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Human-induced changes in the trophic functioning of sandy beaches

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ABSTRACT

The increasing anthropogenic disturbance on coastal ecosystems has threatened ecological interactions and ecosystems functioning. To investigate if human pressure affects the trophic structure of sandy beaches, mass-balanced models were applied on two Brazilian sandy beaches with distinct human impact degree. The food web models included detritus, phytoplankton, macroinvertebrates, fish and seabirds. Macroinvertebrates in non-urbanized sectors represented the highest production fraction consumed by predators. The energy transfer and the cycling indicator were more efficient in the non-urbanized sectors than urbanized ones. The results indicate that macroinvertebrates sensitive to direct human impact such as trampling are important to the trophic functioning of sandy beaches. Establishing a threshold for the number of beachgoers or dispersing recreational activities to avoid crowds may be tangible ways to mitigate the trampling impact on macroinvertebrates.

1. Introduction

The expansion of different human activities and their ecological effects on coastal ecosystems have accelerated with human population growth (Jackson et al., 2001). Exploitation of natural resources, pollution and habitat destruction is usually considered the main drivers of biodiversity loss, which may affect individual species and communities, as well as ecological interactions and ecosystem functioning (Dunne et al., 2002; Thompson et al., 2012). Ecological processes, such as production and nutrient cycling, have been severely altered by human activities in marine and coastal ecosystems (Yang et al., 2010).

Food web supply on sandy beaches depends primarily on their morphodynamics (Brown and McLachlan, 2010). Intermediate and dissipative beaches are usually supplied by phytoplankton productivity from surf zone (i.e. diatoms), while reflective beaches rely mainly on wrack from the sea (Maria et al., 2011; Bergamino et al., 2013). These energy sources support the macroscopic food chain of sandy beaches and include suspension-feeders, scavengers and detritivorous macroinvertebrates and their predators (Inglis, 1989; Colombini et al., 2011). Also, intertidal macroinvertebrates are important prey to fish and shorebirds, playing an important role in energy transfer to higher trophic levels on sandy beaches (Nelson, 1986; Takahashi et al., 1999; Veloso et al., 2003; Tomme et al., 2014).

Abiotic factors, including grain size, beach slope and climate variability were found the main drivers regulating the abundance and distribution of beach biota (Defeo and McLachlan, 2005). However, trophic interactions also play a role in the energy flow and food web studies can improve our understanding of the functional response of sandy beaches to environmental disturbances (Bergamino et al., 2016). In general, sandy beaches have low species diversity and fewer biological interactions compared to other marine ecosystems (McDermott, 1983; Brown and McLachlan, 2010). The majority of beach predators are generalists (Turra and Denadai, 2015), which are relatively less sensitive to cascading extinctions caused by breakdown of trophic interactions (Carboni et al., 2010; Tylianakis et al., 2010). However, predators as shorebirds and commercial fish usually avoid this environment, due to prey scarcity (Dugan et al., 2003; Costa et al., 2017).

Urbanization of sandy beaches has been intensified in the last decades due to an increase in tourism and recreation activities worldwide (Defeo et al., 2009). Several stressors are associated with recreational activities (e.g. trampling and vehicle traffic), urban development (e.g. dune suppression) and management actions (e.g. beach cleaning, coastal armouring and nourishment) (Stelling-Wood et al., 2016). Some macroinvertebrates on the supralittoral (Insecta, Ocypodidae and Talitridae) and intertidal zones (Cirolanidae and Glyceridae) have been considered bioindicators of impacts related to tourism activities (Veloso et al., 2008, 2011; Cardoso et al., 2016; González et al., 2014; Schlacher et al., 2016). So far, responses of human pressure on sandy beaches have been mainly addressed to community structure or individual species (e.g. González et al., 2014; Bessa et al., 2014; Reyes-Martínez

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et al., 2015; Cardoso et al., 2016), and they do not usually consider the species interaction and ecosystem functioning. Some studies considered sublethal aspects of macroinvertebrates in response to anthropogenic changes in the environment (Schlacher and Lucrezi, 2010; Scapini et al., 2005; Bessa et al., 2017). However, food web researches on sandy beaches are still scarce (see Lercari et al., 2010; Bergamino et al., 2013; Reyes-Martínez et al., 2014).

Brazilian sandy beaches of distinct morphodynamics near to urban areas have been threatened by several anthropogenic stressors (Amaral et al., 2016). As a consequence, the discrimination of a single impact from broader urbanization pressures and morphodynamics features on beach biota is challenging. However, previous studies on southeastern Brazilian beaches showed that trampling associated with recreational activities is the main threat for macroinvertebrates and their predators, despite of minimal physical differences between urbanized and non-urbanized areas (i.e. grain size, beach slope or wave action) (Costa et al., 2017; Machado et al., 2016). Thus, this is an encouraging scenario to assess the ecosystem features and trophic links on sandy beaches under distinct levels of human pressure.

The objective of the present study was to compare food web features (i.e. ascendency, connectance, system omnivory, overhead and capacity) and energy transfer efficiency across trophic levels on sandy beaches with distinct human pressure. We tested the hypothesis that food web complexity is lower and energy transfer across trophic levels is less efficient on beaches under higher human pressure, due to the inferior richness and biomass of vulnerable prey species compared to lower pressure beaches (Reyes-Martínez et al., 2014).

2. Material and methods

2.1. Study area

The study was conducted on two sandy beaches, Grussaí and Praia Grande, in the municipalities of São João da Barra (21°41′39.80″S41° 1′23.84″W) and Arraial do Cabo (22°58′23″S 42°1′57″W), respectively, in Rio de Janeiro State (RJ), Brazil (Fig. 1). Praia Grande beach is influenced by coastal upwelling, where cold (18 °C) and nutrient-rich water regularly influence the inner continental shelf, resulting in significantly higher biological productivity (Tavares et al., 2016b). The southern limit of the state includes at least four seabird breeding islands, including the Franceses Island, an important breeding ground of *Sula leucogaster* located 500 m from the Praia Grande Beach (Tavares et al., 2016a). The northern limit comprises mainly a flyway route (Tavares et al., 2016a).

Grussaí is an intermediate beach, with the predominance of medium grain size and intense wave action (Machado et al., 2016), while Praia Grande Beach has dissipative morphodynamics, with the predominance of fine/medium sand and gentle slope (Gaelzer and Zalmon, 2008). Both beaches have a wide coastal strip with areas under considerable human pressure (urbanized sectors) and others with low visitation rates (non-urbanized sectors) (Machado et al., 2016). Arraial do Cabo municipally has 29,000 inhabitants, but the visitation during the summer season (400,000 people from December to March) is about three times higher than the municipality of São João da Barra in the same period (150,000). São João da Barra municipality has 35,000 inhabitants, but Grussaí Beach has regional touristic appeal.

We used the adapted urbanization index from González et al. (2014) as a proxy for selecting the sectors with different degrees of human pressure (Appendix A). The following categories were considered: 1) proximity to urban centers; 2) buildings in the beachfront; 3) beach cleaning; 4) solid waste in the sand; 5) vehicle traffic in the sand; and 6) frequency of visitors. We did not consider the "quality of night sky" as a category for the calculation of the urbanization index (see González et al., 2014), because all the sectors have wide supralittoral, so that light poles are far from the beach and sky conditions are optimal for stargazing (score = 0). Gover's method, $X' = ((\Sigma X - X\ min)/(\Sigma X\ max - X\ min))$, was used to calculate the index, where X is the value assigned to each of the six variables and Xmin–Xmax corresponds to the extreme values of the range (0–5 in this case) (Legendre and Legendre, 1998; González et al., 2014). The index ranges from "0" to "1," where values close to 1 indicate beaches with the highest human pressure. The urbanization level of urbanized beaches is directly associated with highest number of beachgoers in the sampling area (about two people/m^2) and reduced environmental quality (Suciu et al., 2017). As a consequence, macroinvertebrate abundance at Grussaí and Praia Grande beaches is usually lower in urbanized beaches than non-urbanized ones (see Machado et al., 2016; Costa et al., 2017).

2.2. Data collection

Food web models included detritus, phytoplankton, macroinvertebrates, fish and seabirds, based on the annual average values of biomass of each group, which was sampled twice in winter of 2015 (June–September) and twice in summer of 2016 (January–March). The information sources of each species or functional group input into the Ecopath software are detailed below and summarized in Table 1.

2.2.1. Detritus and phytoplankton

Phytoplankton and detritus biomass in the water were determined by the concentration of chlorophyll *a* and organic carbon particulate using images taken by the MODIS instrument on the satellite Aqua (NASA). The resolution of the images is approximately 4.5 km, which allowed the data to be obtained for all sectors and beaches.

The concentration of chlorophyll *a* in the study areas was converted to phytoplankton dry weight (DW) following the conversion factor: 1 mg of chlorophyll *a* = 100 mg DW (Reyes-Martínez et al., 2014). The P/B phytoplankton values followed Lercari et al. (2010).

To determine the biomass of sediment detritus, nine aliquots of sediment were collected in each sector during each sampling period. The organic matter content was determined based on the difference between lyophilized sediment and incinerated one at 350 °C for 12 h (loss-on-ignition method by Goldin, 1987). *Emerita brasiliensis* eggs (EBE) represented the main feeding resource to the fish at Praia Grande Beach (Bode et al., 2003). Thus, we included EBE as a discrete trophic group (detritus) in food web models. The biomass of EBE scraped from females was determined after the eggs were dried at 60 °C for 24 h.

2.2.2. Macroinvertebrates

The macroinvertebrates were collected along three transects (50 m apart) perpendicular to the coastline. Each transect was divided into nine sampling points covering the entire intertidal zone (Machado et al., 2016). Sediment samples were collected using a 20 cm diameter/depth corer (0.188 m^2), sieved (1 mm mesh) in the field and fixed in 10% formalin. In the laboratory the organisms were separated, identified, counted, dried at 60 °C for 24 h, and weighed to determine the DW. The P/B ratio was calculated according to empirical relationships following Brey (2001). Brey (2001) is a virtual handbook that provides equations to describe population dynamics, including growth, mortality and production. For this calculation it was necessary to calculate the individual body mass of each species and the annual average seawater temperature in the municipalities of São João da Barra (25 °C) and Arraial do Cabo (24 °C) (Reynolds et al., 2007). The Q/B ratio was calculated by the equation $\log(Q) = -0.420 + 0.742.\log(DW)$, where DW is the individual dry weight (Cammen, 1980).

2.2.3. Fish

The fish were collected in the surf zone using a beach seine net that was 25 m long and 2.5 m tall, with 10 mm mesh (Costa et al., 2017). The net was hauled parallel to the shore at 1.5 m deep, covering a total area of approximately 500 m^2. Each sampling period included 10 hauls of five minutes. The fish were fixed in 10% formaldehyde, weighed, identified, and their stomachs dissected to analyze the food items with a