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Southern limit of the Western South Atlantic mangroves: Assessment of the potential effects of global warming from a biogeographical perspective

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ABSTRACT

The objective of the present study was to determine the exact location of the latitudinal limit of western South Atlantic mangroves, and to describe how these forests develop at this limit; as well as to analyze the potential responses of these communities to global warming. The study was carried out along the coast of Santa Catarina, Brazil. Specific studies on mangrove structure were carried out in the Santo Antônio Lagoon (28°28′34″S; 48°51′40″W). The coastline of Santa Catarina was surveyed for the occurrence of mangrove species. In the mangrove located at the southernmost distributional limit, the forest structure was characterized. Mean height and diameter, trunks density and basal area were calculated. Climatic and oceanographic factors controlling the occurrence and development of the mangrove forests at their latitudinal limit were analyzed, as well as the possible changes of this limit based on global warming scenarios. The results confirmed that the Santo Antônio Lagoon is the southern limit of the western South Atlantic mangroves. At this limit, the mangrove forests show a low degree of development, defined by low mean diameter and height, and high trunks density and trunks/tree ratio. The observed structural pattern and the local alternation of these forests with salt marsh species are typical of mangrove forests at their latitudinal limits. The absence of mangroves south of Laguna and forest structure at the latitudinal limit are controlled by rigorous climate and oceanographic characteristics. In response to the planetary warming process, we expect that mangroves will expand southward, as a consequence of an increase in air and ocean surface temperatures, a reduction in the incidence of frosts, an increased influence of the Brazil Current and a decreased influence of the Falkland Current, and the availability of sheltered estuarine systems for the establishment of new mangroves.

1. Introduction

Mangroves are forested coastal ecosystems that occur along sheltered tropical and subtropical coasts (Schaeffer-Novelli et al., 2000). They perform many useful functions, such as the protection of coastal zones from waves and winds, and the maintenance of fisheries and biodiversity in the adjacent estuaries and coastal region (Ewel et al., 1998; Mazda et al., 2006; Nagelkerken et al., 2008).

The distribution of mangroves is generally limited to regions where the coldest monthly mean temperature is above 20 °C and the annual thermal amplitude is less than 5 °C (Walsh, 1974; Chapman, 1975); although Ellison (2000) called attention to the coincidence between the latitudinal limits of mangrove species, and the position of the 16 °C winter air temperature isotherm and the latitudinal limit of frosts. The principal explanation for this limitation is related to the poor tolerance of mangrove species to low air temperatures and frosts. Tomlinsom (1986) suggested that temperatures of about 5 °C are already capable of inhibiting the growth of some mangrove species. Stuart et al. (2007) demonstrated that frosts cause embolism in the secondary xylem and can kill the trees. Ellis et al. (2006) stated that frosts can cause premature death of the leaves of *Laguncularia racemosa*, and Krauss et al. (2008) also observed an increase in the mortality of propagules and the incidence of seedlings with severely damaged leaves,

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with the increase in latitude. Suwa and Hagihara (2008) reported a drastic decrease in the net primary productivity of *Rhizophora stylosa* in winter at its northern latitudinal limit in Japan. Kao et al. (2004) demonstrated that the growth of seedlings of *Avicennia marina* was drastically reduced in temperatures lower than 15 °C, while Steinke and Naidoo (1991) reported that at 17 °C the seedlings of this species show almost no growth. Also for this species, Sakai and Wardle (1978) and Wardle (1985) reported death from frosts when the temperature reaches −3 °C. The air temperature, therefore, functions as a physiological barrier to the advance of mangroves into higher latitudes. According to Lovelock et al. (2007) Suwa and Hagihara (2008) and Pellegrini et al. (2009), mangrove forests subjected to stress generally show typical structural characteristics, such as a low degree of development in terms of height and diameter, and a high degree of branching of the trees. Such characteristics are also described for mangrove forests located at their latitudinal limits (Schaeffer-Novelli et al., 1990; Bridgewater and Cresswell, 1999; Stevens et al., 2006).

Other factors, however, can restrict the distribution of mangroves even more sharply than the potential physiological barriers caused by air temperature. Cold currents in lower latitudes, in addition to producing unfavorable climate conditions for the establishment of mangrove species, can limit the dispersal of propagules toward higher latitudes, because the propagules cannot remain viable in low temperatures (Chapman, 1975; Oliveira, unpublished). This may explain the more limited distribution of mangroves on the west coasts of South America, Africa, and Oceania, where cold currents flow toward the equator, compared to the east coasts of these continents, where warm southward currents occur. Some investigators have noted a coincidence between the latitudinal limits and the position of winter isotherms of 15 or 20 °C ocean surface temperature (Tomlinsom, 1986; Woodroffe and Grindrod, 1991; Duke et al., 1998; Alongi, 2002). Aridity and the lack of viable geomorphological characteristics for the occurrence of mangroves are also factors that limit the distribution of this ecosystem (Clüsener and Breckle, 1987; De Lange and De Lange, 1994).

Because of global warming, mangroves are expected to migrate to higher latitudes, replacing salt marshes (Burns and Ogden, 1985; Woodroffe and Grindrod, 1991; Field, 1995; Ellison, 2000; Morrisey et al., 2007; Perry, unpublished; Gilman et al., 2008; Perry and Mendelssohn, 2009). Therefore it is important to locate the present latitudinal limits of mangroves and to understand how they develop at these limits. On the west coast of the South Atlantic, definitions of the latitudinal distributional limit of mangroves have disagreed to some extent, ranging between 28°55′ S (Bigarella, 1946; Chapman, 1976) and 28°30′ S (Schaeffer-Novelli et al., 1990), both within Brazil. The present study aimed to determine the exact location of this latitudinal limit and to characterize the structure of the forests in this location, as well as to analyze the potential effects on and responses of these communities to possible warming of the planet.

2. Material and methods

The coast of the state of Santa Catarina in Brazil, between the Araranguá River (Araranguá Municipality, 28°55′ S) and the Santo Antônio Lagoon (Laguna Municipality, 28°30′ S), was surveyed for the occurrence of mangrove species in the estuaries from august to October of 2004. This region is characterized by a microtidal regime and ocean surface temperatures that vary seasonally between the isotherms of 18 and 24 °C (Stewart, 2008). The wide coastal plain is dominated by extensive sand ridges that form coastal lagoons (Fig. 1). Based on data from 55 years of monitoring at the Laguna meteorological station, operated by the Centro de Informações de Recursos Ambientais e de Hidrometeorologia of Santa Catarina (CIRAM), the climate at Laguna is defined by an annual mean temperature of 19.7 °C, mean temperature of 15.7 °C in the coldest month, mean annual thermal amplitude of 8.0 °C, and mean annual precipitation of 1412 mm. Carpanezzi et al. (1988) reported a mean of 0.3 frosts per year at Laguna, which increases to 2 per year at Araranguá to the south.

In the mangrove identified as the southernmost distributional limit, three plots of 25 m^2 were established in order to characterize its forest structure, using the method proposed by Cintron and Schaeffer-Novelli (1984) and Schaeffer-Novelli and Cintrón (1986). For each plot, the mean height, density of live trunks, number of trunks per tree, basal area, and mean trunk diameter at 1.30 m (D_{130}) were calculated. Mean D_{130} was calculated by the following equation (Eq. (1)):

$$\text{Mean}\, D_{130} = [12{,}732.39\,(\text{live basal area})/\text{live trunks density}]^{1/2}, \tag{1}$$

where Mean D_{130} is expressed in cm, basal area in m^2 ha^{-1} and trunks density in trunks ha^{-1}.

In addition to the structural parameters, histograms were generated for the distribution of trunk diameters, with 1 cm class intervals. The values for trunk density of the plots were compared with the theoretical expected density for the estimated value of mean D_{130}, calculated from the model proposed by Jiménez et al. (1985) for the relationship between mean D_{130} and density. This was based on the analysis of 114 mangrove forests in the Americas, defined by the following equation (Eq. (2)):

$$\ln \text{Density} = 8.92212 - 1.4934\,(\ln \text{Mean}\, D_{130}) \tag{2}$$

In addition to the analysis of structural parameters, a comparison was also made with another sixteen mangrove forests at their latitudinal limit, considering the following parameters: mean D_{130}, mean height, density, physiognomic characteristics, and species composition.

Interstitial water salinity was also measured. In each plot, interstitial water was collected at three random points (replicates) and measured with a field refractometer.

3. Results and discussion

3.1. Structure of the forests

The results confirmed that the Santo Antônio Lagoon (28°28′ S–48°50″ W) in the Municipality of Laguna (Fig. 1) is the southern limit of mangroves in the western Atlantic Ocean, as stated earlier by Schaeffer-Novelli et al. (1990).

South of this point on the Brazilian coast, mangroves are replaced by salt marshes. The plots were established in the southernmost part of the lagoon, near the mouth of the Sambaqui River. In general, the mangrove forests of Santo Antônio Lagoon are quite homogeneous in terms of structural development and species composition. The mangrove forests consist almost entirely of *L. racemosa*; however, a few isolated trees of *Avicennia schaueriana* occur at some points (Fig. 2). This floristic composition concords with the description by Schaeffer-Novelli et al. (1990). The mangrove forests alternate with *Spartina densiflora*, a typical species of the salt marshes, and *Acrostichum aureum* (Fig. 3), a typical pteridophyte of swamps and a species associated with mangrove forests (Tomlinsom, 1986).

The mangrove forests in the Santo Antônio Lagoon show a low degree of structural development (Table 1), defined by low mean D_{130} (2.33–3.08 cm) and mean height (2.62 ± 0.32–3.33 ± 0.54 m),