Marine Pollution Bulletin 129 (2018) 114–125

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Benthic foraminiferal and organic matter compounds as proxies of environmental quality in a tropical coastal lagoon: The Itaipu lagoon (Brazil)

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A R T I C L E I N F O

Keywords:
Biopolymers
Organic matter accumulation
Foraminiferal biodiversity
Anthropic impact
Itaipu lagoon
Brazil

A B S T R A C T

Lagoons in the southeast coast of Brazil have experienced eutrophication due to the exponential increase of human population and sewage discharges. Living benthic foraminifera have demonstrated to be good bioindicators of such impacts. This study aims to evaluate the organic matter accumulation effects on the foraminiferal distribution in the Itaipu lagoon (Brazil). On the basis of the biotic and abiotic analyses, three sectors are identified. The Sector I, an inner area, is characterized by high dissolved oxygen values and foraminiferal species with preference for marine conditions, demonstrating the sea influence. The Sector II, in the mangrove margins, is associated to sandy sediment and biopolymers and mainly represented by euryhaline species. The Sector III is marked by low density or absence of living foraminifera and corresponds to a low quality organic matter enriched area (North, Southwest and Centre).

1. Introduction

Coastal lagoons are very important environments characterized by large biological productivity due to the large number of boundaries and gradients (between water and sediment, pelagic and benthic communities, and among marine, freshwater and terrestrial systems) (Alongi, 1998; Gamito et al., 2005). Besides the natural oscillations, these environments are also affected by anthropogenic activities (Díaz et al., 2014) In the last century, the exponential increase of human population have conducted to the extensive substitution of natural systems into human-dominated establishments, mostly, agricultural and industrial complexes, harbors, aquaculture and urban settlements (Vadineanu, 2005; Prudêncio et al., 2007; Ruiz et al., 2012).

These anthropogenic interventions have prompted the releases of high amount of organic matter (OM) and nutrients, which associated to the long-lasting residence time of the water, tend to turn these areas into eutrophic or even hyper-eutrophic environments (Hearn et al., 1994; Knoppers, 1994). The OM produced (autochthone) or introduced (allochthone) in transitional environments sinks and deposits on the sediments (Fabiano and Danovaro, 1994), which acts as final sink and accumulation spots when it exceeds the degradation capability of microorganisms (Silva et al., 2014).

Approaches for the characterization of OM compounds (biopolymers) of the sediment to determine the trophic status of the coastal ecosystems were developed by assessing the concentrations of lipids (LIP), carbohydrates (CHO) and proteins (PTN), regarded as the main available biopolymers for biota (Fabiano et al., 1995; Silva et al., 2011a, 2011b, Laut et al., 2016b). The use of biopolymers for ecological and monitoring studies provides information of both quantity and quality of OM in the sediment, where in general, PTN and LIP are associated to anthropogenic organic matter, while CHO is more related to phytoplankton and vegetal debris (Cotano and Villate, 2006). These methodologies have been recently applied to determine the effects of OM accumulation on microbiota, particularly for foraminiferal studies (Clemente et al., 2015; Martins et al., 2015, 2016; Laut et al., 2016a).

These organisms are very abundant in sediment, sensitive to

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https://doi.org/10.1016/j.marpolbul.2018.02.018
Received 24 August 2017; Received in revised form 6 February 2018; Accepted 8 February 2018
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variations in environmental conditions (Ferraro et al., 2006; Frontalini et al., 2009). They show quicker responses to environmental changes when compared to the macrofauna (Schönfeld et al., 2012) and, therefore, are frequently considered one the most promising environmental bioindicators in coastal areas (i.e., Alve, 1995; Frontalini and Coccioni, 2011).

The Rio de Janeiro State presents a set of coastal lagoons that, since the 20th century, has been experiencing degradation and eutrophication due to demographic growth in association with lack of urban planning. Some foraminiferal studies have been conducted in these lagoons (Debenay et al., 2001; Raposo et al., 2016; Belart et al., 2017), but a complete characterization of OM including the biopolymeric contents and its relation to foraminifera have never been investigated.

In lights of it, this study intends to evaluate how the OM accumulation in the Itaipu lagoon influences the living benthic foraminiferal distribution by developing an approach combining biopolymers concentrations, sediment grain size, and physical and chemical variables (on low and high tide). On the basis of our results, we aim to obtain information about anthropic and natural influence in the lagoon, and to define sensitive and tolerant species, contributing with valuable data for an effective environmental biomonitoring of coastal lagoons along Brazilian coast.

2. Study area

The Itaipu lagoon is in the southeastern coast of Brazil (Rio de Janeiro State) between the latitudes 22°57′23″–22°57′41″ S and longitudes 43°02′51″–43°02′10″ W (Fig. 1). It covers an area of 1.2 km^2, with an average depth between 0.2 and 2.0 m. This lagoon, along with the Piratininga lagoon (3 km^2), composes the Itaipu-Piratininga Lagoon System, which comprehends an important hotspot of biodiversity in the State of Rio de Janeiro. Its surrounding area presents heterogeneous ecosystems such as lagoon, mangrove, marsh, *restinga* and has dunes sheltering the oldest, ca. 8000 year, shell mounds (*sambaqui*) of the country. The system is covered by the Environmental Protection Area (APA) of the Lagoons and Forests of Niterói (SNUC, 2004). The State of Rio de Janeiro is affected by a warm-humid climate, with a rainy season in summer (December to March) and dry-mild season in winter (June to September) (Peel et al., 2007). The average rainfall is between 1000 and 1500 mm/year (Barbiére and Coe-Neto, 1999).

The Itaipu lagoon can be classified as a typical choked lagoon due to the restricted connection with the sea through a tidal canal (Kjerfve, 1986). It is affected by a micro-tidal regime with a mean height of 0.71 m, reaching up to 1.32 m during spring tide periods (Lavenère-Wanderley, 1999), and regulated by sea waves from the south and southeast after suffering diffraction by the Itaipu inlet and its adjacent islands (Salvador and Silva, 2002).

The lagoon is influenced by the discharge of large amounts of untreated organic waste by Camboatá canal, which connects Itaipu to the Piratininga lagoon (Lacerda et al., 1992). It also receives freshwater input from two rivers in the north section of the water body: João Mendes and Vala (Fig. 1). The deposition of effluents into the lagoon promotes deleterious effect in this sensitive ecosystem. Over the last decades, the surroundings of the Itaipu lagoon have experienced increasing urbanization (Cerda et al., 2013). The occupation on the lagoonal sand banks by poor urban infrastructure, the direct dumped sewage, the riparian forest deforestation, and the slope erosion have driven an intense process of environmental degradation.

3. Methods

3.1. Sample collection

Bottom sediment samples were collected over 12 stations during the austral summer (December 2012 and January 2013) with a small box-corer (Fig. 1). The samples stations location and water depth are reported in Table 1. The physical and chemical variables of the water-sediment interface were measured on both high and low tide, with a multiparametric probes (Sanxin, model SX751). For foraminiferal analyses, replicates of 50 ml each were collected from the first centimeter in three different deployments (Schönfeld et al., 2012). For the sedimentological analysis, 500 ml of the bottom sediments were collected in the same sample stations.

To identify the living organisms, at the moment of sampling, a Rose Bengal solution (2 g of Rose Bengal dye in 1000 ml of alcohol 70%) was added to all samples, which were washed only fifteen days later (Schönfeld et al., 2012).

3.2. Sediment grain-size analyses

Grain-size analyses were conducted using ~30 g of dried sediment. The OM was completely removed by using hydrogen peroxide (10% H_2O_2) and the remaining material was dried at 60 °C and weighed again to calculate the OM. The sediment was washed again through a 0.063 mm sieve, separating the coarser (sand) and fine (silt and clay) fractions. Each fraction was dried and weighed.

3.3. Biopolymers, TOC and TS contents

The determination of protein (PTN), carbohydrates (CHO), lipids (LIP), total organic carbon (TOC) and total sulphur (TS) contents of the Itaipu lagoon samples was carried out following the data previously published in Laut et al. (2016b). PTN concentrations are expressed as albumin equivalents, CHO values as glucose equivalents and LIP concentrations as tripalmitine equivalents. The sum of PTN, CHO and LIP carbon was named as biopolymeric carbon (BPC). The TOC and TS measurements were performed in a carbon and sulphur analyzer (LECO SC 144).

3.4. Foraminiferal analyses

The benthic foraminifera were treated and analyzed according to Schönfeld et al. (2012) and published in Raposo et al. (2016) only as a check list of living benthic foraminifera. Using a stereoscope microscope with increase of 80×, 300 were dead and 300 were living specimens per replicate. In case of few individuals, at least 100 specimens were collected (Fatela and Taborda, 2002). The values of absolute abundance of the stations were determined by averaging the number of specimens in the three replicates. Some stations did not contain the minimum specimens' number and were therefore discarded of the statistical analyzes.

The assemblages' parameters were computed based on the species relative abundances in each station, using the software MVSP 3.1. We calculated species richness (S = number of species), species diversity of Shannon ($H' = \Sigma p_i \ln p_i$) and the species equitability [$J' = H' / \ln(S)$], where p_i is the proportion of the species on the samples were calculated.

The species were identified according to Boltovskoy et al. (1980), Poag (1981), Loeblich and Tappan (1987), Walton and Sloan (1990), Yassini and Jones (1995), Martins and Gomes (2004) and Raposo et al. (2016), and the species nomenclature was standardized according to the platform available online, WoRMS (World Register of Marine Species; Hayward et al., 2016).

3.5. Statistical analyses

In order to create a surface to best represent the empirical reality (Azpurua and Ramos, 2010), variables were interpolated with the software ArcMap 10.4®, by applying two deterministic interpolation methods (Spline and inverse distance weighting, IDW) using the number of nearest input sample points equal to 12 and power exponent of distance as 2. Spline method generated the best surfaces for the abiotic variables (bottom water and sediment measures) and the

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