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Long-term ecological footprints of a man-made freshwater discharge onto a sandy beach ecosystem

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ABSTRACT

Sandy shores comprise one of the coastal ecosystems most vulnerable to human impacts, and they are increasingly affected by a variety of stressors. Local-scale drivers such as man-made freshwater discharges have changed the salinity, temperature and nutrient regimes, leading to the degradation of sandy beaches. However, there is still little understanding about the effects of salinity changes on the structure and functioning of sandy shores at the ecosystem level of ecological organization. This study seeks to identify the main spatial and long-term variations in a sandy beach ecosystem due to salinity changes induced by a freshwater discharge using a trophic network approach and thus linking anthropogenic pressures with functional and structural ecosystem changes. The trophic networks of nine scenarios involving three sampling sites representing different salinity stress regimes and three study phases established between 1987 and 2015 were modelled and compared. The results showed important space-time variations that were reflected at the community and ecosystem levels. A more complex trophic structure was developed with longer distances to the freshwater inflow, with higher biomass, species richness and number of predators. The highly disturbed and undisturbed sites occupied discrete, contrasting and clearly distinguishable states over time, whereas the moderately disturbed site showed a variable pattern over time. Recent trends in ecosystem indicators reflected a more fragile state, characterized by a greater organization (Ascendency) and a lower adaptive potential (Overhead) to address unexpected disturbances. Ecosystem indicators were sensitive enough to distinguish among sites and long-term phases in the ecosystem, where different organization states can persist over time. Future studies aimed at assessing press disturbances on sandy beach ecosystems should emphasize a longer time scale in order to assess the recovery capacity of these systems that are increasingly threatened by long-lasting stressors.

1. Introduction

Sandy beaches provide critical ecosystem services that are being threatened by the increasing demand for natural resources and leisure on the coast, intense coastal development and the accelerated loss of habitat resulting from coastal squeeze (Defeo et al., 2009; McLachlan et al., 2013). Human impacts on these ecosystems are predicted to intensify over the next few decades, and thus it has become increasingly critical to understand how these ecosystems will respond to environmental changes (Brown et al., 2018; McLachlan and Defeo, 2018).

Sandy shores are dynamic ecosystems inhabited by specialized biotic assemblages that are structured mainly by physical forces (Defeo and McLachlan, 2005; McLachlan and Defeo, 2018). In this context, salinity has been identified as a critical variable that can affect biodiversity patterns at multiple scales. At a mesoscale (e.g., a single beach), freshwater discharges appear as strong modifiers of environmental quality, affecting the distribution and life-history traits of the resident macrofauna, as well as nutrient regimes and habitat features (Defeo and Lercari, 2004). At a macroscale, Lercari and Defeo (2015) showed strong environmental and macrofaunal variations in sandy beaches of the Uruguayan coast affected by the discharge of the widest estuary of the world (Rio de la Plata). This was particularly evident at inner estuarine beaches, characterized by strong salinity variations and a decrease in habitat suitability and availability (e.g., low swash and beach width). These comparable results, representing a range of spatial scales, highlight the role of environmental variability and habitat suitability as drivers affecting the structure of the macrofaunal community, thus supporting the notion of scale dependence in sandy beach ecology (McLachlan and Defeo, 2018). Under press disturbances, defined as chronic perturbations that lead to persistent changes in ecosystem

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components (Glasby and Underwood, 1996), beach habitats could become unsuitable for sandy beach macrofauna in the medium- or long-term. However, there is still little understanding of the effects of persistent salinity changes on sandy beach ecosystems, including effects on its structure (e.g., trophic levels) and functioning (e.g., energy flows).

On the Atlantic coast of Uruguay, the 22-km sandy beach fringe between La Coronilla and Barra del Chuy (LCBC) is affected by a man-made freshwater canal discharge (Andreoni Canal) from inland crops (Lercari and Defeo, 1999; Lercari et al., 2002). Studies showed that low salinity levels and high variability generated by short-term fluctuations in the amount of freshwater discharge negatively affected macrofaunal assemblages and their habitat quality and availability (Lercari et al., 2002; Bergamino et al., 2009). The decrease in abundance and biomass of benthic species towards the disturbance source could also affect the ecosystem functions, which could be substantially reorganized as a result of this disturbance, potentially triggering a range of cascading effects (Defeo and de Alava, 1995).

The aim of this study is to identify spatial and temporal variations in a sandy beach ecosystem (LCBC) affected by a man-made freshwater discharge using a trophic networks approach, and thus linking anthropogenic pressures with macrobenthic community and ecosystem changes. The research strategy combined three sampling sites with different degrees of disturbance (defined by reduced average salinity with the proximity to the freshwater discharge) and three phases of study established between 1987 and 2015. The main questions addressed were: To what extent does the chronic impact of a man-made freshwater discharge affect the community and ecosystem structure of a sandy beach? In particular, what is the spatial extent and temporal persistence of the impact as measured by ecosystem indicators?

2. Materials and methods

2.1. Study area

The study was performed along the 22 km of continuous exposed sandy beach between La Coronilla (33°50′S; 53°27′W) and Barra del Chuy (33°40′S; 53°20′W) on the Atlantic coast of Uruguay (Fig. 1). This beach has been described as the southernmost beach of a chain of exposed sandy beaches defined as semi-closed ecosystems on the Atlantic shore of South America. It is characterized by fine to very fine well-sorted sands, a gentle slope, heavy wave action, and a wide surf zone, and it supports the greatest richness, diversity, abundance and biomass of sandy intertidal macrofauna among all Uruguayan beaches (Lercari and Defeo, 2006, 2015). This microtidal dissipative beach is delimited by two freshwater discharges, a natural one in the NE (Chuy Stream)

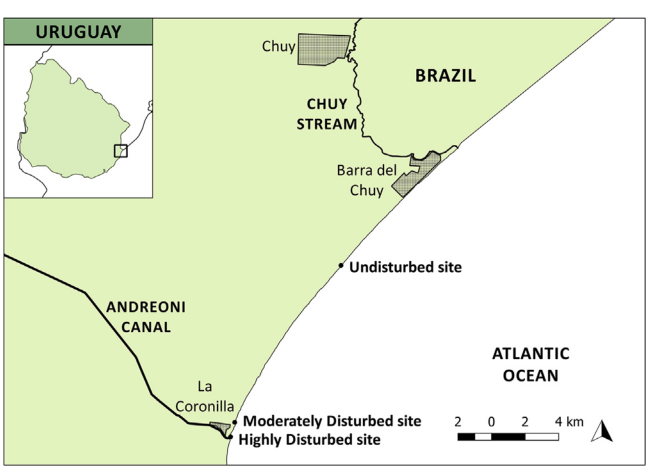

Fig. 1. Study area, showing the location of La Coronilla – Barra del Chuy beach (LCBC) along the eastern coast of Uruguay, the freshwater discharge of the Andreoni Canal and the three sampling sites.

and an artificial one in the SW (Andreoni Canal). The latter is a man-made structure 68 km in length which drains a wide basin (≈270,000 ha) used for agricultural activities. Its discharge on the SW extreme of the beach generally follows a SW–NE direction, producing a strong salinity gradient. The canal flow is highly variable depending on the rainfall and water management regimes of the crops, reaching up to 89 $m^3 s^{-1}$ in winter (Lercari et al., 2002).

2.2. Research strategy

Nine scenarios were analysed through the representation of trophic networks by Ecopath models. Three sampling sites were defined a priori according to the increasing-salinity gradient as an explanatory variable of the observed trends (Table 1: Lercari et al., 2002): a *Highly Disturbed* site (HD), placed at the mouth of the Andreoni Canal; a *Moderately Disturbed* site (MD), located 1 km away from the artificial freshwater discharge; and an *Undisturbed* site (UD), placed 13 km away from the mouth of the Andreoni Canal. The HD site showed significantly lower values of salinity, slope and width of the swash zone (Lercari et al., 2002; Lozoya and Defeo, 2006). In particular, long-term salinity trends showed consistent patterns within sites, exhibiting significantly lower values and greater variability in the HD site (Table 1).

The yellow clam *Mesodesma mactroides* constitutes a major component of the total community biomass at LCBC beach. This species has been subject to a small-scale fishery since the 1960s (Ortega et al., 2012), and has undergone contrasting management phases (Gianelli et al., 2015). Because of its biologic and socioeconomic significance, three phases with contrasting abundance of the yellow clam population stock were selected for the study (Gianelli et al., 2018). The first phase (1987–1993) represented a high abundance of *M. mactroides*, a 32-month fishery closure (April 1987–November 1989), an active fishery with very low fishing intensity (1990–1993) and an informal co-management governance mode. The second phase (1994–2007) included mass mortality events that decimated *M. mactroides* populations across their entire distribution range. The scale and magnitude of the impact prompted a full fishery closure between 1994 and 2008 (Gianelli et al., 2015). The third phase (2008–2015) was characterized by the partial recovery of *M. mactroides* and the implementation of an ecosystem approach to fishing that included co-management as the institutionalized governance mode (Gianelli et al., 2018: Supplementary Materials A).

2.3. Food web modelling

2.3.1. Core routine

Nine trophic models corresponding to the selected sites and phases were built through Ecopath with Ecosim 6 (EwE6), which represents ecosystems as interconnected networks of trophic groups based on biomass and linked by diet information (Polovina, 1984; Christensen and Pauly, 1992). Ecopath is a mass-balanced model, structured by a system of linear equations which represent each functional group (species with similar life history traits and ecological role) in the ecosystem. The master equation describes how group production equals the sum of the entire group losses (Christensen and Pauly, 1998; Christensen and Walters, 2004; Christensen et al., 2005), as follows:

$$B_i(P/B)_i - \sum_{j-1}^{n} B_j(Q/B)_j DC_{jt} - Y_i - B_i(P/B)_i(1-EE_i) = 0$$

where B_i and B_j are, respectively, the biomasses of prey and predators; $(P/B)_i$ is the production/biomass ratio equivalent to the total mortality rate (Z); $(Q/B)_j$ is the consumption/biomass ratio for predator j, DC_{ji} is the fraction of the prey i in the diet of the predator j; Y_i is the total fishery catch rate (manual harvesting of *M. mactroides* was carried out only in the UD site during Phases 1 and 3, see Lercari et al., 2018); and, EE_i is the ecotrophic efficiency, defined as the proportion of the