphidium* spp. were dominant spatially and temporally. Agglutinated species such as *Arenoparrella mexicana* and *Haplophragmoides wilberti* were found in brackish and mixohaline inner portions of the channel, mainly in Largo do Candinho and in the south (next to the Santos channel) and are linked to low values of diversity and evenness. *Pararotalia cananeiaensis* and *Pseudoconion atlanticum* were found in both entrances of the channel and are indicative of higher currents velocity. Difference between surface and bottom salinity is related to increased in dominance of *Pararotalia* sp. p., indicating turbulent water dynamics.

Opportunistic species live in the south entrance close to impacted areas of Santos Channel, and marine species inhabits north entrance, with mixohaline species in the inner portions of the channel, which has predominance of muddy sediments with large amounts of organic carbon. The south of this channel is clearly vulnerable in its southern portion.

**The SubMarine OUT FALL Channel of São Sebastião, São Paulo**

The São Sebastião Channel is located in the inner continental shelf of São Paulo State, southeastern Brazil. Bottom morphology is irregular, greater depths (>45 m) occur in the channel’s axis central region, where the harbor, submarine sewage and petroleum terminal outfall are adjacently located. The northern and southern entrances have, respectively, depths of 20 and 25 m, and lower depths occur on the continental side from the central to northern part of the channel (0–7 m).

The São Sebastião Channel receives petroleum industry effluents from TEBAR (Almirante Barroso Maritime terminal, PETROBRÁS). Considering that this channel is subjected to oceanographic variations and anthropic influences, monitoring the submarine outfall is a challenge. We used foraminiferal species indicators to determine vulnerability and quality of marine sediment and water using 81 sediment samples collected in nine sampling trips seasonally from 1998 to 2002 to study foraminiferal assemblages (Fig. 1.9).

Large numbers of living well-oxygenated foraminiferal species, young and adults of *Quinqueloculina* spp., *Elphidium poeyanum*, *Hanzawaia* spp., *Discorbis williamsoni*, *D. floridana*, *Pyrgo* sp., *Cassidulina minuta*, *C. subglobosa*, and *Pararotalia cananeiaensis* reveal high dynamic currents and penetration of marine currents in the channel, with absence of eutrophication caused by TEBAR and urban sewage of São Sebastião and Ilhabela. Otherwise, the opportunistic tolerant
group Ammonia spp., Buliminella elegantissima, Bulimina marginata, Bolivina striatula, and Fursenkoina pontoni are proliferating where high organic matter indicates terrestrial contribution.

The modern sedimentary processes are directly related to hydrodynamic circulation and bottom topography. The wind-generated currents are the most effective hydrodynamic phenomena, responsible for the bottom sedimentary processes, with currents greater than 1.0 ms$^{-1}$ velocities, and with the predominant northeast direction of current flux. The São Sebastião Channel presents variations in the patterns of diversity, dominance and evenness, relating to spring-summer and autumn-winter variations. These are characteristic of subtropical environments and related to channel oceanography. Additionally, in spring and summer, the South Atlantic Central Water mass, which carries high salinity and low temperature, enters through the southern entrance. Therefore the waters in the channel create microenvironments along the water column, and are responsible for the high phytoplankton diversity within the Channel.

We conclude that the foraminferal associations in the Channel are not totally reducing. In addition, the large number of living organisms, young and adult, reveal that water circulation and dynamics favor the establishment and development of Forams, explaining the absence of eutrophication caused by TEBAR and the urban sewage of São Sebastião and Ilha Bela. However, the low number of species and the opportunistic species resistant to several types of pollution which proliferate in places where organic matter contents are high, indicates terrestrial contribution and anaerobic environments in the central regions of the Channel.
The diversity of species in the channel is not normal for inner shelf regions. This number is comparable to estuarine environments where freshwater limits the distribution of organisms. The low number of species is attributed to different sources of contamination such as municipal sewage, harbor, TEBAR, primary surface runoff, hydrocarbon spills and others.

**Guanabara Bay in Rio de Janeiro Is the Most Polluted Bay in Brazil**

Guanabara Bay is located in the state of Rio de Janeiro. The tropical climate is hot and humid with average temperatures varying between 22 and 26 °C, and average daily high temperatures in summer are 30–32 °C. In the 4 months of the so-called high summer (December–March), “the very hot days” are followed by heavy rains.

On January 18th, 2000, 1292 m³ of fuel oil leaked out into the waters of the Guanabara Bay. The accident is one of many oil spills occurring in Brazil in recent years. This accident happened north of Governador island, and affected a range greater than 50 km², reaching part of the wetland protected area of Guapimirim mangrove, and beaches along Guanabara Bay, causing death of fish and shellfish from contamination and lack of oxygen. Also causing serious social and economic concerns with severe damage to fishing and tourism. These costs that have not been compensated to local communities, which draw their livelihood directly or indirectly from the Bay (Fig. 1.10).

Twenty-six sediment samples collected in July 2000 and February 2001 were analyzed for pH, dissolved oxygen, and foraminiferal distribution. Foraminiferal species correlated with chemical effects related to the oil spill from the pipeline.

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**Fig. 1.10** Guanabara Bay views in the state of Rio de Janeiro. A sampling map with an oil leak patch, and sediment contaminated with oil.
Oil spilled into saline waters alters the oil’s chemical composition allowing the breakdown of components. The oil spill releases H₂S (hydrogen sulfide), ammonia and methane, causing the decrease of pH in sediment, and decrease of oxygenation in water. These changes interfere with the natural environment of the affected region, making it unstable.

In order to assess the environmental quality of the region and the damage to the marine ecosystem that occurred due to the oil leak, sediment and water samples in two seasons, winter 2000 (6 months after the accident) and summer 2001 (1 year after the accident) were collected. We used this material to evaluate the response of foraminifera and chemical data (pH and oxygen) in the face of this and other anthropogenic disasters.

The increase in sediment deposit in Guanabara Bay is an overlapping geological and natural siltation. Bottom sediments are dominated by silted sand and mud. The straightening and channeling of rivers and the destruction of mangroves also increases the volume of sand loads. Grain size distribution reflects the tidal current energy near the bottom, which is directly influenced by bottom morphology and the Guanabara Bay shoreline contour. The large amounts of organic mud is related to the eutrophication of the Bay’s sewage and garbage, especially occurring at the entrance of the Bay.

The circulation and salinity in this bay are subject to tidal movements; wind and river discharge, and fits the model as a salt wedge estuary, where bottom waters are colder and higher in salinity. The highest salinities occur in the entrance of the Bay, and less saline waters occur near the mouths of rivers and wetlands, in the northern portion of the Bay, reaching salinity values below 8. In the central and south portions of the Bay, salinity ranges between 30 and 34.

Guanabara Bay receives huge amounts of mostly untreated industrial and municipal waste daily. The city of Rio de Janeiro Dumps sewage mainly into the waters of the S. J. Meriti River, located to the west of Governador Island. More than 6000 industries pour filth into the Bay’s water. These include 2 commercial ports, 16 marine terminals, 2 naval bases, a shipyard, a large number of ferryboats, fishing boats and yachts, and the largest oil refinery in Brazil, Duque de Caxias (REDUC) dumps more than 1.4 tons of oil and industrial waste daily! And yet the crude oil leak shows ecological deleterious changes in Guanabara Bay!!

**Ecological Accident: REDUC’s Yuck!**

The low pH from the oil spill caused an increase of *Elphidium* spp. in winter (6 months after the accident in January 2000). This relative increase is mainly due to the absence of other species with thinner shells that were quickly dissolved by the toxic effects from the oil leak. Directly next to the REDUC oil refinery, the acidity of the sediment shows that the dissolution of carbonates in the region created complete sterility 1 year after the oil spill incident (Fig. 1.11).
Fig. 1.11  Sediment pH and relative distribution of *Elphidium* spp. in winter and summer
Buliminella elegantissima was found in the environmental preservation area, APA Guapimirim, in winter, although not close to REDUC, indicating that this species does not tolerate acidic pH environments, given the fragility of its thin shell. The damage assessment 6 months and 1 year after the accident was alarming since mortality and other symptoms in the population was still evident after 1 year (Fig. 1.12).

**Domestic Sewage**

The oil spill reached an already stressed and altered ecosystem, Guanabara Bay is highly unregulated and overly urbanized. The dumping of sewage from the city of Rio de Janeiro takes place mainly in the waters of the Rio S. J. Meriti located west of the Governador Island. Our results show that south of Governador Island is seriously compromised because low efficiency of water renewal is unable to export the pollutants from the São J. do Meriti River.

In the northwest and central parts of the bay, low dissolved oxygen values are related to waste discharges, showing also dominance of Buliminella elegantissima. In winter, near Iguacu River, sediment pH is low and highly acidic. The acidity is responsible for foraminiferal low diversity and limits the occurrence of species with fragile shells. On the other hand, thicker tests (shells) of Elphidium spp. were last to

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**Fig. 1.12** Relative distribution of Buliminella elegantissima in winter and summer
disappear, therefore increasing its relative dominance in winter. In summer, this became a barren zone and the dissolution of tests culminated with the total disappearance of these microorganisms 1 year after the accident.

The west margin and inner parts of the bay show high concentrations of nutrients (nitrogen, phosphate and sulfur) due to enrichment from domestic discharge and low renewal efficiency in the waters near Governador and Fundão islands. These locations are seriously impacted because the São J. do Meriti River influences the environments there, and north of the bay. This happens because west of the Governador Island, which would be the “natural” way of water flow, water is stagnated and closed due to silting and garbage littering in the region. Consequently, water passage tends to occur to the north, preventing water renewal.

Most of the bays are characterized by high concentration of oxygen in the sediment, which enables the maintenance of high biological activity. However, large amounts of organic material waste (sewage) can create areas where oxygen consumption exceeds supply, especially during summer months, making the environment anoxic. This is precisely what was observed in the south of the Governador Island. The central region of the Bay has the lowest bottom concentration of oxygen. This fact is also related to the increase in temperature this time of year and the phytoplankton “bloom”, which results in areas of greater eutrophication and subsequent hypoxia (Fig. 1.13).

The seasonal study of Guanabara Bay shows periods of hypoxia similar to those observed in coastal areas like Chesapeake Bay, Gulf of Mexico, and the Continental Shelf of Louisiana. Our study clearly reflects loss of biological communities in rela-
tion to the rest of the Bay. South of Governador Island requires further attention since these regions experience higher quantities of organic dumping from the S. J. do Meriti River. Populations of bacteria and virus exist all over; and their development seem to be related to the amount of silt and clay in the sediment. The accumulation of silt and clay in Guanabara Bay is linked to both a “natural” source, influenced by the river run off, and anthropogenic sources, i.e., sewage outfall. Organic pollution is mainly associated with regular renewal of the water from each tide, favoring the establishment of opportunistic species.

*Buliminella elegantissima* is more abundant in the anoxic regions south of Governador Island and central bay. This finding reinforces that this species is typical of organic matter enriched sediments, with low oxygen, occurring in sediments contaminated by domestic sewage. In addition, this excessive nutrient enrichment favors the proliferation of opportunistic foraminiferal species, increasing local dominance with high growth rates.

Environments with high organic matter concentration are directly related to higher concentrations of fine sediment. This type of sediment is characteristic of low energy environments, which facilitate the deposition of organic matter. Moreover, in these regions, the oxygen concentration is very low. *B. elegantissima* presented its highest relative frequency exactly where hypoxia is enhanced in the region south of Governador Island in winter, and in the central region near the anoxic zone in summer. Anoxic zones are usually located where the increase of bacteria from extreme concentrations of pollutants decreases oxygen concentration.

The hypoxic region of REDUC has greater limitation in productivity although its oxygen concentration is similar to the APA. The dominance values are high both in the region closer to REDUC and in the central part where anoxic zones reflect the establishment of a few species adapted to those polluted and contaminated conditions.

Guanabara Bay is highly impacted, dominated by few a species with a low diversity of fauna. The number of species per sample increases when environmental conditions are more typically saline, but if compared to other less saline lagoons and estuaries in Brazil, Guanabara Bay should have more living foraminiferal species.

### Todos os Santos Bay (Bahia State)

The environmental quality of Landulpho Alves Oil Refinery (RLAM/PETROBRAS) situated on Todos os Santos Bay (TSB) in Bahia was quantitatively and qualitatively assessed in different environments for 2 consecutive years (Sub-tidal area, and Caboto and Camamu controls/subtidal, July—December 2003, July 2004—January 2005) (Fig. 1.14).

Marine and mixohaline species (such as *Bolivina* spp., *Bolivina pulchella*, *Pseudononion atlanticum*, *Fursenkoina pontoni*, *Buliminella elegantissima*, *Bolivina striatula*, *Bulimina marginata*, *Quinqueloculina* spp., *Ammonia* spp.,...
Elphidium spp.) with low influence from continental runoff, are tolerant to high levels of accumulated organic matter, in the southern outermost part of the Bay. These species show tolerance to sediment acidification, indicating that areas closer to the ocean, which should display higher species diversity, decrease instead.

The type of fauna found in Todos os Santos Bay (TSB) indicates that marine waters dominate the environment. On the other hand, the low diversity and strong dominance of a few species is characteristic of poorly preserved estuarine environments where fresh water limits organism distribution.
**Buliminella elegantissima** is the species typical of environments rich in organic matter, which is mainly retained in muddy sediments, found practically in all regions of TSB. Environments with high organic contents have a direct relation to high mud concentrations (Tyson 1995), since in this type of sediment energy is quite low, contributing to the processes of organic matter deposition. In addition, fine sediments have a tendency to retain heavy metals and other pollutants (Kjerfve et al. 1997).

The number of species per sample increases when the environmental features are more typically marine (Phleger 1970). Thus, it was to be expected that TSB presented a higher diversity per sample level than more restricted estuarine environments.

Although TSB is under the influence of continental runoff in the summer and winter, the foraminiferal assemblages indicate that this influence is quite small. Comparison of the present study with the data obtained by Eichler-Coelho (1996) in the Cananéia-Iguape estuarine system (São Paulo State) and the data by Debenay et al. (1997) in Conceição Lagoon (Santa Catarina State) shows that the number of species found is similar to what we have found in the present study. This fact demonstrates that the pollution effects superimpose themselves onto the natural environmental factors, limiting the establishment of non-opportunistic species and facilitating the development of the opportunistic ones.

Species that are abundant in polluted areas are obviously tolerant to the pollutants to which they are subjected, whereas other species can manifest their sensitivity to the same pollutants by their absence (Yanko et al. 1994).

The accumulation of pollutants in coastal areas does not rely entirely on the supply of these materials by rivers, but also from the chemical interaction between those elements and the sediment constituents, and are therefore reflected by the carbon and fine sediment contents which more easily adsorb these types of particles. Such environments present high food concentration for several opportunistic species, a fact revealed in the present study by the occurrence of *Bolivina* spp., *Bolivina pulchella*, *Pseudononion atlanticum*, *Fursenkoina pontoni*, *Buliminella elegantissima*, *Bolivina striatula*, *Bulimina marginata*, *Quinqueloculina* spp., *Ammonia* spp., and *Elphidium* spp. The foraminiferal genera *Ammonia* and *Elphidium* are indicators of pollution levels where *Ammonia* is more tolerant of polluted environments, and *Elphidium* is less tolerant. *Ammonia tepida* is also resistant to low concentration of dissolved oxygen (around 3 mg/l) and high sulfur values characteristic of toxic sediments.

Compared to the samples collected in the RLAM subtidal area, the samples collected in the Caboto and Camamu control regions presented few individuals, low species numbers and the smallest diversities, suggesting that the control areas are not environments like those in the RLAM area, and therefore are not wholly comparable. The diversity variation at the stations may be linked to the amount of organic matter available and to the capacity to retain this food source used by the foraminifers. Sediments with high predominance of silt and clay contain great amounts of retained organic matter making the environment suitable for the establishment of different species.
Analysis of relative abundances suggests that the species *Gaudryina exillis*, *Textularia earlandi*, *Arenoparrella mexicana*, *Haplophragmoides wilberti*, *Trochammina* sp., *Ammotium* spp., *Ammoastuta inepta*, and *Miliammina fusca*, which occur in places more subjected to continental runoff, were grouped because its similarity of occurrence.

The marine species *Globocassidulina subglobosa* and *Uvigerina* spp. are species rarely found in the study region, since they are usually associated to colder water masses. In the south region of the RLAM subtidal area, the penetration of the marine current was evidenced by the presence of *Discorbis* spp. in that region. Evenness is distributed along a gradient, where the lowest environmental stability values occur close to the RLAM and the Mataripe River continental runoff, indicating less environmental stability in those regions, and increase of stability toward the region more subjected to ocean influence to the south. As environmental stress increases, species diversity falls, resulting in an increase of dominance (Odum 1988). The north-to-south diversity increase probably reflects local hydro dynamism, where the saline waters are responsible for water renovation in the southern portion of TSB. The data obtained in the present study reveal that the northern sector, including the regions close to the RLAM, are low-circulation zones, and are thus less subject to water renovation. The analysis carried out over 2 consecutive years shows a relative environmental stability in terms of foraminifera, and do not have an apparent relationship to eventual inter-annual changes.

*Sedimentary and Coral Reef Areas in the Shelf of Rio Grande do Norte State*

Sometimes called “rainforests of the sea”, coral reefs are living polyps held together by carbonate exoskeletons and are some of earth’s most diverse ecosystems. Reefs occupy only 0.1% of the world’s ocean area, while providing a home for an astonishing 25% of all marine species. East and West of Natal, the state capitol of Rio Grande do Norte, sedimentary and coral reef fields of Pirangi, Maracajaú and Açu occur inshore and in inner-shelf environments (Fig. 1.15).

The Açu reefal area is a mesophotic-submerged reef, newly discovered in 2015 by Gomes and collaborators in the oriental shelf area at 60–85 m depth. The small reefs of Pirangi are about 25 km south of Natal in <5 m of water. The Maracajaú is part the Sioba, Cação, Rio do Fogo, and Maracajaú coral reef chain, 60 km north of Natal, and are located 5–7 km from the coast. This reef lies ~5 km offshore at depths of 3–5 m, and consists of knolls and pinnacles that reach up to 6 m in height, and may be partially exposed at low tide (Santos et al. 2007). After its discover, the Açu coral reef area was under investigation and the upwelling of cold waters phenomena associated to foraminiferal assemblages was documented by Eichler et al. (2019a, b).
The shelf is narrow with less than 40 km wide, and shelf break is at ~70 m water depth (Vital et al. 2010a, b; Gomes et al. 2014). Subaqueous dunes and shallow isolated sand bodies are present in the inner shelf. Submerged beach rock marks the middle and outer shelves, and two incised valleys cut the shelf from the coast to the shelf break (Testa and Bosence 1999; Santos et al. 2007; Vital et al. 2008; Gomes et al. 2015, 2016).

Among the anthropogenic activities in the reefal Areas, are the “Marina Badauê Boat Tours” which take tourists to explore the Natural Pools of Pirangi, 800 m from the coast (Fig. 1.16a, b). They leave from Pirangi Beach three times a day year-round; the tour itinerary lasts an average of 2 h, with a stop for swimming and diving in the natural pools (Fig. 1.16c, d).

At low tide, reefs are exposed and small pools are created where small colorful fish can be observed without the use of a mask. The tour company promotes “walking on the reefs” and rents sandals for that purpose (Marina Badaue 2017). In addition to direct impact by tourists, the close proximity to the coast also exposes the Pirangi reefs to domestic and industrial waste from the Pirangi watershed.

Maracajau Reef is considered one of the ten best places in Brazil for snorkeling and scuba diving. At low tide, the area transforms into natural pools of crystalline water with depths of 1–3 m beautifully rich in diverse marine flora and fauna.

Figure 1.17a, b show tourist boats at the Maracajau reefal area; the visitors are swimming and snorkeling rather than walking on the reef (Fig. 1.16d), in water depths greater than at Pirangi. The Maracajau reefs belong to a conservation area
called the “Environmental Protection Area of Coral Reefs” (APARC), created in 2001. According to Araújo and Amaral (2016), the APARC and the adjacent continental shelf are currently experiencing an increase in environmental degradation due to overfishing, coastal development, and increasing tourism.

In Pirangi reefal area, main structures of support for living corals and other reef inhabitants occur as patches, constructed primarily of dead sponges and algae, instead of sedimentary rocks composed of coral exoskeletons typical of coral reefs in other parts of the world, such as the Great Barrier Reef, Australia (Maxwell 1968, 1969; Maxwell and Swinchatt 1970; Flood and Orme 1988). Maracajáí patch reefs occur on sand stones that formed as beachrock (Castro and Pires 2001; Martinez et al. 2012). Brazilian reefs are distinct from reefs of Caribbean, Indian, and Pacific oceans with regard to their faunal composition; there are fewer coral species, several of which are endemic (Leão et al. 2016). Fleshy macroalgae and turf algae also compete for space on the reefs.

High algal abundance (Francini-Filho et al. 2013) and low coral cover (Barradas et al. 2010; Medeiros 2009; Azevedo et al. 2011; Krajewski and Floeter 2011; Martinez et al. 2012) are common substrata, as we observed at Pirangi. Although the dominance of algae is generally considered a negative health indicator for coral reefs (Venera-Ponton et al. 2011), this statement is not necessarily true for all reef ecosystems, especially those with relatively low coral diversity. In some Hawaiian
reefs, for example, there is high percentage of macroalgae cover; however, all essential ecological processes remain intact, and algae are considered important contributors to the general health of these reefs (Vroom et al. 2006; Vroom and Braun 2010), similar to our Pirangi reefal site. Sponges represent another major component of substrate cover.

The three-dimensional sponge structures offer complex spaces that increase the variety of microhabitats and elevates the diversity of local fish and invertebrates (Buhl-Mortensen and Mortensen 2004; Mortensen and Buhl-Mortensen 2005; Souza et al. 2015).

The distributions and abundances of the tests of symbiont-bearing benthic foraminifera can offer valuable clues to the health of a coral-reef ecosystem (e.g., Hallock et al. 2003; Barbosa et al. 2009, 2012). Variations in the total abundances of the two most common species, Amphistegina gibbosa and Amphisorus hemicrithii, show that overall, in the sediments of the Rio Grande do Norte reefs, Amphistegina tests were far more abundant than Amphisorus tests. Amphisorus are more abundant were people walk upon the reefs than Amphistegina. It may be related to its flat morphology, capable of living under things which tolerate heavy weights (Fig. 1.18).

However, because we were dealing only with the presence of tests in sediments, bottom water hydrodynamics must also be considered when assessing the distributions of these tests. Sediment data from the parts of Pirangi and Maracajaú reefs

Fig. 1.17 (a) General view of Maracajaú reefal area. (b) Presence of many tourist boats. (c) Detailed view of visitors swimming instead of walking on the reef. (d) Relative depth showing a swimmer being very conscious of protecting the reefal area.
affected most by tourist’s anthropogenic disturbance activities revealed that *Amphistegina* tests were less abundant here. *Amphistegina* was not abundant at any of the stations sampled in the tourist area at Pirangi in 2013, but had low numbers at four stations within the tourist area. In 2014, *Amphistegina* was abundant at ten of the 11 tourist-frequented areas in Pirangi. At Maracajáu in 2013, the highest numbers of *Amphistegina* tests were found in the reef-margin area, and were absent where reefs were trodden upon. *Amphisorus* tests were found even where people often walk, mainly on soft corals and seagrass beds. *Amphisorus* is typical seagrass-associated species (Reich et al. 2015; Hohenegger 1994). They found them living in abundance on macroalgae on reefs in the northwestern Pacific, and on vegetation free substrates were noted the same in Pirangi, Maracajau and Açu coral reef areas. *Amphistegina* spp. are usually found associated with reefal or firm phytal substrates, and *A. gibbosa* generally does not live abundantly in very shallow waters (Hallock 1999; Baker et al. 2009). Tests of the two species of foraminifers assessed were particularly depauperate in the Pirangi samples collected in 2013 in 12 samples out of 30, and 4 samples out of 25 in 2014. At Maracajáu in 2013, tourists were diving close to the impacted area which was not sampled in 2014. In the more extensive patch reef system of Maracajáu, the community appeared healthier, except where tourist activities impact had physically damaged the reef substrate.

Coral death from anthropogenic disturbance is a particular concern for reefs that are walked upon, or otherwise heavily visited by tourists, but reefs nearby rivers are also at risk. Agricultural land use has increased the amount of sediment, nitrogen, and phosphorus accumulating in coastal-marine environments and high turbidity blocks light penetration, which is indispensable for symbiont-bearing foraminifera (Fujita 2004).

Among the studied reefs, only those at Pirangi are very close to a major city (Natal, the state capital). The shallowest part of the Pirangi reefal area, closest to Pium River, is expected to suffer negative effects. However, *Amphistegina* was com-
mon and abundant at the closest stations sampled in 2013. The Maracajaú reefal area is farther away from the coast, compared to Pirangi, and the foraminiferal tests appeared better preserved, although the relative distributions of *Amphistegina* and *Amphisorus*, and the impact of trampling are similar.

Many foraminiferal shells in our samples from the Pirangi reefs were broken, corroded, unusual brownish and yellowish discoloration, with few living individuals, indicating reworking of the sediment. Araújo and De Jesus Machado (2008) and Oliveira-Silva et al. (2012) also found broken and corroded tests on the Abrolhos offshore carbonate shelf reefs, near Bahia state. *Quinqueloculina* had discolored and eroded shells and were reported by Oliveira-Silva et al. (2005) at sites hydrodynamically influenced by the high volumes of water carried by the Doce River onto a narrow shelf. It is possible that Pium River has a similar reworking effect at Pirangi. The eroded and broken tests of specimens suggest that some components of the foraminiferal assemblage in seafloor sediments off the Rio Grande do Norte coast may be relict. In particular, brown or black specimens of *Quinqueloculina lamarckiana* dominant porcelaneous species (without algal symbionts), are widespread and indicate that erosion may be taking place in the inner shelf of the area, reworking old sediments.