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Are there general spatial patterns of mangrove structure and composition along estuarine salinity gradients in Todos os Santos Bay?

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ABSTRACT

Species distribution and structural patterns of mangrove fringe forests along three tropical estuaries were evaluated in northeast of Brazil. Interstitial water salinity, percentage of fine sediments and organic matter content were investigated as explanatory variables. In all estuaries (Jaguaripe, Paraguaçu and Subaé estuaries), it was observed similar distribution patterns of four mangrove species and these patterns were mostly related with interstitial water salinity. *Rhizophora mangle* and *Avicennia schaueriana* tended to dominate sites under greater marine influence (lower estuary), while *Avicennia germinans* and *Laguncularia racemosa* dominated areas under greater freshwater influence (upper estuary), although the latter showed a wider distribution over these tropical estuarine gradients. Organic matter best explained canopy height and mean height. At higher salinities, there was practically no correlation between organic matter and density, but at lower salinity, organic matter was related to decreases in abundances. The described patterns can be related to interspecific differences in salt tolerance and competitive abilities and they are likely to be found at other tropical Atlantic estuaries. Future studies should investigate anthropic influences and causal processes in order to further improve the design of monitoring and restoration projects.

1. Introduction

Mangroves are the salt-tolerant evergreen forests found in the intertidal zones of sheltered shores, estuaries, tidal creeks, backwaters, lagoons, marshes and mudflats of the tropical and subtropical latitudes (Sandilyan and Kathiresan, 2012). Mangroves trees and shrubs are physiologically and morphologically adapted to grow in waterlogged and anoxic soils and to cope with daily fluctuations in environmental parameters, such as salinity (Alongi, 2008).

Mangrove ecosystems support ecological functions of considerable biological, social and economic value (e.g. Alongi, 2002; Walters et al., 2008). Some mangrove functions and services may be lost due to degradation related to human activities such as mariculture (mainly shrimp culture), agricultural, industrial and urban development (Polidoro et al., 2010; Sandilyan and Kathiresan, 2012; Hamilton, 2013) and also as a result of climate change (Gilman et al., 2008).

Studies on mangrove forest structure usually include characterization of species distribution and forest structure patterns (Smith III, 1996), which can be assessed at different spatial scales: global (e.g. Ellison et al., 1999), regional (e.g. Ellison et al., 2000) and local. The latter includes studies along estuarine gradients (e.g. Chen and Twilley, 1999) or, more frequently, across intertidal gradients (e.g. Castaneda-Moya et al., 2006). At the local scales, interactions between mangrove plant species and different physicochemical variables can generate zonation patterns along estuarine gradients (e.g. when a species or group of species occurs at distinct portions of an estuary) (e.g. Duke et al., 1998; Hogarth, 2007) and/or patterns related to structural gradients (e.g. when there is an increase or a decrease in structural development along an environmental gradient).

Mangrove structural gradients and species zonation can be related with local clime (e.g. temperature and precipitation) and with species physiological responses to physicochemical gradients (e.g. salinity, pH, nutrient and sulphide concentration, soil texture, Eh, topography) (Chen and Twilley, 1999; Duke et al., 1998; Lugo and Snedaker, 1974; Mckee, 1993; Naidoo, 2006; Saintilan, 1998; Smith III and Duke, 1987). Additionally, it have been suggested

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that biological variables such as plant-soil-microbial interactions (Sherman et al., 1998), propagule predation (Cannicci et al., 2008) and species competition (Ball, 1988) can also influence mangrove forest structure.

Regarding mangrove forest structure, the majority of the studies have focused on species zonation across intertidal gradients reporting changes in species distributions and in forest development (e.g. Schaeffer-novelli et al., 1990; Mckee, 1993; Ukpong, 1997; Castaneda-Moya et al., 2006; Estrada et al., 2013). Mangrove species zonation at the estuarine salinity gradient, from euhaline to oligohaline zones (*sensu* Venice system), is less investigated and some relied on few sampling stations (i.e. ≤4) along entire systems (e.g. Chen and Twilley, 1999; Silva et al., 2005). Nevertheless, some general expectations can be draw. For instance, intertidal zonation studies indicated that *Avicennia* is more salt tolerant and may be able to colonize areas with relatively high levels of interstitial salinity whereas, at places with more fresh or brackish water, *Rhizophora* (Sherman et al., 1998, 2003) or *Laguncularia racemosa* (Estrada et al., 2013) would predominate. In relation to structural development, less favorable environmental conditions can limit forest stature, for example, low nutrient availability (Chen and Twilley, 1999) and high salinity (Naidoo, 2006).

There is no widely accepted model on mangrove trees species distribution and or forest structure along the estuarine salinity gradient (Saenger, 2002). Twilley and Day Jr. (2013) suggested that *Avicennia germinans* and *Laguncularia racemosa* are mostly located at the mid and lower estuary and Rizophora mangle and *Avicennia schaueriana* at lower estuarine zones. Nevertheless, there is still a lack of studies properly (i.e. well replicated) designed to formally test differences in mangrove forest structure and composition along estuarine salinity gradients. Furthermore, quantification or statistical testing of mangrove zonation patterns is rare (Ellison et al., 2000). The present study tested if mangrove forests along estuarine gradients in Todos os Santos Bay (i) would show structural trends related to physicochemical variables and (ii) would present differences in species distributions along these gradients.

2. Material and methods

2.1. Study area

The Todos os Santos Bay (TSB) (Fig. 1), centered on 12°50′ S and 38°38′ W, is the second largest bay in Brazil, with an approximate area of 1.200 km^2. The climate at the entrance of TSB is tropical humid, with an average annual temperature and precipitation of approximately 25 °C and 2.100 mm, respectively. Summer is generally dry with warmer temperatures, while the winter is wet and cooler (Cirano and Lessa, 2007). The TSB is mesotidal with semi-diurnal tides and is essentially marine, reflecting small fluvial discharges derived from the main drainage basins from three main tributaries, Paraguaçu, Jaguaripe and Subaé Rivers. Besides some already described impacts (e.g. Hatje and Barros, 2012), considerable areas of the TSB margins are still occupied by mangrove forests and a large part of these forests are associated with the estuarine systems of Jaguaripe, Paraguaçu and Subaé rivers (Fig. 1).

2.2. Mangrove sampling

Along the Jaguaripe, Paraguaçu and Subaé Rivers ten, nine and ten sampling stations, respectively (Fig. 1), were established in order to cover the entire salinity gradient of each (see Barros et al., 2012). Data collection occurred between March and November 2011, during low spring tides. Margins with small human settlement and sedimentary rocks outcrops were avoided and, whenever possible, the margin to be sampled was randomized. At each station, three 10 × 10 m quadrats parallel to the water body were marked, 10 m away from each other and 10 m inland from the beginning of the mangrove area (i.e. at the fringe forest, e.g. Estrada et al., 2013).

The characterization of mangrove forest structure was based on Schaeffer-Novelli and Cintrón (1986). In each quadrat, live individuals with height ≥1 m were identified according to species (*sensu* Tomlinson, 1986), had their total height measured or estimated using a 4 m graduated rod and had the circumference at breast height (CBH − 1.30 m above ground level) of each live trunk measured with a tape measure. When was not possible to measure CBH at 1.30 m (e.g. individuals smaller than 1.30 m or with foliage at this height), it was measured below the first branch. Considering the species *Rhizophora mangle*, in the presence of rizophores above 1.30 m, CBH was measured above the highest rizophore.

From field data, CBH was transformed into diameter at breast height ($DBH = CBH/\pi$) and then into basal area [$BA = \pi \times (DBH/2)^2$], converting square centimeter into square meter. For each quadrat, the following structure parameters were calculated: canopy height (average height of the five tallest individuals, in m), total live basal area (m^2 ha^{-1}), live basal area for each species (m^2 ha^{-1}), live trunk density (number of live trunks ha^{-1}), live trunk density for each species (indiv ha^{-1}) and mean diameter (cm). The voucher specimens were deposited at the Alexandre Leal Costa Herbarium of Universidade Federal da Bahia.

2.3. Soil physicochemical variables

Interstitial water salinity, organic matter content and sediment were sampled at each quadrat, during low tide. The interstitial water samples were collected in July 2011 (winter) and March 2012 (summer) on all estuaries. A random sample of interstitial water was collected at each quadrat, at 50 cm depth. Interstitial water was collected using a hose, syringe and a PVC tube with small holes near a capped end (adapted from Schaeffer-Novelli and Cintrón, 1986). After collection, the interstitial water samples were stored in glass vials and kept under refrigeration until the decantation of the suspended sediments. After decantation, interstitial water was carefully extracted and measured with an optical refractometer.

Sediment samples were haphazardly collected on each quadrat at around 50 cm depth. These replicated sediment samples were mixed and manually homogenized to form a single composite sample each station. These composite samples were divided into two portions one for determination of grain size and other for organic matter, and frozen until analyses.

To estimate organic matter content (%) approximately 5 g of powdered sediment were oven-dried at 60 °C to constant weight and ignited at 550 °C for 4 h in a muffle furnace (Dean, 1974; Heiri et al., 2001). Percentage of sand, silt and clay were estimated using a laser diffraction particle analyzer (Horiba LA-950). For these, sediments samples were pre-treated with hydrogen peroxide (H_2O_2) for organic matter digestion (EMBRAPA, 1997). After digestion, samples were washed for salt extraction and conducted to analyses.

2.4. Statistical analysis

In order to have better estimates of biological and environmental variables, multiple samples were collected at each station (three quadrats at each sampling station). Therefore, mean values of all biological and environmental variables from each station of the three estuaries were used to conduct the statistical analysis.

Simple linear regressions were used to investigate potential relationships between each physicochemical variable (interstitial