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Is mangrove planting insufficient for benthic macrofaunal recovery when environmental stress is persistent?

Paulo R. Pagliosa[a,b,*], Mariana S. Oortman[b], André S. Rovai[b], Eduardo J. Soriano-Sierra[b]

[a] Departamento de Geociências, CFH, Universidade Federal de Santa Catarina, Florianópolis, SC 88040-900, Brazil
[b] Núcleo de Estudos do Mar, CCB, Universidade Federal de Santa Catarina, Florianópolis, SC 88040-900, Brazil

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ABSTRACT

Mangrove restoration or rehabilitation is usually based on planting native or exotic species and these actions rarely result in a return to the natural variability of biological assemblage structures and functions that is self-sustaining. One of the major causes of this failure is not attempting to remove stressors that limit natural ecosystem processes (*i.e.*, in mangroves, any act that disturbs the hydroperiod, input of resources, or constrains regulators) in the framework for restoration. Despite this scientific consensus, this has not been put into practice. Here, we analysed a field experiment carried out over 12 years ago, to compare three planted and three reference mangrove stands (natural and previously undisturbed), with no attempt to remove the various causes of disturbance. Forest structure and productivity, sediment features, pollutants, and benthic macrofauna, which are all equally adapted to the mangroves natural conditions and are sensitive to physical disturbances and pollution, were assessed. Values for all environmental variables and almost all species and trophic groups densities differed between planted and reference sites. The fauna in planted areas was qualitatively the same as that in the reference areas, but the assemblages reflected environmental stressors, mainly pollutants (trace metals and nutrients) in the sediment and also hydroperiod alterations (differences in elevation), but not forest structure or functioning. The results indicate that: (i) forest structure and productivity in planted areas were not as would be expected for a time frame of 12 years; (ii) even with constant potential recolonisation of species from surrounding reference areas, planting alone was not sufficient for ecosystem and benthic macrofaunal recovery. We recommend that ecological engineering follows the best practice available to restore mangrove ecosystems by removing the environmental stressors, establishing natural topography, and assessing the long-term success of the projects.

1. Introduction

Mangroves represent a small (0.1%) and ever-decreasing amount of the earth's continental surface in terms of area, but together with other coastal wetlands, they account for over half of the carbon stocks in the ocean's sediments (Nellemann et al., 2009; Giri et al., 2011). Maintaining these deposits has been a key factor in discussions regarding potential human and biological adaptations to ongoing climate changes (Gilman et al., 2008; Alongi, 2014). However, mangrove loss is not a novel problem and is occurring at rates ranging from 0.7 to 2.0% a year (FAO, 2007; Lewis, 2009). Given their role in global climate balance, coastal protection, economic use, as well as the threats to their long-term survival, there are compelling reasons for ecologically restoring mangroves.

Mangrove restoration efforts commonly focus on the planting of a single native or exotic species (Ellison, 2000; Dale et al., 2014). This sort of action within the context of restoration projects is hereafter called Mangrove Planting (MP). These attempts usually tend to be inefficient and lead to poor development of planted individuals (Ren et al., 2009; Rovai et al., 2012). This outcome ought to be anticipated, since mangrove structure and function are mainly dependent on the hydroperiod (*i.e.*, flooding frequency, duration, and depth), regulators (*i.e.*, soil chemistry) and resources (*i.e.*, nutrients and radiation) (Twilley and Rivera-Monroy, 2005). On the contrary, true Ecological Mangrove Restoration (EMR; *sensus* Lewis, 2005) occurs when stressors are eradicated, which allows natural recovery to occur *via* secondary succession (Lugo et al., 1981; Cintrón-Molero, 1992). As a result of the natural development of

* Corresponding author at: Universidade Federal de Santa Catarina, CFH, Departamento de Geociências, Florianópolis, SC 88040-900, Brazil.
E-mail addresses: paulo.pagliosa@ufsc.br (P.R. Pagliosa), mariana.serwy@gmail.com (M.S. Oortman), asrovai@gmail.com (A.S. Rovai), sierra_ejs@yahoo.com.br (E.J. Soriano-Sierra).

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stands, the reestablishment of the associated benthic macrofauna is expected (Fondo and Martens, 1998; Sasekumar and Chong, 1998; Al-Khayat and Jones, 1999; Bosire et al., 2004; Chen et al., 2007, 2015; Chen and Ye, 2011; Leung and Tam, 2013; Tang et al., 2012). The benthic fauna that colonises mangrove soils is well adapted to naturally stressful conditions. Organisms that are tolerant to salinity variation, desiccation, low soil oxygen concentrations, and a high content of organic matter are dominant (Cannicci et al., 2008; Lee, 2008; Nagelkerken et al., 2008). In addition to these soil chemistry regulators, benthic macrofaunal species composition and distribution also respond to the presence or absence of native species of the mangrove local flora (Chen et al., 2015), the age of the stands (Morrisey et al., 2003), rate of litterfall productivity (Oliveira et al., 2012), pneumatophore density, and crown size or shading (Chapman and Tolhurst, 2004). Considering the close relationship between biological variables (*i.e*., abundance, productivity) and physico-chemical factors in mangroves, both megabenthic epifauna and macrobenthic fauna (epi- or infauna) have been used as bioindicators of pollution (Faraco and Lana, 2003) as well as of recovery in MP projects (Bosire et al., 2008). Because of its economic importance, close relationship with primary production and ease of handling and monitoring, the mangrove megafauna (*e.g*., fishes, crabs, gastropods, and prawns) have received more attention (Ellison, 2008). Studies that have included macrofauna (*e.g*., polychaetes, oligochaetes, insects, amphipods, isopods, and small crabs and molluscs) as a performance measurements in MP or EMR projects are scarce (Dale et al., 2014), due to generally more laborious handling of samples and the need for greater taxonomic expertise in relation to other faunal groups. However, the macrofauna is less motile and displays more diverse lifestyles and trophic interactions than the megafauna. These characteristics confer to the macrofaunal community a unique role in mangrove ecosystem functioning.

Considering that both environmental degradation and ecological restoration influence mangrove stand structure and the macrofaunal community, both may be used as performance measures to assess the effectiveness of MP and EMR projects. Here, we extend the results of previous assessments of MP projects in southern Brazil (Rovai et al., 2012, 2013) and evaluated forest structure and productivity, soil properties, and the macrobenthic epifaunal and infaunal communities in three planted mangrove stands and three adjacent natural stands, over two consecutive years. In planted stands, no attempts were made to properly evaluate environmental disturbances, therefore, stressors (*i.e*., landfill, embankment, and excavation) were never eliminated (Rovai et al., 2012). Assuming that merely planting mangrove trees in disturbed areas is not an effective ecological restoration practice, the macrofaunal community is expected to reflect more the environmental stressors, mainly soil pollution (*i.e.*, metals and nutrients) and an altered hydroperiod. Thus, we hypothesize that the macrofauna of planted areas with persistent environmental stressors cannot recover properly and would be expected to have impoverished species composition, abundance, and trophic groups when compared to undisturbed stands.

2. Material and methods

2.1. Study area

The study was conducted in the Island of Santa Catarina, southern Brazil (Fig. S1). The regional climate is subtropical and humid, with a mean annual temperature of 21 °C and a total precipitation of 1,200 mm yr^{-1} well distributed along the year. The tidal cycle is semidiurnal, with nocturnal inequalities, and the regime is microtidal with mean amplitude of 0.83 m for spring tides and 0.15 m for neap tides. The local tidal force is mainly influenced by the winds, with those from the northeast being the most frequent in the summer and those from the south the most intense during the winter (Cruz, 1998).

The region represents the southernmost limit of the mangrove distribution on the American Atlantic coast. Due to climatic and oceanographic conditions, the structural development of mangrove forests is reduced (*i.e*., smaller diameter and tree height) compared to that of lower-latitude forests (Schaeffer-Novelli et al., 1990; Rovai et al., 2016). The species *Avicennia schaueriana*, *Laguncularia racemosa*, and *Rhizophora mangle* occur in the area, the first two being the most abundant (Rovai et al., 2012). Current estimates show that about 40% of regional mangrove forests were lost during the last century (Trindade, 2009). Although mangrove wood had been used by traditional coastal communities, the most significant losses directly relate to changes in the hydrodynamics of the ecosystem, caused by drainage works (enlargement, channel straightening, installing drainage systems, and flow control of the water courses) and landfill actions for construction of roads and land development.

2.2. Mangrove plantings

About 12 years ago, three independent MP projects were carried out in the Island of Santa Catarina as compensation for environmental damage caused by three different enterprises. Each project was located on distinct watersheds. The projects were developed and implemented by independent wetland scientists (Matos, 2002; Huber, 2004).

In the Itacorubi mangrove (27°34′59.16″S-48°30′50.11″W) a toxic leachate from a 60-year old deactivated landfill (dump) situated on the landward portion of the mangrove forest caused the massive mortality of the vegetation. The MP project was based on single plantings of *A. schaueriana* seedlings in a 0.35 ha area of. At the Saco Grande mangrove (27°32′50.80″S-48°30′14.29″W) the topography of an area of 0.30 ha was altered by a landfill used for private housing development. The main restoration action was the planting of *L. racemosa* and *A. schaueriana* seedlings. In the Ratones mangrove (27°28′23.46″S-48°29′42.13″W), seedlings of *A. schaueriana* and *R. mangle* were planted in an area of 0.24 ha where topography was altered by the excavation of aquaculture ponds.

2.3. Field experimental design and sampling procedures

The goal of the field experiment and sampling procedures were: (i) to evaluate the environmental differences between planted and reference treatments, testing the effectiveness of MP projects carried out 12 years ago; (ii) to assess structure (total abundance, richness and abundance of selected species) and function (abundance of trophic groups) of the macrofaunal benthic community between planted and reference treatments, on the two sampling dates (January 2011 and January 2013); and finally, (iii) to assess the relationship between environmental variables and the species spatial pattern, as well as the consistency of the responses on the two sampling dates, in order to verify which key environmental factors were more associated with benthic macrofaunal recovery.

To achieve these goals, reference areas were selected adjacent to planted stands in each of the three mangrove sites. Reference areas were no more than 500 m distant from the planted areas and corresponded to sites that had experienced no modification in vegetation cover in the last 50 years. The areas were selected from historical aerial imagery analysis and field inspections. In each site (Itacorubi, Saco Grande, and Ratones) and treatment (planted and reference), three plots (from 5 to 10 m apart to each other) were established where forest structure and functioning, and soil and macrofaunal characteristics were measured. Plot size varied (6, 25,