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Baseline

Marine benthic communities affected by the Doce River (southwestern Atlantic): Baseline before a mining disaster

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ABSTRACT

Prior to Brazil's worst environmental disaster, caused by a mining dam collapse, we had carried out a study of the marine benthic macrofauna (11–51 m depth) under the influence of the Doce River. Our results showed significant diversity, in which mollusks, polychaetes, and crustaceans had the highest frequency, density, and abundance, represented by 162 families in summer and 173 in winter. Our results suggested that richness, abundance, and diversity increase with distance from the coast. Furthermore, with increasing distance from the coast and river mouth, in addition to increasing depth, there was a differentiation in composition and abundance. Multivariate analyses showed depth, carbonate, and organic matter as important factors that explain variations in composition and diversity across the continental shelf. The results could provide an invaluable baseline for measuring the effects on shallow and mesophotic communities of one of the largest tailings dam failures worldwide.

In November 2015, after the Fundão tailings dam collapse, about 50 million m^3 of iron waste spilled into the Doce River (eastern Brazil), reaching the Atlantic Ocean two weeks later, and resulting in the worst Brazilian environmental accident in history (Escobar, 2015; Agurto-Detzel et al., 2016). The ecological consequences for the river and adjacent ocean are still unclear (Escobar, 2015; Miranda and Marques, 2016; Gomes et al., 2017; Segura et al., 2016; Mazzei et al., 2017; Hatje et al., 2017; Queiroz et al., 2018). Hatje et al. (2017), studying the impacts of the iron tailing spill between the dam and the river plume in the ocean, showed that the highest estimated transport of dissolved metals was observed for Fe (58.8 $\mu g\,s^{-1}$), Ba (37.9 $\mu g\,s^{-1}$), and Al (25.0 $\mu g\,s^{-1}$) and established that Fe, As, Hg, and Mn exceeded sediment quality guidelines.

Currently, there is no comprehensive information combining spatial and temporal data to explain the diversity and distribution of marine benthic communities affected by the Doce River. These data would be fundamental since this region has considerable biodiversity and productivity and is affected by activities such as fishing, mining, and the oil and gas industry. As far as we are aware, our study was the only spatial (across the continental shelf) and temporal (summer/winter) characterization of benthic assemblages performed before the accident, and so constitutes an important baseline for further studies regarding the consequences of the toxic brown mudflows and other human impacts.

The objectives of our study were to quantitatively and qualitatively analyze the composition, frequency of occurrence, richness, diversity, density, and distribution of the benthic macrofauna on the continental shelf under the influence of the Doce River and determine the effects of environmental variables (sedimentary facies, distance from the coast, depth, and organic matter).

The region has two well-defined seasons: dry winter (April to September) and wet summer (October to March), with an average monthly rainfall of 145 mm and temperatures of 22 to 26 °C. The flow regime of the Doce River shows high levels from November to April and low levels from May to October (average river flow rates of 1296 m^3/s and 525 m^3/s, respectively), in accordance with the amount of precipitation falling on the watershed (Marta-Almeida et al., 2016; Hatje et al., 2017). Detailed information on our study site (Sampling stations, Doce River drainage, discharge, and the mineral deposits) are provided

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in Interactive Map file and Support Information I.

Collections in the area influenced by the Doce River occurred from December 11–19, 2010 (summer) and July 12–18, 2011 (winter). We used a regular sampling grid (20 stations), parallel to the coastline (11–51 m depth) (Support Information I). Each station was sampled three times using a Van Veen grab sampler or a box corer with an upper window. Sediment was fixed aboard with 4% formaldehyde and neutralized with sodium tetraborate.

Density was estimated over the same area as that used for the sediment samples (($0.04\,m^2$). To determine the ecological indices, we used the most common macrofauna benthic groups (Polychaeta, Crustacea, and Mollusca) identified to family level. The organisms with the lowest abundance were regarded as a single group named “Other,” comprising Nemertea, Echinodermata, Sipuncula, Turbellaria, Pycnogonida, and Echiura.

To test the influence of the mouth of the Doce River on the distribution of macrofauna across the stations analyzed, we studied four profiles parallel to the coastline: Profile A (stations 01 to 05, 11–26 m depth); Profile B (stations 06 to 10, 26–32 m); Profile C (stations 11 to 15, 35–43 m); and Profile D (stations 16 to 20, 44–51 m depth) (Interactive Map File – Sampling Map). We hypothesized that the distances from the Brazilian coast and the Doce River mouth influenced the benthic community descriptors (i.e., composition, richness, and abundance). Detailed information on methodology and statistical analysis (ANOVA, Tukey's, ANOSIM, and CCA) are provided in Support Information I.

Polychaeta showed the highest relative abundance and frequency of occurrence within the benthic community, followed by Crustacea and Mollusca (Support information II – Figs. S1 and S2). This polychaete dominance pattern in the macrofauna has often been observed in studies targeting communities in coastal regions (Diener et al., 1995; Ellingsen, 2002, and Zalmon et al., 2013). However, our results showed that Crustacea were more abundant during the winter, owing to the increased numbers of Chevaliidae (Amphipoda).

In both periods, Polychaeta were predominant in most sampling stations. However, crustaceans had the highest relative abundance for stations 07 and 14. Mollusks were not greatly represented (low frequency and abundance) over the entire sampling area (Support Information II – Fig. S2).

Absolute abundance and relative frequency data of the 10 most abundant families of the macrofauna (Polychaeta, Crustacea, and Mollusca) can be found in Support information II – Table S1. Forty-four Polychaeta families were identified, of which Spionidae and Syllidae were the most abundance (18% and 16%, respectively). In winter, there was an inversion of dominance between these families (with Spionidae representing 13% and Syllidae 20%).

Among the crustaceans, Peracarida were dominant, representing 99% of the total group. Amphipoda was the most abundant order (83% and 88% of the total crustaceans collected in summer and winter, respectively), represented by 26 families, followed by Tanaidacea (5% and 4%, 12 families), Isopoda (4% and 3%, 15 families), Cumacea (4% and 3%, four families), and Decapoda (3% and 2%, 19 families). Although the Chevaliidae are highly abundant amphipods, especially in winter, Ampeliscidae and Phoxocephalidae were the most frequently occurring.

Bivalvia was the most abundant class among the mollusks (72% and 81% of the total mollusks collected in summer and winter, respectively), represented by 24 families, with Corbulidae and Ungulinidae being the most representative. Gastropoda (23% and 14%) were represented by 19 families; while Scaphopoda (4% in both periods) and Polyplacophora (1% in both periods) were represented, in each case, by two families.

In summer, 10,384 specimens were collected, comprising 56% Polychaeta, 34% Crustacea, 3% Mollusca, and 7% other groups. In winter, 16,953 specimens were collected, comprising 49% Crustacea, 43% Polychaeta, 4% Mollusca, and 4% other groups. The total abundance of benthic macrofauna in the area influenced by the Doce River mouth was, overall, higher in winter than summer, especially in profiles closest to the coast (Support Information II – Fig. S1). The heaviest rainfall in the region usually occurs during summer; consequently, there are probably more nutrients entering coastal ecosystems in this period (Hatje et al., 2017). Therefore, greater density and abundance in the winter may be due to the time it takes for the nutrient flow in the food chain to be reflected in the composition of the benthic groups. Another hypothesis that can be put forward is that the penetration of fresh water and sediments (Akoumianaki et al., 2012) could temporarily reduce diversity since the resulting silt load increases water turbidity and reduces light penetration, which adversely affects primary productivity (Cloern, 1987; Martins et al., 2013). If this hypothesis is correct, the huge brown plume and mining waste that spread out along the coast after the disaster would affect the primary production (Gomes et al., 2017) and reduce the benthic biodiversity of the continental shelf.

When, in our study, we considered macrofaunal distributions across profiles parallel to the coast, Polychaeta was the dominant group in summer and winter, except in Profile B, where Crustacea was the most abundant (Fig. 1).

Densities at stations close to the coast (profile A, 11–26 m depth) were lowest for all groups in summer and winter, and this trend was particularly strong in winter (Fig. 2). Indeed, the lowest Polychaeta densities were found in Profile A (the lowest one was 49.00 ± 11.90 specimens/$0.04\,m^2$ in winter), whereas the highest were in Profiles C and D (furthest from the coast); and the highest record was 157.00 ± 25.75 specimens/$0.04\,m^2$ in winter.

Crustaceans and mollusks were more abundant in intermediate profiles (Profile B) during winter. The lowest crustacean densities occurred in Profile A (11–26 m depth), especially in winter. Mollusca showed low densities across all profiles in the summer. However, the

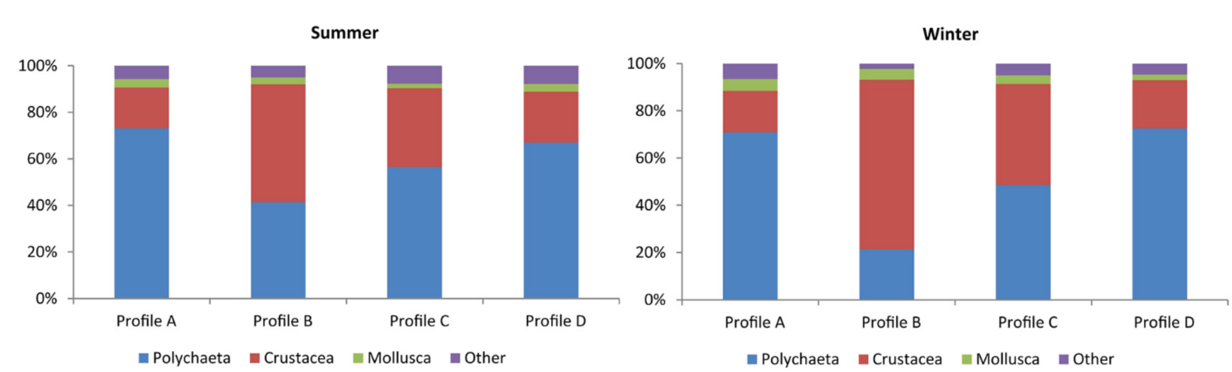

Fig. 1. Relative abundance (%) of the main macrofaunal groups in the area influenced by the Doce River mouth (eastern Brazil) for profiles A (11–26 m depth), B (26–32 m), C (35–43 m), and D (44–51 m) in summer and winter.

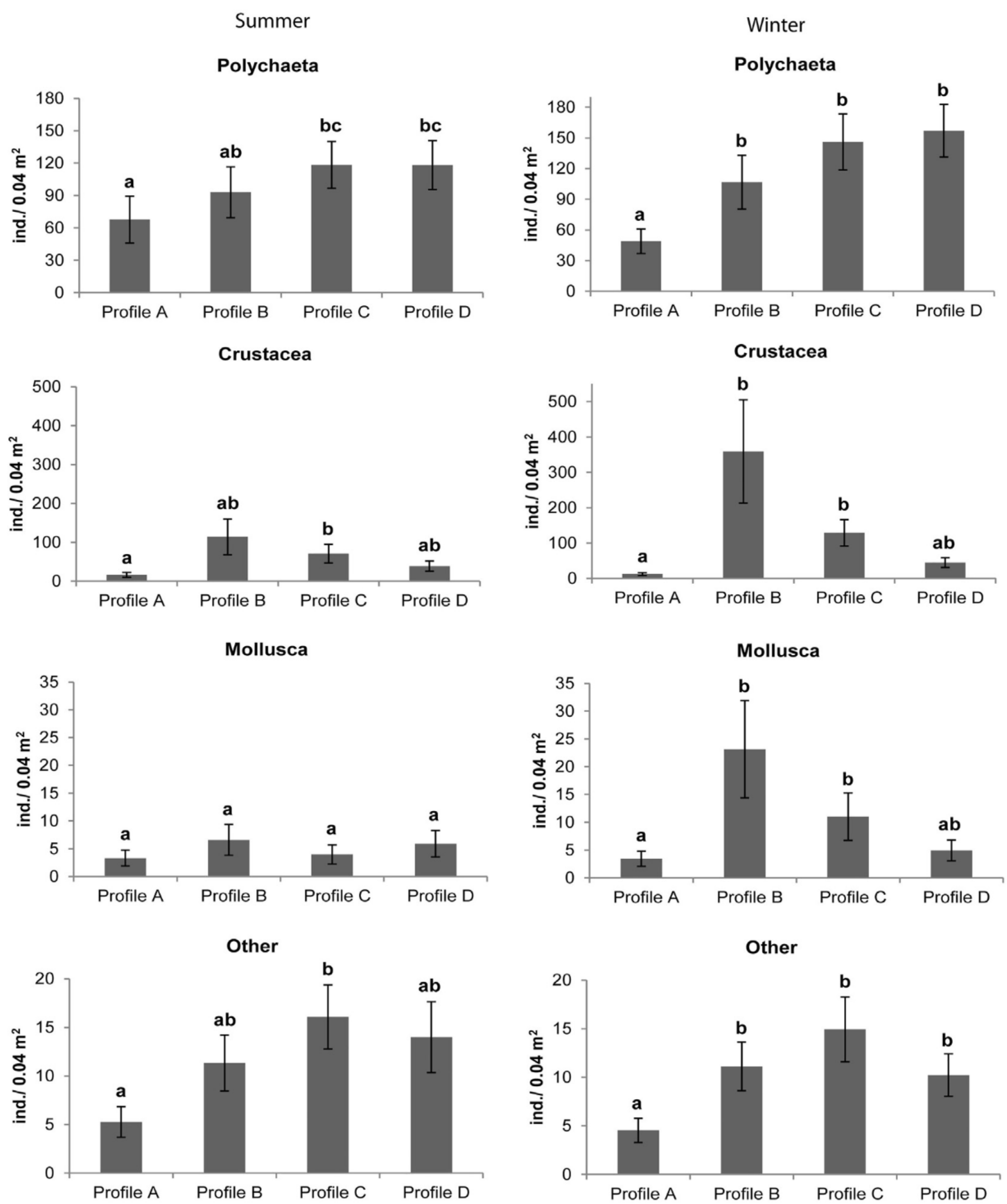

Fig. 2. Density (number of specimens per 0.04 m^2) of the main macrofaunal groups in the area influenced by the Doce River (eastern Brazil) among profiles A, B, C, and D in summer and winter. Mean + standard error. Different letters above the bars show statistically different means at the 0.05 significance level (Tukey's test).

highest mollusk density was observed in Profile B (26–32 m depth) during winter. For the other groups, density was low across all profiles, especially in Profile A, in summer and winter (Fig. 2).

The ANOSIM analysis showed a difference between stations closer to the coast (A and B, 11–32 m depth) and those further offshore, represented by the deeper stations in mesophotic ecosystems (C and D, 35–51 m depth) (Table 1).

The highest density values were observed in Profile B, ranging from 224.73 ± 99.81 specimens/0.04 m^2 in summer to 499.67 ± 263.80 specimens/0.04 m^2 in winter (Fig. 3). Profile A had the lowest density values in both periods (92.33 ± 27.55 in summer and 69.07 ± 6.90 in winter) and, overall, this was significantly different from the other profiles (ANOVA, $p < 0.05$; Fig. 3). As with density, richness and diversity values were significantly higher with distance from the coast. The greatest taxa richness was observed in Profile C during winter (50.40 ± 4.45), whereas the lowest richness was found in the profile

Table 1
ANOSIM macrofaunal analysis results in the area influenced by the Doce River mouth (eastern Brazil) from profiles A, B, C, and D in summer and winter. Significant values in bold, $p < 0.05$.

	Statistical R		p (significance)	
	Summer	Winter	Summer	Winter
Profile A, B	−0.040	0.072	0.619	0.214
Profile A, C	0.480	0.660	**0.016**	**0.008**
Profile A, D	0.564	0.776	**0.008**	**0.002**
Profile B, C	0.164	0.104	0.119	0.167
Profile B, D	0.236	0.437	**0.032**	**0.002**
Profile C, D	0.012	0.240	0.405	0.063

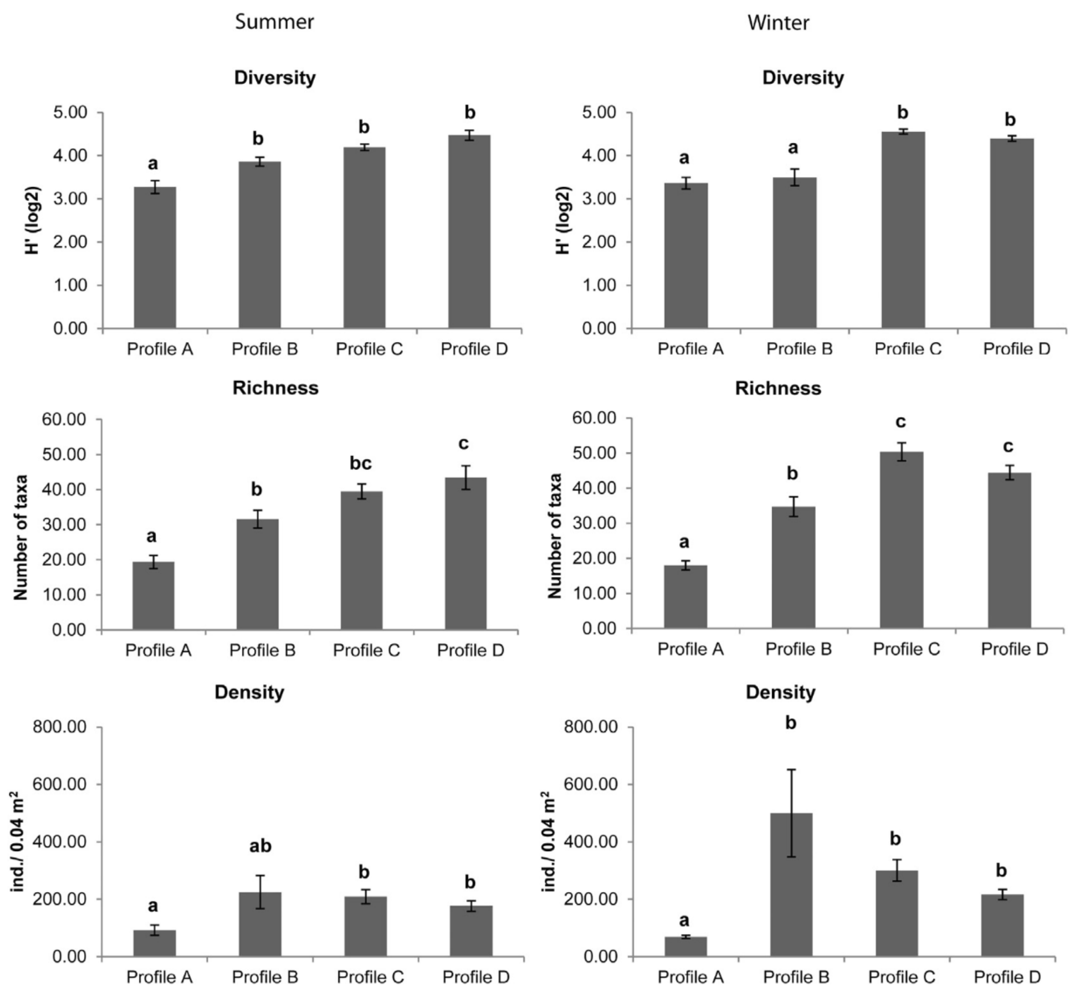

Fig. 3. Shannon-Wiener Index (H′-log2), richness (S), and total density of macrofauna in the area influenced by the Doce River mouth (eastern Brazil) for profiles A, B, C, and D in summer and winter. Mean + standard error. Different letters above the bars show statistically different means at the 0.05 significance level (Tukey's test).

near the coast (A) in the same period (18.00 ± 2.21) (Fig. 3).

In summer and winter, the shallowest part (01 to 05) and central region (08 to 10) of the sampled area had the lowest densities (Fig. S3). The highest richness values were observed, in both periods, in the 07 station and some stations of the region further from the Doce River mouth (Fig. S4). In addition, 11 stations also recorded high taxa richness in winter. The diversity showed lower values for 02 and 04 stations in summer and 03 and 07 in winter (Fig. S5). The region furthest from the mouth of the Doce River had the highest diversity, especially in winter.

These results show a spatial variation, combined with differences in distance from the coast, for the richness and diversity parameters. Richness and Shannon-Wiener's diversity were positively correlated with distance from the coast and mesophotic habitats, in both seasons. The density had the lowest values in stations located closer to the coast and the highest values for profiles at a moderate distance from the coast. The latter pattern was especially evident in the winter, probably due to greater turbidity closer to the coast, which has a direct influence on primary productivity (Marta-Almeida et al., 2016), limiting the occurrence of organisms, especially Polychaeta, that are mostly filter feeders (Eisenbarth and Zettler, 2016).

Depth, which increases with the distance from the coast, influences the sedimentation pattern and hydrodynamic conditions, as well as affecting the amount of light available to primary producers (Akoumianaki et al., 2012; Martins et al., 2014). Moreover, the region influenced by the Doce River plume is mostly shallow (~12 m depth) and, consequently, waves and wind can cause suspension of sediments, which changes the configuration of the physical environment, the biogeochemistry and the availability of light, and affects the structure and composition of macrofauna (Gomes et al., 2017; Mazzei et al., 2017). The implications of this disturbance could be a decrease in diversity or density or both (Kenchington et al., 2001). The instability that arises from Doce River streamflow fluctuations and physical disturbances in the coastal environment (i.e., waves) can severely disturb the area near the coast, which explains why it was found to be less diverse (inner profile) in this study. Similar studies conducted on continental shelves in the Southeast and South of Brazil and the Mediterranean Sea have shown that reduced diversity in the shallower areas resulted from physical changes (Akoumianaki et al., 2012; Alves et al., 2014; Zalmon et al., 2013, 2015).

The cluster analysis showed the formation of three faunal groups (Fig. 4). The first group comprised stations close to the Doce River mouth, which were characterized by a substrate of mud and fine sand. The highest contribution values in this group were obtained for the Capitellidae and Magelonidae (Polychaeta), at 27.58% and 13.94%, respectively. The second group mostly comprised stations where the granulometric characteristics were medium sand without the presence of biodetritus. Spionidae and Syllidae (Polychaeta) showed the highest values for clustering in these stations (17.3% and 13.27%, respectively). The third group included stations, mostly in offshore areas distant from the Doce River mouth, that were characterized by the presence of biodetritus, mesophotic habitats (30–51 m depth) and

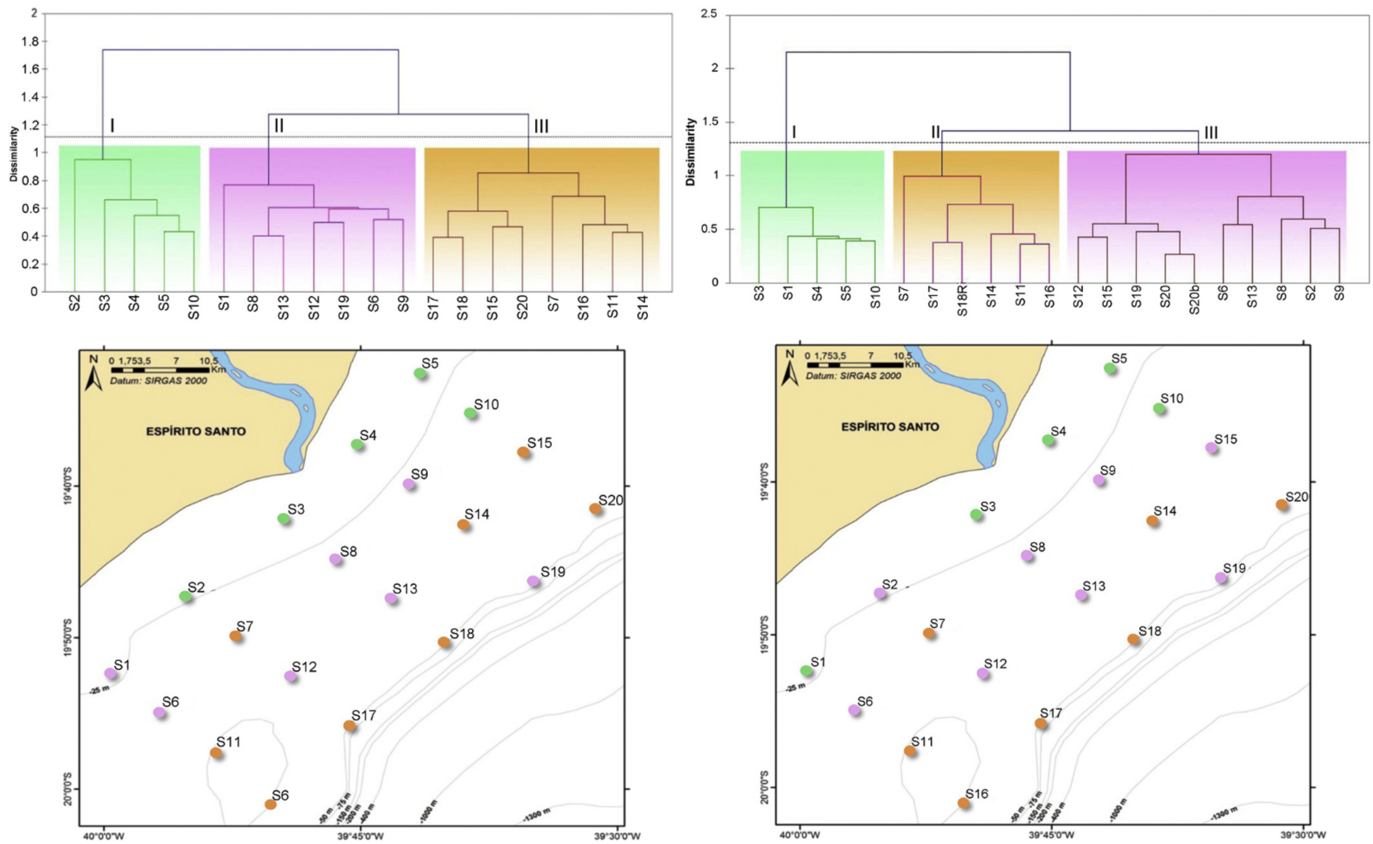

Fig. 4. Hierarchical clustering analysis, Ward's method, and Bray-Curtis' dissimilarity index based on benthic macrofauna in the area influenced by the Doce River mouth (eastern Brazil), and sampling map with the representation of groups (I, II, and III) formed by the Bray-Curtis cluster analysis, in summer (left side) and winter (right side).

average-to-high $CaCO_3$ concentrations. In winter, the cluster analysis showed a pattern very similar to that presented in summer, with clusters relating strongly to granulometry (Fig. 4).

The results reveal depth, sedimentology, carbonate, and organic matter to be important factors in explaining variations in macrofauna composition and abundance throughout the area influenced by the Doce River plume. Salinity, temperature, and sediment grain size are also important factors (Table 2; Fig. 5).

The presence of physical structures, such as pebble or gravel deposits, and biogenic structures, such as rhodolith beds, as well as the tubes and galleries produced by benthic communities, increase heterogeneity (Ellingsen, 2002) and provide microhabitats that animals can use as a refuge when environmental disturbances occur (Woodin, 1981; Powell and Mann, 2016). The CCA results support this hypothesis, because with greater distance from the coast there is also greater variability of substrate (sandy, sandy-muddy, reefs, sand with biodetritus, and sand with rhodoliths) and depth (greater environmental stability); and these factors can help to explain the variation of diversity and richness between the shallow (11–29 m depth) and mesophotic ecosystems (30–51 m depth). As observed in our study of the area influenced by the Doce River, benthic communities with the most heterogeneous habitats appear to have greater abundance and diversity (Brooks et al., 2006; Sampaio et al., 2016), Furthermore, the profiles that were more distant from the coast could have a mixture of coastal and ocean species, which would increase richness in general.

The results could be an invaluable baseline for measuring and monitoring the impacts of the mining disaster that affected shallow and mesophotic ecosystems along the Doce River plume. Toxicological bioassays have revealed that, after the disaster, the mud and soil characteristics presented potential cytotoxicity and danger of DNA damage to organisms (Segura et al., 2016). Hatje et al. (2017) suggest that bottom trawling, episodes of heavy rain and continuous stirring of the upper layers of marine sediments in the fishing grounds on the inner shelf may increase the turbidity of the coastal waters and act as a source of several major and trace elements. The study by Queiroz et al. (2018) reported that the mine tailings are mostly composed of Fe (mean values for Fe: 45,200 ± 2850; Mn: 433 ± 110; Cr: 63.9 ± 15.1; Zn: 62.4 ± 28.4; Ni: 24.7 ± 10.4; Cu: 21.3 ± 4.6; Pb: 20.2 ± 4.6, and Co: 10.7 ± 4.8 mg kg^{-1}), and appear as Fe-oxyhydroxides in the estuarine soils. This research also stated that Fe reduction pathways might increase contamination risks and trace metal bioavailability, which would probably impact the benthic communities described in this paper (Tables S1 and S2).

Recent research has investigated impacts on biodiversity in the area under the influence of the Doce River. Mazzei et al. (2017) report the

Table 2
Main results from the canonical correspondence analysis (CCA) based on benthic macrofauna of the area influenced by the Doce River mouth (eastern Brazil) in summer and winter. Environmental variables (coarse sand (CS) = % of coarse sand; fine sand (FS) = % of fine sand; $CaCO_3$ = % of calcium carbonate in the sediment).

	Summer			Winter	
	Axis 1	Axis 2		Axis 1	Axis 2
Water depth	−0.7425	−0.3939	**Coarse sand**	−0.5520	−0.1150
$CaCO_3$	−0.7018	0.3296	**Silt**	0.6062	0.3563
Organic matter	0.0255	0.6592	**$CaCO_3$**	−0.6756	0.0445
Fine sand	−0.0332	−0.4286	**Organic matter**	−0.0916	0.5528
Coarse sand	−0.2097	0.0546	**Water depth**	−0.5400	−0.6263
Temperature	0.1818	−0.2183	**Temperature**	0.2413	0.2026
Salt	0.0081	−0.3431	**Salt**	−0.2102	−0.3878

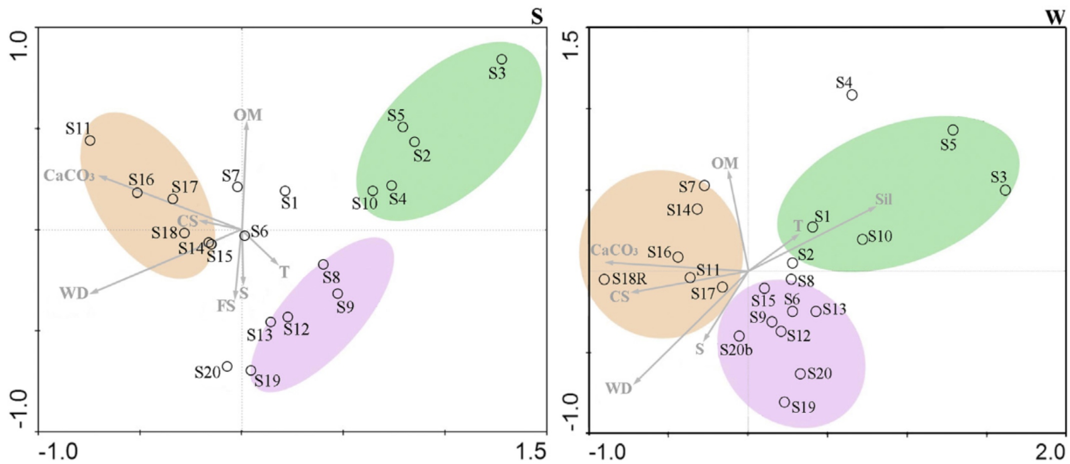

Fig. 5. Ordination diagram with the canonical correspondence analysis results based on sampled collections of the benthic macrofauna of the area influenced by the Doce River mouth (eastern Brazil) in summer (S) and winter (W). Environmental variables (coarse sand = % of coarse sand; fine sand = % of fine sand; silt = % of silt; $CaCO_3$ = % of calcium carbonate in the sediment; OM = organic matter in the sediment; WD = water depth; Temp = temperature; Salt = salinity).

discovery of a shallow reef complex and discuss some potential ecological risks to benthic organisms and fish. Gomes et al. (2017) investigated short-term impacts on the estuarine macrofaunal assemblages and discovered that rapid sedimentation after the tailings dam failure caused the loss of surface-dwelling taxa. Hatje et al. (2017) suggested that the tailing spill caused an increase in suspended sediment loads. This increase probably impacted the macrofauna by significant shifts (i.e., plankton and contaminants) in the benthic-pelagic coupling and the sedimentation on the seafloor, where the heterogeneous seascapes and biodiversity described in this baseline study occurred.

Marta-Almeida et al. (2016) showed that the dispersion of the waters was essentially southward, due to the wind regime. However, episodic frontal systems, leading to wind reversion, and oceanic mesoscale features contributed to the offshore dispersion of the plume. The marine area more often in contact with the polluted waters was located on the inner shelf; however also impacted the outer shelf and shelf break. Overlapping the maps of oceanic dispersion provided by Marta-Almeida et al. (2016) and our sampling design in shallow and mesophotic habitats (11–51 m depth), we found that the benthic biodiversity (Tables S1 and S2) had been severely affected by multiple negative impacts (rapid burial, bioaccumulation, biomagnifications, development of algal blooms, physiological stress, and exposure to pollutants).

Finally, the long-term impacts of the mining disaster are still poorly studied in the marine environment, and appropriate in-depth monitoring needs to be performed. With similar methodology and the sampling sites used in this baseline study, repeat surveys could identify the impact of the tailings dam collapse on benthic communities by means of a BACI (Before-After, Control-Impact) sampling framework. In this way, the baseline research presented here could assist with impact assessment, environmental monitoring, and restoration of this important marine ecosystem.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.marpolbul.2018.08.020. These data include the Google map of the most important areas described in this article.

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