# ANALYSIS OF MANGROVE FOREST SUCCESSION, USING SEDIMENT CORES: A CASE STUDY IN THE CANANÉIA –IGUAPE COASTAL SYSTEM, SÃO PAULO-BRAZIL

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## ABSTRACT

Sediment cores are an essential tool for the analysis of the dynamics of mangrove succession. Coring was used to correlate changes in depositional environments and lateral sedimentary facies with discrete stages of forest succession at the Cananéia-Iguape Coastal System in southeastern Brazil. A local level successional pattern was examined based on four core series T1) a sediment bank; T2) a smooth cordgrass *Spartina alterniflora* bank; T3) an active mangrove progradation fringe dominated by *Laguncularia racemosa*, and; T4) a mature mangrove forest dominated by *Avicennia schaueriana*. Cores were macroscopically described in terms of color, texture, sedimentary structure and organic components. The base of all cores exhibited a similar pattern suggesting common vertical progressive changes in depositional conditions and subsequent successional colonization pattern throughout the forest. The progradation zone is an exposed bank, colonized by *S. alterniflora*. *L. racemosa*, replaces *S. alterniflora* as progradation takes place. As the substrate consolidates *A. schaueriana* replaces *L. racemosa* and attains the greatest structural development in the mature forest. Cores collected within the *A. schaueriana* dominated stand contained *S. alterniflora* fragments near the base, confirming that a smooth cordgrass habitat characterized the establishment and early seral stages. Cores provide a reliable approach to describe local-level successional sequences in dynamic settings subject to drivers operating on multiple temporal and spatial scales where spatial heterogeneity can lead to multiple equilibria and where similar successional end-points may be reached through convergent paths.

## RESUMO

Testemunhos de sondagem apresentam-se como importantes ferramentas para análise da dinâmica sucessional de bosques de mangue. A sucessão dos bosques de mangue, no litoral sul do Estado de São Paulo (Brasil), foi determinada com base em quatro testemunhos de sondagem: T1) banco de sedimento; T2) banco de gramínea *Spartina alterniflora*; T3) bosque de mangue em progradação, dominado por *Laguncularia racemosa*; e T4) bosque de mangue maduro, dominado por *Avicennia schaueriana*. Os testemunhos foram descritos macroscopicamente em função de cor, textura, estruturas sedimentares e componentes orgânicos. A base de todos os testemunhos apresentou padrão semelhante, sugerindo colonização similar por bosques de mangue , em toda sua extensão. Áreas em progradação apresentam banco de sedimento exposto, colonizado por *S. alterniflora*. Faixa de *L. racemosa* substitui a gramínea, com a progradação. À maior consolidação do sedimento, passam a dominar outras espécies típicas de mangue, como observado no bosque maduro, onde *A. schaueriana* alcança grande desenvolvimento estrutural. No testemunho coletado na área colonizada pelo bosque maduro dominado por *A. shaueriana,* há fragmentos de *S. alterniflora* próximo à base, confirmando o papel da gramínea como espécie pioneira. Os testemunhos analisados refletem a zonação e a sucessão dos bosques de mangue da região.

*Descriptors*: Sediment cores, Mangrove, Zonation, Succession, Cananéia-Iguape Coastal System, Brazil.
*Descritores*: Testemunhos, Manguezal, Zonação, Sucessão, Sistema Costeiro Cananéia-Iguape, Brasil.

## INTRODUCTION

Mangrove forests are ecosystems of great complexity. They are open environments, where significant linkages occur between the land (lithosphere and hydrosphere), the estuary (basin physiography), and the ocean and atmospheric (climate) systems. Alluvial and estuarine deposits are sensitive indicators of allogenic processes such as climate, tectonism and base-level change. Mangroves respond actively to coastal processes and sediment input (CUNHA-LIGNON et al., 2009; SOUZA FILHO et al., 2006) and are considered one of the best geo-indicators for the detection of modifications in coastal zone dynamics (MORTON, 2002; SOUZA FILHO et al, op. cit.).

Mangrove settings are geomorphic units within which second order controls (erosion and deposition *sensu* Inman and Nordstrom 1971) makes differentiation of mangrove forests possible. The interrelationships between hydrology, tidal and factors have received considerable attention by Watson (1928), Davis (1940) and Chapman (1944). The subject has been reviewed by Walsh (1974) and Lugo and Snedaker (1974). Baltzer (1974) examined the role of sedimentological processes in patterning mangrove structure, including deposition, maturation and senescence. Bird and Barson (1977) studied physiographic changes on mangrove fringed shorelines in Australia by comparing historical maps and air photographs. Enos and Perkins (1979) studied the stratigraphy of Florida Bay mangrove islands where sea level has been rising for at least 5,000 years. West (1956) and Vann (1959) have emphasized the control of geomorphic processes on vegetational patterns and species assemblages. Mangrove ecosystems reflect close linkages between vegetational assemblages and geomorphologically defined habitats (WOODROFFE, 1992) and hydrography or hydrodynamics (e.g. DI NITTO et al., 2008). Pioneering work on mangrove ecology from a geomorphic perspective was done in the Grijalva Delta by Thom (1967) and by Semeniuk (1983) in Northern Australia, but much more work remains to be done to explain spatial heterogeneity and patterning in mangrove wetlands particularly in the New World.

The "classical" pattern of zonation represents just one of several patterns of spatial organization. In fact the works of Thom (1967) and Thom et al. (1975) describe "atypical" spatial patterns (SNEDAKER, 1982). This reflects the spatial complexity of evolving depositional environments, shifting constraints and increasing system complexity over time. Classical successional models underestimate environmental dynamism and focus on singular and stable conditions. These are not the circumstances that prevail in dynamic estuarine environments where spatial heterogeneity can lead to multiple equilibria and locally stable "states". Furthermore, focusing on successional "end-points" and "climax states" neglects that equifinal states may be reached by different paths as individual system components respond to environmental variations. Only coring provides the tool to examine, interpret and infer the stages leading to such convergent outcomes.

Cores can provide detailed records of mangrove species responses to climate change, sea-level change and local-level dynamics. Recently, Ellison (2008) reviewed sediment core and pollen analysis studies. Dahdouh-Guebas and Koedam (2008) have demonstrated how complementary such analyses are with other retrospective methods.

In Brazil, Pereira (1998) used cores to describe the development of the coastal plain and mangrove colonization at Guaratiba (State of Rio de Janeiro), defining three landscape-level developmental phases: bay, lagoon and mangrove. In eastern Amazonia, cores were used to describe coastal environmental changes and Holocene mangrove ecosystem dynamics (BEHLING; COSTA, 2001; BEHLING et al., 2001; COHEN et al., 2005). Amaral et al. (2006) provide information on the Late development Holocene of a mangrove at Itanhaém (State of São Paulo).

The causes of mangrove community changes identified in the palaeoecological record can only be inferred by comparison with ecological studies in the modern environment, but such linkages remain to be established (ELLISON, op. cit.).

Relatively few studies have used sedimentary facies to describe modern mangrove responses to fluctuations in sea level and local-level dynamic factors, considering that mangrove zonation is the dominant theme in a voluminous mangrove literature.

The objective of this study is to examine the links between physically-evolving habitats (driven by changes occurring on relatively short temporal and local spatial scales) and mangrove forest succession (driven by the life-history of mangroves themselves) using sediment cores taken from the Cananéia-Iguape Coastal System (São Paulo – Brazil).

## THE CANANÉIA-IGUAPE COASTAL SYSTEM

### Geographic Setting

The Cananéia-Iguape Coastal System (Fig. 1) is located between latitudes 24°40'S and 25°20'S along the southern tract of the coast of São Paulo State, (southeastern Brazil). This coastal system is shaped by three main islands (Cardoso, Cananéia and Comprida), separated by meandering channels (Cananéia, Cubatão and Pequeno), and rivers that flow

into the Atlantic Ocean. The channels reflect hydrodynamic patterning influenced by tidal currents and freshwater inputs to the system (TESSLER; SOUZA, 1998). There is a tendency for the channels to trap and accumulate sediments, leading to the formation of larger-scaled, distinctively-shaped, depositional units or architectural elements, such as banks, islands and spits, which are typical features of the silting-up (sink) environment, in which mangrove forests develop (TESSLER; FURTADO, 1983); intense erosion occurs on the concave margins and sediment deposition takes place on the convex margins of the Cananéia Channel (TESSLER; MAHIQUES, 1998).

### Climate

The Cananéia coastal region has a mild subtropical climate but temperatures can drop below freezing in winter. Summers are wet and winters are considerably dry. Maximum rainfall occurs from January and March, with a monthly average of 266.9 mm. Precipitation minima occur from July to August with a monthly average of 95.3 mm. The average annual rainfall over a 29-year period is 2,300 mm. The average annual temperature is $23.8^{o}C$, the highest monthly average is $27,8^{o}C$ (February) and the lowest is $19,8^{o}C$ (July) (SILVA, 1989). Tides are microtidal (<2 meters spring range) and semidiurnal (with diurnal inequality). Mean tidal amplitude is 0.82 m; mean tidal amplitude for the spring tides is 1.25 m (MESQUITA; HARARI, 1983).

### Study Site

The Baguaçu mangrove forest is located in the Cananéia-Iguape Coastal System. Mangrove stands of varying levels of structural development are a predominant supratidal feature of this coastal system. Cunha-Lignon and Schaeffer-Novelli (in press), have described mangrove colonization in this area using aerial photography and satellite images. The Baguaçu forest did not exist in 1981, but by 1997, the study site had been occupied by mangroves.

## METHODOLOGY

Sediment cores were taken at four different sites, within study area, in July 2003: T1) a sediment bank; T2) a smooth cordgrass *Spartina alterniflora* bank; T3) mangroves in an active progradation zone, dominated by *Laguncularia racemosa;* and T4) mature mangrove forest, dominated by *Avicennia schaueriana* (Fig. 2). The location of the sampling points was determined using a 12-channel, GARMIN, model 48, GPS receiver.
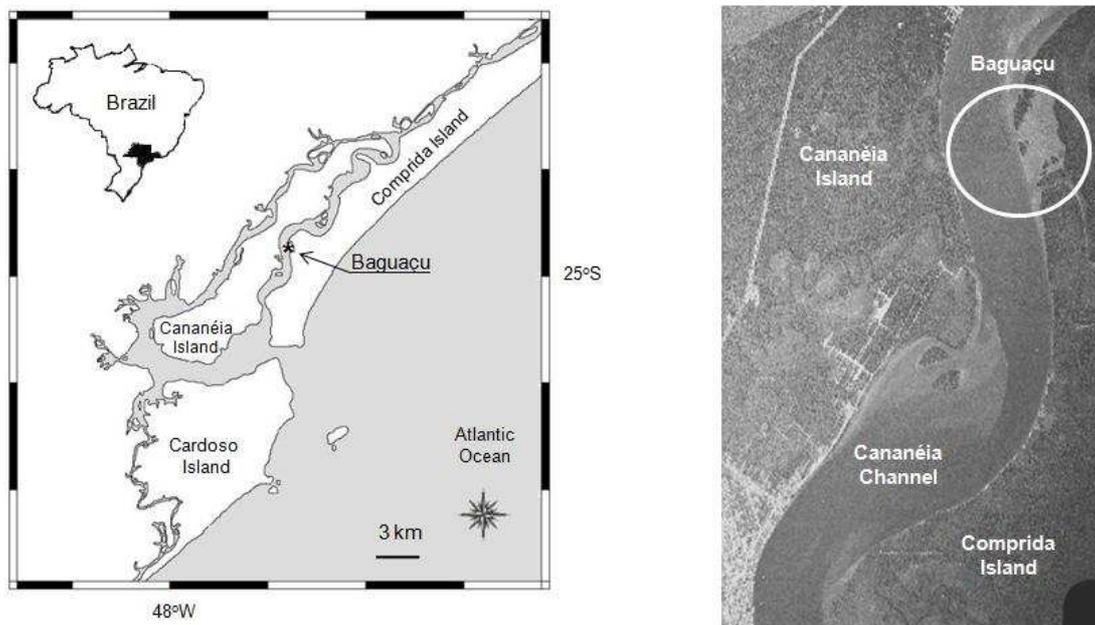


Fig. 1. Map of the Cananéia-Iguape Coastal System, Southern coast of the State of São Paulo, showing location of the Baguaçu study area.
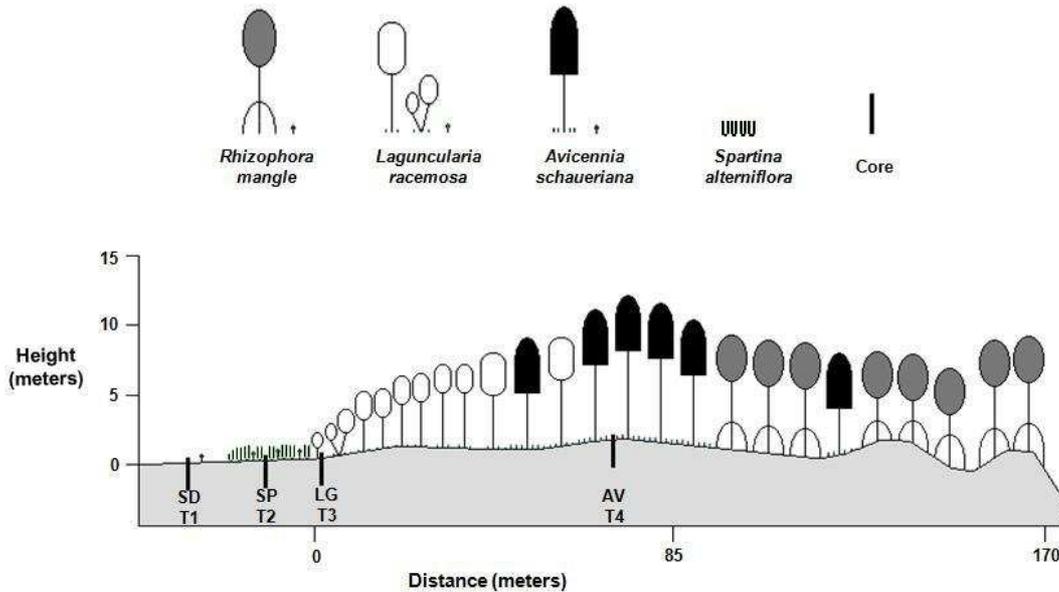
Fig. 2. Location of sedimentation units and cores sampled in the Baguaçu study area. **T1**: sediment bank; **T2**: *Spartina alterniflora*; **T3**: *Laguncularia racemosa*; and **T4**: *Avicennia schaueriana.* Diagram by Ricardo Menghini.

Each PVC core was of about 150 cm in length and 75 mm in diameter. After sampling the cores were cut longitudinally, measured, photographed and macroscopically described. The sediment cores were described in terms of texture, color, macroscopic composition (shells and plant fragments, etc.), sedimentary structures (lamination, bioturbation), particles (woody and organic plant debris) and intraclasts. A soil color chart (OYAMA; TAKEHARA, 1987) was utilized to classify the colors observed along the sedimentary column. The grain size was described according to the Wentworth scale (1922).

## RESULTS

Table 1 and Figure 2 show the locations of the cores in the study area. The legend (Fig. 3) is the same for Figures 4 to 7.

Table 1. Location of core sampling points in the study area.

| Cores | Coordinates Latitude / Longitude | Characteristics |
|---|---|---|
| T1 | 47°W53'50.033''/24°S 58'43.275'' | sediment bank |
| T2 | 47°W53'49.628''/24°S58'41.204'' | bank dominated by *S. alterniflora* |
| T3 | 47°W53'49.655''/24°S58'40.814'' | mangrove forest undergoing progradation, dominated by *L. racemosa* |
| T4 | 47°W53'49.763''/24°S58'39.350'' | mature mangrove forest, dominated by *A. schauerina* |

Core T1 (Fig. 4), 106-cm long was extracted from the sediment bank, is formed by two sedimentary units; a basal portion 21 cm thick composed by fine and very fine sands with irregular clayey lenses showing a mottled pattern, and an overlying layer composed by sandy muds. From the base to 53 cm, the dominant color was grayish olive (7.5Y5/2), with olive black mud (10Y 3/1). There is a conspicuous fining upward as a result of increasing mud. Between 93 and 89 cm shell fragments (bivalves) occur. At 83 cm millimetric concentrations of plant fragments were observed. At 49 cm millimetric to centimetric scattered plant fragments were prominent. Between 53cm and 10 cm, the color darkens to olive black (10 Y 3/2) and the sedimentary structures change from laminated to massive. From 21 to 0 cm, sandy-mud prevails and organic matter content increases. Between 9 and 3 cm, a black layer (10 Y 2/1) becomes prominent. At the core top olive black (10 Y 2/1) mud dominates.

Core T2 (120 cm in length) (Fig. 5) is also composed two major sedimentary units, a sandy sequence, from 120 to 23 cm and a muddy sequence, from that depth to the top. Between 120 and 112 cm, very fine olive black sand (7.5Y3/2) is dominant, and a few millimetric carbonate fragments are present. From 112 to 108 cm, very fine and fine sand is dominant, with a few scattered milimetric bioclasts (gastropods). Between 112 and 104 cm the gray sediment (7.5 Y 4/1 (gray) is dominant. At 108 cm, millimetric plant fragments occur. Between 108 and

104 cm, a massive very fine sand layer with scattered plant fragments is present. A clayey nodule, within very fine sand with little organic mater was found between 104 and 101cm, the dominant color is olive black (10Y3/1). Between 102 and 98cm, there is very fine sand with a concentration of bioclasts. From 92 to 88 cm plant fragments and a few millimetric scattered bioclasts are found. A gray color (7.5Y4/1) is dominant between 102 and 86cm. Between 86 and 82 cm massive dark olive gray (2.5 GY 4/1) colored fine sand becomes prominent. Between 82 and 73 cm there is a fine gray (7.5Y4/1) sand layer with scattered small (<1cm) plant fragments. Between 73 and 69 cm there is a massive fine sand lens with little organic matter. Between 73 and 67 cm the color 2.5 GY 4/1 (dark olive gray) is dominant. Muddy sand, rich in organic matter is found between 69 and 67cm. From 23 to 10 cm sediments grade from very fine sandy mud to mud with very fine sand and a massive structure with decimetric plant fragments (*S. alterniflora*) is found. Nuclei rich in organic matter are scattered from 10 cm to the core top. The uppermost 44 centimeters are gray (7.5Y4/1).
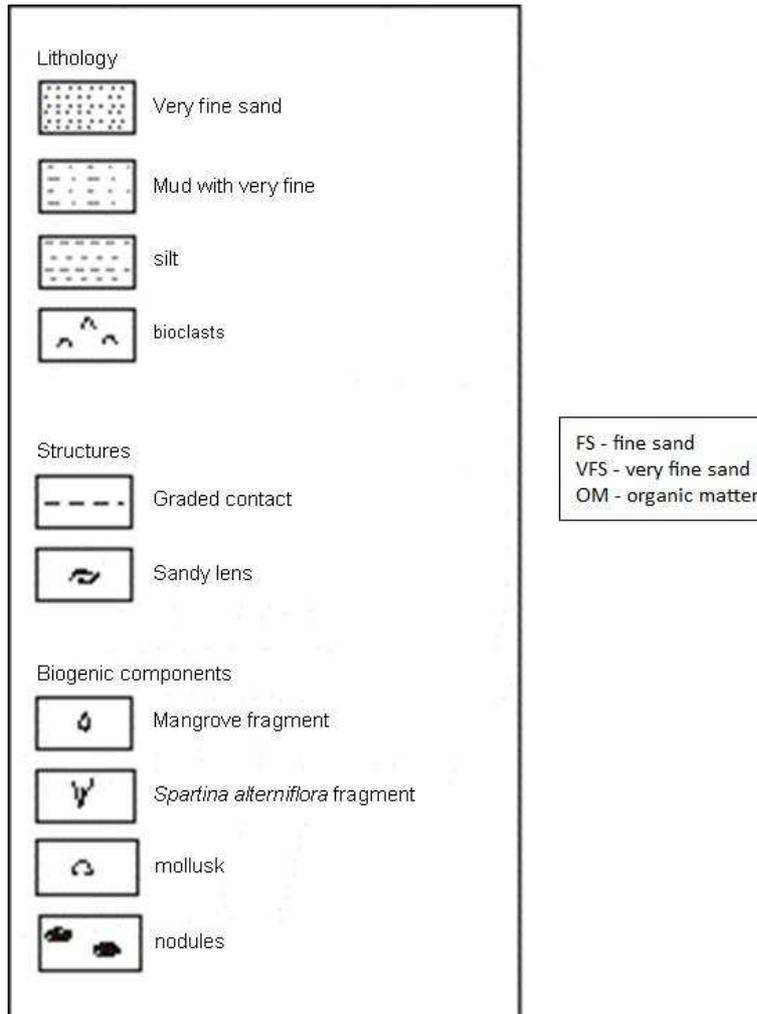


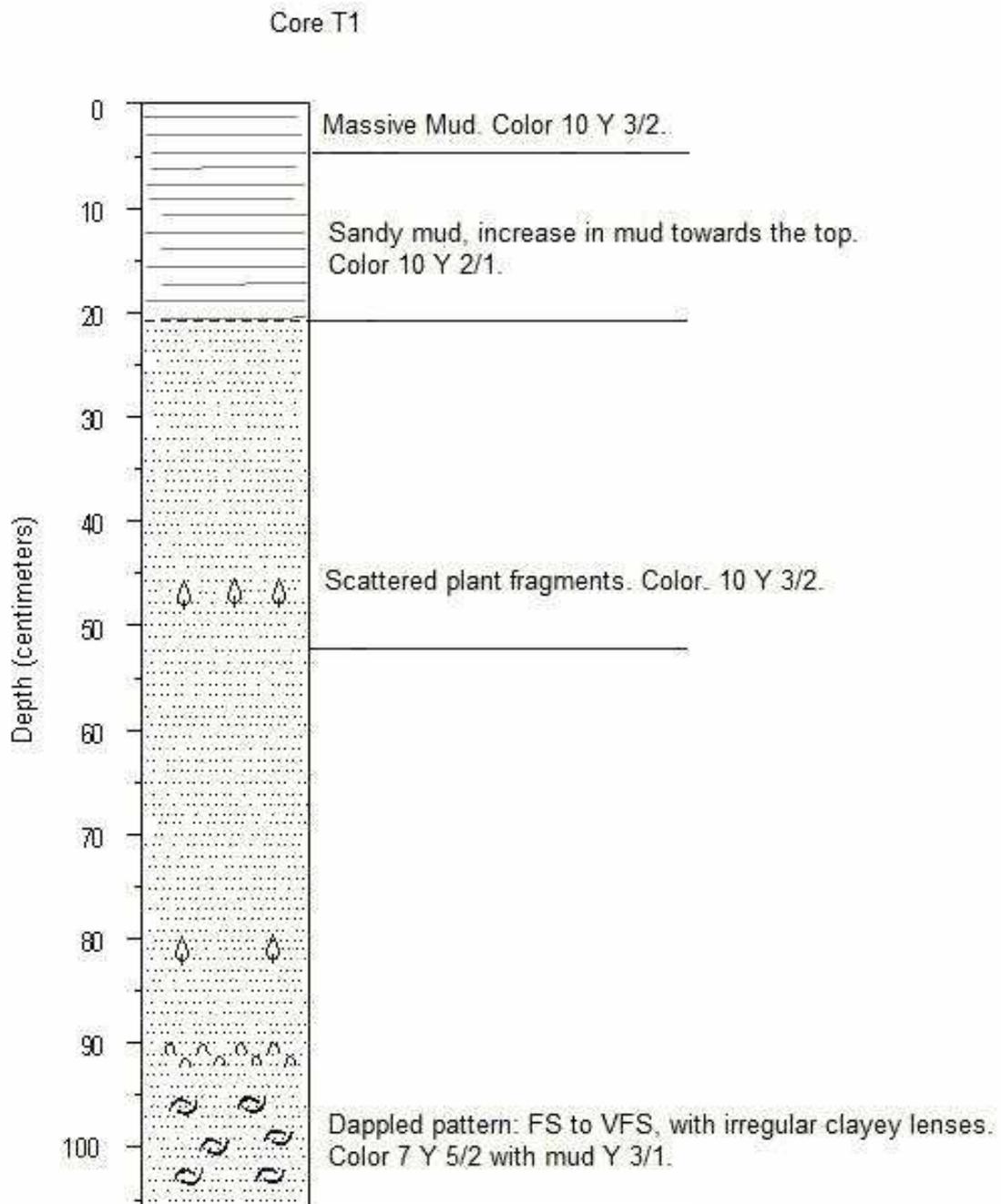Fig. 3. Key to the macroscopic description of the cores.

Core T1

Fig. 4. Vertical facies succession according to the macroscopic description of the core from the sediment bank (T1).
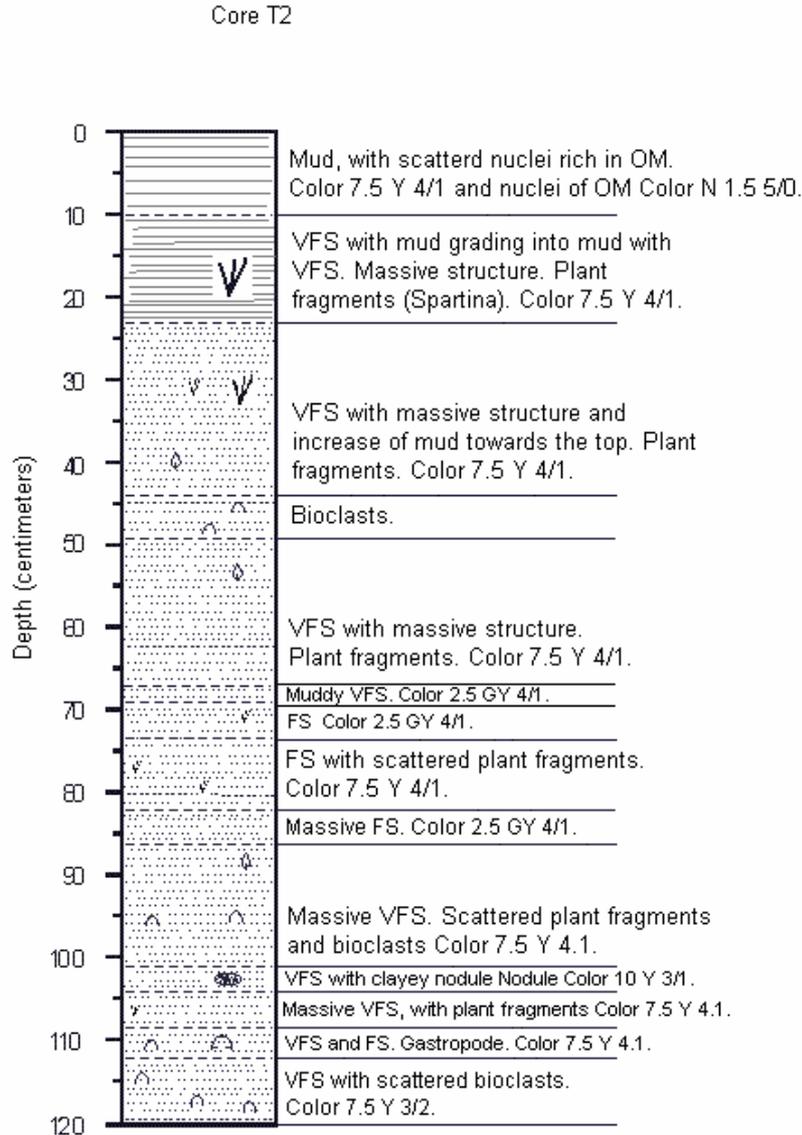
Core T2



Fig. 5. Vertical facies succession according to the macroscopic description of the core from the *Spartina alterniflora* area (T2).

Core T3 (110 cm in length) (Fig. 6) also exhibits the two sequence pattern, observed in cores T1 and T2, with sands from the base to 30 cm, and muds from that level to the top. Fine and very fine sand are dominant between 110 and 96 cm, Irregular scattered centimeter-sized interbedded clayey lenses form a mottled pattern where a grayish olive color (7.5Y5/2) dominates, with darker olive black (10Y3/1) mud lenses interbedded. A similar mottled pattern is found between 96 and 70 cm, with bioclasts at the top. At 74 cm fragments of *S. alterniflora* are found.

Between 70 and 57 cm fine sand is found and the diminishing mottled pattern grades into a massive structure, with an increase of organic matter and plant fragments at 69 cm. At 68 cm, there is an aggregation of carbonate fragments. Between 57 and 51 cm the pattern continues with a greater concentration of plant fragments. At 56 cm mangrove woody debris (probably of *L. racemosa*) is found, and at 52 cm pockets of plant fragments of less than centimeter size are found. From 51 to 30 cm very fine sand with mud dominates, grading into mud at the top. From 70 to 30

cm an olive black color (10Y3/2) dominates. At 42 cm there are embedded plant fragments and *S. alterniflora* debris occurs throughout the sequence. Between 30 and 6 cm, an olive black mud (7.5Y2/2) dominates. In this section fragments of *S. alterniflora* are found from 26 cm to 16 cm, indicating the occurrence of cordgrass before the establishment of the *L. racemosa* forest. There is an increase in organic material and plant fragments towards the top. From 6 cm to the top, black mud (10YR7/1 and N1.5-5/0) and much organic material and recent plant fragments (leaves and roots) are found.

Core T4 (95 cm long) (Fig. 7), contains a remarkable quantity of roots and leaves. Between 95 and 73 cm, fine sand and very fine sand are dominant, with irregular clayey lenses forming a mottled pattern. At 89 cm there are scattered millimetric plant fragments. Between the base and 60 cm, the sediment is grayish olive (7.5Y5/2) with olive black mud (10Y3/1). From 60 cm to the top, the texture is that of massive mud with a low concentration of sand. As mud becomes dominant the color darkens to olive gray (2.5 GY 3/1). Between 58 and 49 cm, there is a larger concentration of brownish-red plant fragments, micro roots and millimetric leaf fragments. Between 49 and 31cm scattered large roots and mangrove leaves and millimetric plant fragments are found, Between 31 and 20 cm, there are scattered filamentous plant fragments suggesting colonization by *S. alterniflora* before the mangrove forest was established. Between 20 cm and the top, large roots, leaves and *A. schaueriana*'s branches are present.

The base of all the cores showed a similar structure at the four sites, an irregular mottled pattern alternating between very fine and fine sand and the presence of clayey lenses. This pattern may correspond to the subaqueous environment, of tidally-influenced sand and muds prior to the upbuilding (aggradation) by the *Spartina* banks.
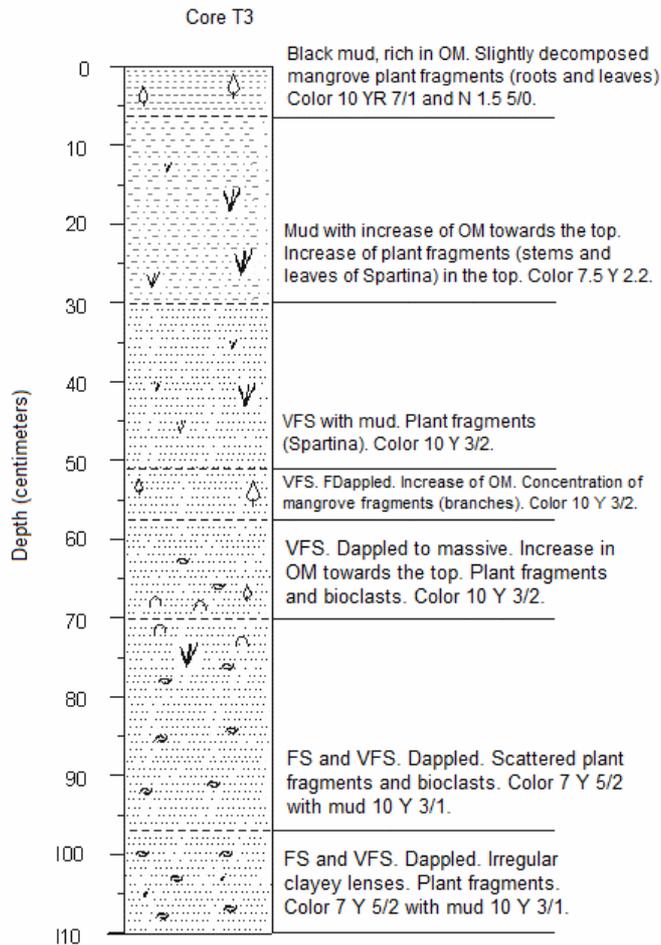


Fig. 6. Vertical facies succession according to the macroscopic description of the core from the *Laguncularia racemosa* area (T3).
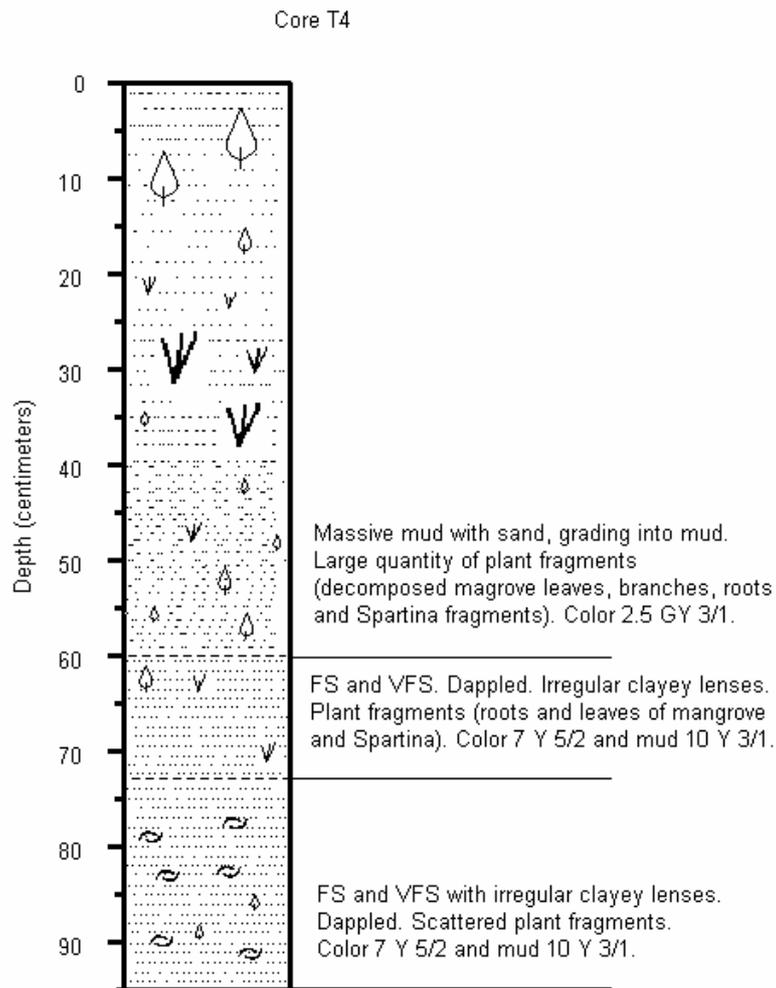
Fig. 7. Vertical facies succession according to the macroscopic description of the core from the *Avicennia schaueriana* area (T4).

## DISCUSSION

The response of coastal features to sea level change involves pattern formation due to the interaction between allogenic and autogenic processes. Scour emerging from local instabilities leads to eventual broader-scale self-organization and stability downstream. Increased muddy sedimentation towards the inner part of the forest reflects changes in hydrodynamics and the increasing competence of the woody vegetation for retaining sediments. The limit between the basal sands and the uppermost muds establishes a chronological and functional datum.

The interaction between substrate and vegetation creates conditions for further organization and spatial patterning. According to Connel and Slatyer (1977), pioneer species colonize the bare (the prograding sediment banks). Later these species facilitate colonization by others (young mangrove seedlings in this site). As the forest develops, the *S. alterniflora* bank becomes shaded and pioneer species die off. Connel and Slatyer's (op. cit.) model provides an illustrative parsimonious description of the

successional process of mangrove forest development consistent with the coring data.

Accretionary facies may be inferred from the structure of core T3 (prograding mangrove forest, dominated by *L. racemosa*). According to Cunha-Lignon et al. (2009), the area described by the T3 core formed within 6 months (from November 2002 to May 2003) (Fig. 8). Smooth cordgrass fragments are observed in the section between 75 and 40 cm (small fragments) and from 30 to 15 cm (larger fragments).

The presence of *S. alterniflora* fragments at different levels suggests fluctuations in the depositional/erosional processes associated with the growth of the bank. The sedimentation rate of the area of the mature mangrove forest (core T4), may be different than that of the active (but mostly physical) progradation site. Considering the multitemporal series of aerial photographs and satellite image, it is estimated that the Baguaçu area mangrove colonization started between 1986 and 1990 (Fig. 9).
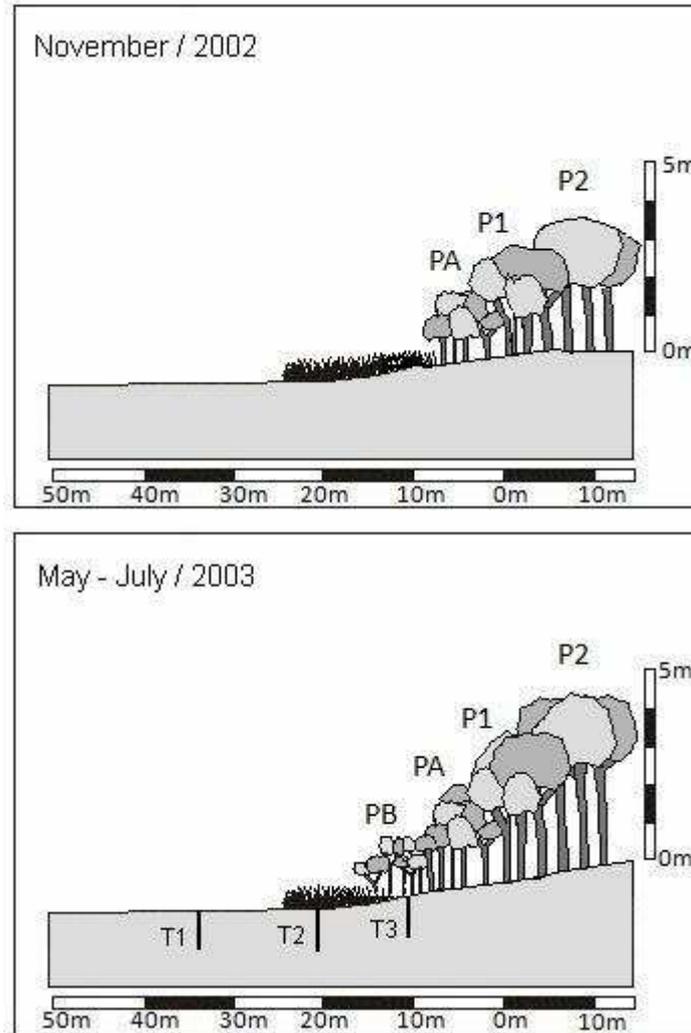


Fig. 8. Baguaçu study area in November/2002 and May-July/2003, showing permanent plots within the mangrove forests study site, Cunha-Lignon (2005). Core T3 is at the B Plot (PB), May-July/2003.
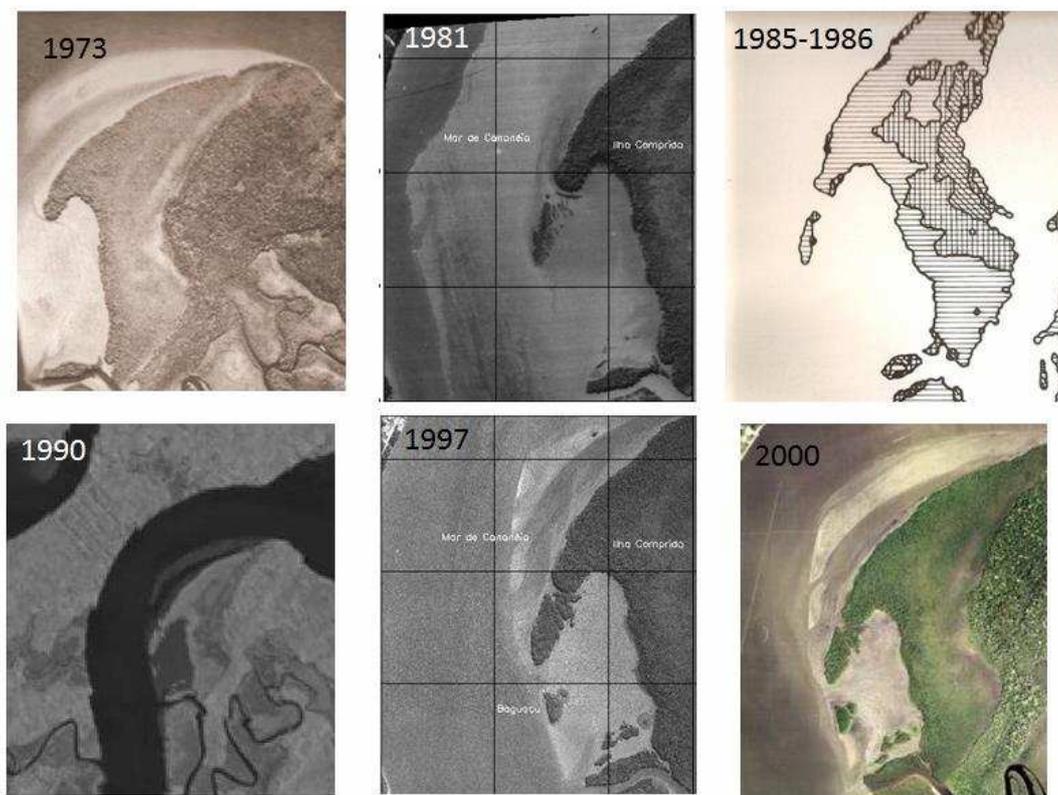
Fig. 9. Aerial photographs multitemporal series and photointerpretation of satellite images in different scales, Baguaçu study area between 1973 and 2000. 1985-1986 photointerpretation by Hertz (1991).

According to Saito et al. (2001a; 2001b), sedimentation rates in the Cananéia-Iguape Coastal System are variable, ranging from 0.53 to 0.98 cm·y⁻¹, reflecting spatial complexity and local inputs.

The core descriptions show how important this tool is for the documentation of short-term aperiodic events and successional processes at local scales, such as in the Baguaçu study area. Initially there is a rapid progradation leading to sediment bank formation, with alternating fine sand and mud reflecting an abundant local supply of sediment, followed by a balance between deposition, erosion and colonization by *S. alterniflora* and, then *L. racemosa*.

In the inner area cores, where the forest is more structurally developed, the same sequence was observed, with posterior colonization by *A. schaueriana*. The pattern observed in the four cores studied supports the zonal and succesional sequence suggested by Dias-Brito and Zaninetti (1979). Ball (1980) reported that mangrove zonation is a result of different interrelationships between components and physical factors as well as the competitive abilities of mangrove species.

Fromard et al. (1998) described young mangrove forest dominated by *L. racemosa* and mature forest by *Avicennia* in French Guiana. Davis (1940) reported *S. alterniflora* in pioneer communities. This smooth cordgrass helps to the sediment fixation and to the establishment of young *Rhizophora*. Cores at the Baguaçu site suggest that *L. racemosa* is not the pioneer but a seral stage that develops later than *Spartina*. The core sampled in the area colonized by mature *A. schaueriana*, showed *S. alterniflora* fragments near to the base, confirming an initial smooth cordgrass seral stage.

Méndez Linares et al. (2007) used geomorphological and ecological methods to explain the development and distribution of six mangrove communities in an actively accreting area. That study and this one suggest that the process of horizontal succession may be deduced from stratigraphy's 'vertical succession'.

## Conclusions

Sediment cores are an indispensable tool for probing the short-term successional dynamics of mangrove forests in areas undergoing active sedimentation.

The Baguaçu site cores provide a depiction of the progradational process in an area of rising sea level. That is, short-term local level accretionary processes can be superimposed on, and can modify or obliterate long-term trends and changes. Peripheral accretion can increase the size of the forest stands in spite of larger-scaled relative sea level rise. This implies that, at least in the Cananéia region, the analysis of sediment cores in mangroves must recognize that mangrove vegetation responds quickly and efficiently to short-term changes in sedimentary balance and that these local responses can obliterate or alter long-term trends in relative sea-level change. We suggest that slow rising sea level trends acts at the system level accelerating dynamic adjustments at landscape or setting scale by increasing spatial heterogeneity and diversity, but local-level structuring responds to local-level, shorter-term processes. Mangrove growth is able to influence these local processes promoting longer-term stability while increasing spatial diversity.

The base of all the cores showed a similar pattern at all of the four sites studied, an irregular mottled pattern alternating between very fine and fine sand and the presence of clayey lenses. It is suggested that the formation of the basal structure in the study area (sediment bank before its colonization by mangrove forest), follows a similar pattern throughout the area.

This study highlights the role of *S. alterniflora* as potential initial stabilizer, which by reducing sheet erosion by its and its expansion via rhizomes and appears to prepare a substrate favorable to the settlement of the smaller *L. racemosa* propagules, which although small and potentially easily uprooted by waves and currents. These propagules are abundant, and easily trapped within the smooth cordgrass habitat. *L. racemosa* is in fact considered as a weedy species that pioneers readily into disturbed sites (TOMLINSON, 1986). Thus, early successional stages are fast growing (herbaceous) elements (*S. alterniflora*) and/or easily replaced woody stages (*L. racemosa*) which are afterward outshaded and replaced by *A. schaueriana* which can develop a robust root system that is not only resistant to erosive episodes, but which can promote rapid sedimentation to replace sediments scoured during brief erosive events.

A significant aspect of this study is that the Baguaçu forest is located in an area marked by a conspicuous rise in sea level in the last century (MESQUITA, 2003). But in this sense, it must be noted that, in the time scale of this study (decadal), mangroves may not be responding to small variations in sea level but are instead responding to changes in sedimentary balance which in turn may be triggered by long-term sea level change at broader scale.

These data indicate the process of horizontal accretion and successional change can be deduced from stratigraphy's 'vertical succession' and relative sequence of accretionary deposits.

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