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The role of mangrove revegetation as a means of restoring macrofaunal communities along degraded coasts

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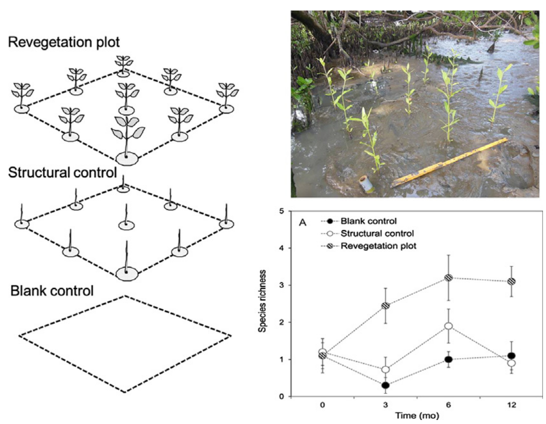
HIGHLIGHTS

- We address the need to understand how mangrove revegetation can build resilience.
- Experiments assessed changes to sediment dynamics & macrobenthic communities.
- The faunal communities of revegetation plots were compared to controls over time.
- Revegetation was associated with an increase in abundance & diversity of macrofauna.
- We advocate revegetation to aid recovery & help restore degraded ecosystems.

GRAPHICAL ABSTRACT



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ABSTRACT

As coastal habitats face unprecedented pressure globally, there is a need to better understand how revegetation can fortify or restore biodiversity. We examined the early-stage outcomes of mangrove revegetation efforts for benthic invertebrate communities within degraded mangrove habitats in south eastern Brazil. We followed changes in macrofaunal abundance and species richness within small-scale *Avicennia schaueriana* revegetation plots over a 12 month period. The assemblages of revegetation plots (RP) became progressively more diverse when compared to structural (SC) and blank controls (BC). The trajectory of change also differed with RP communities demonstrating convergence with those of remnant mangrove forest. After 12 months, RP had greater abundances of crustaceans (41%) and polychaetes (13%) as well as higher but variable numbers of gastropods and bivalves than both SC and BC. A spatial examination of revegetation outcomes showed that success may vary across sheltered vs. exposed coastal microhabitats. Indeed, subsequent analysis using generalised linear mixed models pointed to a stronger influence of tidal height, than many of the commonly attributed sedimentary variables such as grain-size and organic matter content as determinants of community structure. Given the encouraging results of this study, we advocate an intensification of revegetation initiatives to augment natural recovery, increase benthic biodiversity and restore ecosystems services to degraded coasts.

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1. Introduction

Mangrove forests are integral and highly productive habitats across tropical and sub-tropical coastlines. They provide numerous ecosystem services including: shoreline protection (Everard et al., 2014); a vital role in carbon export and sequestration (Lee et al., 2014); nurseries for fish and crustacean species (Nagelkerken et al., 2008), offsets to atmospheric CO_2 (Alongi, 2012) and resources for human populations (Alongi, 2002). Despite these values, mangrove forests are under pressure globally through coastal development, land reclamation and a variety of other activities. Indeed, over the past 50 years approximately one-third of the world's mangroves have been lost (Alongi, 2002, Polidoro et al., 2010) with estimates in some parts of Asia and the Pacific being considerably higher (>70%). In Brazil as elsewhere, there is increasing concern about the loss of forests through failure to enforce environmental policies (Rovai et al., 2012). This is a concerning tendency given the challenges posed by climate change (Hoegh-Guldberg and Bruno, 2010) and those such as sea level rise that are predicted to be especially detrimental to mangrove forests (Gilman et al., 2008).

The successful restoration of degraded or damaged ecosystems is in part indicted by the re-establishment of a level of diversity and community structure that reflects pre-disturbed or adjacent unaffected areas (Ruiz-Jaen and Aide, 2005). While the benefits of habitat restoration offer powerful and compelling justification for management responses, (i.e., in terms of increasing habitat stability; Everard et al., 2014; and even as a means of restoring ecosystem services; Kaly and Jones, 1998), there has often been less attention given to assessments of whether ecosystems and their constituent parts (e.g., faunal communities; Ellison, 2000) are restored to a desired baseline or functional condition for the majority of habitats. Indeed, the degree to which restored areas will resemble pristine habitat will depend on the level of complexity examined (Peters et al., 2015), the geographic or environmental context assessed (e.g., taking into account hydrology; Lewis, 2005) and the timescale over which assessments are made (Barak et al., 2016). The strong supportive role of mangroves to different taxa (Nagelkerken et al., 2008) suggests that their restoration will have profound and beneficial effects for macrobenthic communities (Leung and Tam, 2013), however it may be helpful to gauge 'success' in the context of a return (or convergence) with communities that typify remnant forests. The success or failure of revegetation initiatives can be assessed by evaluating relevant end-points such as the rebuilding of macrofaunal communities (for a review see; Bosire et al., 2008) or the restoration of ecosystem function, both of which may be influenced by the speed, degree and environmental context with which assessments are made.

The aim of this study was to follow changes in macroinvertebrate communities that could be directly attributed to small-scale mangrove revegetation efforts. We hypothesized that planting cultivated mangroves within degraded patches of remnant mangrove forest would lead to positive changes in the abundance and diversity of infaunal and epibenthic communities (hereafter 'macrobenthic communities'). Further, we attempted to resolve the spatial dynamics of revegetation outcomes by comparing plots located in different microhabitats reflecting sheltered vs. exposed hydrodynamics as well as tidal height. Finally, we compared the relative importance of the abiotic factors wave exposure, tidal height, sediment grain size and organic matter content as drivers of change to communities using generalised linear mixed models. We tested the following hypotheses; (1) that there would be marked differences in the restoration outcomes (trajectories over time) of macrobenthic communities sampled from revegetation plots and controls; (2) that changes observed within plots would evidence convergence with those of typical remnant mangrove communities, and (3) that the nature of the abiotic/biotic environment (covariates; wave exposure, tidal height and sediment characteristics) of revegetation plots would be useful predictors of overall community abundance and diversity.

2. Methods

2.1. Study site

This study was done in Araçá Bay, a semi-enclosed coastal inlet located adjacent to the city of São Sebastião in south eastern Brazil (Fig. 1A). Over the past century this bay has undergone substantial change, with a marked reduction in the area of mangrove forest (Mani-Peres et al., 2016) due to a combination of disturbance including harbour development, land-clearance and nutrient inputs (Amaral et al., 2010; Gorman and Turra, in review). The bay is typical of many degraded parts of the Brazilian coast and hence the outcomes of our study are likely to be of relevance for the broader biogeographical region. Remnant stands of mangrove forest comprise of *Rhizophora mangle* (Linnaeus, 1753), *Avicennia schaueriana* (Linnaeus, 1764) and *Laguncularia racemosa* (Linnaeus, 1807) (Amaral et al., 2015). Within remnant forests are 'degraded patches' of unvegetated bare ground (i.e., ranging from 1 to 10 m in diameter) where mangrove trees have been lost through erosion and 'wash-out' (Amaral et al., 2015).

2.2. Collection, germination and cultivation

Mature propagules of the mangrove *Avicennia schaueriana* were collected from Araçá Bay in November 2013. Propagules were placed in large plastic trays covered with freshwater for ~10 days which has the effect of helping to open/split the outer seed coat and encourage the growth of primary roots. *Avicennia* spp. is typically crypto-viviparous with an embryo that emerges from the seed coat but not the fruit before it abscises and the whole fruit is considered one propagule (Tomlinson, 1986). Germinated propagules were planted in 10 cm depth × 10 cm diameter washed and halved cardboard milk containers containing sediment collected from within mangrove stands in Araçá Bay. Seedlings were protected from excessive sunlight by 60% shade cloth, watered daily with freshwater and irrigated bi-weekly with freshly collected seawater to facilitate isotonic stabilisation. Cultivation lasted for ~90 days and resulted in the accumulation of a stock of about 200 seedlings (mean height ± SD, range: 24 ± 6.3 cm, 9 cm) for use in experiments.

2.3. Experimental treatments

Seedlings were introduced into Araçá Bay as replicate ($n = 12$) revegetation plots (Fig. 1B) during March 2014. Plots were established in the centre of degraded patches contained within remnant forests of the mangrove *Avicennia schaueriana*. In order to assess variation in revegetation outcomes across exposed vs. sheltered microhabitats, half of the plots were established on the exposed 'Pernambuco Island' in the centre of the bay, while the others were established on the sheltered 'Pernambuco Point' located on the western shore (Fig. 1A). To resolve the influence of structural vs. biological attributes of revegetation, each site incorporated; (1) a 50 × 50 cm square revegetation plot (RP) comprising of 9 seedlings; (2) a structural control plot (SC; 50 × 50 cm) consisting of bamboo stakes of a similar diameter and height as seedlings; and (3) an undisturbed blank control plot (BC; 50 × 50 cm, Fig. 1B). Because planting involved the extraction of a volume of sediment 10 cm deep × 10 cm diameter (i.e., the volume of the milk containers), the same process of extraction and replacement was applied to the structural control but not to the blank control. The survival of seedlings in each plot was monitored every 3–4 days and any losses were replaced immediately with similar sized seedlings from the stock of reserves.

2.4. Shifting community structure

Changes to the macrobenthic communities of revegetation plots and controls were monitored over a 12-month period. The permanent loss