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Sewage input reduces the consumption of *Rhizophora mangle* propagules by crabs in a subtropical mangrove system

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A B S T R A C T

Mangrove forests are highly productive and play a major role in global carbon cycling. Their carbon accumulation can be influenced through the consumption of nutrient-poor leaves and propagules by herbivore crabs. Anthropogenic nutrient input from sewage contamination is widespread in these often naturally nutrient-limited ecosystems. We hypothesised that sewage-mediated nutrient input to mangrove stands of Paranaguá Bay (southern Brazil), would alter the nutrient sources available for crabs, e.g. through microphytobenthos increase, and that this would reflect in their feeding behaviour. We predicted that propagules of *Rhizophora mangle* in contaminated stands would experience lower grazing pressure from their two main local consumers (*Ucides cordatus* and *Goniopsis cruentata*). We compared herbivory rates on *R. mangle* propagules in sewage contaminated and uncontaminated mangrove stands. We found that herbivory rates were significantly lower in contaminated than uncontaminated forests, but this pattern could not be clearly attributed to increased nutrient availability.

1. Introduction

Human activities have caused an increased rate in global mangrove forest area loss since the 1980s, mainly due to habitat conversion for aquaculture (Ellison, 2008; Valiela et al., 2001). Further human-induced pressures include unsustainable resource extraction, coastal development, sea level rise, pollutants and eutrophication (Alongi, 2002; Valiela et al., 2001; Van Lavieren et al., 2012).

The consumption of mangrove propagules by herbivores is crucial to mangrove forest conservation as it can directly affect the establishment of young trees (Clarke and Kerrigan, 2002; Dangremond, 2015; Ellison, 2000; Smith, 1987) and may influence ecosystem regeneration (Dahdouh-Guebas et al., 1998; Ferreira et al., 2015). Mangrove propagules are mostly consumed by sesarmid and ocypodid crabs (Cannicci et al., 2008; Longonje and Raffaelli, 2014). Crab herbivory is influenced by crab abundance (Feller et al., 2013; Van Nedervelde et al., 2015), canopy development (Clarke and Kerrigan, 2002) and propagule species (Cannicci et al., 2008; Van Nedervelde et al., 2015). Palatability and nutritive quality can also determine herbivory levels to a certain extent. Some crab species tend to favour propagules with a lower amount of defensive compounds such as tannins coupled with higher nutritive quality determined by crude fiber, protein and sugar contents or low C:N ratios (McKee, 1995; Smith, 1987; Van Nedervelde et al., 2015). However, other species such as *Neosarmartium meinerti*, do not select propagules (Dahdouh-Guebas et al., 1997).

Nitrogen and phosphorus limitation may constrain growth and primary production of mangrove systems (Alongi, 2011; Reef et al., 2010). Mangrove systems are used worldwide as disposal or treatment areas for nutrient-rich domestic sewage (Amaral et al., 2009; Wong et al., 1997; Ye and Tam, 2002). Impact assessments have suggested beneficial effects of sewage input on certain

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ecosystem functions such as higher primary productivity and an increase in plant biomass in *Rhizophora mangle* stands (Onuf et al., 1977), whereas others have found that nutrient input from sewage negatively impacted mangrove systems, by increasing tree mortality (Lovelock et al., 2009), and potentially affecting higher trophic levels. For instance, mangrove folivory levels may increase with higher nutrient content (Faraco and Lana, 2004), although herbivore responses to nutrient enrichment may be species-specific (Feller and Chamberlain, 2007). In a global synthesis, He and Silliman (2015) found that, in contrast to saltmarshes, nutrient enrichment in mangrove ecosystems seems to affect neither the abundance of herbivores nor herbivory levels in general.

An overall increase in the biomass of ocypodid fiddler crabs and sesarmids in sites subject to wastewater discharge compared to control sites was reported for African mangrove stands (Bartolini et al., 2011; Cannicci et al., 2009). This biomass increase may result from the increased growth of microalgae, bacteria and diatoms, which comprise the main food sources for smaller fiddler crabs (Meziane and Tsuchiya, 2002). Bartolini et al. (2011) also recorded significantly lower ecosystem engineering activity in terms of sediment reworking by ocypodid fiddler crabs in impacted areas due to a reduced effort on searching for food. In the long term, nutrient enrichment may thus lead to anoxic conditions with potentially negative implications for the ecosystem as a whole.

We investigated *Rhizophora mangle* propagule consumption in mangrove stands of Paranaguá Bay (Southern Brazil), one of the largest and most preserved subtropical estuarine systems in the South-Western Atlantic. Two local mangrove crab species, *Ucides cordatus* and *Goniopsis cruentata*, account for most of the consumption of fallen propagules. *Ucides cordatus* is the main grazer of the propagules of the red mangrove *Rhizophora mangle* in local forests. Some of its populations are known to be food-limited in other Brazilian mangrove forests (Nordhaus et al., 2006).

Our field study tested the hypothesis that domestic sewage contamination in mangrove stands leads to altered propagule herbivory rates resulting from nutrient input. We predicted that, by stimulating growth of alternative food sources, such as microphytobenthos, sewage-mediated nutrient input would offer more favourable feeding conditions for the crabs. We expected that a potential increase of alternative, nutrient-rich food sources would in turn result in reduced grazing pressure on *R. mangle* propagules in sewage contaminated mangrove stands.

2. Material and methods

2.1. Study area

The field experiment was carried out in the Paranaguá Bay Estuary Complex in South Brazil (Fig. 1), one of the largest estuarine systems of the South-Western Atlantic. Its ocean-exposed outskirts are dominated by rocky and sandy shores while the intertidal flats in the inner system are colonised by saltmarshes and mangroves. Weather conditions are subtropical with 2500 mm mean annual rainfall (Lana et al., 2001). The mangrove forests are of ecological, social and economic importance for the region, mainly supporting artisanal fisheries carried out by vulnerable coastal communities (Faraco et al., 2010). Three mangrove species co-occur in the area, namely *Rhizophora mangle*, *Laguncularia racemosa* and *Avicennia schaueriana* (Faraco and Lana, 2003). The red mangrove *Rhizophora mangle* dominates the fringes (Schaeffer-Novelli et al., 1990). Among the local mangrove macrofauna, the burrowing ocypodid crab *Ucides cordatus* and the non-burrowing grapsid crab *Goniopsis cruentata* are numerically dominant. Both species are major consumers of dispersing propagules of *R. mangle* (McKee, 1995). While *G. cruentata* is an opportunistic generalist feeder (de Lima-Gomes et al., 2011), the predominantly herbivorous diet of *U. cordatus* is mainly composed of mangrove detritus, which they consume inside their burrows (Nordhaus et al., 2009). *U. cordatus* also appears to be the most important consumer of *R. mangle* propagules in the study area (Wellens et al., 2015).

With limited wastewater treatment, discharge of domestic sewage is one of the major anthropogenic impacts on mangrove forests in Paranaguá Bay, mostly concentrated near the city of Paranaguá. Without the implementation of sewage treatment in the future, this is likely to intensify as the population in the Paranaguá region is increasing (Cunha et al., 2011).

2.2. Selection of study sites

Three mangrove sites with similar canopy cover, tree species composition and tidal range within each of two contamination conditions, i.e. with and without contamination from domestic sewage (further referred to as "contaminated" and "uncontaminated", respectively), were selected along the Cotinga Channel in Paranaguá Bay (Fig. 1). Contaminated sites were located near Paranaguá city, and have historically received sewage from multiple sources. The contamination gradient is well-documented. Barboza et al. (2013) showed that hydrodynamics cause rapid dilution and dispersal of contaminants from the inner towards the outer sector of the bay. Uncontaminated sites were selected far from human settlements and receive no inputs of wastewater. All study sites were located on different isles of the bay, separated by tidal creeks or channels.

Selection of contaminated and uncontaminated sites was based on a previous local study of sediment concentrations of the faecal sterols coprostanol and epicoprostanol (Martins et al., 2010). Coprostanol has been established as an indicator of domestic sewage contamination as it is a digestion product specific to humans and other higher vertebrates (Leeming et al., 1996). Through wastewater treatment or anaerobic digestion in the environment, its isomer epicoprostanol is formed and used to indicate the presence of treated or aged sewage components (McCalley et al., 1981; Mudge and Seguel, 1999). Martins et al. (2010) compared superficial sediments of numerous tidal flats in the Paranaguá Estuarine System, many of which are adjacent to mangrove vegetation. Relatively high concentrations of coprostanol were evident mainly in sites close to Paranaguá city where most of the sewage effluent originates.

Contaminated sites (C1-3) of the present study are in the vicinity of sampling points "B12", "B6" and "B14" from the 2010 study which were found to be affected by "intermediate sewage contribution" based on faecal sterol concentrations (Table 2 in Martins et al., 2010). Furthermore, sites C1 and C2 are located very close to the entrance of a small river, Rio do Chumbo, which is the main release point of sewage from Paranaguá into the bay. High concentrations of coprostanol ($>1.00\ \mu g\ g^{-1}$) were previously detected in this area (Camargo et al., 2011). Uncontaminated sites (U1-3) are closest to "B16" and "B7" with very low to below-detection-limit levels of faecal sterols (Table 2 in Martins et al., 2010). Several more studies examining sewage contamination in Paranaguá Bay provide evidence for the sewage input to individual study points. Contaminated sites C1-3 are covered by "Sector 1" of a recent study which found high levels of coprostanol ($>1.00\ \mu g\ g^{-1}$) in 2009 (de Abreu-Mota et al., 2014). In contrast, "Sectors 2 and 3" from the same study, representing environmental characteristics similar to site U2, had sediment coprostanol levels of $<0.15\ \mu g\ g^{-1}$ which is below the defined sewage contamination threshold of $0.5\ \mu g\ g^{-1}$ (Gonzalez-Oreja and Saiz-Salinas, 1998). Unpublished data from a 2011 survey (César C. Martins, personal communication) further