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Photosynthetic performance of restored and natural mangroves under different environmental constraints

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A B S T R A C T

We hypothesized that the photosynthetic performance of mangrove stands restored by the single planting of mangroves species would be lowered due to residual stressors. The photosynthetic parameters of the vegetation of three planted mangrove stands, each with a different disturbance history, were compared to reference sites and correlated with edaphic environmental variables. A permutational analysis of variance showed significant interaction when the factors were compared, indicating that the photosynthetic parameters of the restoration areas differed from the reference sites. A univariate analysis of variance showed that all the photosynthetic parameters differed between sites and treatments, except for photosynthetic efficiency (α_{ETR}). The combination of environmental variables that best explained the variations observed in the photosynthetic performance indicators were Cu, Pb and elevation disruptions. Fluorescence techniques proved efficient in revealing important physiological differences, representing a powerful tool for rapid analysis of the effectiveness of initiatives aimed at restoring coastal environments.

1. Introduction

Mangroves are known for providing both direct and indirect goods and services that benefit humanity on both a local and global basis (Alongi, 2011; Donato et al., 2011; Nellemann et al., 2009; Walters et al., 2008; Wells et al., 2006), given their distribution ranging from tropical to temperate regions across all continents (Giri et al., 2010; Morrisey et al., 2010; Soares et al., 2012; Spalding et al., 2010). However, mangroves have been disappearing at an alarming rate (FAO, 2007; Lewis, 2009). Losses during the last quarter of a century have ranged consistently between 35 and 86%, and rates continue to rise increasingly rapidly, principally in developing countries, where >90% of the world's mangroves are located (Duke et al., 2007). In accordance with this trend, Brazil has lost at least 100 000 ha of mangroves over the last 25 years (FAO, 2007; MMA, 2010), mainly due to urbanization and shrimp farming; these estimates are very likely to increase (Pagliosa et al., 2012; Rovai et al., 2012a). The country harbors the second largest mangrove area in the world (MMA, 2010; Spalding et al., 2010), which makes it a critical player in the mitigation of the effects of CO_2 and climate change stabilization (Pagliosa et al., 2012; Rovai et al., 2012a).

In the context of this worrying worldwide scenario of the Anthropocene (Steffen et al., 2011), mangrove restoration is

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mandatory. However, most attempts to restore mangroves often fail completely and evidence for successful restoration on a large scale is nearly non-existent (Erftemeijer and Lewis, 2000; Lewis, 1990, 1999, 2000, 2005, 2009). In Brazil, less than 0.01% of the mangrove area already lost has been restored and the trials conducted have yielded very low survival rates (Rovai, 2012). Additionally, it is common to see restoration success based on seedling or tree development (i.e., production of leaves, growth rates, etc.) over a short period of time, whereas periods ranging from 10 to 50 years are required to evaluate success based on vegetative structural characteristics (Crewz and Lewis, 1991; Lugo, 1992; Luo et al., 2010; Rovai et al., 2012b; Shafer and Roberts, 2008). Moreover, ecosystem functionality can take over a century to be restored (Moreno-Mateos et al., 2012).

Ecophysiological approaches have been extensively applied in mangrove ecosystems, with the aim of determining the way in which some environmental parameters affect the metabolic responses of mangrove species, such as for instance the nutritional supply (Feller et al., 2003; Lugo et al., 2007), drought (Sobrado, 1999), salinity (Lugo et al., 2007; Yan and Guizhu, 2007) and also variations in the concentration of heavy metal pollutants (Defew et al., 2005) and coal dust loading on leaves (Naidoo and Chirkoot, 2004). Among ecophysiological measurements, the evaluation of quenching from chlorophyll fluorescence has become one of the most powerful and widely used techniques to achieve photosynthetic responses against different stressors. Successful applications of these dissipative parameters for evaluating environmental stressors have been obtained using other groups of marine photosynthetic organisms, such as macroalgae (Scherner et al., 2012) and seagrasses (Silva et al., 2009). In mangroves, chlorophyll fluorescence analysis has been used to detect impacts caused by salinity changes (Tuffers et al., 2001) and as a biomarker of heavy metal pollution in *Avicennia marina* (Macfarlane et al., 2003). However, data on the rate of photosynthesis in mangrove trees as a functional marker of their health are rare (Herteman et al., 2011), and virtually absent as an indicator to assess restoration. In this work we hypothesized that the photosynthetic performance of mangrove stands (*Avicennia schaueriana* Stapf et Leechman ex Moldenke, Acanthaceae), which have been restored by the single planting of a mangroves species, is lowered due to residual stressors that are impairing the ecosystem's functioning. To test our supposition, the photosynthetic parameters of the vegetation of three planted mangrove stands were compared with reference sites and correlated to environmental variables.

2. Material and methods

2.1. Study area

The investigated mangroves are Itacorubi (ITA), Saco Grande (SGR) and Ratones (RAT) and are located in three independent watersheds on Santa Catarina Island, southern Brazil (Fig. 1). The regional climate is sub-tropical humid with no characteristic dry season but with a reduced rain volume from April to September (Cruz, 1998). The local tide is microtidal (Melo et al., 1997) with south and north winds being the main physical agents influencing the local hydrodynamics. Mangroves and salt marshes are located at the estuarine end of these watersheds, draining the upland terrain through meandering rivers that cut through light to moderately urbanized short coastal plains (Pagliosa and Barbosa, 2006) that formed during the late Quaternary.

Considering the latitudinal limit of distribution of the studied mangroves (Soares et al., 2012), the stands still exhibit structurally well-developed old-growth forests dominated by *A. schaueriana*, followed by *Laguncularia racemosa* L. Gaertn. F., Combretaceae and *Rhizophora mangle* L., Rhizophoraceae, without marked zonation patterns (Cintrón, 1981; Soriano-Sierra, 1993).

2.2. Sampling design

The characteristics of the mangroves enabled the selection of: a) three restoration areas (RT) that were managed by single planting about ten to twelve years ago and immediately left to regenerate naturally; and b) two types of reference areas (chosen within each mangrove sub-setting), these being a natural regeneration (RG) and an old-growth stand (OG), approximately ten and fifty years old, respectively. *A. schaueriana* is 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 ITA, SGR, and RAT, respectively) (Rovai et al., 2012b). Restoration stands are dominated by *L. racemosa* (80.6 and 90.2% for SGR and RAT, respectively), except for one site (ITA) where *A. schaueriana* prevails (99.7%). *R. mangle* is virtually absent in restoration stands. Average diameter at breast height ($\overline{DBH}$) and height are at least twice as large in old-growth stands (9.55, 8.97 and 14.66 cm, and 6.34, 5.63 and 9.23 m for ITA, SGR, and RAT, respectively) compared to restoration (3.14, 2.69 and 2.55 cm, and 3.06, 2.12 and 2.28 m) and natural regeneration stands (2.52, 3.02 and 5.95 cm, and 2.42, 2.32 and 3.96 m). The reference stands were selected using 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 distance from the restoration acting as an orientation (a detailed description of the study sites is given in Rovai et al., 2012b).

The restoration area of the Itacorubi mangrove suffered a massive mortality event (sensu Jiménez et al., 1985), probably caused by a toxic landfill leachate from a deactivated landfill that had been sited on top of the landward portion of the mangrove forest six decades before. The topography of the restoration areas of the Saco Grande and Ratones mangroves was altered by dirt used to fill a housing development area and by the excavation of material used to build aquiculture ponds, respectively. Planting was carried out on the latter two mangrove stands without attempting to reestablish the topography. The restoration areas of Itacorubi, Saco Grande and Ratones measured approximately 0.35, 0.30 and 0.24 ha, respectively; however, planting was carried out only on part of the damaged area (0.02, 0.02 and 0.10 ha, for ITA, SGR and RAT, respectively).

Measurements were made during the hottest months, from November 2010 to March 2011. The experimental design was a 3 × 3 factorial, completely randomized, with three distinct mangroves (ITA, SGR, and RAT), each one subjected to three different treatments (RT, RG, and OG stands). In each treatment, nine trees were

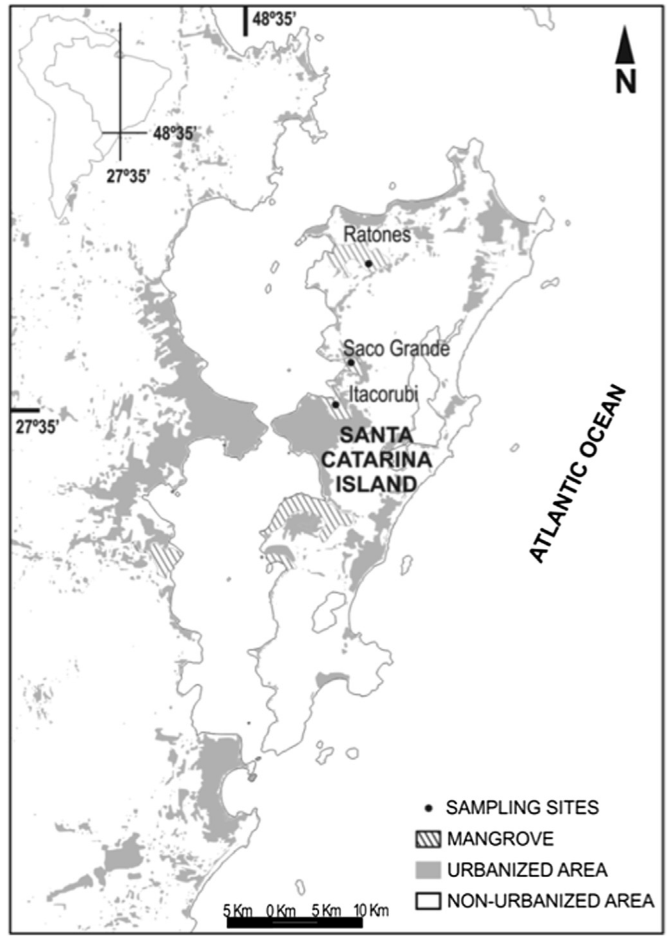

Fig. 1. Map indicating the three mangroves (Itacorubi, Saco Grande and Ratones) within which the experimental stands (restored, regenerated and old-growth areas) were sampled.