Wetlands Ecol Manage (2012) 20:447–459
DOI 10.1007/s11273-012-9269-z

ORIGINAL PAPER

Secondary succession impairment in restored mangroves

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Received: 20 February 2012 / Accepted: 30 August 2012 / Published online: 18 September 2012

Abstract In this work it was hypothesized that secondary succession on sites that have been managed by single planting of mangrove species is compromised by residual stressors, which could reduce the ecosystem's structural development and lower its functions. Forest structure and environmental characteristics of three planted mangrove stands are compared with reference sites. Structural attributes showed significant differences in the comparison of planted and reference stands. *Avicennia schaueriana* was the dominant species within both natural regeneration and old-growth stands in terms of basal area (99.2 and 99.4 %, 69.6 and 84.5 %, and 59.0 and 87.1 % for Itacorubi, Saco Grande, and Ratones, respectively). Restoration stands

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were dominated by *Laguncularia racemosa* (80.6 and 94.2 % for Saco Grande and Ratones, respectively), except at one site (Itacorubi), where *A. schaueriana* prevailed (99.7 %). Even though restoration and regeneration stands at Itacorubi showed similar species composition and dominance, cohort sorting revealed an inferior regeneration potential in the restoration stand. Multiple correlation analysis indicated that variables related to elevation disruptions ($p_w = 0.521$) were the environmental drivers responsible for the differences observed in forest structure. At restoration sites an impaired pattern of secondary succession was observed, indicating that single species plantings may be ineffective if characteristics of the site, as well as of the area surrounding it, are not considered. The inadequate management of restoration sites can therefore have implications for both immediate and long-term large-scale ecosystem services.

Keywords Mangrove restoration · Structural development · Ecosystem functionality · Residual stressors · Mangrove planting

Introduction

Despite their undisputed ecological and economic importance (Wells et al. 2006; Walters et al. 2008; Nellemann et al. 2009; Alongi 2011; Donato et al. 2011), mangroves are disappearing worldwide by 0.7 (FAO 2007) to 2 % (Lewis 2009a) per year, mainly due to aquaculture, urbanization, coastal landfill, pollution, upstream land use (Duke et al. 2007), and harbor development activities. Brazil has lost at least 50,000 ha of mangroves over the last 25 years, mainly along the southern coast (FAO 2007), and these estimates are very likely to increase (Metzger et al. 2010; Rovai et al. 2012). If mangrove forest destruction continues at the same pace, a no-net-loss of mangrove areas would require effective restoration of 2,000 ha.year^{-1} and double that amount to bring back what has already been lost (Rovai 2012).

As in other locations worldwide, unsuccessful outcomes in restoring Brazilian mangroves are habitually related to the inadequacy of methods that are used, which are based on simple planting and repetitive replanting of mangrove propagules/seedlings rather than an initially assessment of the reasons for the absence of mangroves and a determination of why natural recovery did not occur (Lewis 1982, 1990, 1999, 2000, 2005, 2009b; Cintrón-Molero 1992; Field 1998; Erftemeijer and Lewis 2000).

Substrates of restored mangroves can present problems related to physical structure and stability, moisture (determined by appropriate tidal fluctuation concomitant with soil aeration), nutrition and toxicity (Mckee and Faulkner 2000), which will in turn determine forest development. Nonetheless, where plantings are successful, periods exceeding two decades may be necessary to evaluate restoration success based on the vegetation's structural attributes (Crewz and Lewis 1991; Lugo 1992; Luo et al. 2010). Thus, simple planting success should not be considered ecological restoration, even if it appears successful from a short-term perspective (Ellison 2000; Lewis 2009b), since the time lag required to assess actual functional performance can be longer than the time lag needed to evaluate short-term forest structural traits (Mckee and Faulkner 2000).

Nevertheless, experimental approaches, coupled with the assessment of exploratory variables, are reliable tools for the evaluation of ecological functions based on forest structure. In this work it was hypothesized that secondary succession in restoration sites that have been managed by single planting of mangrove species is compromised by residual stressors, which reduce the ecosystem's structural development and lower its functioning. To test our assumption, vegetation structural characteristics of three planted mangrove stands are compared with reference sites and correlated to edaphic and oceanographic variables. Even though limitations inherent to the time frame that was used (data collected at only two points in time) may constrain extrapolations to similar-aged stands, the replication of locales (sub-settings) and stands captured enough environmental variability, bringing representative information to bear and thus allowing us generalize about other mangrove restoration investigations.

Methods

Field sites and sampling strategy

The investigated mangrove sites are located in three independent watersheds located in Santa Catarina Island, southern Brazil (Itacorubi 27°34′38″S/48°31′04″W; Saco Grande 27°32′40″S/48°30′47″W and Ratones

27°28′14″S/48°29′35″W). The regional climate is subtropical humid with no characteristic dry season but with reduced rain volume from April to September (Cruz 1998). The local tide is micro-tidal (Melo et al. 1997), with south and north winds being the main physical agents influencing the local hydrodynamic. Mangroves and salt marshes are located at the estuarine end of these watersheds, which drain upland terrain through meandering rivers that flow through lightly to moderately urbanized short coastal plains (Pagliosa and Barbosa 2006) formed during the late quaternary. Considering the latitudinal limit of distribution of the studied mangroves (Soares et al. 2012), stands still exhibit structurally well-developed old-growth forests dominated by *Avicennia schaueriana* Stapf & Leechman ex Moldenke, Acanthaceae followed by *Laguncularia racemosa* L. Gaertn. F., Combretaceae and *Rhizophora mangle* L., Rhizophoraceae interspersed with gaps opened naturally or due to human interferences without marked zonation patterns (Cintrón 1981; Soriano-Sierra 1993). This situation enabled the selection of three planted sites and two different temporal reference sites.

All three restoration areas were treated with single planting about 10 to 12 years ago and immediately left to natural regeneration. To allow for proper comparison as well as to help verify any trend regarding the time since restoration actions took place, two types of reference stands were chosen within each mangrove sub-setting: one consisting of a natural regeneration area, approximately 10 years old, and the other an old-growth mangrove stand (over 50 years). The identification of the reference stands was performed by visual interpretations of historical aerial images complemented by field surveys. To minimize noise related to the environmental gradient (i.e., flooding frequency), areas were carefully surveyed and the reference stands were placed at a similar distance from the water's edge, with the restoration stand serving as a reference point. At the Itacorubi mangrove site, all of the treatments were placed 5–20 m from the water's edge. At Saco Grande and Ratones, mangrove restoration stands were situated 126 and 119 m from the water's edge, respectively; thus, natural regeneration and old-growth stands were correspondingly placed at a distance of 100 and 81 m (Saco Grande) and 115 and 62 m (Ratones) from the water's edge.

The Itacorubi restoration stand suffered a massive mortality event (sensu Jiménez et al. 1985) that was probably caused by toxic leachate from a landfill (deactivated six decades ago) located on top of the landward portion of the mangrove forest. The topography of the Saco Grande and Ratones restoration stands was altered by dirt used to fill a housing development area and by excavation of material to built aquaculture ponds, respectively. On those two last mangrove stands, planting was carried out without any attempt to reestablish the historical topography. Itacorubi, Saco Grande, and Ratones restoration sites measured ca. 0.35, 0.30, and 0.24 ha, respectively; however, planting was carried out on only a part of the damaged area (0.02, 0.02 and 0.10 ha, for Itacorubi, Saco Grande, and Ratones, respectively).

The experimental design was a 3 × 3 factorial, with locations (Itacorubi, Saco Grande, and Ratones mangrove sub-settings) and treatments (restoration, natural regeneration, and old-growth stands) as the main factors. Three plots were set to assess forest structure in each treatment-site combination.

Forest structure and environmental data

In each site and treatment, forest structure and environmental variables were investigated. Forest structure was described on the basis of density and basal area of trees (Cintrón and Schaeffer-Novelli 1984). Plot size varied (6, 25, and 100 m^2) according to forest density, in order to assure homogeneity in terms of structural characteristics (species composition and structural development of individuals). Within the plots, all trees above 1 meter in height, dead or alive, were identified to species level and the diameter at breast height (DBH) and heights (only for the live ones) were measured for each stem. Where stands presented shrub-like structure and branch profusion below 1.3 m (restoration and natural regeneration stands), diameter was measured at 5–15 cm above soil surface.

Interstitial salinity was monitored monthly (May to July 2011). Pore water was obtained from PVC tubes (5 cm in diameter; 80 cm in length) perforated at the lower extremity, which were inserted into the sediment to a depth of 40 cm (Cintrón and Schaeffer-Novelli 1984). Salinity was measured with a field refractometer (0.1 psu). Sediment samples of the first 20 cm (from surface) were collected separately for determination of size fractions, organic matter, nutrients (C, N, P), and water content. Because sediment properties can vary widely over tidal, dial, and seasonal time-scales, all samples were collected within 1 h of the time selected for sampling (Tolhurst and Chapman 2005), for each mangrove sub-setting. PVC cores (5 cm in diameter) were used to collect samples for nutrient analysis and plastic containers for the other parameters. Samples were immediately taken to laboratory, where they were either kept frozen (samples for nutrient analysis) or processed immediately, using conventional methods to determine: size fractions and organic matter (Wentworth 1922; Suguio 1973); water-content (Tolhurst and Chapman 2005); concentration of C, N (plasma mass spectroscopy; ICP-MS); and P (Áspila et al. 1976). Topography was measured using a real-time kinematic geographic positioning system and altitudes were adjusted according to regional tidal gauge records (vertical datum from Imbituba harbor, Santa Catarina State, Brazil). Sediment compactness was measured according to the number of hits needed for complete penetration of a metal rod into the sediment. Tide data for the year 2011, obtained from Brazilian Navy's Board of Hydrography and Navigation, were used to estimate the average flooding frequency in terms of events, i.e., number of times that the tides exceeded the elevations measured in the field.

Statistical analysis

The forest structural data distribution pattern was analyzed using multi-dimensional scaling ordination (MDS) on the basis of Bray-Curtis dissimilarity on square root-transformed data as descriptors. The significance of the differences between sites, treatments, and their interactions was evaluated through permutational multivariate analysis of variance (McArdle and Anderson 2001), carried out with the PERMANOVA program (Anderson 2005). The analysis was made on unrestricted raw permutation data and run 9,999 times. Sites were held as random factors, and treatments as fixed. The relationship between environmental variables and forest structural characteristics was explored by using Spearman rank correlation between two similarity matrices (Bray-Curtis for biotic data and Euclidean distance for environmental, both on square root-transformed data), successively testing every possible combination of environmental parameters to indicate which arrangement best explained the observed multivariate community patterns. Both ordination (MDS) and correlation data analyses (BIOENV routine) were performed using PRIMER statistical software (Clarke and Gorley 2006).

Results

A. schaueriana was the dominant species (Table 1) within both natural regeneration and old-growth stands in terms of basal area (99.2 and 99.4 %, 69.6 and 84.5 %, and 59.0 and 87.1 % for Itacorubi, Saco Grande, and Ratones, respectively) and stem density (99.0 and 98.0 %, 46.7 and 54.3 %, and 62.8 and 59.8 % for Itacorubi, Saco Grande and Ratones, respectively). On the other hand, restoration stands were dominated by *L. racemosa* in both basal area and density (80.6 and 90.2 %, and 94.2 and 99.2 % for Saco Grande and Ratones, respectively), except for one site (Itacorubi) where *A. schaueriana* prevailed (99.7 and 99.5 %, respectively), *R. mangle* was virtually absent in restoration stands.

Although species richness in restoration sites was similar to reference sites, the former sites had lower basal area and were denser (Table 1). DBH and average height were at least twice as large in old-growth stands compared to restoration and natural regeneration stands, while these last two presented similar values.

Overall forest structural attributes (species composition; $\overline{\text{DBH}}$; minimum, maximum and average height; stems density; basal area; and the ratio of stems/individual) were used to verify similarity between treatments. Ordination analysis coupled with permutational analysis of variance showed no significant difference between mangrove sub-settings, but significant differences between treatments (Fig. 1; Table 2). The MDS indicated that overall forest structural attributes of 10- to 12-year-old planted stands differed from reference sites. Pair-wise tests showed significant difference among all treatments, except for the Itacorubi mangrove site, where restoration and natural regeneration stands were similar.

Although Itacorubi restoration and regeneration stands presented some similarities in terms of overall structural attributes, the former showed a lower number of individuals in younger cohorts (Fig. 2). Conversely, younger cohorts in restoration stands of the other two study sites leveled off or surpassed those

Table 1 Structural attributes (mean ± SE) of the mangrove forests studied in southern Brazil

Site/treatment		Spp.	Absolute density stems.ha^{-1} (%)	Basal area m^2.ha^{-1} (%)	$\overline{\text{DBH}}$ (cm)	Mean height (m)
ITA	RT	*As*	4333 ± 1115 (99.5)	6.89 ± 2.38 (99.7)	3.14 ± 0.22	3.06 ± 0.16
		Rm	22 ± 22 (0.5)	0.02 ± 0.02 (0.3)		
	RG	*As*	4311 ± 1294 (99.0)	2.27 ± 0.80 (99.2)	2.52 ± 0.17	2.42 ± 0.25
		Rm	44 ± 30 (1.0)	0.02 ± 0.01 (0.8)		
	OG	*As*	844 ± 240 (98.1)	4.12 ± 1.68 (99.4)	9.55 ± 2.00	6.34 ± 0.81
		Lr	17 ± 12 (1.9)	0.02 ± 0.02 (0.6)		
SG	RT	*As*	800 ± 323 (9.8)	0.81 ± 0.42 (19.4)	2.69 ± 0.16	2.12 ± 0.05
		Lr	7333 ± 2253 (90.2)	3.37 ± 1.15 (80.6)		
	RG	*As*	2200 ± 688 (46.7)	2.13 ± 0.93 (69.6)	3.02 ± 0.08	2.32 ± 0.13
		Lr	2133 ± 640 (45.3)	0.81 ± 0.28 (26.5)		
		Rm	378 ± 131 (8.0)	0.12 ± 0.06 (3.9)		
	OG	*As*	417 ± 122 (54.3)	3.80 ± 1.56 (84.5)	8.97 ± 1.09	5.63 ± 0.40
		Lr	333 ± 130 (43.5)	0.69 ± 0.35 (15.3)		
		Rm	17 ± 9 (2.2)	0.01 ± 0.01 (0.2)		
RAT	RT	*As*	185 ± 185 (0.8)	0.60 ± 0.60 (5.8)	2.55 ± 0.21	2.28 ± 0.24
		Lr	21852 ± 7991 (99.2)	9.64 ± 4.10 (94.2)		
	RG	*As*	1911 ± 506 (62.8)	3.65 ± 1.16 (59.0)	5.95 ± 1.02	3.96 ± 0.66
		Lr	1089 ± 262 (35.8)	2.47 ± 0.78 (40.0)		
		Rm	44 ± 30 (1.5)	0.07 ± 0.05 (1.1)		
	OG	*As*	306 ± 77 (59.8)	6.25 ± 2.87 (87.1)	14.66 ± 0.98	9.23 ± 0.67
		Lr	200 ± 66 (39.1)	0.89 ± 0.26 (12.4)		
		Rm	6 ± 6 (1.1)	0.04 ± 0.04 (0.5)		

ITA Itacorubi; *SG* Saco Grande; *RAT* Ratones mangroves; *RT* Restoration; *RG* Regeneration; *OG* Old-growth stands; *As*, *A. schaueriana*; *Lr*, *L. racemosa*; *Rm*, *R. mangle*; $\overline{\text{DBH}}$ Diameter at breast height

observed in natural regeneration stands. Itacorubi differed from the other sites since it had been planted in a pre-existing suitable topography rather than in an excavated or dirt-filled site.

The correlation analysis indicated clay content, interstitial salinity, inorganic phosphorous content, elevation, and soil compactness as the set of variables that best explained the pattern of distribution of forest structure observed in the MDS ($p_w = 0.521$).

Even though substrate composition was expected to vary from site to site, the history of each stand (treatments) seems to have been a determining factor in the differences observed for P, N, water content, elevation, compactness and silt, and sand and clay proportions (Fig. 3). Only organic matter did not show much variation between stands. The Ratones site had a higher percentage of gravel and sand, mainly at the restoration stand, while the Saco Grande and Itacorubi sites showed elevated proportions of clay and silt. Elemental composition varied between stands, but without evident patterns. C and N contents did not show much variation, with peaks of 112.26 and 6.73 mg.g^{-1}, respectively, at the Ratones natural regeneration stand. Phosphorous (total, organic, and inorganic) at the Ratones restoration stand was remarkably lower (approximately five times less) than at all other stands.

Interstitial salinity (psu) did not differ between treatments within each site. Stands in the Ratones site had lower values, around 25, while Saco Grande and Itacorubi showed slightly higher values, ranging from 28.3 to 31.9. Water content was lower in restoration stands from Saco Grande and Ratones (about 54 %) compared to all other treatments, which varied from 64 to 76 %. Soil compactness was much higher in Ratones restoration stands and in both Saco Grande restoration and natural regeneration stands. Within every location, higher elevations were detected in restoration stands. Extreme values were observed at Ratones, where elevations varied from 0.33 (pond

Fig. 1 Multi-dimensional scaling (MDS) run on overall forest structural attributes of the mangroves studied, southern Brazil. Symbols represent sub-settings (*squares* Itacorubi; *circles* Saco Grande; *triangles* Ratones) and colors treatments (*black* restoration stands; *white* regeneration stands; *gray* old-growth stands)

bottom) to 0.75 m (sand bar artificially created to confine pond water), and at Saco Grande, close to 1 m with reference to mean sea level. Flooding mirrored elevation, with fewer events estimated for the Saco Grande and Ratones restoration stands, with Ratones varying from 67 (sand bar) to 123 (pond bottom) times per year.

Discussion

Factors hindering secondary succession

In restorations stands where edaphic conditions were physically disrupted, the system seems to have remained arrested in a lower level of structural development, dominated by *L. racemosa*. This species is known for its ability to dominate disturbed environments (Smith III 1992; Soares 1999; Menghini 2008; Menghini et al. 2011). It was observed in restoration sites that *L. racemosa* outnumbered *A. schaueriana* and *R. mangle*, and presented high values of trunk density and branched architecture, which is typical of mangrove forests under stressed conditions (Pellegrini et al. 2009; Soares et al. 2012). In fact, structural data from one of the restoration stands (Ratones) revealed that the massive planting of *A. schaueriana* propagules (75 % of a mixed planting with *R. mangle*) was futile, since *L. racemosa* is the dominant species, with *A. schaueriana* or *R. mangle* virtually absent. Additionally, though changes in species composition are expected, the most common pattern observed for mangrove restoration sites under similar biogeographical constraints is an increase in volunteer *L. racemosa* at sites where other species had been planted (Shafer and Roberts 2008).

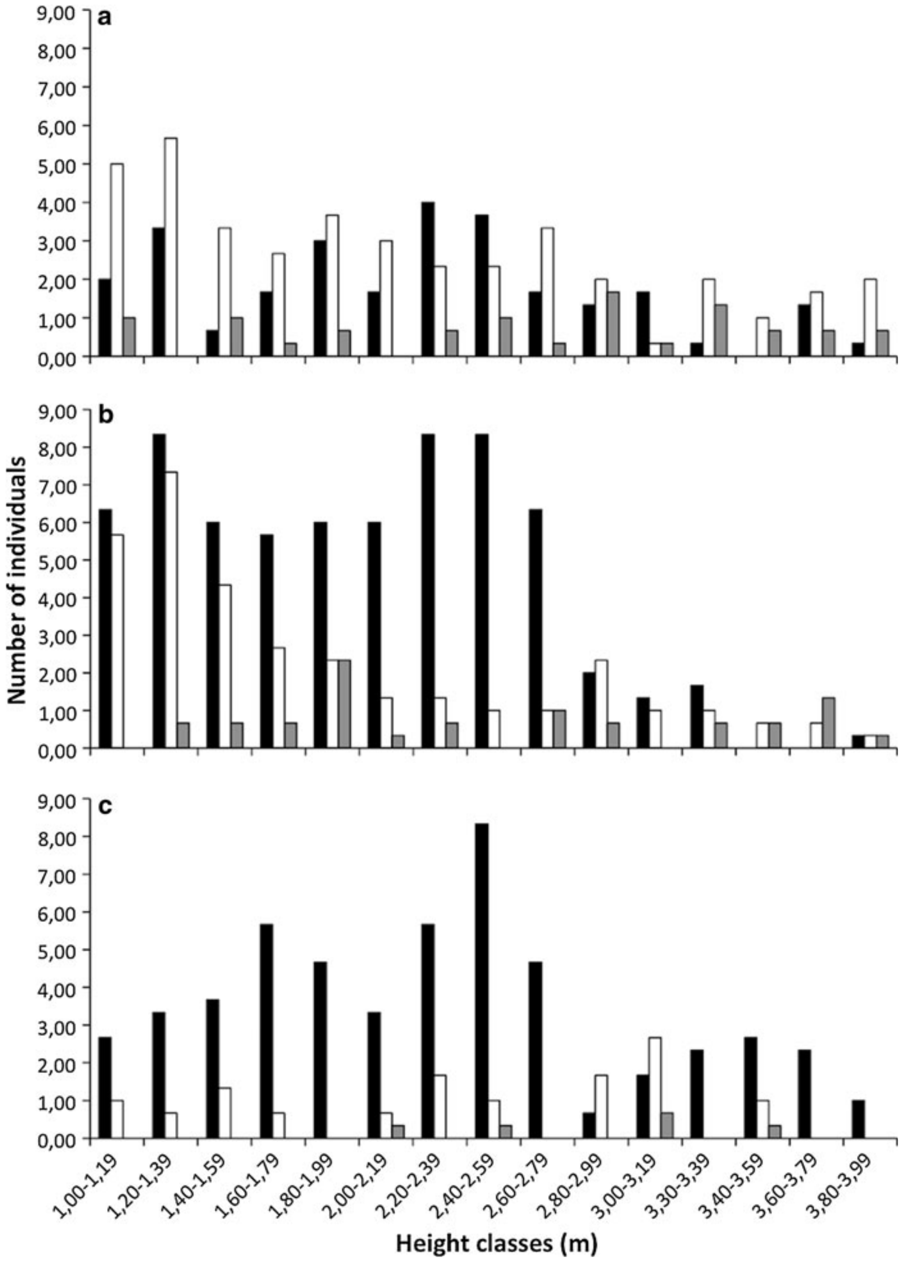
The lowest structural development occurred at Saco Grande and Ratones restoration sites due to inappropriate planting elevation (either too low or too high). These sites differed from the others because substrate was either too compact (Saco Grande) or composed largely of sand (Ratones). Ground elevation determines

Table 2 Results of the PERMANOVA and pair-wise comparisons of treatments within the mangroves studied in southern Brazil

Source of variation	*df*	MS	*F*	P(MC)
Lo	2	5220.8231	3.4263	0.0314
Tr	2	10134.8250	6.6512	0.0016
Lo x Tr	4	1523.7537	7.5152	0.0001
Residual	18	202.7559		
Pair-wise tests				
ITA				RT-RG-RF
SG				RT-RG-RF
RAT				RT-RG-RF

Lo Locals (Itacorubi, Saco Grande, and Ratones); *Tr* Treatments (restoration, regeneration, and old-growth stands). *Underline* denotes no significant differences

Fig. 2 Number of individuals sorted by classes of height (up to 4 m in height) in the mangroves studied, southern Brazil. **a** Itacorubi; **b** Saco Grande; **c** Ratones; *black* restoration; *white* regeneration; *gray* old-growth stands



flooding frequency and duration (Lewis 2005), which subsequently affects other sediment characteristics, such as grain size, nutrient content, and sediment compactness, contributing to the variable structure of mangrove forests (Reef et al. 2010). Altered patterns of secondary succession have been identified for reforested stands, with the prevalence of lower structural development or high mortality rates being attributed to modifications related to substrate elevation (Proffitt and Devlin 2005; Bosire et al. 2006; Primavera and Esteban 2008; Shafer and Roberts 2008).

Mangrove forests are very sensitive to edaphic disruptions, mainly to shifts in substrate elevation, and the system's ability to return to a more complex level of organization is strongly affected by the intensity and frequency of the stressor (Cintrón and Schaeffer-Novelli 1983). Re-grading sites to correct site elevation is mandatory for restoration projects, and ignoring

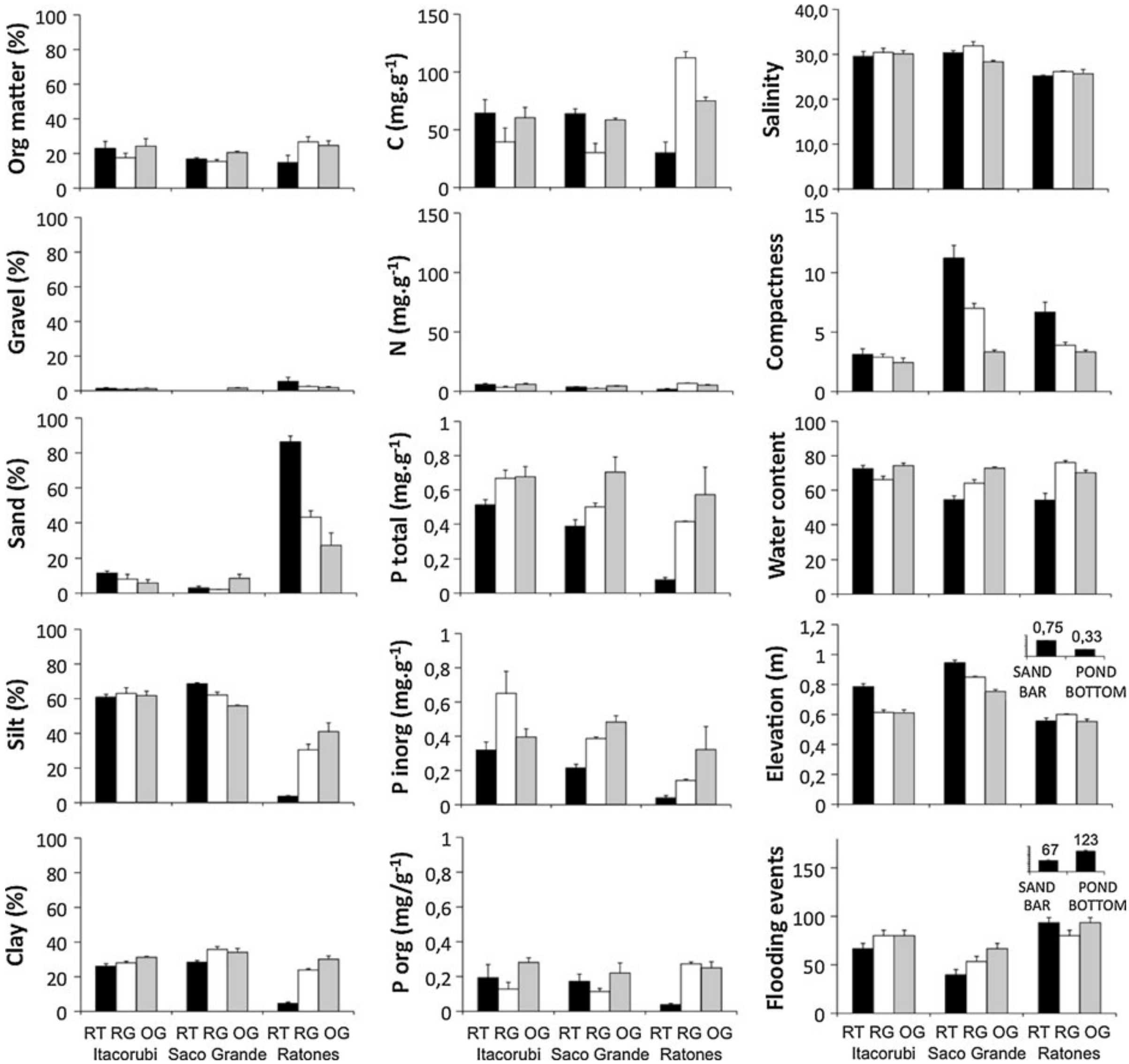


Fig. 3 Environmental variables (mean ± SE) investigated, illustrating variations between restoration (RT), natural regeneration (RG, and old-growth (OG) stands throughout the mangroves (Itacorubi, Saco Grande, and Ratones) studied in southern Brazil. Details of topographic alterations for the restoration stand at Ratones are given in the elevation and flooding events graphics

that step has led to numerous failures (Lewis 2005 and references therein). Since all but one of the sites in this study involved excavation or dirt filling, careful surveys of site topography in comparison to nearby reference mangrove stands would have increased overall planting success of these sites.

Despite the fact that the Itacorubi restoration and regeneration stands did not differ in terms of overall structural attributes, a comparison based on the number of individuals sorted by classes of height, representing different cohorts (Jiménez 1990), revealed an inferior regeneration potential for the former, since it presented lower densities in its younger cohorts. Although we did not investigate sediment toxicity, heavy metals on restored stand soils are known to hamper vegetation development (Mckee and Faulkner 2000), which could be a partial explanation for the particular case of the Itacorubi location, considering the composition of its cohorts, since the heavy metal contents in its soils are greater than those observed in the other studied locations (Pagliosa et al. 2004; Pagliosa and Barbosa 2006). Therefore, care must be taken to avoid drawing early conclusions, as monitoring periods ranging from 10 through 25 (Crewz and Lewis 1991) to 50 years (Lugo 1992; Luo et al. 2010) may be required to evaluate mangrove restoration success based on vegetative structural characteristics. Additionally, the time lag required to assess ecosystem functionality is longer than the time lag needed to assess survival of the vegetation or its structural attributes (Mckee and Faulkner 2000).

Secondary succession patterns and stands development

Understanding natural patterns of succession in a given area could lead to significant improvements and cost savings in the design and implementation of restoration projects (Shafer and Roberts 2008). Natural secondary successional process within the studied region begins with *R. mangle*, *L. racemosa,* and *A. schaueriana* colonizers. Even though *R. mangle* highly dominates early colonizing stages, the species ratio is inverted as stand matures, culminating in well-developed (density and basal area) *A. schaueriana* old-growth stands (Cintrón 1981; Soriano-Sierra 1993). It was observed that natural regeneration stands that were colonized by different species now seem to be developing into more structurally developed stands dominated by *A. schaueriana*.

Our findings support that even after a decade of planting followed by natural regeneration, environmental shifts still favor the persistence of *L. racemosa* hindering progression towards a climax forest form, whereas natural regeneration stands seem to follow the natural secondary succession pattern typical of this latitudinal region. Based on the experiment conducted, a conceptual model is proposed for secondary succession for the mangroves studied as a function of the impacts suffered (Fig. 4).

When a gap is opened due to a natural impact (i.e., death of an old tree, lightning strike, wind damage, etc.), secondary succession culminates in old-growth *A. schaueriana*-dominated stands (scenario a). At some point, a leakage in the landfill at the Itacorubi restoration stand caused the stand's massive mortality. However, topographic features, mainly those related to elevation, were not substantially altered, and since such events tend to be episodic, vegetation seems to be following patterns of secondary succession similar to those described for natural hazards (scenario b). Where elevation was severely disrupted, as at the Saco Grande and Ratones restoration stands, secondary succession showed a different pattern. Those stands seem to have remained in a lower level of structural development, densely dominated by stunted and bushy *L. racemosa* individuals (scenario c).

The cost of ongoing restoration practices: structural and functional loss in the ecosystem

Old-growth forests are the high-end manifestation of secondary succession, expressing nature's labor in terms of spatial and time scales. These mature assemblages develop self-regulation mechanisms that allow them to cope with higher-magnitude disturbances and to renew themselves throughout time, thus maintaining complexity, functionality, and adaptive capacity (Lugo 1978, 1980; Lugo et al. 1981). On the other hand, there is no guarantee that young cohorts will develop into mature-like stands, and even if they were on track, they might not have time to build up enough resilient properties to ensure the stability needed to culminate in secondary succession (Cintrón and Schaeffer-Novelli 1983). In fact, wetlands from throughout the world show that even a century after restoration efforts, the biological structure (driven mostly by plant assemblages) and the biogeochemical functioning (driven primarily by the storage of carbon in wetland soils) have remained on average one-third lower than in reference sites (Moreno-Mateos et al. 2012), indicating that if current restoration practices persist, loss of wetland ecosystem function and structure will spread globally.

Mangrove rehabilitation is possible by removing the stressors and ensuring the reestablishment of the subsidiary energies, chiefly hydrology (Lugo et al. 1981; Lewis 1982, 2005, 2009c, 2011, Cintrón and Schaeffer-Novelli 1983; Cintrón-Molero 1992). Nonetheless, failure to observe basic ecological principles for the mangrove, as in the cases studied, may lead to the development of non-analogous, structurally limited forms, with implications for both immediate and long-term large-scale ecosystem services.

Due to their open system and dynamic nature, mangroves do not conform to the classical concept of forest development and function. Unlike terrestrial vegetation, mature mangrove forests remain net

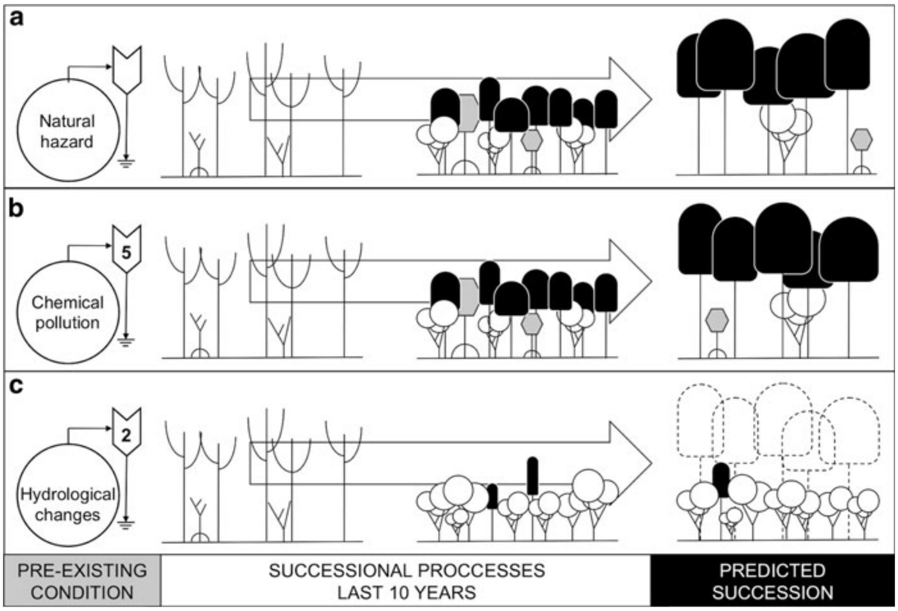


Fig. 4 Observed and predicted secondary succession for the mangroves studied, according to impacts suffered. **a** A gap opened by a natural impact. Secondary succession culminates in old-growth *A. schaueriana*-dominated stands. **b** Massive mortality is most likely caused by a leakage in the landfill (stand case at Itacorubi restoration site); however, topographic features, mainly related to elevation, are not substantially altered. Vegetation follows patterns of secondary succession similar to those described for natural hazards (above). **c** Elevation is severely disrupted (stand cases at the Saco Grande and Ratones restoration site). Forest remains stuck in a lower level of structural development, dominated by *L. racemosa*. Black = *A. schaueriana*; white = *L. racemosa*; grey = *R. mangle*. Symbols illustrating stressor types after Lugo et al. (1981)

producers of carbon, presenting higher gross primary production/respiration ratios (P_G/R) than younger and more disturbed stands (Lugo 1980; Alongi 2011). Because the ecological value of old mangrove forests is much greater than that of restored forests or plantations (Nickerson 1999), and it is in their senescent form that ecosystem services such as carbon sequestration peak, management policies should give priority to overall plans in maintaining their existence (Alongi 2011). It is generally accepted that the capacity of the environment to deliver ecological services needs to be increased rather than just maintained. Therefore, restoration projects must be designed to allow the development of systems with analogous complexity and functionality.

At their geographical limits, species may have a smaller degree of tolerance to environmental changes, as they must allocate more resources to dealing with limiting factors and climatic stressors. Climate change is an emerging variable that must be taken into consideration. Recent data show that mangroves are able to cope with sea-level rise (Alongi 2008); however, the matter of how less-developed marginal forests will respond to these increased rates coupled with local stressors and limiting factors, including altered atmospheric conditions and accelerated sea-level rise, triggered by climate change, remains to be studied.

Final remarks

The experimental design we used allowed (1) the identification of changes in secondary succession due to residual impacts, and (2) the acquisition of inferences regarding the fate of structural development and functioning. Ten to twelve years after a single planting was followed by natural regeneration, restoration sites exhibited secondary succession patterns that differed significantly from adjacent reference sites. This study demonstrated that the isolated planting of single mangroves species targeted for the rehabilitation of degraded areas could be ineffective if site characteristics (topography, pollutants inputs, proximity to propagule sources) are not taken into consideration. Additionally, mangrove stands are contained within sub-settings, which in turn constitute a module of the landscape. Thus, stands are necessarily subjected to oscillations in higher levels of organization and the success of isolated approaches will invariably depend on the environmental conditions of the higher levels (Lugo 1978, Schaeffer-Novelli et al. 2005). Nevertheless, to fully validate the interpretation of the findings, long-term assessments must be performed.

Aligned to this study, a recent critical review on mangrove restoration in Brazil (Rovai 2012) identified recurrent traps and outlined a few steps to follow when mangrove planting is required, in order to avoid common failures. The author suggests:

(1) Conduct a pilot study consisting of monitoring natural recovery and assessing environmental factors related to hydrology and edaphic conditions, both within the restoration site and in nearby areas to verify which species presents the greatest tolerance to the conditions in which they are likely to develop (environmental drivers). This information could be valuable for appropriate species selection. This is similar to steps 1 and 2 in the Ecological Mangrove Restoration (EMR) approach (Lewis 2009c).
(2) Examine climate records for low frequency but consequential events (droughts, storms). Use local knowledge to complement robust data and weather records.
(3) Properly address spatial and temporal replication, and include reference sites from nearby and within restoration site (to assess natural recovery within restoration site). This allows more robust statistical inference and results can be more acceptably extrapolated.
(4) Consider establishment of long-term research plots and multiple sequential research programs.

Finally, to avoid the inevitable failure of poorly planned and executed restoration activities and the degradation of the services provided by mangroves, review policies and practices that perpetuate mangrove conversion as well as the criteria used for establishing compensatory measures and effective rehabilitation.

Acknowledgments We are thankful to the Coordination for the Improvement of Higher Level Personnel (CAPES) and to the National Council for Scientific and Technological Development (CNPq) for having supported this research. We are also thankful to the staff of Carijós Ecological Station, managed by the Chico Mendes Institute for Biodiversity Conservation (ICMBio), for logistic support and site access permission. The first author is especially grateful to Mr. Roy "Robin" Lewis III and associates for facilitating his participation in the ninth teaching (Hollywood, FL, March 2011) of the Mangrove Forest Ecology, Management and Restoration Training Program, which contributed greatly to the development of the ideas discussed here. We must also thank the two anonymous reviewers for their valuable contributions.

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