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Mangrove clearing impacts on macrofaunal assemblages and benthic food webs in a tropical estuary

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ABSTRACT

Despite over 21,000 ha of mangrove forests being removed per year in Brazil, ecological changes following mangrove deforestation have been overlooked. Here we evaluated changes in benthic macrofaunal assemblages and food-webs at a mangrove removal and natural sites in a tropical estuary in Eastern Brazil. The impacted site had coarser sediment particle sizes suggesting significant changes in sedimentation processes after forest clearing. Spatial differences in macrofaunal abundance, biomass and diversity were not directly associated with the removal of mangrove forests, supporting recolonization of impacted areas by estuarine fauna. However, benthic assemblage composition, infaunal $\delta^{13}C$ signatures and food-web diversity markedly differed at the impacted site being strongly related to sedimentary changes. The loss of infaunal trophic diversity that followed mangrove removal suggests that large-scale forest clearing may impact estuarine food webs, with potential consequences to nearby coastal ecosystems given the high clearing rate of mangrove forests in Brazil.

1. Introduction

Wetlands are greatly important for coastal and marine ecosystems as they increase sediment trapping, organic degradation and carbon sequestration (Alongi et al., 2000; Donato et al., 2011). Also, wetlands sustain a number of habitats and their associated benthic assemblages that are central for the maintenance of ecological processes in coastal ecosystems (Lana and Guiss, 1991, 1992; Netto and Lana, 1999; Nagelkerken et al., 2008), providing a number of ecological services that are under great threat by coastal development, pollution and climate change (Kennish, 2002; Alongi, 2008; Bernardino et al., 2015; Gomes et al., 2017). Human development have also increased the rate of clearance of mangrove forests for construction of ports, marinas, housing and shrimp farms (Lotze et al., 2006; Pendleton et al., 2012; Suárez-Abelenda et al., 2014; Kauffman et al., 2017). Mangrove deforestation is widespread and occur at fast rates in some coastal areas in Brazil for shrimp farming (Ferreira and Lacerda, 2016). In Brazil, an average 21,000 ha per year of mangrove forests were lost during the last decades (SEEG, 2017), and land use change near urban centres are likely mostly responsible for the high rates of mangrove loss (Magris and Barreto, 2010).

Mangroves provide habitat to benthic assemblages that are key to organic matter assimilation, degradation and directly influence a variety of ecosystem services (Cannicci et al., 2008; Kristensen et al., 2008, 2014). Mangrove trees increase sedimentary complexity, alter sediment grain size and provide additional organic resources to the estuarine fauna by increasing tidal trapping (Lana and Guiss, 1991; Furukawa and Wolanski, 1996; Netto and Lana, 1997; Bouillon et al., 2004; Levin et al., 2006). Mangroves also shade underlying sediments and increase buried root fibers, resulting in rapid biogeochemical reactions of underlying sediments (Whitcraft and Levin, 2007). As a result, mangrove forests may naturally promote higher benthic faunal abundance and a wide variety of distinct ecosystem services compared to unvegetated nearby sandflats (Kristensen et al., 2008; Gonzalez-Ortiz et al., 2016).

Food sources and trophic interactions in benthic food webs within mangroves are more complex compared to areas without aboveground vegetation. Mangrove forests provide a range of organic sources to the benthic and pelagic fauna in estuaries, including plant detritus, epiphytic macroalgae and particulate organic matter trapped by their root structures (Kristensen et al., 2008; Giarrizzo et al., 2011). As a result, benthic food webs may use a variety of food sources, including mangrove-derived, terrestrial or marine organic carbon available in estuarine ecosystems (Bouillon et al., 2002a, 2002b, 2008; Demopoulos

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et al., 2007; Kristensen et al., 2008, 2010). The loss of mangrove forests consequently may lead to changes in biodiversity and on food web dynamics due to loss of habitat and changes in the deposition, degradation and assimilation of organic matter by benthic consumers (Demopoulos et al., 2007; Sweetman et al., 2010).

Mangrove forests are typically removed by cutting down of the above-sediment vegetation with the below-ground root structures left intact. The removal of the aboveground vegetation significantly changes particle sedimentation and sediment organic matter availability with consequences to benthic assemblages (Sjoling et al., 2005; Granek and Ruttemberg, 2008; Sweetman et al., 2010; Sabeel et al., 2015). Although complete removal of epifaunal organisms will follow mangrove clearance, infaunal invertebrates may quickly colonize sediments after initial disturbance thus leading to similar assemblage patterns with other estuarine areas (Pagliosa and Lana, 2005). In areas where mangrove forests were introduced, benthic assemblages also show marked differences in macrofaunal composition, dominance, diversity and food webs when compared to non-vegetated areas or to native ecosystems (Demopoulos et al., 2007; Demopoulos and Smith, 2010; Sweetman et al., 2010; Sabeel et al., 2015). However, the effects of changes in sediment composition and organic availability that follow clearing of mangroves are unclear. Given that most mangrove forests in Brazil are cleared in estuaries near urban centres or by shrimp aquaculture, there is an urgent need to quantify clearing impacts on benthic assemblages and food webs in estuaries.

Assessment of impacts on Brazilian mangroves have typically focused on sewage pollution and oil spills (e.g. Faraco and Lana, 2003; Leite et al., 2014; Bernardino et al., 2016; Boehm et al., 2016), with little attention to the impacts of forest removal on benthic assemblages and food webs (Pagliosa and Lana, 2005). Here we used a simple study design to test for local changes in benthic macrofaunal assemblages and food web structure between natural mangrove forests and a mangrove removal site within a tropical estuary in Brazil. We hypothesized that (i) changes in benthic macrofaunal assemblages between natural and impacted sites would be evident due to forest clearance; and (ii) food webs would be markedly distinct between natural and impacted sites as a result of changes in assemblages and on food sources.

2. Materials and methods

2.1. Study site and sampling

This study was carried at the Piraquê-Açu-Mirim (PAM) estuary (17°58′S; 40°00′W) located within the Eastern Brazil Marine Ecoregion and with about 20 km^2 of preserved mangrove forests. The estuary is under a semi-diurnal microtidal regime (< 2 m) and has a Y-shape morphology with extensive mangroves (dominated by *Rhizophora mangle* and *Avicennia schaueriana*) and tidal flats. Coastal development led to mangrove removal in some areas for agriculture, housing construction and piers to access the river. In one area, we selected a mangrove removal site (about 1000 m^2) that has been cleared of mangroves over 20 years ago for housing construction and access to the estuary. This removal site (study site R1, Fig. 1) had no above-ground biomass or any visible root structures present along its intertidal region and was 0.5to 1 km away from natural mangrove forests (study sites M1 and M2). Other areas impacted by mangrove removal within the PAM estuary were lost and not reclaimed, and were heavily modified by sediment accretion, so those areas could not be compared to the R1 site. Although we have sampled only one mangrove removal site, it had a comparable tidal elevation and salinity gradient of the two other natural sites at the estuary, which were representative of variable mangrove forests within the region (Underwood and Chapman, 2005).

Sampling occurred in January 2013 along 3 study sites representing two natural mangrove forests with distinct structure (M1 and M2) and one mangrove removal site (R1). At each study site, two habitats were sampled representing the forest or removed mangrove area (Vegetated), and the lower intertidal mud flats (Non-vegetated; Supplemental Fig. S1). In each habitat, intersticial salinity was measured in situ with a refractometer and the number of mangrove roots was counted within a 1 m^2area postitioned at three random points per plot described above. In each habitat, two random plots were centered at least 5 m from the forest fringe and 3 random macrofaunal samples (0.008 m^2, 10 cm depth) and one composite sediment sample (mix of three random 0–5 cm surface sediments) were taken within each plot. At the removal site, plots were centered based on same tidal level as the fringe location of nearby mangrove stands, and sampling occured as in the natural mangrove sites.

Organic sources for stable isotope analysis (mangrove leaves, roots, macroalgae, fitoplankton and zooplankton) were sampled qualitatively on field and immediately frozen at − 20 °C or processed in laboratory. Although no temporal replicates for stable isotope analysis were taken, all samples from natural and removal sites were taken at the same period, thus representing spatial comparisons within the study area. Plankton tows (300 μm mesh size) were taken during 10 min (six tows) near the three study sites and frozen in laboratory. Surface sediments (0–2 cm) from each site were randomly sampled at each distance per site and frozen until analysis.

2.2. Laboratory analysis

Macrofaunal samples were preserved in formalin for a least 48 h, sieved (500 μm) in fresh water and preserved in 70% Ethanol until analysis. In the laboratory all organisms were sorted and identified to the lowest taxonomic level. After sorting, total macrofaunal biomass (wet preserved weight) was determined with a 0.001 g precision balance. Mangrove detrital organic matter (leaves, roots) sampled by faunal corers were sorted and weighted after drying for 48 h at 45 °C, and reported separatelly as detrital organic matter. The sediment organic content that did not include macrodetrital particles (leaves and roots) was measured by weight loss after 4 h at 500 °C. The sediment particle size was determined by dry-sieving and reported as percent weights of gravel, coarse sand, medium sand, fine sand, and mud sediment fractions.

2.3. Stable isotope analysis

The most abundant macrofaunal organisms at natural and mangrove removal sites and habitats (vegetated and unvegetated) were selected for stable isotope analysis. Individuals were taken from preserved samples if no fresh individuals were available. Macroinfaunal organisms fixed in 4% formaldehyde solution can potentially introduce artifacts in $\delta^{13}C$ values, although these are usually small compared to the wide natural $\delta^{13}C$ variability in marine food sources (Fry and Sherr, 1984; Edwards et al., 2002; Sarakinos et al., 2002). In this study, we corrected for preservation artifacts by adding 1‰ to $\delta^{13}C$ from previously preserved macrofaunal organisms (Sarakinos et al., 2002; Demopoulos et al., 2007). From all individuals, only muscle tissue (for shelled organisms) was taken for analysis totalling an approximate dry weight of 0.5 mg. Samples were sent to the Washington State University (USA) and combusted in a Eurovector elemental analyzer and resulting N_2 and CO_2 gases were separated by gas chromatography and admitted into an IRMS mass spectrometer for determination of $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios (reproducibility: ± 0.5 ‰ for $\delta^{15}N$ and ± 0.2 ‰ for $\delta^{13}C$). Macrofaunal C-isotopic ratios were measured against a Pee Dee Belemnite (PDB) standard for $\delta\ ^{13}C$ and atmospheric nitrogen for $\delta\ ^{15}N$. Results are expressed as delta (δ) notation, where δX (‰) = $[(R_{sample}/R_{standard})\text{-}1] \times 10^3$, where $R = {}^{15}N/{}^{14}N$ or $R = {}^{13}C/{}^{12}C$.

2.4. Statistical analyses

Spatial changes on sedimentary properties (sediment grain size, organic content and detritus biomass) and patterns of faunal density,