Effects of seasonal contaminant remobilization on the community trophic dynamics in a Brazilian tropical estuary


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HIGHLIGHTS

• Potential remobilization over the wet season promoted changes in the estuarine biota.
• Community trophic diversity decreased in the wet season at the DRE.
• Bottom-dweller fishes also exhibited the smallest niche widths in the wet season.
• The diet of a resident species differed from the observed for other estuaries.

GRAPHICAL ABSTRACT

In 2015, a wave of iron ore tailings mud from the Fundão dam rupture impacted the Doce river estuary (DRE). After five years, rainy events are triggers can induce remobilization of contaminants from estuarine bottom.

ABSTRACT

In tropical estuaries, wet seasons are responsible for the downstream transport of allochthonous material from the upper basin and flooded plains. Although allochthonous matter is commonly associated to nutrient and detritus input, pollutants are also transported throughout the basin or suspended from the river bottom via strong streamflow remobilization and rainfall dynamics. We assessed community and population trophic niche-based patterns using organisms’ stable isotopes signatures in the wet and the dry seasons to test if estuarine trophic diversity is affected by remobilization of metal-contaminated material from a mining dam collapse that occurred in the Doce river basin, Brazil. Trophic depletion was detected community-wide and in a key consumer group (bottom-dwelling fishes) at the end of the wet season in the impacted Doce river estuary (DRE). Conversely, higher trophic diversity values were recorded in a well-preserved estuary used as control site. Stable isotopes mixing models indicated in the DRE that G. genidens, a predator fish species, presented poor-quality diet based on pollutant-tolerant tiny organisms, a finding that strongly contrasts from diet described in other, little-impacted Brazilian estuaries. Although wet seasons are expected to increase trophic, functional and taxonomic diversity in tropical estuaries, in the DRE the rainfall-driven dynamics poses a threat to the community due to the presence of ore tailings.

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1. Introduction

Estuaries shelter highly productive, but vulnerable, habitats (e.g., mangrove forests, tidal flats), which act as nursery areas for crustaceans and fish (Barletta and Lima, 2019; Elliott and Hemingway,
2002; Kennish, 2002). They also are crucial to connect land-riverine-ocean environments through nutrient exchange that enhance local primary and secondary productivity (Abrantes and Sheaves, 2010; Mallin et al., 1993; Ram et al., 2003). Worldwide, however, estuaries face anthropogenic impacts such as dredging, sewage, mining run-off, habitat loss and fishing.

The freshwater inflow over estuarine water bodies is known as one of the most important forces structuring estuarine circulation and, consequently, the nutrient input into estuaries (Abrantes et al., 2013; Day et al., 2012). In rainy periods, upstream discharge reaches its maximum level. As riverine and estuarine plains are flooded and drained, terrestrial and watershed systems connect to downstream environments and huge amounts of sediment and organic subsidies are transported toward estuarine and coastal areas (Abrantes and Sheaves, 2010; Bergamino et al., 2017; Kim et al., 2020). However, rainfall also induces the leaching and subsequent transport of pollutants once deposited in sediments or recently added to watersheds (Chaininian et al., 2012; Hamzeh et al., 2014; Herrero et al., 2018; Schulz, 2001).

The seasonal periodicity of rainfall has contrasting effects on estuarine communities. In near-pristine or, at least, well-preserved estuaries and coasts, wet seasons are highly productive and responsible for an increase of diversity at the taxonomic-, functional- and trophic-scales (Abrantes et al., 2014; Passos et al., 2016; Santos et al., 2015). In contrast, in polluted basins rainfall events can mobilize contaminants from sediment or nearby land bodies, thus making pollutants available to estuarine biota (Coulliouette and Noble, 2008; Hitchcock, 2020), including heavy metals (Conrad et al., 2020). On 5th November 2015 a huge amount (~ 43 million·m³) of metal-contaminated mud from the Fundão dam collapse spilled into the Doce river, southeast Brazil. The sediment remained in the basin, and only ~ 0.5% (15 × 10⁴ ton) are estimated along the Doce river basin would be the main source of future impacts (Helmreich, 2018; Fernandes et al., 2016; Hatje et al., 2017). Initially, in recent years, in comparison to DRE the PAE is a well-preserved estuary, see material and methods section), as commonly verified for Brazilian estuaries and coastal zones (Campos et al., 2015; Figueiredo and Pessanha, 2016).

1.2. Is the niche of DRE resident consumers varying in response to seasonal dynamics?

We test if American soles (Achiridae) present niche shrinking during the rainy season in comparison to the dry season in the DRE and if the inverse pattern can be observed at the control site. American soles are bottom-dwelling fishes associated to coastal rivers and estuaries that inhabit and feed on sand and mud bottoms. We expect that at the control site larger niche sizes (represented by larger areas for isotopic standard ellipses) will be verified in the wet season due to the major input of allochthonous material (Abrantes et al., 2014). In the DRE, the impacts caused by remobilized contaminants would mimic the impacts on basal food resources diversity detected after the first mud passage: a decrease in diversity and the dominance of few benthic prey groups (Gomes et al., 2017) would limit the isotopic niche width of fishes that rely on small benthic resources such as the American soles.

1.3. Are the DRE resident consumer’s diet affected by anthropogenic impacts?

The DRE demersal community is dominated (70% of the fish capture in abundance) by sea catfishes (Ariidae), mainly due to the guri catfish Genidens genidens (authors’ unpublished data). This resident species is the most abundant fish in the DRE during both wet and dry months and is known to feed upon large crustaceans (shrimps and crabs) and small fishes (Chaves and Vendel, 1996). Thus, we use G. genidens to assess differences in feeding patterns between the DRE and the other Brazilian estuaries and to evaluate if impacts in the Doce river basin affect this species.

2. Material and methods

The DRE is located in the southeastern region of Brazil, under a humid tropical climate with a wet season occurring from October to March and a dry season from April to September. In the wet season, suspended sediment load and streamflow are strongly intensified by rainy events; these are responsible for 94% of suspended sediment supply (Oliveira and Quaresma, 2017). The control site, the Piraquê-Açu estuary (PAE, 19°58′S; 40′00′W), is located about 50 km south of DRE and is under similar climate and precipitation regimes (Fig. 1). Although some sites in the PAE were impacted by drought or deforestation events in recent years, in comparison to DRE the PAE is a well-preserved estuary with an area over 10 km² of preserved mangrove forests within a protected area (Bernardino et al., 2018; Gomes et al., 2021).

Fish and macroinvertebrates were collected for stable isotopes analysis using a bottom trawl net hauled by a fishery boat. Sampling was conducted in February and March (end of wet season) and August and September (end of dry season) of 2019. Additionally, phytoplankton, zooplankton, insect larvae, shrimps, crabs and small-sized fish were collected to evaluate potential food sources of G. genidens. Decapods and small-sized fish were recovered from bottom trawl sampling. Zooplankton was captured using plankton nets with 200 μm mesh size and insect larvae sorted from sediment cores. Zooplankton was kept alive in an aerated seawater aquarium overnight to allow gut clearance. Phytoplankton and detritus were obtained from POM (particulate organic matter) samples: water was sieved through 60 μm mesh to remove the largest particles and zooplankton, and then filtered through pre-combusted glass-fiber filters. All biological material was kept frozen at −20 °C until laboratory processing.

In the laboratory, samples were extracted from main consumers (fish and macroinvertebrates): muscle tissue from the anterio-lateral portion of the trunk for fish; muscle tissues from abdominal segments...
for shrimps or chelipeds for crabs; soft tissues avoiding shell and other carbonate fragments for gastropods. Zooplankton and insect larvae samples were prepared as a pool of many individuals of each group to reach enough material for analysis. All samples were dried in a standard laboratory oven at 60 °C during 24 h, and then homogenized. For \( \delta^{13}C \) signatures, we acidified subsamples of POM and zooplankton samples to remove the carbonate content.

Samples were analyzed for stable carbon and nitrogen isotopes using an elemental analyzer (Flash, 2000; Thermo Scientific, Milan, Italy) coupled to an isotope ratio mass spectrometer (Delta V Plus with a Conflo IV interface, Thermo Scientific, Bremen, Germany). The laboratory data were calibrated using reference materials (USGS-24, IAEA-CH6 and IAEA-600 for carbon and IAEA-N2, IAEA-NO-3, IAEA-600 for nitrogen). The analytical precision of the measurements was <0.15‰ for carbon and nitrogen based on internal standards. Stable isotope values are expressed using \( \delta \) (delta) notation and parts per thousand (‰) as follows:

\[
\delta X = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 10^3,
\]

where \( X \) is \( ^{13}C \) or \( ^{15}N \) and \( R = ^{13}C/^{12}C \) for carbon and \( ^{15}N/^{14}N \) for nitrogen.

In order to avoid any bias resulting from chemical interference in the isotopic signatures, we did not extract lipids using chemical solvents, such as methanol-chloroform (Boecklen et al., 2011; Post et al., 2007). Given this, the \( \delta^{13}C \) signatures of the consumer samples were corrected for lipid-rich tissue samples (C:N > 3.5), following Post et al. (2007).

To test our first hypothesis on trophic diversity loss or gain in late-wet compared to late-dry season, we modeled the \( \delta^{13}C \) and \( \delta^{15}N \) signatures of consumers using the ‘rkin’ package (Eckrich et al., 2020) to compute three trophic diversity estimators: minimum convex polygon (MCP), standard ellipse area (SEA) and kernel utilization density (KUD). All estimators allow to calculate the community niche size from \( \delta^{13}C \) and \( \delta^{15}N \) values distributed in a bivariate isotopic space at different contours levels (50%, 75% and 95%). For this, we inserted the model fish species comprising >1% of the total abundance (number of individuals) in both wet and dry seasons and abundant macrofauna taxa (Table S1).

We estimated niche shifts of American soles using the package ‘SIBER’ (Jackson et al., 2011) to minimize the sample size effect on niche width estimation. Thus, we provide robust isotopic niche measures through the sample-size corrected standard ellipses area (SEAc).

Finally, we addressed mixing models to assess the contribution of distinct energetic-content food sources to \( G. \) genidens diet. Potential food sources were chosen and collected considering common prey items in the literature (Chaves and Vendel, 1996; Rabitto and Abilhôa, 1999) and preliminary analysis of stomach contents. A two-source Bayesian mixing model was tested combining low- and high-energy resources. The former were composed of zooplankton (copepods), insect larvae (Chironomidae) and phytoplankton and detritus (POM), whereas in the latter shrimp (Penaeidae), crabs (Callinectes sp.) and fish (Engraulidae) were pooled.

All analysis were conducted in R software (R Core Team, 2020).

3. Results

3.1. Does the DRE present trophic diversity loss during seasonal remobilization events?

Five and eleven fish species comprised >1% of the total catch in both wet and dry seasons in the DRE and control site, respectively, and for invertebrates, fiddler crabs (\textit{Minuca rapax}) in the DRE and gastropods (\textit{Gastropoda}) and hermit crabs (\textit{Paguroidea}) in the control site were abundant in both seasons. For DRE, most of the trophic diversity proxies and their predictable contours were lower in the wet period than in the dry period; the inverse pattern was observed in the control site (Table 1; Fig. 2). Exceptions were noted for DRE in KUD (at 95% contour) and MCP (at 75% and 95% contours) estimates in the DRE (Table 1).

3.2. Is the DRE resident consumer’s niche varying in response to seasonal dynamics?

American soles’ species recorded in each study area and tested here are in Table S2. The modeled niche widths (i.e., SEAc values) of DRE American soles was 2.7% in the wet season compared to 7.8% in the dry season, corroborating the hypothesis of niche shrinking during DRE rainy seasons. The opposite pattern was detected at the control site with larger niches in the wet (5.0%2) than in the dry (1.3%2) season (Fig. 3).

3.3. Are the DRE resident consumer’s diet affected by anthropogenic impacts?

Best-explanation stable isotope mixing models indicated that \( G. \) genidens fed on low-energy sources in the DRE in strong contrast to decapods and fish-based diet in other Brazilian estuaries (Fig. 4).

4. Discussion

We compared the impacted DRE to a nearby-50 km well-preserved estuary, the Piraquê-Açú (PAE). The PAE shows relatively low heavy-metal contamination in comparison to estuaries near urban centers or heavily impacted (DRE) (Hadlich et al., 2018), which supports the assumption of PAE as a valid control site in that respect. More than two years after the impact, the DRE sediment still record high concentrations of Cd, Cr, Pb, As, Cu and Zn indicating chronic contamination (Gabriel et al., 2020b). Despite their close proximity, the community
trophic dynamics between seasons differed considerably between estuaries.

4.1. Does the Doce river estuary (DRE) present trophic diversity loss during seasonal remobilization events?

In the DRE, lower trophic diversity values in the wet season indicates basal resource loss and homogenization of trophic pathways along the food chain after rainfall events. δ¹³C and δ¹⁵N signatures are time-integrated measures reflecting feeding patterns for the last one-to-three months in fish (Mont’Alverne et al., 2016; Oliveira et al., 2017). The results we present are based on sampling the two last months of each season and therefore are sufficient to emulate the trophic processes of main consumers in each (wet and dry) period. The first mud passage strongly affected DRE communities and impacts were detected through rapid macrofaunal (macroinvertebrates) diversity loss and fish niche shifts (Andrades et al., 2020; Gomes et al., 2017). As predicted -but not tested- by other studies (e.g., Cordeiro et al., 2019; Hatje et al., 2017; Rudorff et al., 2018), our study reinforces the hypothesis that rainfall and associated sediment remobilization can boost deleterious effects on the aquatic community of the DRE.

4.2. Is the DRE resident consumer’s niche varying in response to seasonal dynamics?

Estuaries worldwide are known to be biologically productive environments that, for a stopover or the duration of a full life-stage, support migratory shorebirds and transient fishes with opportunities such as

Table 1

<table>
<thead>
<tr>
<th>Estimators</th>
<th>Contours</th>
<th>DRE Wet</th>
<th>DRE Dry</th>
<th>Control Wet</th>
<th>Control Dry</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>50%</td>
<td>75%</td>
<td>95%</td>
<td>50%</td>
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<tr>
<td>MCP</td>
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<td>5.82</td>
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<td></td>
<td>36.21</td>
<td>35.60</td>
<td>23.23</td>
<td>24.72</td>
</tr>
<tr>
<td>SEA</td>
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<td>10.05</td>
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<td></td>
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<td>49.89</td>
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<tr>
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<td></td>
<td>95%</td>
<td>107.80</td>
<td>43.42</td>
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</tr>
<tr>
<td>KUD</td>
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<td>32.93</td>
<td>15.16</td>
<td>11.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>95%</td>
<td>54.04</td>
<td>35.87</td>
<td>28.06</td>
</tr>
</tbody>
</table>

Fig. 2. Bivariate isotopic niche space of estuarine community calculated using MCP, SEA and KUD estimators and predicted contours (see Table 1) for the wet and dry seasons in the DRE and the control site.

Doce river estuary

Control
abundant food and calm waters (Day et al., 2012; Mu and Wilcove, 2020; Whitfield, 2017). Resident fauna continuously depends upon resources locally provided and may be more susceptible to both acute and chronic impacts over single ecosystems. In this sense, the shrinking isotopic niche of DRE-resident American soles (Achiridae) during the wet season was remarkably higher than the pattern observed for the whole community of consumers. This highlights that estuarine residents are possibly heavily affected by the ecological consequences of seasonal remobilization events. Many Brazilian estuarine fish species breed and recrui during wet season months, including the American soles (Oliveira and Fávaro, 2010). This is particularly concerning due to the high energetic demands and costs faced by fish in this stages, which can impair early stage development if the estuarine environment do not provide suitable habitats and food supply.

4.3. Are the DRE resident consumer’s diet affected by anthropogenic impacts?

The low-energy diet of G. genidens in the DRE is in discordance to that known for other sites. In Brazilian estuaries, juveniles and adults of this species often feed upon protein-rich preys such as fish and large crustaceans (crabs and shrimps), while polychaetes and mollusks are rarely mentioned (Chaves and Vendel, 1996; Dantas et al., 2019; Mishima and Tanji, 1982; Rabitto and Abilhôa, 1999). The unexpected results of the mixing models are reinforced by a preliminary examination of stomach contents in which Chironomidae larvae appear as the most abundant prey item (authors’ unpublished data). In general, insect larvae, copepods and detritus are preyed upon by small-sized fish occupying the lowest levels of the food web and not by large predators such as G. genidens. The abundance of Chironomidae larvae doubled after the spill reached the DRE while macrofaunal diversity decreased as a whole (Gomes et al., 2017). Chironomidae are relatively tolerant to pollution (Kiffney and Clements, 1994; Tudorancea and Tudorancea, 2002), including by heavy metals from ore tailings (Smolders et al., 2003). Thus, the poor-quality diet of G. genidens in the DRE seems to be result from the paucity of rich-protein basal resources and prevalence of pollution-tolerant preys.

4.4. Conclusions

The DRE and basin have faced historical (e.g., invasive species, basin deforestation, agriculture, energy-producing dams) and recent (e.g., dam collapse) impacts that have contributed to biodiversity losses for more
than a century. However, recent and present evidences highlight the fact that ecosystem functioning was severely altered by the latest and more acute impacts. Remobilization and transport of contaminated mud during the wet season appear to lead to trophic diversity depletion, niche shrinking in bottom-dwelling resident consumers and poor-quality diet of an estuarine fish. These effects can be attributed to the deposition of the contaminated fine sediment after their local remobilization or transport from upstream during the wet season thus changing estuarine bottom-dwelling resident consumers and poor-quality diet of an estuarine fish. Chronic trace metal effects of mine tailings on estuarine assemblages revealed by environmental DNA, Peer. J. 7, e1042. https://doi.org/10.7717/peerj.8042.


