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VARIAÇÃO ESPAÇO-TEMPORAL DAS ASSEMBLEIAS BENTÔNICAS ESTUARINAS DA BAÍA DE TODOS OS SANTOS

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Este manuscrito representa o trabalho de graduação do Curso de Graduação em Oceanografia, Universidade Federal da Bahia, como requisito parcial para obtenção do grau de Bacharel em Oceanografia.

Orientador: Prof. Dr. Francisco Carlos Rocha de Barros Junior

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Esse registro de gratidão fica no papel, mas a vida vai seguindo e novas memórias vão sendo construídas a cada momento.

“Se a maioria dos homens o soubesse, fosse qual fosse a sua categoria social, compartilharia comigo, numa época ou noutra, os sentimentos que o oceano me inspira.”

(Herman Melville, Moby Dick)

APRESENTAÇÃO

Este trabalho tem como objetivo principal analisar a variação espaço-temporal da estrutura das assembleias da macrofauna bentônica dos três principais estuários da Baía de Todos os Santos (BTS). Foi utilizado o banco de dados do Laboratório de Ecologia Bentônica (LEB-UFBA) com quase 2 décadas de amostragem dos estuários dos rios Paraguaçu, Jaguaripe e Subaé. Além do banco de dados da macrofauna bentônica, também foram utilizados dados de salinidade e de granulometria. O presente trabalho é um Trabalho de Conclusão de Curso apresentado na forma de um manuscrito que será submetido posteriormente a uma revista científica.

SPATIAL AND TEMPORAL VARIABILITY OF ESTUARINE BENTHIC ASSEMBLAGES IN TODOS OS SANTOS BAY

Abstract

Estuaries are heterogeneous coastal transitional environments that, in addition to the natural disturbances of different scales, have suffered several pressures resulting from the growing urban development. In this context, long-term environmental monitoring is an essential tool for ecosystem preservation, through the understanding of temporal patterns and creation of ecological models, for example. Frequently, among the biological metrics that have been used in estuarine environments monitoring, benthic communities have been assessed. This happens due to its advantageous characteristics (e.g., relatively low mobility and relatively long life cycles) and due to the influence of environmental variables (e.g., grain size, salinity, depth, and temperature) on its distribution, whose spatial and temporal variation is well-defined within the estuaries. However, there are few monitoring studies in tropical estuaries using a large temporal scale. The main objective of this work is to perform a temporal and spatial analysis of the structure of the benthic macrofauna in the three main estuaries of Todos os Santos Bay in the last 20 years of sampling data. We also aimed to identify the patterns within the benthic structure in these estuaries, as well as the changes between and within estuarine zones throughout the sampling campaigns. For this, we used data of abundance, salinity, and grain size from the database of the Benthic Ecology Laboratory. As a result, we corroborate that the richness increases along the estuarine gradient of the three estuarine regions, with a greater amount of taxa in the external region of the estuary than in the internal region that is less saline. The nMDS pointed out the dissimilarity that separated the more saline zones from the less saline, and the similarities within each zone remained practically constant throughout the sampling campaigns. Polychaetes, crustaceans, and mollusks dominated the richness and abundance of estuaries, as expected in tropical estuaries. Orbiniidae, Cirratulidae, Nereididae, and Tellinidae were the common taxa to the three estuaries that contributed to the differences found over time in the different estuarine zones. Still, there must be more investment in conducting long-term monitoring in tropical estuaries, to enable better monitoring of estuarine ecosystems in Brazil.

Keywords: benthic macrofauna, tropical estuary, salinity gradient, long-term monitoring

1. Introduction

The crescent human development is causing an increase in the human pressure on coastal environments. The actual development model is tied up in the achievement of new technologies and methodologies applied to expanding the ocean's usage (e.g., ports and mills, shipping, aquaculture, and offshore platforms and mining) (Halpern et al., 2019). As a result, in many cases, the quality and the services of marine and coastal environments are altered (Booi et al., 2022), the natural coastline protection is lost (McLusky & Elliott, 2004), and the biodiversity is highly affected (e.g. Waltham et al., 2020; Cordeiro et al., 2022). Thus, there is an urgent need to develop environmental indices (e.g., AZTI's Marine Biotic Index (AMBI) and Environmental Quality Index (EQI – US/EPA)) and to create environmental monitoring programs (e.g., California Cooperative Oceanic Fisheries Investigations – CalCOFI, Bermuda Atlantic Time-series Study – BATS, and the Global Environment Monitoring System for the Ocean and Coasts – GEMS Ocean), as well as to establish reference areas (e.g., Pedreira et al., 2017).

Environmental monitoring has been widely recognized as an essential tool for maintaining ecosystems’ services (Magnusson et al., 2013; Waltham et al., 2020), especially considering the goals of the Decade of Ocean Science for Sustainable Development (2021 – 2030). Also, information from monitoring programs can establish thresholds and build “efficient natural observatories” (Cordeiro et al., 2022). Depending on the objective and necessity of the monitoring program, it is possible to identify several approaches, to answer specific or general questions (Thrush et al., 2021). Furthermore, monitoring is a powerful approach to assess whether regulated standards have been exceeded, to detect and assess the impacts of human-generated disturbance, to assess the responses to restoration efforts, or to assess the ecological state of ecosystems (Downes et al., 2002). The latter usually is a long-term monitoring program, which includes a large-scale sampling to produce a considerable database that can be used to evaluate environmental changes and for ecological modeling (e.g., Costa et al., 2022).

Long-term monitoring generates a database built, commonly, on more than five years of sampling (Thrush et al., 2021). Then, ecosystem patterns and processes can be tracked and understood at different levels of organization (Cordeiro et al., 2022), producing robust temporal trends (Currie & Small, 2005; Giron-Nava et al., 2017). Indeed, it is frequently used to identify and manage threatening processes and provide warning signals of impending environmental changes (Downes et al., 2002; Hampton et al., 2019). For example, the long timescale of the monitoring may support the prediction of faunal responses against human impacts (Giron-Nava et al., 2017; Hampton et al., 2019). Nonetheless, long-term monitoring is usually associated with high investments, and well-designed methodology, with high labor sampling and processing, although it is difficult to maintain (Lindenmayer et al., 2014; Cordeiro et al., 2022).

There are many challenges to carrying out long-term monitoring. In that way, Cordeiro and collaborators (2022) analyzed some of the best-funded Brazilian Long Term Ecological Projects (PELD) and found an uneven distribution between regions and ecosystems. Some challenges also include the unstable public funding dependence (Caughlan & Oakley, 2001), different methods applied through monitoring programs, including data set extent and taxonomic resolution (Thrush et al., 2021), their achieving cost (Currie & Small, 2005), and the societal value (Waltham et al., 2020). Another common challenge in long-term monitoring is to design programs that can distinguish changes in biota due to natural conditions or due to anthropogenic impacts, especially in highly dynamic natural ecosystems such as estuaries (Elliott & Quintino, 2007; Dauvin & Ruellet, 2009).

Estuaries are semi-enclosed transitional environments where seawater is diluted with river water (Pritchard, 1967), and where occurs a great variability in their environmental conditions (McLusky & Elliott, 2004; Thrush et al., 2013). That variability includes anthropogenic influences, but also natural variations, such as salinity, grain size, turbidity, and depth, as well as the availability of organic matter (Barros et al., 2008). Estuaries located in tropical regions are still relatively understudied (Barros et al., 2012), and frequently are bordered by mangrove forests (e.g., Costa et al., 2015; Hatje et al., 2021), saltmarshes (Reis et al., 2019), and contain large seagrass beds (Sena et al., 2022). Tropical estuaries promote a range of interconnected ecosystem services, such as nursery habitats, sources of freshwater, food supply, and frequently support traditional coastal communities (McLusky & Elliott, 2004; Thrush et al., 2013; Booi et al., 2022) being one of the most relevant and productive systems on Earth (Zapata et al., 2018).

Most long-term monitoring in tropical estuaries comprise not only physical (e.g., salinity and granulometry) and chemical parameters (e.g., heavy metals and nutrients), but also include biotic metrics, such as fish and/or invertebrates (Downes et al., 2002). Benthic assemblages are very frequent in aquatic monitoring studies (Thrush et al., 2021; Cordeiro et al., 2022). They are central in substrate-water interface processes and realize important estuarine ecosystem functions, such as substrate oxygenation and organic matter degradation (Martins & Barros, 2022). Benthic organisms have relatively low motility, compared to vertebrates, and present a relatively long-life cycle, in contrast to zooplankton for example. Thus, they are essential for identifying and tracking ongoing process changes when monitoring natural aquatic systems (Engle & Summers, 1999; Lu et al., 2008; Dauvin et al., 2010).

However, benthic organisms exhibit high spatial and temporal variation in dynamic environments, and in estuaries, this understanding is essential for improving the management (Currie & Small, 2005; Thrush et al., 2021). Within tropical estuaries, the richness of benthic assemblages generally increases from the oligohaline zone towards the euhaline zone (i.e., freshwater to marine waters) (e.g., Barros et al., 2012; Krull et al., 2014). That distribution can be explained by natural filters (e.g., Alves et al., 2020) hampering the survival or the settlement of some species in the superior portions of the estuary. Benthic community structure may follow a gradual change along the estuary, where some of the species are concentrated in the lower estuary while others at the upper estuary, and the mid-estuary has both species types at the edge of their range (Attrill & Rundle, 2002).

The changes in the structure of benthic organisms alongside an estuary are closely related to different biogeochemical and physical processes of different estuarine portions (Rossi & Underwood, 2002), and also to biological interactions (such as colonization, predation, and competition). Salinity is the major influencer (Attrill & Rundle, 2002; Whitfield et al., 2012) since the estuaries have, by definition, a salinity gradient. Also, the strong relationship between benthic organisms and the granulometry of the sediments they inhabit is noticeable, since they might need an optimal range of percentage mud to occur (Anderson, 2008; Thrush et al., 2013). For instance, different grain sizes that compose the estuaries substrate support a variety of benthic species, according to their behavior and functional trait, which in turn will determine what ecological functions are performed and at which intensity in different estuarine zones (Martins & Barros, 2022).

In Todos os Santos Bay (Bahia, Brazil), some studies indicated that there is a greater richness in the more saline part of the estuaries compared to the central and upper regions (e.g., Barros et al., 2014; Hatje et al., 2006; Alves et al., 2020). However, there are still not many established long-term monitoring studies along estuaries on the Brazilian coast (Cordeiro et al., 2022), or even in tropical estuaries in general. Therefore, the biological patterns, similarities, and spatial and temporal changes in Brazilian estuaries need to be explored. This work aimed to analyze temporal and spatial variations in benthic assemblage structure in three tropical estuaries using monitoring data collected in the past two decades. We also aimed to identify the patterns within the benthic structure in the estuaries, as well as the changes between and within estuarine zones throughout the sampling campaigns.

2. Methodology

2.1 Study area

The present study was conducted in Todos os Santos Bay (TSB) along the estuarine portions of the three principal tributaries Paraguaçu, Jaguaripe, and Subaé rivers (Figure 1). TSB is the second-largest bay in Brazil, located on the northeast coast. TSB is mostly shallow, with an average depth of 9.8 m but with some deeper parts (i.e., 50 m), and which domain is designed by tidal currents (Cirano & Lessa, 2007). Paraguaçu estuary is distinguished for being the Bahia state's genuinely major river (approximately 600km of extension) and TSB's larger freshwater contributor (Cirano & Lessa, 2007). Meanwhile, its hydrological cycle, since 1986, is subject to the opening of the floodgates of the Pedra do Cavalo Dam, located in the region above the estuary (Barros et al., 2008). Jaguaripe River is relatively well-preserved with mostly pristine mangrove forests along its margin (Hatje & Barros, 2012; Krull et al., 2014). Subaé River had a lead smelter, deactivated in 1993, in the upper part of the estuary and associated with local heavy contamination in its vicinity (Hatje et al., 2006; Hatje & Barros, 2012). Nonetheless, Subaé is one of the main sources of suspended particulate matter for the TSB (Hatje et al.,2006).

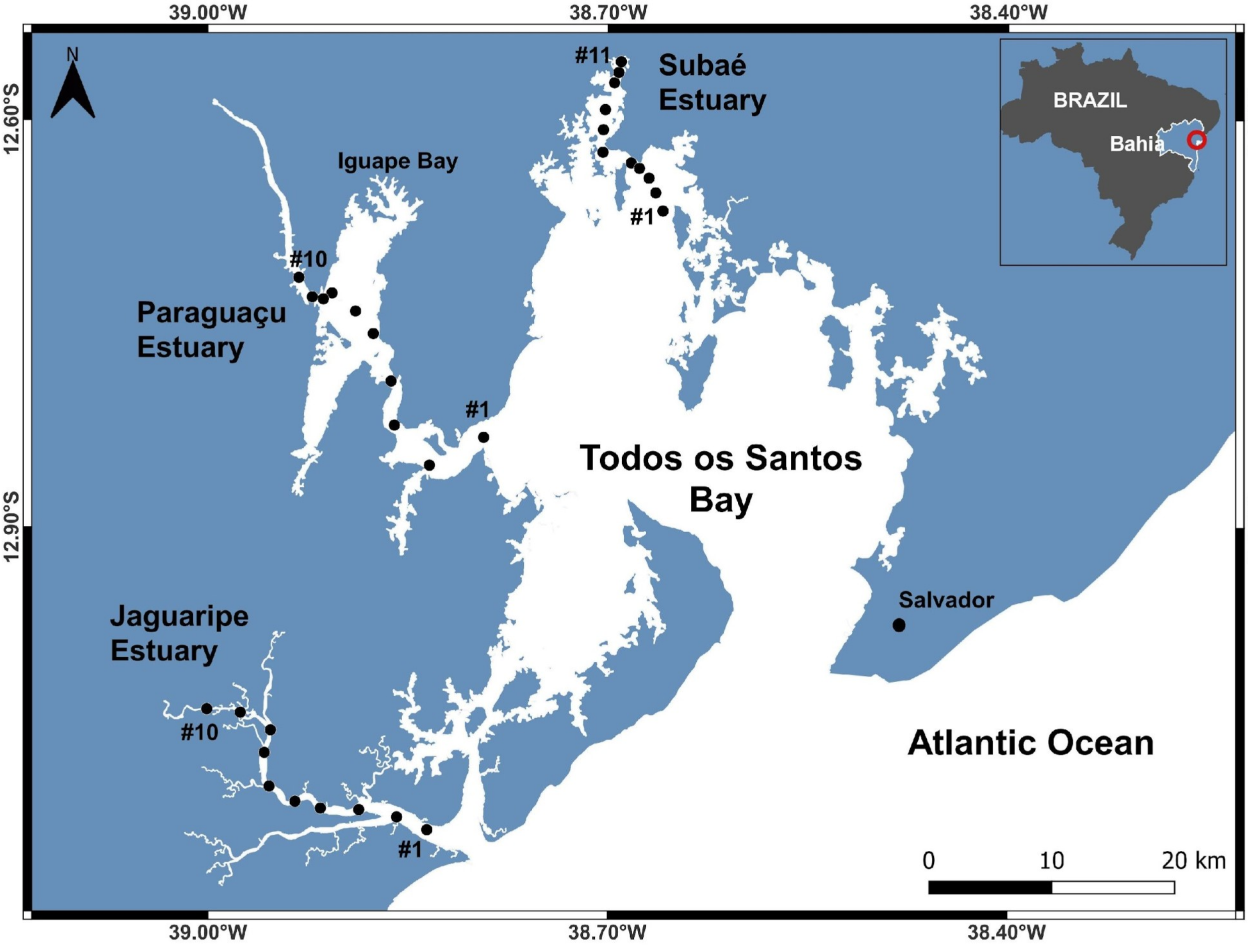


Figure 1: Todos os Santos Bay, Bahia, Brazil. Distribution of sampling stations (black dots) along the Paraguaçu, Jaguaripe, and Subaé estuaries.

2.2 Data source

The benthic macrofaunal data analyzed here was achieved by research previously done by the Benthic Ecology Laboratory – UFBA (data available in Barros et al., 2021). The samplings were carried out at different times in each of the estuaries, resulting in a database of 18 years of research (Table 1). Although the campaigns were carried out in different dry and rainy periods, the present study did not have as an objective the climatic analysis of the three estuaries.

Table 1: Sampled estuaries and their respective sampling campaign dates. Rainy (☁) and dry (☀) periods were highlighted.

Paraguaçu	Jaguaripe	Subaé
May/2005 ☁	May/2006 ☁	June/2004 ☁
December/2005 ☀	August/2007 ☀	March/2006 ☀
June/2011 ☁	July/2010 ☁	December/2009 ☀
August/2014 ☀	August/2014 ☀	April/2011 ☀
October/2022 ☀	March/2019 ☀	March/2013 ☀
	July/2022 ☁	December/2022 ☀

The samples were collected along the salinity gradient of the three estuaries. We sampled 10 fixed sampling stations in the river Paraguaçu and Jaguaripe, and 11 fixed stations along the estuary of Subaé (Figure 1). At each estuary, the stations were placed at an increasing distance from the mouth of the estuary: from marine water to freshwater. On each sampling occasion (Table 1), at each sampling station we sampled two sites distant about 20 – 50 meters. At each site of Jaguaripe and Subaé estuaries, 4 replicates were manually collected by divers with a PVC corer (0.0078 m^2), while in Paraguaçu, 3 replicates were collected at each site using a van Veen (0.054 m^2), due to stronger currents and no visibility. Exceptions occurred in two sampling campaigns at Subaé: in December/2009, per sampling station, 1 replicate was collected using van Veen (0.054 m^2) and 3 replicates were collected using corer (0.0078 m^2) (each replicate were washed in 3 different mesh sizes) (see details in Souza & Barros, 2015); and in April/2011, the replicates were collected using a van Veen (0.054 m^2).

Samples were washed in the field using 0.5 mm mesh, fixed in 70% alcohol, and frozen. In the laboratory, the samples were sorted under a stereoscopic microscope and all the invertebrates were identified mostly at the family level, which can efficiently distinguish ecological patterns (e.g., Souza & Barros, 2015). All specimens were preserved in alcohol 70% and stored after identification.

Salinity was obtained by measurements on the surface and in the water column at each station, using a refractometer or a multiparameter sonde (Hidrolab©). To investigate variations in the distribution of organisms between estuarine salinity zones, the Venice System (1958) was adopted to classify each sampling station as euryhaline (30–40), polyhaline (18–30), mesohaline

(5–18) and oligohaline (0.5–5). To group the sampling stations of the different estuaries according to this system, we adopted the classification suggested by Krull and collaborators (2014).

One sediment sample was collected at each station for grain size analyses. Sediments were washed with water and sieved to separate the coarser/sandy fractions (pebble, granule, very coarse sand, coarse sand, medium sand, fine sand, and very fine sand) from the fine fractions (silt and clay). The coarser/sandy fractions were dried in an oven and sieved on a mechanical shaker with a series of sieves (i.e., 2 mm, 1 mm, 0.5 mm, 0.250 mm, 0.125 mm, and 0.63 mm meshes). The fine fractions were placed in beakers to decant and then dried in an oven. The weight of the sediment fractions was obtained on an analytical balance. All detailed field and laboratory procedures were previously reported elsewhere (e.g., Barros et al., 2008, 2012; Hatje et al., 2006).

2.3 Data analysis

To analyze the grain size composition of estuaries we used Sysgran© 3.0 (Camargo, 2006), following the Folk & Ward (1957) default method. To estimate the benthic assemblage richness and density, replicates of each station were pooled, since the sites did not show a significant difference between them (Supplementary material 1). For other analysis, in order to focus on the most influential taxa, ensure data robustness, and reduce noise in the dataset, all the replicates, and only those benthic macrofaunal taxa that (i) contributed to 90% of the total abundance (i.e., all stations and campaigns summed) of each estuary, and (ii) that were identified in at least two campaigns were considered, and referred in this study as “filtered data”.

To analyze the spatial pattern of the benthic macrofauna, through the similarity between the stations throughout the collection campaigns, the Non-Metric Multidimensional Scaling (nMDS) of each estuary was performed using a Bray-Curtis similarity matrix from the abundance data, considering its good performance in abundance databases (Clarke et al., 2014). Also, abundance data allows the understanding of numerical representation of each taxa and their contribution to the overall community structure. A dummy variable of value 1 was added to account for the presence of zeros rather than treating it as missing data. Also was utilized the Bray-Curtis distance and the number of 999 permutations.

To assess the significance of the differences found between the benthic assemblages structures of each sampling station and zone over time were executed two pair-wise comparisons, with unrestricted permutation of raw data, from Permutational Multivariate Analysis of Variance (PERMANOVA) with three factors, (i) campaign (fixed, nested within station, 5 levels for Paraguaçu and 6 levels for Jaguaripe and Subaé); (ii) sampling station (fixed, 10 levels for Paraguaçu and Jaguaripe and 11 levels for Subaé); and (iii) estuarine zone (fixed, 4 levels for all estuaries) respectively. Once the PERMANOVA showed significant differences ($p < 0.05$) in almost all sampling stations at all the campaigns for the estuaries (probably caused mostly by the natural variation on these heterogeneous estuaries than by our methodology itself), the average similarities (from Bray-Curtis similarity matrix) between the stations, between the zones, and within the zones along the sampling campaigns at each estuary were calculated and analyzed.

To identify the taxa that most contributed to spatial differences in the assemblages, the Similarity Percentages Routine (SIMPER), with two factors (A = zone, B = station), was conducted with the Bray-Curtis similarity matrix. All statistical analyses were performed using Primer© (v. 6.1.13) +PERMANOVA (v. 1.0.3) software (Clarke et al., 2014). Density and richness analysis were made in R© software (v. 4.1.2) (R Core Team, 2021).

3. Results

3.1 Environmental variables

In the three estuaries, a general decrease in salinity was observed at each sampling occasion towards the upper portion (i.e., oligohaline zone) of each estuary (Figure 2), but some variation was observed. The salinity of the Paraguaçu estuary (Figure 2a) starts to decrease from station #7 (mesohaline zone). A relative increase in salinity values was observed through the campaigns, with high values recorded in August/2014. The salinity of the Jaguaripe estuary presented its lowest values in the campaign of August/2007, with values close to zero from station #4 to #10 (Figure 2b). In this estuary, the highest value (i.e., 40.9) was recorded in

August/2014, and salinity reached a value close to zero at least in one station in all campaigns (Figure 2b). Unlike the other estuaries, the last stations of Subaé, on some occasions, presented a high salinity value, especially in March/2013, when the values along the estuary fluctuated between 28.0 and 31.9 (Figure 2c). The highest salinity values (i.e., above 40) in this estuary, were found in the first stations in December/2009 campaign while the lowest salinity values were observed on June/2004.

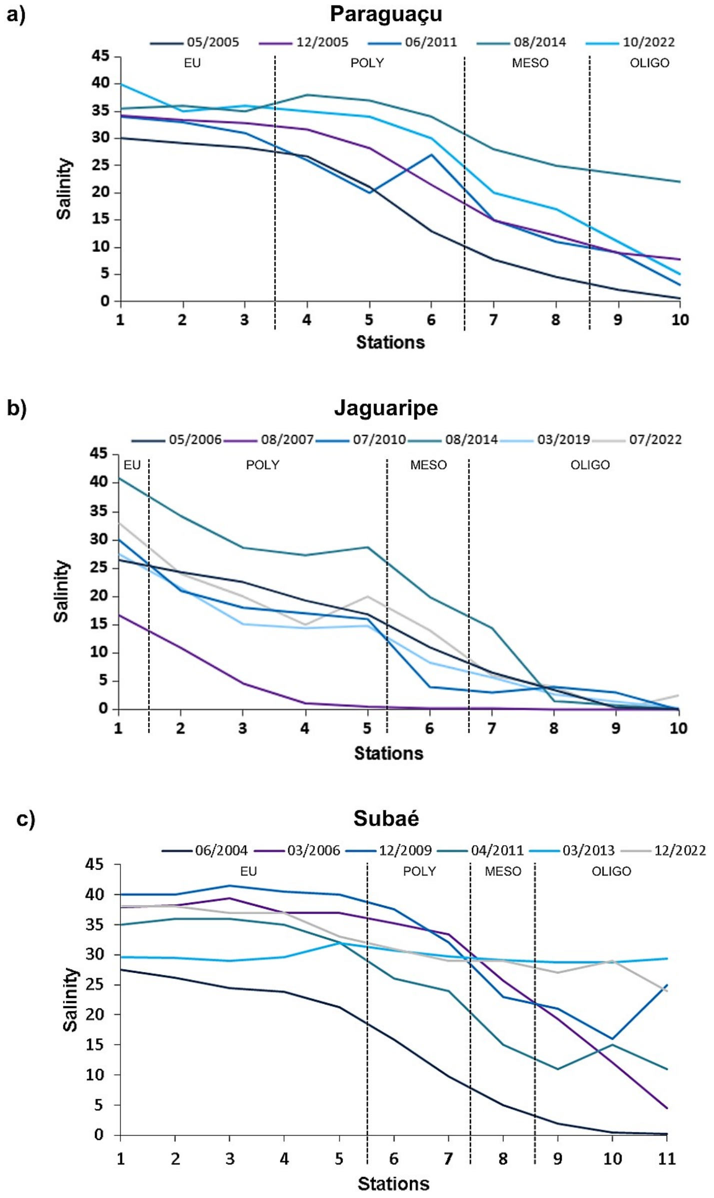


Figure 2: Distribution of salinity along the Paraguaçu (a), Jaguaripe (b), and Subaé (c) estuaries at different campaigns and estuarine zones (euhaline: EU, polyhaline: POLY, mesohaline: MESO, oligohaline: OLIGO).

In the three estuaries, we observed a general decrease in particle size towards the stations closest to the mouth, with some variations through the campaigns (Figures 3 – 5). Paraguaçu grain size was mainly poorly selected. There was a predominance of fine sizes in stations #1 to #4, with more than 70% of the sediment composed of silt and clay, on December/2005 and August/2014 (Figure 3). In stations #5 to #10, medium and coarse sand were predominant, with a consistent heterogeneity (i.e., medium and fine sand) in stations #5 to #7. In Jaguaripe, the grain size was mainly moderately selected. We observed a predominance of medium and fine sand, which more frequently comprised more than 70% of the sediments in stations #4 and #5 (Figure 4). In Subaé, the grain size was mainly poorly selected. We observed the predominance of fine sizes in stations #1 to #4, with more than 70% composed of silt and clay at different campaigns (Figure 5). Stations #2 to #5 showed relatively high temporal variability, for instance, in station #2 the grain size from June/2004 until December/2009 was markedly coarser but from April/2011 until December/2022 was markedly finer.

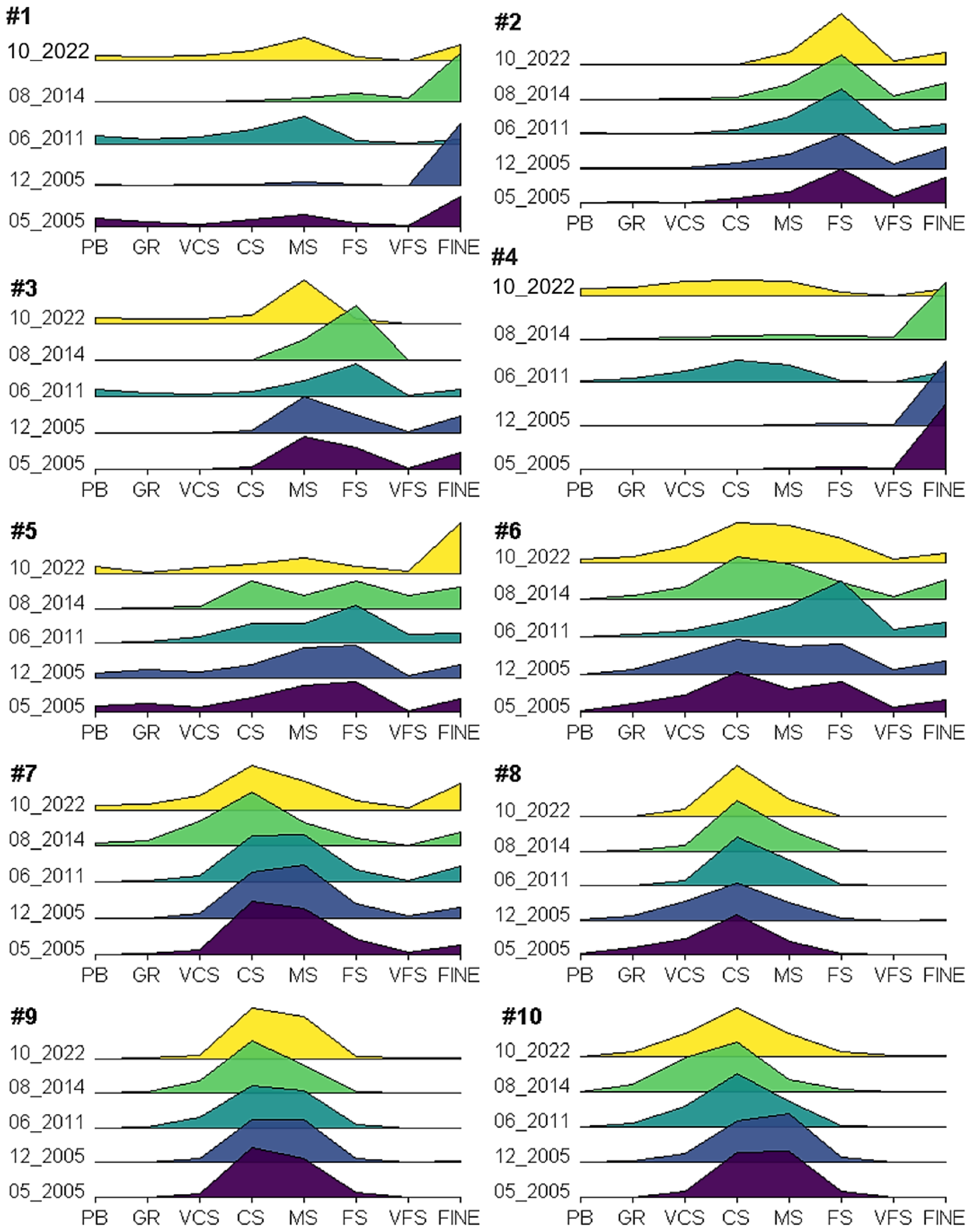


Figure 3: Granulometric composition of Paraguaçu stations (%) at different campaigns (pebble: PB, granule: GR, very coarse sand: VCS, coarse sand: CS, medium sand: MS, fine sand: FS, very fine sand: VFS, silt, and clay: FINE).

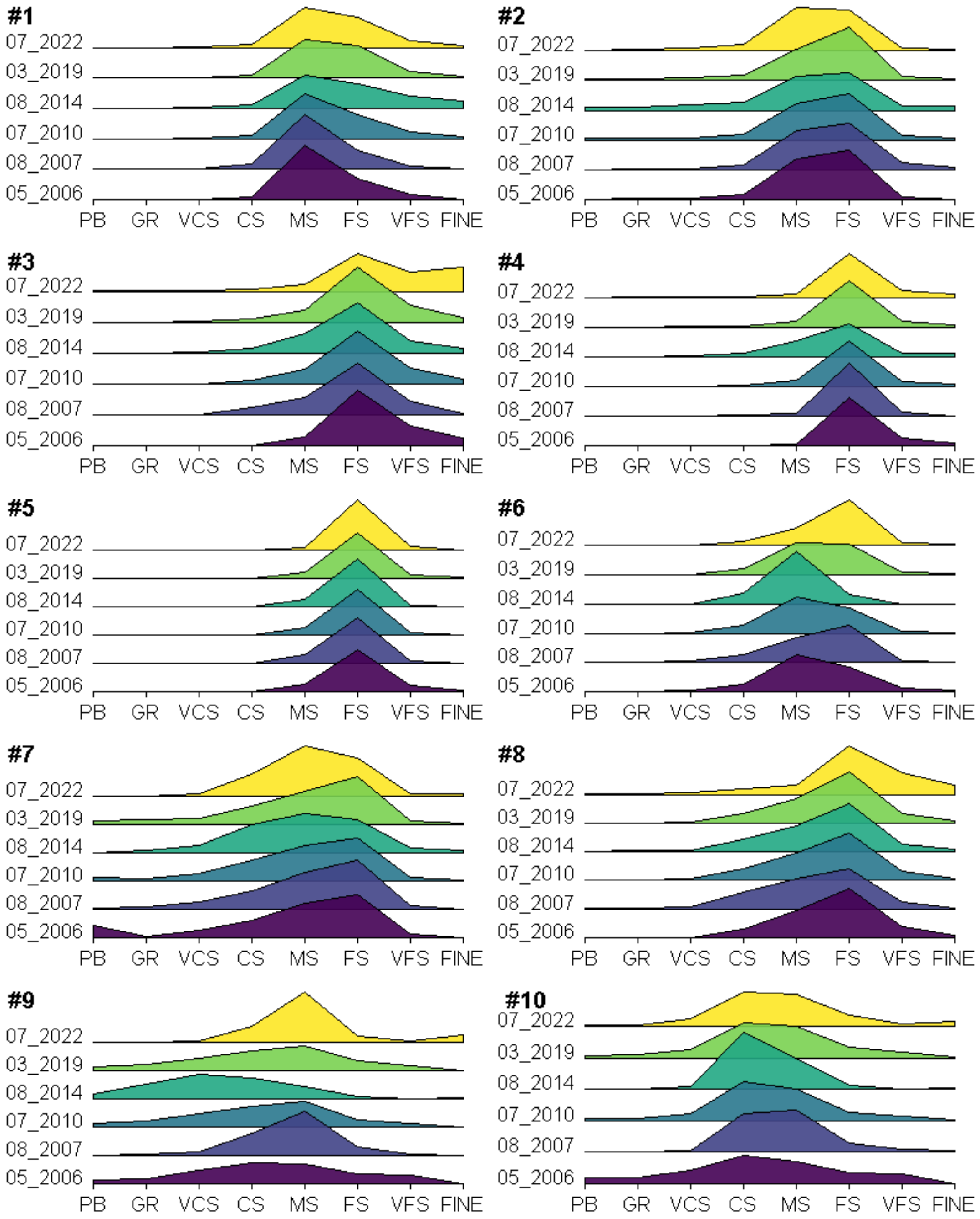


Figure 4: Granulometric composition of Jaguaripe stations (%) at different campaigns (pebble: PB, granule: GR, very coarse sand: VCS, coarse sand: CS, medium sand: MS, fine sand: FS, very fine sand: VFS, silt, and clay: FINE).

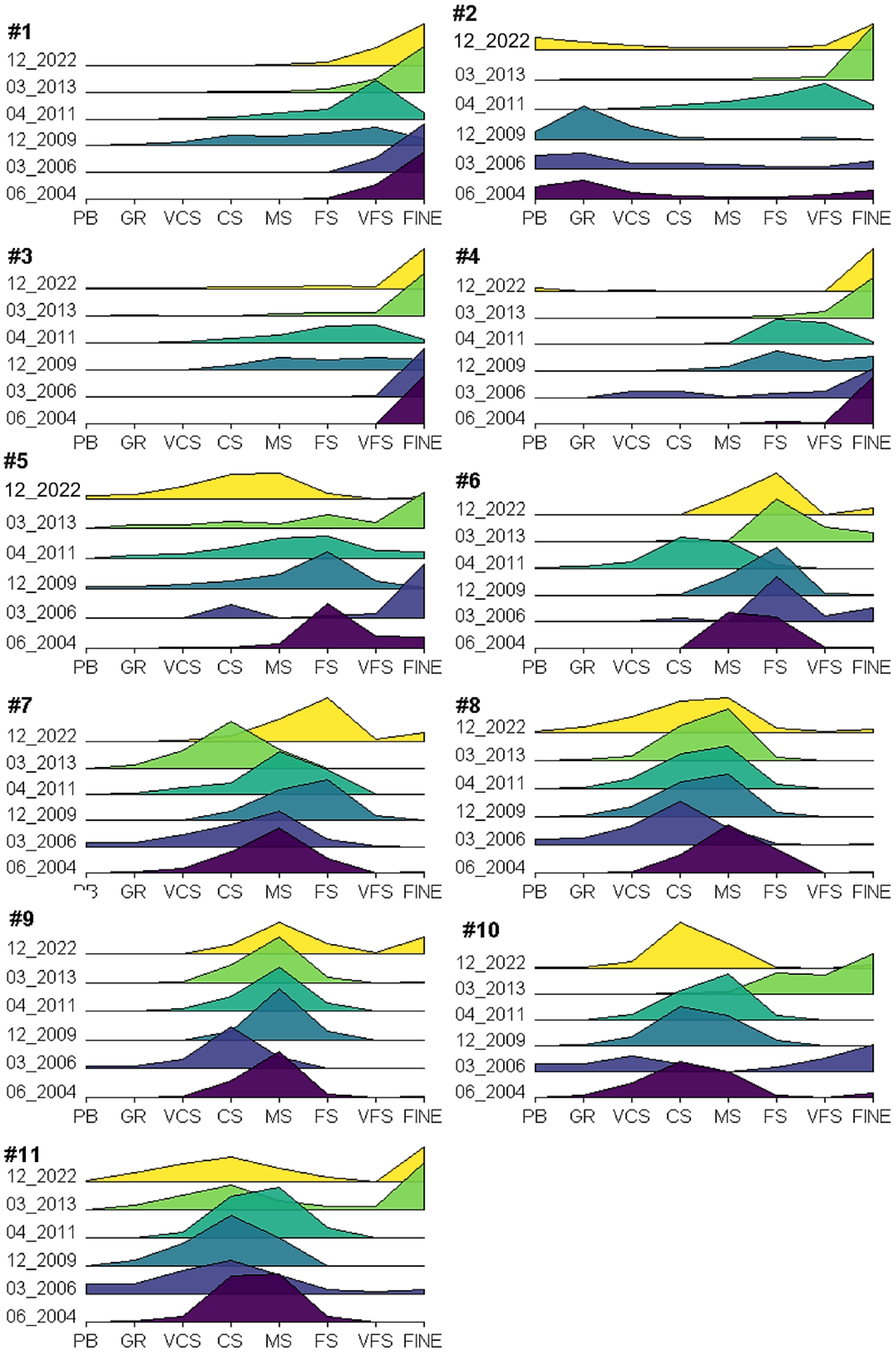


Figure 5: Granulometric composition of Subaé stations (%) at different campaigns (pebble: PB, granule: GR, very coarse sand: VCS, coarse sand: CS, medium sand: MS, fine sand: FS, very fine sand: VFS, silt, and clay: FINE).

3.2 Benthic data

3.2.1 Richness and density patterns

All three estuaries presented 66 taxa in common and a general increase in richness from oligohaline to euhaline zones (Figure 6). Overall, there was an increase in the total number of taxa found, from the first to the last collection campaign.

In Paraguaçu River, a total of 125 taxa were recorded, and only 23 taxa were exclusive to that estuary. In the four campaigns, high values of richness were observed in stations #2, #5, and #6, within the euhaline and polyhaline regions, respectively, and a decreasing trend from station 6 (Figure 6a). The second last campaign (i.e., August/2014), was the only one to present a station with no benthic macroinfauna (i.e., #1). In the Jaguaripe River, 93 taxa were identified and only 12 taxa were exclusive to that estuary. The highest values of richness were observed in the euhaline and the polyhaline zones (Figure 6b). Starting from station #3, there is a decrease in richness. The data observed in July/2022 showed the highest values, while the lowest occurred in the second campaign, 6 years before. Station #10 in the first and second-last campaigns (i.e., May/2006 and March/2019), presented no invertebrates. In Subaé River, 99 taxa were observed accounted for, and only 8 taxa were exclusive to this estuary. Benthic macrofauna presented high values of richness in station #2, followed by a decrease, although it is still possible to visualize punctual high values of richness in other stations (i.e., stations, as in #4 and #7) (Figure 6c). Some stations showed no benthic macrofauna (i.e., were filled with zero values: #5 in (June/2004), #9 in (April/2011), and #11 in (June/2004).

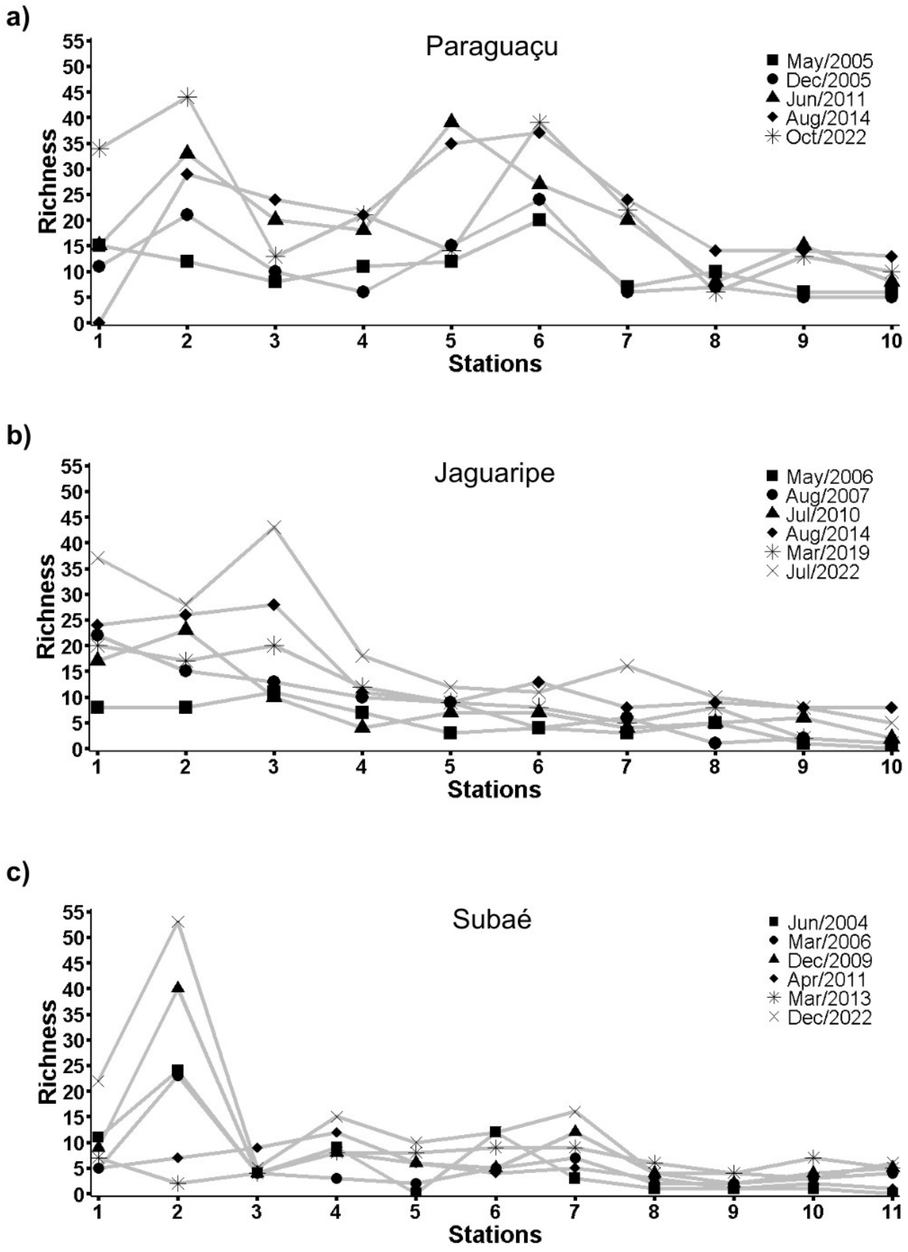


Figure 6: Richness of the benthic macrofauna along the (a) Paraguaçu, (b) Jaguaripe, and (c) Subaé estuaries at different campaigns.

There were no clear patterns in the benthic invertebrate densities along the three estuarine gradients (Figure 7). Paraguaçu estuary showed the lowest densities, in comparison with Jaguaripe and Subaé, with a relatively small variation through campaigns (Figure 7a). The highest values were found in the middle of the estuary, between stations #4 and #7, and in #1 (October/2022). The high density at station #1 in 2022 was mainly to the abundance of Cirratulidae (1,417 individuals/m²), which accounted for 14% of Polychaeta's total density (>53%), followed by Mollusk (>17%, where Tellinidae accounted for 8% of this total) and Crustacea (>10%, where Cirolanidae accounted for 8% of this total). Jaguaripe estuary in general showed a decrease in density towards the upper region (Figure 7b), but not in #3 (all campaigns, except for July/2010), #9 (August/2014 and July/2022), and #10 (July/2010, August/2014, and July/2022). The highest densities between the three estuaries, reaching more than 18,000 individuals/m², were found in Jaguaripe at #3 and #9 (July/2022), due to Magelonidae (12,853 individuals/m²) and Nereididae (17,340 individuals/m²) respectively, which accounted for 18% and 29% of the Polychaeta total density (>80%) respectively, followed by Mollusk (>10%, where Tellinidae accounted for 6% of this total) and Crustacea (>2%). In Subaé estuary, #2 showed the highest densities in almost all campaigns (Figure 7c). The exception was observed in the last stations in December/2009, reaching 11,619 individuals/m² in station #9. This maximum value was caused by Tellinidae (11,602 individuals/m²), which accounted for 36% of the total density of Mollusk (>39%). Different from the other two estuaries, the mollusk Tellinidae was concentrated in the upper estuary in Subaé.

Nonetheless, from the filtered data were obtained 9 taxa in common between the three estuaries: 7 polychaetes, 1 mollusk (Tellinidae), and 1 Nemertea (Supplementary material 3). Their density varied greatly not only along the campaigns but also between the estuaries. Spionidae, Pilargidae, Capitellidae, Tellinidae, and Nemertea were well distributed along the entire estuaries. Conversely, Cirratulidae, Magelonidae, and Orbiniidae were concentrated in the euhaline and polyhaline zones. Nereididae was found in almost all zones in Paraguaçu but was more concentrated in the oligohaline zone of Jaguaripe and Subaé.

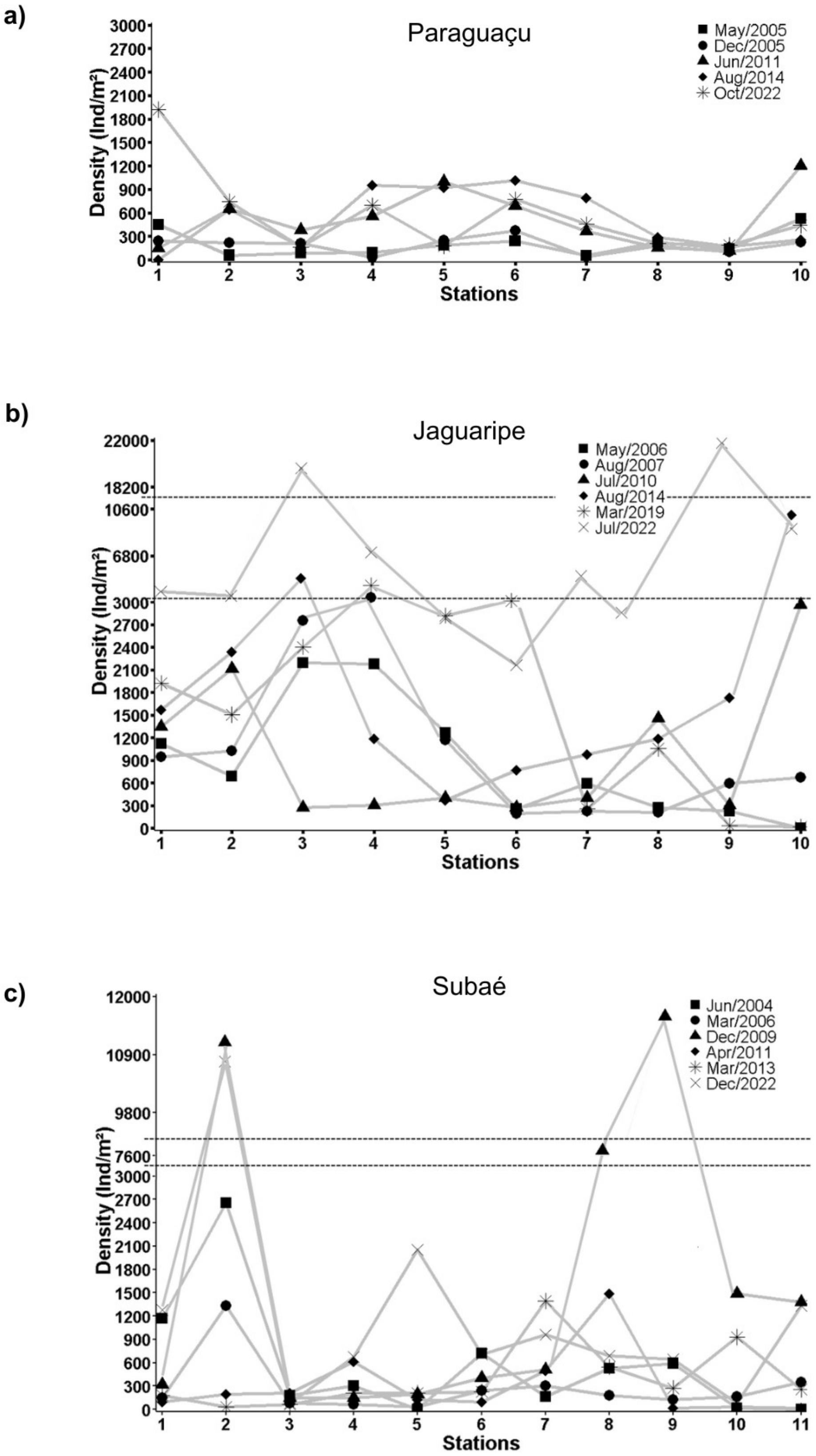


Figure 7: Density (individuals per m²) of the benthic macrofauna identified in the respective campaigns along the sampling stations of the Paraguaçu (a), Jaguaripe (b), and Subaé (c) river estuary.

Overall, Polychaeta was the most abundant and rich group, followed by Mollusk and Crustacea (Figure 8). Exceptions were observed in two campaigns in Paraguaçu (May and December/2005) (Figure 8a) and in Subaé (December/2009 and April/2011) (Figure 8c) estuaries, where Mollusk had the higher densities. Jaguaripe estuary showed the highest percentages of Polychaeta in density and richness (Figures 8c and 8d). In general, both the richness and density increased along the campaigns in all estuaries. Other less common taxa encountered included ophiuroids, chordates, cnidarians, insect larvae, sipunculids, pycnogonids, nematodes, and nemerteans.

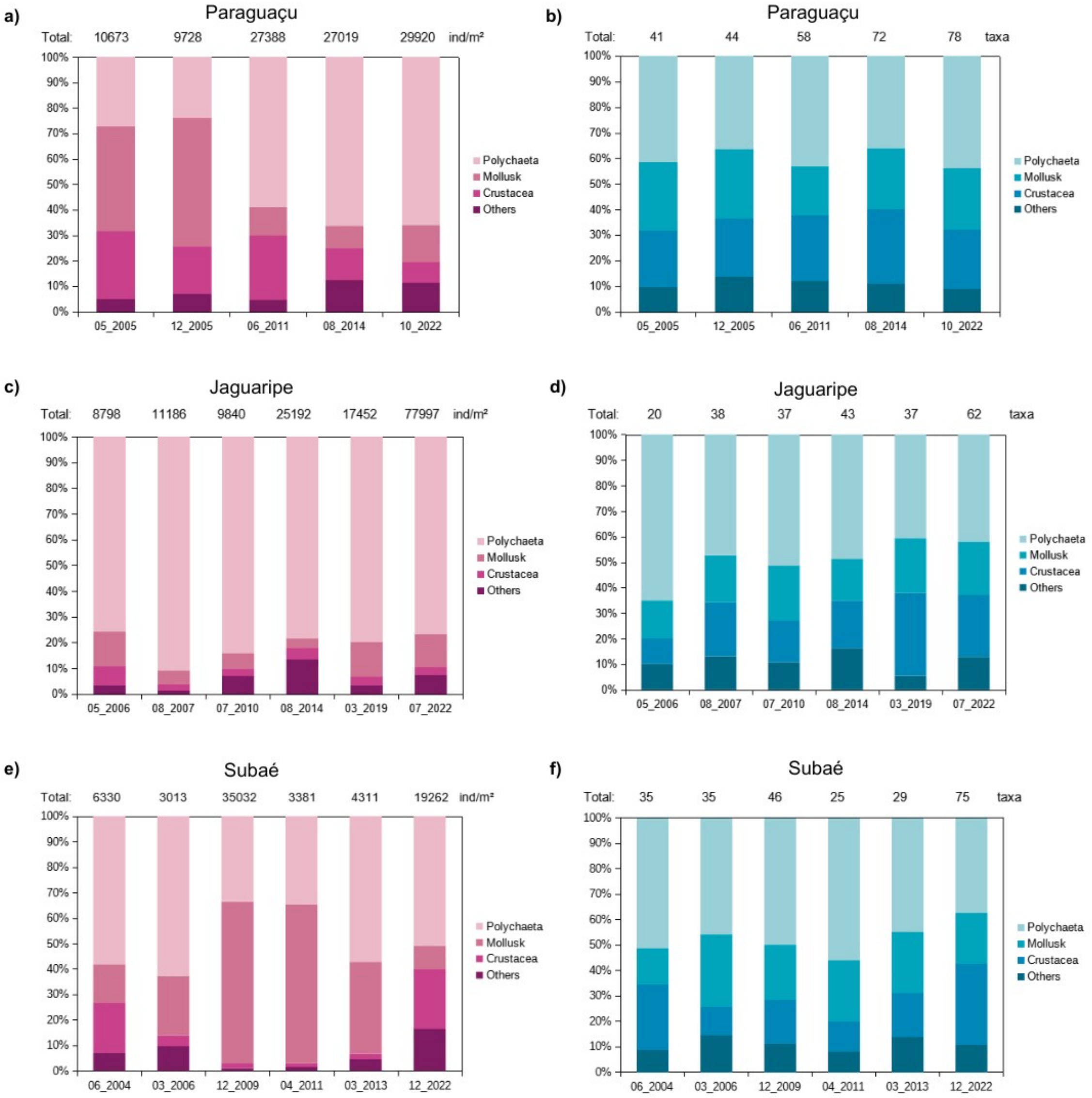


Figure 8: Percentual density (individuals per m²) (pink) and richness (blue) of the benthic macrofauna along the Paraguaçu (a-b), Jaguaripe (c-d) and Subaé (e-f) river estuaries at different campaigns.

3.2.2 Multivariate patterns

In the filtered data of Paraguaçu, Jaguaripe, and Subaé Rivers were 35, 13, and 28 taxa respectively. The structure of the benthic macrofauna underwent modifications throughout the campaigns, although it is possible to see a distinction between the more saline stations with the less saline stations (Figure 9). That distinction is better visualized in the Jaguaripe estuary (Figure 9b), even though its stress is 0.2, like the nMDS of the other two estuaries, which suggests a reasonably good fit between the nMDS plot and the similarity matrix.

In Paraguaçu nMDS, stations #1 (August/2014) and #10 (June/2011) are markedly dissimilar to the other stations (Figure 9a). The dissimilarity from station #1 was caused by the extremely low density, while the dissimilarity from station #10 was caused by the high density present at the respective stations (Figure 7b). In Jaguaripe nMDS, most of the less saline stations, such as #9 and #10, were dissimilar to the others in different campaigns (Figure 9b). In addition, the stations between #1 and #4 were very similar. In Subaé, although most stations are mixed, it is possible to see some similarity between saline and less saline stations (Figure 9c). Stations #3 and #4 from different campaigns were slightly similar. Stations #8 and #9 (December/2009) were markedly dissimilar from the other stations because of the high densities found at those stations (Figure 7c). Stations #9 (June/2009) were dissimilar from others #9 in different campaigns because showed only one taxon (Nereididae).

The average similarity within the estuarine zones was approximately greater than 50%, with the SD lower than 10% (Figure 10). The average similarity in Paraguaçu varied between 36 and 47%, in Jaguaripe varied between 46 and 67%, and in Subaé varied between 51 and 65%. Overall, the benthic composition within the zones showed few modifications, with punctual higher and lower average similarities values, along the campaigns in all three estuaries. The composition within the oligohaline zone remained very similar through the campaigns, once the highest values of similarity were found there. The average similarity within the stations reached 100% in #1 in Paraguaçu (August/2014), #10 in Jaguaripe (May/2006 and March/2019), and #2, #5, #9, and #11 in Subaé at different campaigns. (Supplementary material 2).

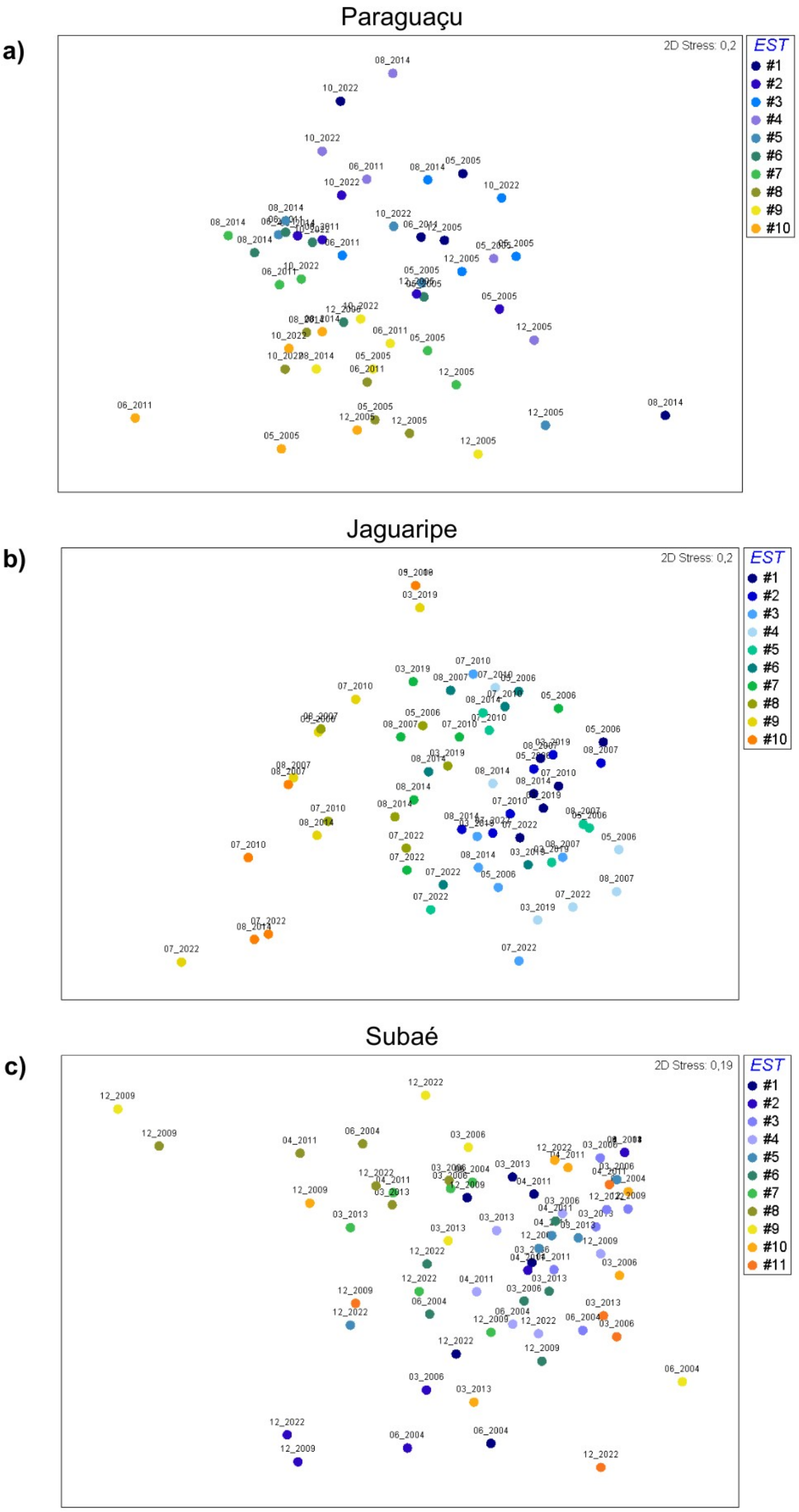
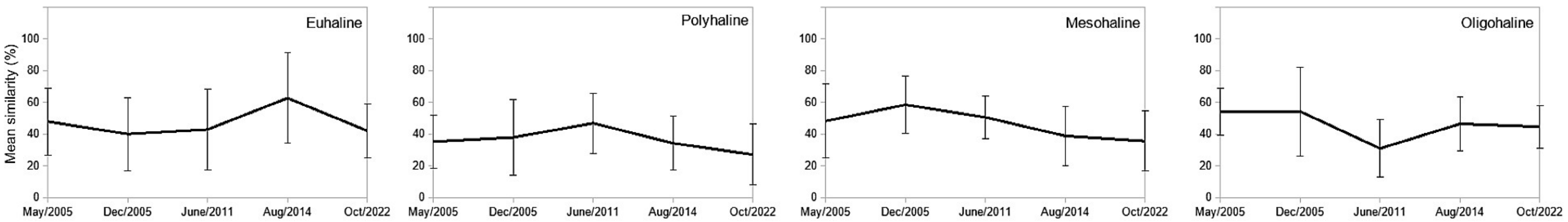
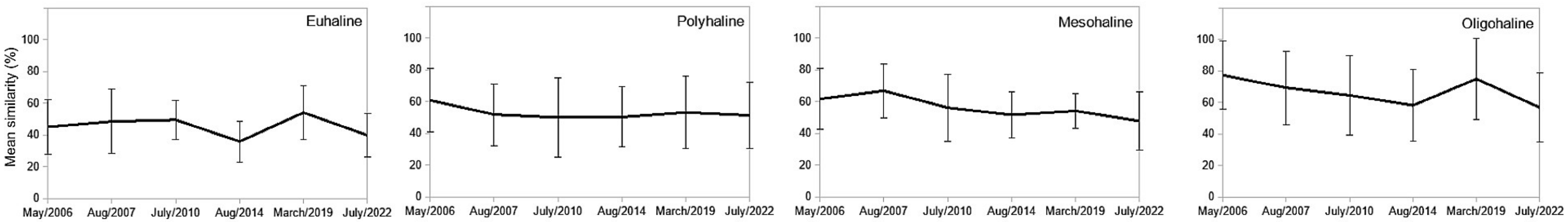


Figure 9: Non-metric multidimensional scaling (nMDS) according to the filtered abundance matrix of the taxa in the estuary stations of the Paraguaçu (a), Jaguaripe (b), and Subaé (c) estuaries at different campaigns.

a) Paraguaçu



b) Jaguaripe



c) Subaé

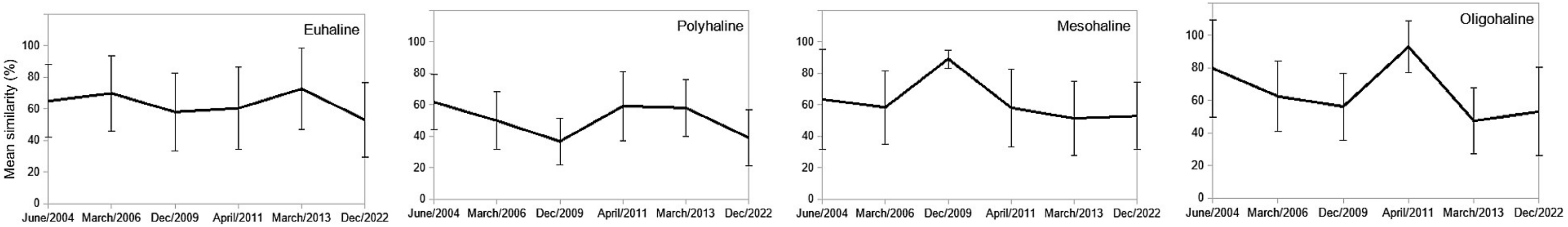


Figure 10: Average (± SD) similarity within the estuarine zones in the (a) Paraguaçu, (b) Jaguaripe, and (c) Subaé estuaries at different campaigns.

The SIMPER routine identified those taxa that most contributed to differences observed between estuarine zones (Table 3). Three taxa commonly contributed to the differences in the estuaries' euhaline zones: Cirratulidae, Tellinidae, and Orbiniidae. These last two also commonly contributed to the polyhaline zone. Tellinidae was the only common taxa in the mesohaline zone but was also common with Nereididae in the oligohaline zone.

In the Paraguaçu estuary, a total of 14 taxa contributed to the differences in the euhaline zone, 16 taxa in the polyhaline zone, and 7 taxa in the mesohaline and oligohaline zones (Table 3). The taxa that contributed the most for the Paraguaçu euhaline zone was Nuculidae (23.63%), for polyhaline and mesohaline was Tellinidae (13.68% and 40.83% respectively), and for oligohaline was Veneridae (25.56%). In the Jaguaripe estuary, a total of 7 taxa contributed to the differences in the euhaline zone, 6 taxa in the polyhaline zone, and 5 and 3 taxa in mesohaline and oligohaline zones (Table 4). The taxa that contributed the most to the differences in the Jaguaripe zones were Orbiniidae (41.01%), Magelonidae (34.42%), Tellinidae (45.42%), and Nereididae (72.48%) respectively. In the Subaé estuary, a total of 13 taxa contributed to the differences in the euhaline zone, 5 taxa in the polyhaline zone, and 4 and 12 taxa in mesohaline and oligohaline zones (Table 5). Tellinidae contributed the most for the differences in the Subaé euhaline, polyhaline, and mesohaline zones (30.27%, 61.49%, and 60.85% respectively), and Nereididae contributed the most for the oligohaline zone (34,97%).

Table 3. Major contributors (%) to differences in Paraguaçu, Jaguaripe, and Subaé estuarine zones (euhaline: Eu, polyhaline: Poly, mesohaline: Meso, oligohaline: Oligo) from SIMPER.

	Paraguaçu				**Jaguaripe**				**Subaé**			
Taxa	**Eu**	**Poly**	**Meso**	**Oligo**	**Eu**	**Poly**	**Meso**	**Oligo**	**Eu**	**Poly**	**Meso**	**Oligo**
Ampharetidae	0	0	0	0	0	0	0	0	0	0	5,34	0
Amphiuridae	5,95	0	0	0	0	0	0	0	0	0	0	0
Branchiostomatidae	0	0	0	0	10,77	0	0	0	0	0	0	0
Capitellidae	0	0	0	0	0	3,91	17,86	0	6,78	11,08	9,55	6,13
Cirolanidae	0	0	0	20,17	0	0	0	0	0	0	0	0
Cirratulidae	15,16	9,13	0	0	17,09	8,39	0	0	2,57	0	0	4,40
Cnidaria	0	0	0	0	0	0	0	0	1,83	0	0	0
Corbulidae	3,06	0	0	0	0	0	0	0	0	0	0	0
Glyceridae	3,19	5,35	12,61	8,39	0	0	0	0	0	0	0	0

Goniadidae	0	0	0	0	0	0	0	0	8,83	4,12	0	2,43
Lumbrineridae	2,20	0	0	0	0	0	0	0	0	0	0	0
Magelonidae	0	2,97	0	0	3,51	34,42	0	0	2,50	0	0	0
Maldanidae	2,04	3,72	0	0	0	0	0	0	1,90	0	0	0
Nemertea	2,64	5,55	10,35	5,41	0	0	0	0	3,94	9,06	0	7,25
Nereididae	7,38	8,04	3	5,72	0	0	0	72,48	0	0	15,66	34,97
Nuculidae	23,63	0	0	0	0	0	0	0	0	0	0	0
Oligochaeta	0	0	0	4,35	0	0	0	0	0	0	0	0
Onuphidae	0	2,81	0	0	0	0	0	0	0	0	0	0
Orbiniidae	2,63	3,60	0	0	41,01	18,01	0	0	12,35	7,94	0	6,38
Ostracoda	0	0	0	0	0	0	0	0	0	0	0	4,29
Paguridae	0	5,54	0	0	0	0	0	0	0	0	0	0
Paraonidae	0	2,74	5,53	0	12,72	20,41	6,21	0	0	0	0	0
Pilargidae	0	0	8,23	0	0	0	6,57	0	2,01	0	0	8,75
Poecilochaetidae	2,15	9,67	0	0	0	0	0	0	0	0	0	0
Sipuncula	2,37	0	0	0	0	0	0	0	2,58	0	0	0
Solecurtidae	0	0	0	0	0	0	0	0	2,17	0	0	0
Spionidae	9,06	8,40	0	0	3,72	0	16,58	9,19	0	0	0	2,07
Sternaspidae	0	2,70	0	0	0	0	0	0	12,97	0	0	3,44
Syllidae	0	4,85	0	0	0	0	0	0	0	0	0	6,73
Tellinidae	8,55	13,68	40,83	23,91	4,52	6,35	45,42	8,43	30,27	61,49	60,85	3,83
Trichobranchidae	0	3,17	0	0	0	0	0	0	0	0	0	0
Veneridae	0	0	10,55	25,56	0	0	0	0	0	0	0	0
Total (%)	90,01	91,92	91,1	93,51	93,34	91,49	92,64	90,1	90,7	93,69	91,4	90,67

4. Discussion

The present study showed the spatial and temporal variation of the benthic assemblages through the past two decades in Paraguaçu, Jaguaripe, and Subaé estuaries of Todos os Santos Bay. The increasing number of taxa towards the saltiest portion of the three estuaries was observed as similar to what is reported in other studies of tropical and temperate estuaries (e.g., Dauvin, 2008; Barros et al., 2014; Krull et al., 2014; Martin et al., 2019; Alves et al., 2020; Rahman et al., 2022). However, this pattern differs from other studies' findings of high richness in the less saline estuarine portion (e.g., Fujii, 2007; Whitfield et al., 2012). Various research in tropical (e.g., Jayachandran et al., 2020; Mulik et al., 2020; Coelho et al., 2022) and even temperate (e.g., Rodrigues et al., 2006; Bacouillard et al., 2020) estuaries found a similar richness value (i.e., 125, 93, and 99 taxa in Paraguaçu, Jaguaripe, and Subaé respectively), although their higher taxonomic resolution was species and not families as in the present study. Polychaeta was the dominant group as frequently observed for estuaries around the world (Rodrigues et al., 2006; Fujii, 2007; Sivadas et al., 2011; Ribeiro et al., 2016; Lana & Bernadino, 2018; Rahman et al., 2022) followed by Mollusk and Crustacea, showing some variability in distinct zones (Figure 8).

Although the benthic assemblages structures did not show a marked division between the different estuarine zones, the less saline stations (i.e., oligohaline) and higher saline stations (i.e., euhaline) were clearly different (Figure 9). In general, the highest values of richness were found in the polyhaline and euhaline zones of the estuaries. The euhaline portion is inhabited by organisms physiologically adapted to finer sediment and higher salinity composition (e.g., Pearson & Rosenberg, 1978), such as the Polychaeta families Cirratulidae and Magelonidae, that showed high densities and significant contributions to the differences found in the estuaries euhaline and polyhaline estuarine zones. The presence of tubicolous polychaetes, such as Magelonidae, in soft sediments is essential to the sediment oxygenation, through the ventilation of the tubes (e.g., Martins & Barros, 2022). Despite the lower richness at the estuaries' oligohaline zones, they were dominated by the mollusk Tellinidae and the polychaeta Nereididae, which showed high densities (Supplementary material 3) and significantly contributed to the differences from other zones. The distribution of benthic organisms along the estuarine gradient is related to the different physical variables of each estuarine zone (e.g., Ysebaert et al., 2003; Krull et al., 2014, Mulik et al., 2020) and benthic traits (e.g., van der Linden et al., 2017; Martins & Barros, 2022). However, this richness pattern confronts the classic ecological model proposed by Remane (1934), since it was not observed peaks of richness in oligohaline zones, but a general increase in taxa towards the more saline parts of the estuaries. This difference is possible due to the study area covered by Remane in the Baltic Sea, in which biotic composition and environmental characteristics (e.g., climate, geomorphology, salinity, and hydrodynamic) differs from tropical estuaries, such as the TSB estuaries, which reduces the applicability of this model, and enhances the creation of new conceptual models (e.g., Whitfield et al., 2012).

Benthic structure in the Paraguaçu estuary varied relatively little over time, although there have been minor changes in the similarities of the stations throughout the campaigns. The high richness found in Paraguaçu might be influenced by the sediment heterogeneity, facilitating different organisms to inhabit that area (Munguia et al., 2011; Carvalho et al, 2017). Nonetheless, Nereididae was well distributed along the entire estuary through the campaigns (Supplementary material 3), contributing to the differences found in the four zones of Paraguaçu, unlike what was found in the other estuaries, where this taxon occurred only in the upper region. Despite the high dominance of polychaetes in Paraguaçu, the mollusks (i.e., Nuculidae, Tellinidae, and Veneridae) were the principal contributors to the variability found between different estuarine zones. Also, the dominance of Nereididae in the upper estuary and of Veneridae and Tellinidae in the lower estuary, represented by the genera *Laeonereis* (Nereididae), *Anomalocardia* (Veneridae), *Chione* (Veneridae)*,* and *Macoma* (Tellinidae), was reported by van der Linden and collaborators (2017), in another two Brazilian estuaries.

In station #2 of Paraguaçu, high richness values were found. Once the granulometry and salinity in this station are consistent with the pattern found on that estuarine gradient, its location near a small affluent of the Paraguaçu river might have some influence over these richness values. Barros and collaborators (2008) also found high values in station #2. Also, they suggested that an oil company shipyard could be affecting neighboring environmental conditions in areas nearby station #2, once it is a potential source of Polycyclic Aromatic Hydrocarbons (PAHs), although the PAHs analyzed by them in this station were below detection limits. The relatively high values of richness in stations #5 and #6 still need to be investigated, even though Barros and collaborators (2012) have found similar values of richness. Possibly, the location of these stations inside a small bay (Iguape Bay) with high grain heterogeneity and high salinity values may explain these values. The singularity of Paraguaçu is linked to its geographic characteristics, such as the influence of the Pedra do Cavalo dam in the upper portion of the estuary, since it controls the freshwater flows entering the estuary (Cirano & Lessa, 2007; Barros et al., 2008). Given the environmental heterogeneity of the Paraguaçu estuary and the existence of different patterns of its trace metals distribution (Hatje & Barros, 2012), a complex benthic distribution is suggested.

The Jaguaripe River estuary presented high values of richness in the first three stations (i.e. in the euhaline and polyhaline zones) that persisted through the campaigns. In the euhaline, polyhaline, and oligohaline zones, the polychaetes Orbiniidae, Magelonidae, and Nereididae were the major contributor to the differences found, and in the mesohaline zone, the mollusk Tellinidae was the major contributor. As found by Magalhães & Barros (2011), *Magelona papillicornis* (Magelonidae), *Leodamas cirratus* (Orbiniidae) and *Laeonereis culveri* (Nereididae) were the dominant species in the same three estuaries, with the *L. culveri* being sometimes the only polychaeta found at the upper region. As in the present study, Orbiniidae also contributed to differentiate three tropical intertidal areas in Bijagós Archipelago, because of its higher density found by Coelho and collaborators (2022). Nonetheless, high abundances of Magelonidae were also found in the upper region of several other Brazilian estuaries (Lana & Bernadino, 2018).

Overall, the Jaguaripe estuary presented a particle size distribution relatively more uniform, with sediments moderately selected, than the other two estuaries, as observed by (Hatje & Barros, 2012), which remained throughout the campaigns. The majority of the nMDS obtained in this estuary showed that the benthic composition was maintained in most sampling periods, with some exceptions (e.g., 2010), which is consistent with the richness pattern found. One of the results obtained by Krull and collaborators (2014) indicated that the distribution of benthic assemblage in the Jaguaripe estuary was correlated with the metals Sr and Cu. However, strontium reflects more the marine influence on organisms than acts as a contaminant, and the concentration of copper found by Hatje and collaborators (2009) is below the level considered toxic to biota. In that way, Jaguaripe is still considered little anthropologically impacted (Hatje & Barros, 2012) thus benthic assemblages are mostly under the action of natural stressors.

In the Subaé estuary, different patterns of richness and salinity were shown in comparison with the other two estuaries analyzed in the present study. However, in this estuary, the mollusks Tellinidae were the major contributor to the differences found in the euhaline, polyhaline, and mesohaline zones, while in the oligohaline zone, the polychaeta Nereididae was the major contributor, similarly to Paraguaçu. Tellinidae showed a great distribution along some estuaries (e.g., Lana & Bernadino, 2018; Ysebaert & Herman, 2002), despite its major concentration in the oligohaline and mesohaline zones of Subaé estuary (Supplementary material 3). This pattern was also observed by Dauvin (2008) and Fujii (2007) in *Macoma balthica* communities and by Barros and collaborators (2012). This is probably linked to its tolerance to low salinity, and its association with a variety of grain sizes (Costa et al., 2022), once this bivalve exhibit burrowing behavior.

We observed that the Subaé estuary showed a high temporal variability, i.e. a dissimilarity between the stations throughout the campaigns. The grain size composition of Subaé has changed more throughout the campaigns than the other two estuaries. Also, although the grain size of Subaé has a low degree of selection, as Paraguaçu, it showed a lower richness overall. The richness remained low along the estuary, except for station #2, and the salinity remained high almost in all the stations. Stations #1 - #3 are located far from the mouth of this river, unlike the first stations from the other two estuaries. Nonetheless, the different patterns found in the granulometry of station #2 might indicate some seasonal change in the local grain size, that could be influencing the local benthic assemblage, as the presence of coarser sediments (Figure 5). The stations of the upper portion of Subaé presented low richness, and also presented higher salinity values than is expected in this region (Figure 2). One possibility is that the shallower depth of the last stations increases the evaporation rate, which in turn interferes with local salinity (Cirano & Lessa, 2007), and influences consequently the benthic fauna. Another justification for the low richness values in the upper portion of Subaé is the influence of the waste reservoir of a lead smelter that was deactivated in 1993 in the upper portion of the estuary. However, according to Hatje et al. (2006), the proximity of the smelter does not explain the high concentrations of metals in the innermost stations of the estuary. The co-occurrence of metals, such as Cu, Pb, and Cd, whose values were between TEL and PEL (Probable Effect Levels) in most stations (Hatje et al., 2009), is one of the factors that might promote degradation of the benthic assemblage. This estuary is considered one of the most contaminated by metals of the Todos os Santos Bay (Hatje et al., 2009), although it still has a key role in supporting local traditional communities.

5. Conclusions

In general, the largest variations found in the estuaries of the Paraguaçu, Jaguaripe, and Subaé were more spatial than temporal. Although a consistent pattern of richness (i.e., values increasing towards the lower estuary) and dominance (Polychaeta, Mollusk, and Crustacea respectively) has been observed in the three estuaries, each one has its own singularity and stressful variables at its estuarine zones. However, not many monitoring studies have used a large time scale and made public access to the databases generated by them, as the present study, which revealed the difficulty to compare with results worldwide. Also, few studies apply and maintain the same sampling and laboratory methodologies, which makes this study important, once it was possible to properly evaluate the benthic assemblages' historical trends in three different estuaries.

Still, there is a need to investigate the multivariate relationship between the benthic assemblages and their environment, in order to provide an analytical comprehension of the granulometry and salinity influences on the benthic assemblages and their temporal variations, for example. Nonetheless, as a strategy for future conservation, it is necessary more investment in conducting long-term monitoring initiatives in tropical estuaries, in order to enable better monitoring and assessment of estuarine ecosystems especially in Brazil: ‘‘The science we need for the ocean we want’’, as says the motto of the Decade of Ocean Science for Sustainable Development.

6. References

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APPENDIX A. Supplementary materials

Supplementary material 1

Results from the test of significant difference between the sites in the three estuaries. Permutational Multivariate Analysis of Variance (PERMANOVA) with three factors, (i) campaign (fixed, nested within station, five levels for Paraguaçu and six levels for Jaguaripe and Subaé), (ii) station (fixed, ten levels for Paraguaçu and Jaguaripe and eleven levels for Subaé); and (iii) site (fixed, twenty levels for Paraguaçu and Jaguaripe and twenty-two levels for Subaé) respectively.

Table 1. PERMANOVA *p* values between the sites of each station in the Paraguaçu, Jaguaripe and Subaé estuaries at different campaigns.

Paraguaçu	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
05_2005	1	0.61	0.58	0.49	0.40	0.91	1.0	0.52	0.29	0.19	-
12_2005	0.62	0.10	0.10	0.70	0.10	0.69	0.91	0.72	0.3	0.11	-
06_2011	0.91	0.90	0.09	0.41	0.90	0.71	0.09	0.10	0.91	0.28	-
08_2014		0.36	1.0	0.10	0.32	0.20	0.31	0.24	0.10	0.29	-
Jaguaripe											
05_2006	0.10	0.04	0.88	0.60	0.17	0.090	0.60	0.23	0.97		-
08_2007	0.02	0.41	0.94	0.05	**0.03**	0.13	**0.04**	0.32	0.31	0.10	-
07_2010	0.85	0.55	0.29	0.34	0.47	**0.03**	0.10	0.19	0.75	**0.03**	-
08_2014	0.24	0.22	0.54	0.79	0.35	0.72	0.90	0.58	0.87	0.67	-
03_2019	0.78	0.20	0.60	0.58	**0.03**	0.18	0.80	0.33	1.0	1.0	-
Subaé											
06_2004	0.20	0.09	0.25	0.32		1.0	0.89	0.36	**0.03**	1.0	
12_2009	0.31	0.09	0.51	0.90	0.19	0.52	0.29	0.11	0.10	0.19	0.79
03_2013	0.03	0.57	0.57	0.36	0.49	0.63	0.74	0.91	0.90	0.41	0.46
03_2006	0.66	0.89	0.36	0.58	0.55	0.75	0.68	0.63	0.40	**0.03**	0.25
04_2011	1.0	0.43	0.48	0.72	0.89	0.89	0.25	0.41	1.0	1.0	1.0

Supplementary material 2

Average similarities in the Paraguaçu (Table 2), Jaguaripe (Table 3) and Subaé (Table 4) estuaries at different campaigns. E = Euhaline, P = Polyhaline, M = Mesohaline, O = Oligohaline, St = Station, SD = Standard Deviation. In bold values above the total mean.

Table 2.1. Average similarities (± SD) within the stations in the Paraguaçu (PG) estuary at different campaigns.

PG	**May/2005**		**Dec/2005**		**June/2011**		**Aug/2014**		**Oct/2022**		**Total**	
St	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	54.03	13.72	42.71	17.99	42.59	15.38	**100**	0	50.45	13.41	57.95	21.49
2	45.83	23.86	45.79	14.22	**52.45**	8.41	**52.59**	10.03	46.30	9.31	48.59	3.21
3	**43.97**	22.69	31.62	31.15	33.87	38.20	**35.71**	11.13	29.41	18.98	34.92	5.00
4	**34.41**	16.31	**45.98**	17.48	**35.59**	25.98	21.86	17.28	13.18	12.47	30.20	11.45
5	**41.34**	18.22	**40.15**	30.40	**50.76**	11.00	36.14	11.31	29.31	18.50	39.54	7.01
6	30.17	13.38	27.76	16.52	**54.36**	9.01	**44.83**	13.27	38.92	16.48	39.21	9.74
7	**48.84**	19.78	**58.81**	21.67	**55.04**	9.13	42.88	17.46	30.63	16.63	47.24	9.92
8	**47.69**	26.50	**58.26**	14.05	**46.21**	15.19	34.83	18.73	40.67	19.61	45.53	7.81
9	**51.43**	15.59	**47.72**	27.77	32.31	9.54	**46.59**	21.11	**46.29**	10.08	44.87	6.54
10	**56.58**	13.71	**60.90**	26.65	29.62	23.60	46.38	10.98	43.14	16.10	47.32	10.97

Table 2.2. Average similarities (± SD) within the estuarine zones in the Paraguaçu (PG) estuary at different campaigns.

PG	**May/2005**		**Dec/2005**		**June/2011**		**Aug/2014**		**Oct/2022**		**Total**	
Zone	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
E	**47.94**	21.05	40.04	23.15	42.97	25.43	**62.77**	28.56	42.05	17.08	47.15	8.23
P	35.31	16.74	**37.97**	23.64	**46.90**	18.94	34.28	17.04	27.14	19.21	36.32	6.39
M	**48.26**	23.39	**58.53**	18.27	**50.62**	13.29	38.86	18.55	35.65	18.86	46.39	8.26
O	**54.01**	14.90	**54.31**	28.00	30.96	18.05	**46.49**	16.83	44.71	13.53	46.10	8.50

Table 2.3. Average similarities (± SD) between the estuarine zones in the Paraguaçu (PG) estuary at different campaigns.

PG	**May/2005**		**Dec/2005**		**June/2011**		**Aug/2014**		**Oct/2022**		**Total**	
Zone	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
E x P	41.63	20.04	39.00	23.42	**44.94**	22.50	**48.52**	27.49	34.59	19.65	41.74	4.79
E x M	**48.10**	22.02	**49.29**	23.17	**46.80**	21.74	**50.81**	27.64	38.85	18.09	46.77	4.17
E x O	**50.98**	19.07	**47.17**	26.15	36.97	23.51	**54.63**	25.81	43.38	15.81	46.63	6.12
P x M	**41.79**	20.67	**48.25**	23.88	**48.76**	17.00	36.57	17.80	31.39	19.52	41.35	6.70
P x O	**44.66**	18.47	**46.14**	26.70	38.93	20.16	40.38	17.98	35.93	19.20	41.21	3.74
E x P	**51.14**	19.82	**56.42**	23.73	40.79	18.65	42.67	18.11	40.18	17.02	46.24	6.43

Table 3.1 Average similarities (± SD) within the stations in the Jaguaripe (JAG) estuary at different campaigns.

JAG	**May/2006**		**Aug/2007**		**July/2010**		**Aug/2014**		**March/2019**		**July/2022**		**Total**	
St	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	45.09	17.41	**48.57**	20.32	**49.59**	12.35	35.90	12.95	**54.18**	16.95	39.82	13.69	45.52	6.14
2	**41.01**	18.93	**45.94**	17.97	**40.84**	18.60	**38.34**	17.46	32.13	22.60	29.96	17.25	38.04	5.47
3	**74.02**	8.39	57.36	12.06	59.72	25.28	57.14	13.72	49.93	10.18	**65.61**	13.23	60.63	7.56
4	**65.11**	16.58	**61.47**	16.49	52.93	27.51	54.59	18.63	**76.73**	10.40	57.25	18.09	61.35	8.00
5	**63.40**	17.77	42.88	23.07	46.80	23.13	51.27	19.65	**54.05**	17.98	**52.69**	16.46	51.85	6.39
6	**61.77**	19.35	**66.90**	17.13	56.24	21.11	51.68	14.57	54.16	11.14	47.84	18.39	56.43	6.32
7	**78.11**	13.95	56.85	19.92	50.27	20.60	47.69	13.51	**61.15**	17.67	48.50	17.29	57.10	10.54
8	**58.78**	21.74	**73.39**	18.42	**77.77**	11.63	45.56	19.72	47.31	18.18	44.85	17.96	57.94	13.35
9	72.68	17.43	87.14	12.12	**73.21**	29.32	55.16	20.48	**91.67**	14.43	57.67	24.58	72.92	13.55
10	**100**	0	60.32	26.96	57.27	25.28	**84.42**	9.69	**100**	0	76.31	11.45	79.72	17.01

Table 3.2. Average similarities (± SD) within the estuarine zones in the Jaguaripe (JAG) estuary at different campaigns.

JAG	**May/2006**		**Aug/2007**		**July/2010**		**Aug/2014**		**March/2019**		**July/2022**		**Total**	
Zone	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
E	45.09	17.41	**48.57**	20.32	**49.59**	12.35	35.90	12.95	**54.18**	16.95	39.82	13.69	45.52	6.14
P	**60.88**	20.07	51.91	19.44	50.07	24.87	50.34	18.94	**53.21**	22.66	51.38	21.02	52.96	3.69
M	**61.77**	19.35	**66.90**	17.13	56.24	21.11	51.68	14.57	54.16	11.14	47.84	18.39	56.43	6.32
O	**77.39**	21.51	**69.42**	23.35	64.63	25.33	58.21	22.64	**75.03**	26.04	56.83	22.08	66.92	7.80

Table 3.3. Average similarities (± SD) between the estuarine zones in the Jaguaripe (JAG) estuary at different campaigns.

JAG	**May/2006**		**Aug/2007**		**July/2010**		**Aug/2014**		**March/2019**		**July/2022**		**Total**	
Zones	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
E x P	**52.99**	20.42	**50.24**	20.06	**49.83**	22.92	43.12	18.81	**53.70**	21.65	45.60	20.31	49.24	3.79
E x M	**53.43**	20.21	**57.74**	20.91	**52.92**	17.61	43.79	15.89	**54.17**	14.35	43.83	16.70	50.98	5.30
E x O	**61.24**	24.45	**58.99**	24.25	**57.11**	24.08	47.06	22.88	**64.61**	25.88	48.33	21.77	56.22	6.46
P x M	**61.33**	19.93	**59.41**	19.92	53.16	24.29	51.01	18.16	53.68	20.88	49.61	20.57	54.70	4.26
P x O	**69.14**	22.38	**60.67**	23.20	57.35	26.19	54.27	21.24	**64.12**	26.74	54.10	21.73	59.94	5.41
E x P	**69.58**	22.01	**68.16**	22.27	60.44	24.77	54.95	21.44	**64.60**	25.24	52.34	21.69	61.68	6.42

Table 4.1. Average similarities (± SD) within the stations in the Subaé (SB) estuary at different campaigns.

SB	**June/2004**		**March/2006**		**Dec/2009**		**April/2011**		**March/2013**		**Dec/2022**		**Total**	
St	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	**62.87**	15.06	**59.23**	21.38	41.74	19.24	**82.14**	30.93	**68.52**	25.44	33.83	15.86	58.06	16.16
2	56.99	10.06	46.68	15.48	50.79	15.79	55.64	19.99	**100**	0	48.76	12.54	59.81	18.33
3	60.60	16.07	**78.57**	17.74	**73.78**	22.70	52.40	16.78	**80.00**	22.41	**83.93**	17.53	71.55	11.30
4	44.61	18.91	**73.10**	21.58	**68.57**	28.88	43.45	17.89	53.88	16.12	46.54	24.26	55.02	11.73
5	**100**	0	**91.67**	14.43	55.48	18.73	68.45	24.13	61.39	24.82	51.81	11.39	71.47	18.14
6	**62.56**	14.14	48.12	16.13	40.81	17.30	**65.83**	21.17	49.73	19.32	43.25	18.63	51.72	9.35
7	**60.88**	20.38	**51.66**	20.34	32.77	10.40	**52.52**	20.70	**66.41**	11.80	34.84	15.93	49.85	12.41
8	**63.50**	31.95	58.35	23.30	**89.26**	5.78	58.16	24.60	51.40	23.47	52.91	21.30	62.26	12.70
9	47.83	30.36	**70.41**	25.97	**69.61**	16.22	**100**	0	50.01	14.81	52.15	26.92	65.00	18.08
10	**91.67**	14.43	60.29	18.41	46.07	21.07	**87.50**	21.65	35.56	22.11	**70.83**	24.41	65.32	20.41
11	**100**	0	56.99	17.74	53.26	16.38	**91.67**	14.43	57.02	17.52	36.48	17.45	65.90	22.40

Table 4.2. Average similarities (± SD) within the estuarine zones in the Subaé (SB) estuary at different campaigns.

SB	**June/2004**		**March/2006**		**Dec/2009**		**April/2011**		**March/2013**		**Dec/2022**		**Total**	
Zone	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
E	**65.02**	23.12	**69.85**	24.07	58.07	24.50	60.42	26.27	**72.76**	25.78	52.97	23.75	63.18	6.80
P	**61.72**	17.56	49.89	18.44	36.79	14.83	**59.18**	21.97	**58.07**	18.05	39.04	17.83	50.78	9.81
M	**63.50**	31.95	58.35	23.30	**89.26**	5.78	58.16	24.60	51.40	23.47	52.91	21.30	62.26	12.70
O	**79.83**	30.01	62.56	21.80	56.31	20.55	**93.06**	15.90	47.53	20.45	53.15	27.18	65.41	15.98

Table 4.3. Average similarities (± SD) between the estuarine zones in the Subaé (SB) estuary at different campaigns.

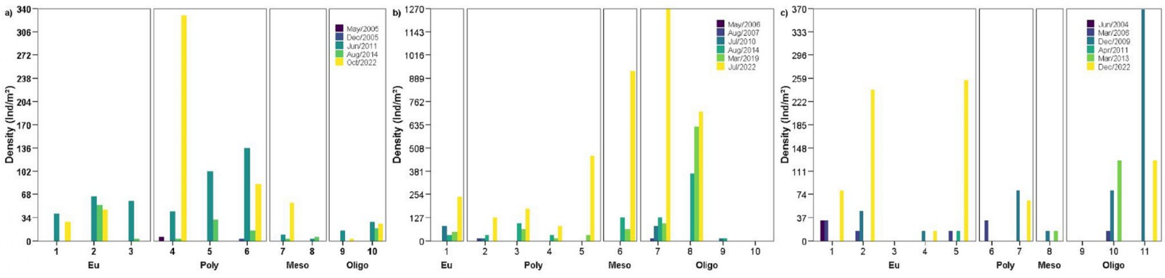
SB	**June/2004**		**March/2006**		**Dec/2009**		**April/2011**		**March/2013**		**Dec/2022**		**Total**	
Zones	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
E x P	**63.37**	21.73	**59.87**	24.34	47.43	24.17	**59.80**	25.13	**65.41**	24.74	46.01	23.09	56.98	7.53
E x M	**64.26**	24.82	**64.10**	24.33	**73.66**	24.17	59.29	26.02	62.08	26.63	52.94	23.36	62.72	6.22
E x O	**72.42**	26.89	**66.21**	23.51	57.19	25.32	**76.74**	27.85	60.14	26.86	53.06	25.09	64.29	8.35
P x M	**62.61**	23.38	**54.12**	20.58	**63.02**	27.74	**58.67**	22.88	**54.73**	20.26	45.97	20.15	56.52	5.83
P x O	**70.78**	27.25	**56.23**	21.44	**46.55**	20.80	**76.12**	24.90	52.80	20.20	46.10	24.87	58.09	11.51

Supplementary material 3

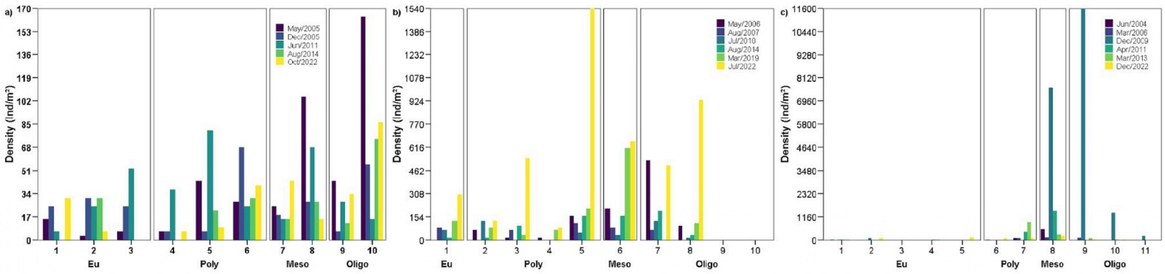
Figures of the density of the common taxa (n = 9) between the Paraguaçu, Jaguaripe and Subaé estuaries at different campaigns.

Figure 1: Density of the common taxa in the Paraguaçu (a), Jaguaripe (b) and Subaé (c) estuaries at different campaigns (euhaline: Eu, polyhaline: Poly, mesohaline: Meso, oligohaline: Oligo).

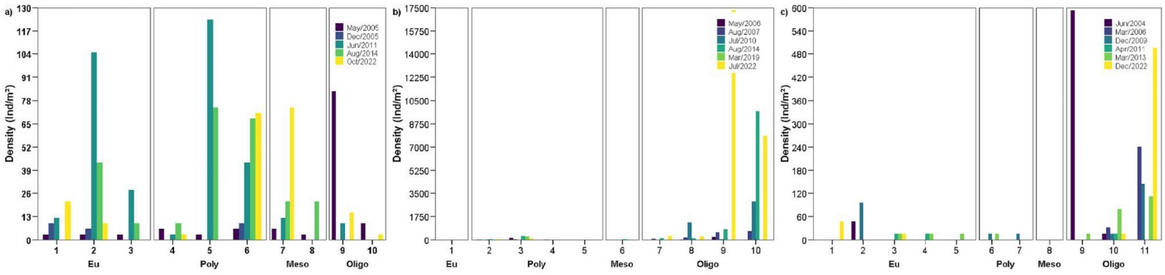
Spionidae



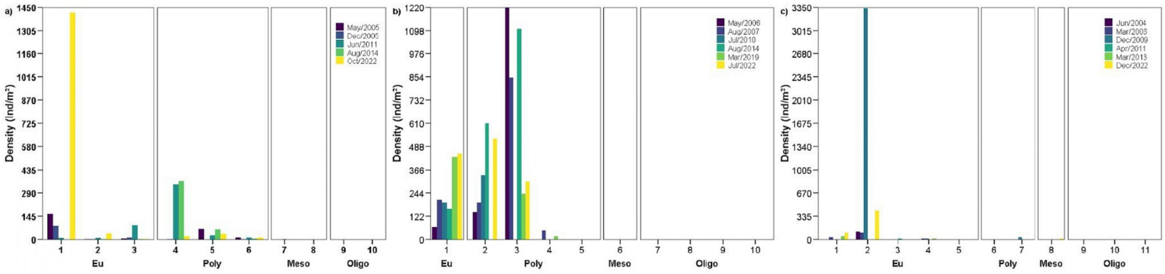
Tellinidae



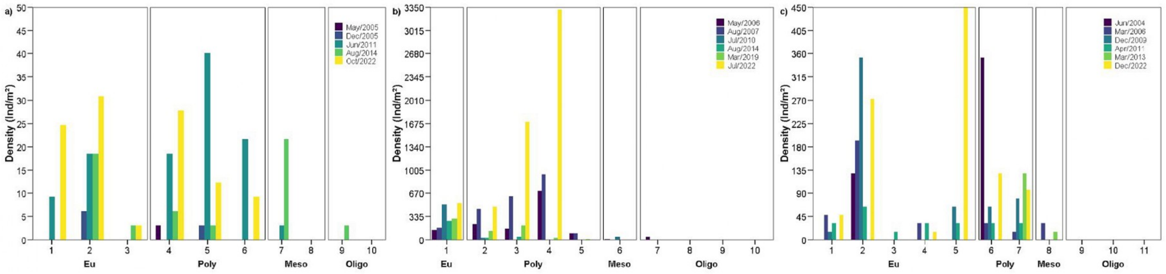
Nereididae



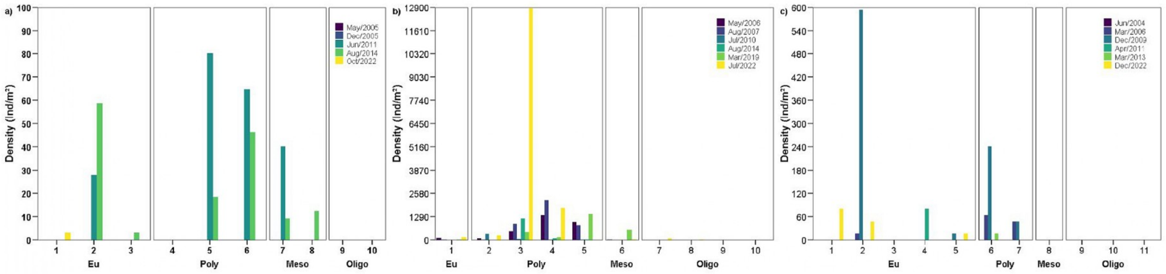
Cirratulidae



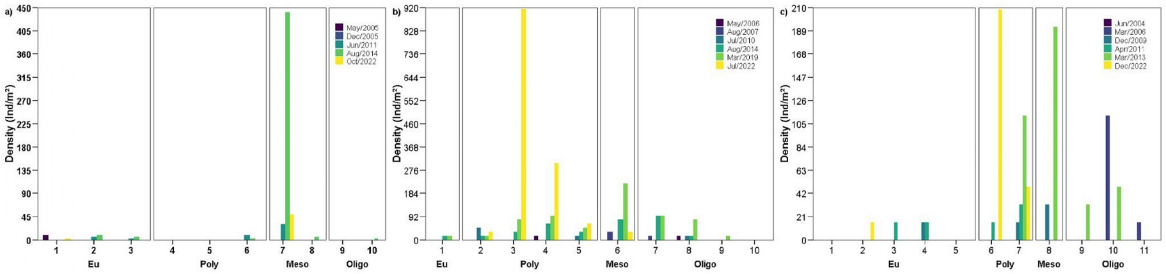
Orbiniidae



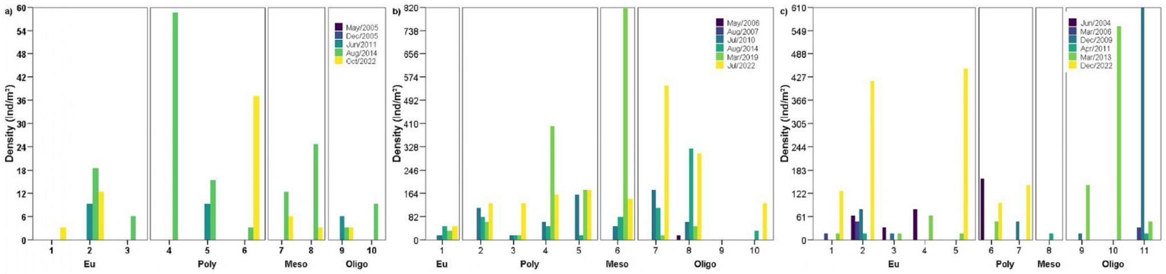
Magelonidae



Pilargidae



Capitellidae



Nemertea