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Prediction of Wetland Loss Due to Sea Level Rise Around the Largest Port Area in Latin America

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ABSTRACT: Santos's mangroves are important wetlands located in Brazilian coast, a fishing area inside Santos Bay. The overall healthy mangroves area along the riparian zones influencing the Santos Estuary is around 25.20 km^2. The resulting tidal level recorded from Port of Santos tide gauge (from 1940 to 2014), also located in the estuary, shows consistent increasing trend. One healthy mangrove was selected for a previous qualitative biological survey to better understand the characteristics of the habitat to be monitored and evaluated about the possible impacts in the next decades. The mangroves situated a few meters upper from the sea level and some other areas have the risk to be submerged till 2085 which will seriously affect the riparian mangroves biome. Indeed, the mangrove area is confined downward by the low tide level and upward by existing structures, roads, rural and urban areas.

1 INTRODUCTION

Mangroves are wetlands that occur in tropical and subtropical areas, bathed by tidal movements, by the exchange of organic matter between fresh and salty water. It receives debris from soils, rocks, and mainly organic matter, usually brought by rivers. A portion is transformed into smaller particles by the action of crabs and other animals, serving as food for snails, larvae, and soil microorganisms, which supply nutrients to water flora, which will later serve as food for several animals [9].

Santos's mangroves are important wetlands located on the Brazilian coast, in an estuarine rural tropical area within Santos (Figure 1). The most extensive mangrove study in the Santos Estuary [9] classified their characteristics in 1985 as high: 67.85%; low: 4.14%; degraded: 8.53%; amended: 19.48%. High mangrove is the vegetation with trunks that support large leaf mass. Low mangrove is the vegetation with smaller diameter of tree cup. Degraded mangrove is partial or total cut areas, exposing dark substrate (dominance of decomposed organic matter exposure) with cut logs or small regeneration shrubs. Amended mangrove presents structural modifications of total or partial character by the installation of paths or roads, constructions, or embankments and even agricultural or aquaculture activity. The study was developed by means of remote sensing techniques from satellite and orthophoto images.

Therefore, in this paper only healthy mangroves were considered, that is, degraded and amended were disregarded. The overall mangroves area of healthy mangroves (high and low) along the riparian zones influencing the Santos Estuary was around 25.20 km^2. The study informs the areas of each mangrove swamp according to its characteristics.

According to [1], it is concluded that mean sea level rise will have a considerable impact upon the mangrove areas, with approximately 1.0 m rise estimated from 1990 to 2100. Baixada Santista is a lowland situated a few meters upper from the sea level and some areas have the risk to be submerged in the end of this century. The increasing in the salinity intrusion upward the estuary due to higher tidal levels will seriously affect the riparian mangroves biome. With the confirmation of the 1.0 m sea level rise scenario, the first estimation was that there will be a loss of 50% of the riparian zones with healthy mangroves [2] of Santos Estuary. The sea level rise is a threat particularly to the wetlands of the South Atlantic. In general, the sea level rise will flood the estuarine saline areas, such as mangroves, and the sea level rise will submerge wetlands causing the death of vegetation by salt stress [10].

An important observation is that the mangrove area of Santos Estuary (Figure 1) is confined downward by the mean sea level and upward by high tide level, Port of Santos structures, industrial plants (Cubatão petrochemical and steel complex), roads and urban areas (including stilt houses).

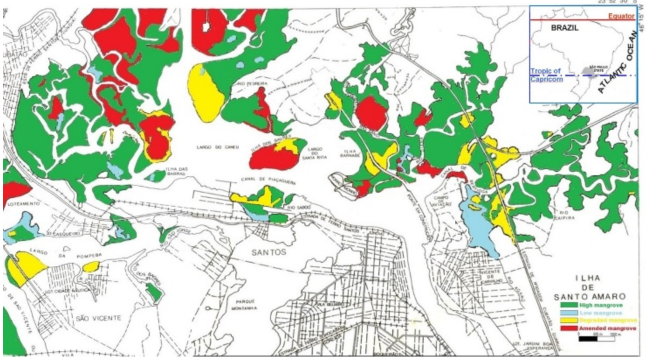

Figure 1. Mangrove distribution in Santos Estuary (adapted from [9]).

As a result of the likely reduction of mangrove areas in the Santos and São Vicente Estuaries, due to the mean sea level rise, some of the ecological functions of this coastal ecosystem may be compromised, including the retention of sediments and pollutants, export of organic matter and nutrients to the adjacent coastal waters and restriction of critical habitat for some species that use the mangrove at some stage of their life cycle.

Regarding the mangrove, [4] state that the coastal wetlands can deal with changes in sea level when they are able to stay at the same elevation relative to the tidal range. That can happen if sediment increase is equal to the rise in sea level, or if the wetland is able to migrate (when the mangrove moves) upward.

According to [15], the vulnerability of mangroves to climate change is moderate, and, although the increase in winter temperatures can enhance growth, the rising sea level and saline intrusion can cause significant reduction. Potential changes in hydrological regimes projected to occur over the next 100 years will lead probably to the loss of wetlands, deterioration of water quality and damage to fisheries production [11].

The study of [2, 13] consider that the increase does not show itself which areas will submerge if the sea level rises a meter or more but is the most important factor when looking for that answer. In this sense, the evaluation carried out for the study area is restricted only to the rising sea level.

Beyond the biological loss and its biodiversity, there will be serious physical consequences due to the partial loss of a natural filter for the fine (clay and silt) sediment transport in suspension, from the rivers into the estuary and the erosion of the former riparian areas submerged. Indeed, the complex mangrove roots trap large quantities of fine sediment in suspension, like silt and clay. Without this retention, a larger amount of sediment will be carried to the Port of Santos nautical areas, silting, and increasing the dredging volumes of maintenance. The study [8] described that up to 80 % of the sediment transported by the tides may be retained in mangrove areas, but the mechanism of retention of this sediment is unclear. Hence, meanwhile the sea level rise will increase the depth, the siltation certainly will overcome many times this favorable increasing of depth, and the result will be an increasing cost of maintenance dredging, with volumes larger than the current ones.

In an agreement between the Hydraulic Laboratory and CODESP (Port of Santos Authority) it was decided to define a characteristic stretch of the preserved mangrove of Largo de Santa Rita (Ilha Barnabé) for a previous qualitative biological survey to better understand the characteristics of the habitat (Figure 2). Although the Santos Estuary is a studied region, there was no prior knowledge of the mangrove preservation status in this area of Ilha Barnabé. The small bay has depths less than 3 m, and the land stretch has well-defined limits of port structures, railways, and highways, making it possible to estimate the potential loss of mangrove areas in the coming decades, due to mean sea level rise [3]. Observe in the figure the landfill of the railroad crossing the mangrove of Ilha Barnabé. The railroad separated the mangrove plain in the middle of the seventies, thus more than forty years ago.

Figure 2. The location of the mangrove bank studied. In detail, aerial photo with at first plan, River Jurubatuba, and after, Largo de Santa Rita.

The main objective of this paper is to estimate the potential loss of healthy mangrove area in the coming decades due to the rise in the mean sea level.

2 MATERIAL AND METHODS

2.1 *Experiment in Tide Condition of Equinoctial Syzygy*

To get advantage of the equinoctial spring tide, on September 6th, 2002, the staff made the topographic survey of the levels (Chart Datum, CD) of flooding of the mangrove (Figure 3). The CD of Brazilian Navy for the Port of Santos was used as level of reference and horizontal coordinates are referred to the System UTM – Córrego Alegre, used in Brazil.

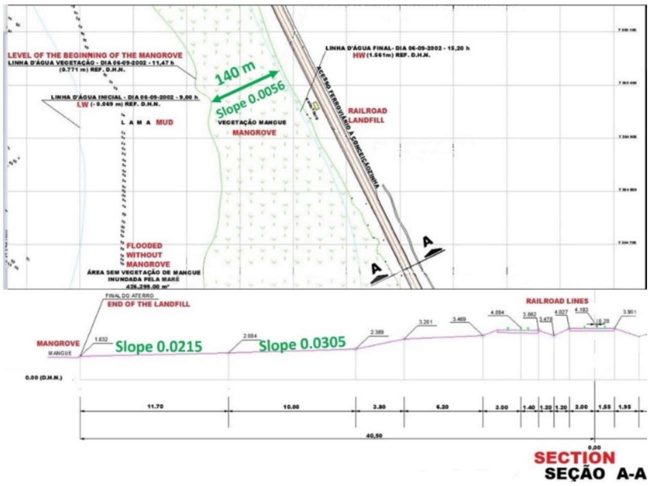

Figure 3. Field conditions for the experiment in equinoctial spring tide.

2.2 *Characterization of the Mangrove Structure*

Three plots were positioned, each 15 m x 15 m (Figure 3), Plot I nearby the railway and in the central portion of the mangrove, Plot II near River Jurubatuba in the north portion of the mangrove and Plot III was the closest to Santos Port. The species Avicennia schaueriana, Rhizophora mangle and Laguncularia racemosa were identified and measurements of the diameter of each tree were taken, according to the methodology described in [12]. The average heights were determined with rods, replacing the rangefinder and inclinometer. It is determined the relative frequency by species.

The measurements of the trees were classified at intervals established by the methodology recommended in [12], that is: < 2.5 cm, > 2.5 cm and < 10.0 cm and > 10.0 cm, according to the diameter at breast height (DBH), around 1.3 m from the ground, with the aid of a measuring tape.

Once the field data was available, for each sampling plot the parameters of mean forest height (H_{mean} in m), maximum height (H_{max} in m), mean diameter at breast height (DBH_{mean} in cm), basal area (BA in $m^2.ha^{-1}$), relative density (RD in %) of each species and relative contribution in basal area of living trunks with DBH higher than 10.0 cm ($RBA_{DBH} > 10$ cm in %).

2.3 *Rise of Mean Sea Level*

The assessment of mean sea level rise for Port of Santos shows a reliable consistence in comparison with several international recommendations and with similar trends in other two locations of São Paulo State Coast, giving confidence to its use for estimative impacts due to the maritime consequences of climate changes. The estimative from 1940 to 2100 is 1.1 m, following from 1940 to 2014 a rate of 0.33 cm/year, which should increase in the next decades in a similar trend of UK recommendations (Table 1) for a moderate scenario [1].

Table 1. UK recommended net sea level rise rates and cumulative amounts, relative to 1990 [6].

Time period	Moderate rate (mm/yr.)/cumulative SLR since 1990 (m) at end of period
1990-2025	3.5/0.12
2025-2055	8.0/0.36
2055-2085	11.5/0.71
2085-2115	14.5/1.14

3 RESULTS

3.1 *Characterization of the Flooding and Levels*

The following data were obtained in the field:

- Low water: - 0.069 m (CD)
- High water: 1.561 m (CD)
- Level of beginning of the mangrove vegetation: 0.771 m. Practically mean sea level
- Flooding area between low water and the beginning of the mangrove vegetation: 426,299 m^2
- Flooding area of the mangrove up to high water: 466,668 m^2
- Total flooding area: 892,967 m^2

Calculated slopes:

- Maximum in the mangrove plain: 0.0056
- Lowest landfill of the railroad: 0.0215 and 0.0305

According to [7], in 1985 mean sea level was 80 cm (CD), with mean higher high water 145 cm (CD).

3.2 *Mangrove Structure*

A total of 108 trees were measured (Figure 4), 79 of which were Avicennia schaueriana, 23 trees of Rhizophora mangle and 6 trees of Laguncularia racemosa. From these data, the respective basal areas (m^2) were calculated, presenting the main structural parameters of the plots (Table 2).

Table 2. Structural parameters of the plots.

Parameter	Plot I	Plot II	Plot III
H_{mean} (m)	6,9	7.8	5.7
H_{max} (m)	14.0	12.0	12.0
DBH_{mean} (cm)	8.68	11.28	8.08
BA ($m^2.ha^{-1}$)	7.9	18.8	16.4
$RD_{Avicennia}$ (%)	48.0	100	68.0
$RD_{Rhizophora}$ (%)	32.0	0	30.0
$RD_{Laguncularia}$ (%)	20.0	0	2.0
$RBA_{DBH>10\ cm}$ (%)	56.9	93.23	75.47

Figure 4. Photo of the mangrove aspects in the three plots during the survey.

3.2.1 *Plot I*

This area had 23 adult individuals (absolute basal area = 0.176736 m^2), most of which are individuals with DBH > 10.0 cm (absolute basal area = 0.10222013 m^2). The DBH_{mean} = 8.68 cm. The plot showed 2 young individuals (absolute basal area = 0.00079577 m^2), one of the species *Rhizophora mangle* and one of *Avicennia schaueriana*. H_{mean} = 6.9 m and H_{max} = 14.0 m. In terms of distribution of individuals by species, *Avicennia schaueriana* was represented in greater number (48.0%), with 12 (absolute basal area = 0.07366193 m^2), followed by *Rhizophora mangle* (32.0%) with 8 (absolute basal area = 0.083856 m^2) and *Laguncularia racemosa* (20.0%) with 5 (absolute basal area = 0.020014 m^2). The total BA = 7.9 $m^2.ha^{-1}$ and the $RBA_{DBH>10\ cm}$ = 56.9%.

3.2.2 *Plot II*

The plot was composed only by the species Avicennia shaueriana, which had 31 adult individuals (absolute basal area = 0.422748 m^2) and 2 young individuals (absolute basal area = 0.00059476 m^2). H_{mean} = 7.8 m and H_{max} = 12.0 m, with the total BA = 18.8 $m^2.ha^{-1}$ and the $RBA_{DBH>10\ cm}$ = 93.23%.

3.2.3 *Plot III*

The region offered the largest number of adult sampled with 48 individuals (total basal area = 0.366860 m^2). It also presented only 2 young individuals (total basal area = 0.00091944 m^2) of the species *Rhizophora mangle* and *Avicennia schaueriana*.

In terms of individuals distribution by species, the plot presented 34 (68.0%) belonging to *Avicennia schaueriana* (total basal area = 0.3024443 m^2), 15 (30.0%) to *Rhizophora mangle* (total basal area = 0.06425731 m^2), and only one individual (2%) of *Laguncularia racemosa* (total basal area = 0.025783 m^2). The height measurements were H_{mean} = 5.7 m and H_{max} = 12.0, with the total BA = 16.4 $m^2.ha^{-1}$ and the $RBA_{DBH>10\ cm}$ = 75.47%.

3.3 *Mean Sea Level Rise*

The following data are estimations of mean sea level rise in comparison of 1985, from Table 1:

- In 2055: 38 cm.
- In 2085: 73 cm.
- In 2115: 116 cm.

4 DISCUSSION

As mentioned in the Introduction, the scope of the survey of the mangrove was a qualitative biological survey in order to better understand the characteristics of the habitat.

Comparing the plots of the mangrove, this is observed that Plot II had the largest BA (with 18.8 $m^2.ha^{-1}$), the highest H_{mean} = 7.8 m and the highest $RBA_{DBH>10\ cm}$ = 93.23%. Then, Plot III had a BA with 16.4 $m_2.ha^{-1}$ and $RBA_{DBH>10\ cm}$ = 75.47%, but H_{mean} = 5.7 m was smaller compared to Plot I (6.9 m) with BA = 7.9 $m^2.ha^{-1}$ and $RBA_{DBH>10\ cm}$ = 56.9%.

The specie *Avicennia schaueriana* was dominant in the three plots, and it is interesting to highlight that in Plot II its frequency was 100%. The genus *Avicennia* is more tolerant to environmental stress and thus can be abundantly found in areas with human induced disturbances [12].

In terms of relative density, *Avicennia schaueriana* was present in 73.15% of the cases, followed by *Rhizophora* mangle with 21.3% and *Laguncularia racemosa* with only 5.55%.

Indeed, according to [14], *Avicennia* is a specie of mangrove typical of low tidal and medium low tidal zones, near mean sea level; and *Rhizophora* of medium low tidal and medium high tidal zones.

Finally, it is noted that most of the sampled trunks are in the DBH range > 2.5 cm and > 10.0 cm, demonstrating that the plots are composed of mature individuals. According to [12], in the stages of greater ripening of a forest, an increase in diameter results in the death of a much smaller number of individuals.

According to [14], in a mangrove area near Santos, compared to an environmental protection area in Guanabara Bay, the main structural characteristics of plots in the mangrove forest are: DBH_{mean} from 3.6 to 12.3 cm, H_{mean} from 2.7 to 11.6 m, H_{max} from 6.5 to 16.7 m, BA from 8.5 to 24.8 $m^2.ha^{-1}$ and $RBA_{DBH>10\ cm}$ = 46 %. However, most of Guanabara Bay comprises the second largest Brazilian industrial region, the second largest port, two refineries, oil storage and distribution companies, naval services, dockyards, and intense maritime and terrestrial's transportation activities. According to the same paper [5], 40% of the Guanabara Bay mangrove were decimated as the coast underwent a process of intense urbanization. Thus, we have observed that those mangroves were gradually destroyed and modified by deforestation for different purposes, different types of landfills, slum occupation and urban expansions, rectification, course alteration and canalization of rivers and canals, discharge of domestic sewage and industrial effluents, refineries and port activities, predatory fishing, predatory crab harvesting, garbage from many different sources and urban garbage deposition. Therefore, the mangroves outside the environmental protection area mentioned have as main structural characteristics of plots in the mangrove forest: DBH_{mean} = 5.07 cm, H_{mean} = 4.9, BA = 13.2 $m^2.ha^{-1}$ and $RBA_{DBH>10\ cm}$ = 22 %.

Comparing the structural parameters of the mangrove of Santos with those of Guanabara Bay, one can characterize the mangrove habitat of Largo de Santa Rita as reasonably preserved, in spite of its separation by the railroad landfill.

The original idea of this previous survey was that the studied mangrove area would be monitored over time with more plots, which unfortunately did not happen. Due to restriction of financial resources, it was not possible to continue monitoring annually, as would be recommended.

The real threat for the mangrove healthy now is the mean sea level rise in stretches where the wetland remained surrounded by obstacles, or by terrains with higher slopes than the usual for the mangrove growth, or the inevitable situation of limiting expansion on islands. As an example, the study showed that the highest slope of the wetland plain evaluated was 0.0056, yet much more mild than typical landfills (in this case 0.0215). According to [14], mangroves plains have slopes from 0.0033 to 0.0050. Hence, the slope measured could be considered at the order of magnitude of the higher limit of this vegetation. Due to those limitations for migration upward of the mangroves and through the assessment of the areas in Figure 1, the expectancy of probable losses of mangrove areas in 2085 were estimated in Figure 6, with the following considerations:

- Around 2085, according with the estimation made in item 3.6, mean sea level will reach the high-water level of 1985 (see item 3.1), which was the highest level for the roots of the mangrove in 1985 (Figure 5).
- All the mangroves located in islands without higher lands will disappear, since it would not have possibility to migrate upward. The high and low mangroves in this case correspond to 2.22 km^2.
- Considering the reality of port, industrial and urban expansions over the mangrove region, from 1985 to the present, it is probable that more of the original mangrove has been degraded or altered in comparison with Figure 1. High and low mangroves lost in those expansions from 1985 to 2020 correspond to 0.61 km^2.
- In regions confined by roads and their landfill, the mangrove migration would be precluded due to the high slope of the landfills in comparison with the maximum slopes typical of mangrove plains. Examples of this occurrence is the big mangrove area of Cubatão in the north western portion of Figure 1 (limited by the railroad line) and the mangroves crossed by the roads (in the eastern portion of Figure 1). Computing these areas, the loss will be of 6.79 km^2.

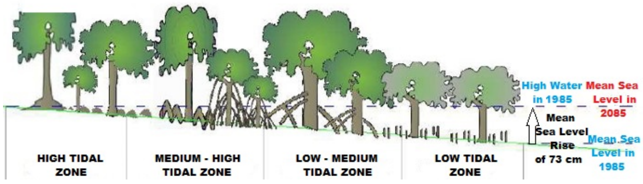

Figure 5. Typical mangrove plain and the mean sea level rise expected in 1985.

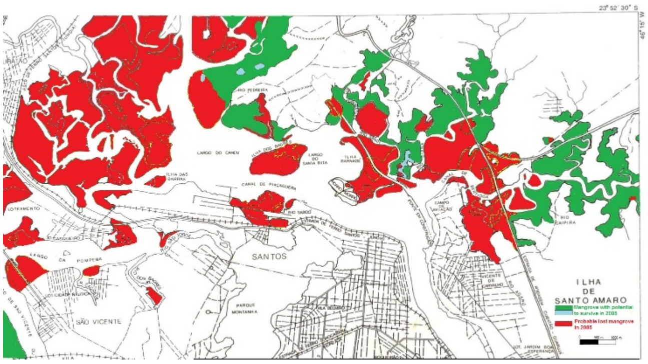

Figure 6. Expectancy mapping of the mangrove in 2085.

5 CONCLUSIONS

From a first survey it was possible to characterize the mangrove habitat of Largo de Santa Rita as reasonably preserved. While these mangroves are located in the area of the Port of Santos, with visible anthropic influence, it is worth mentioning that, only with this previous survey, it was possible to detect that the number of species is expressive, as well as of high biological importance.

In 2085, from the original 25.20 km^2 healthy mangroves will remain only 15.58 km^2, or 62% of the original vegetation, due to sea level rise. This figure supposes no new port structures, industrial plants, roads, and urban areas in regions of mangrove, also is expected that the upward terrain where the remaining mangrove could migrate has mild slopes to support the new mangroves. Otherwise, the loss will be greater. The following suggestions can be listed:

- A mandatory starting point for future research directions would be to update the study carried out by [9], whose survey is over 35 years old, aiming to precisely characterize mangroves that have degraded or amended in this period.
- A new topographic survey that allows to precisely define the slopes of the land above the mangroves.
- To focus on studies in the mangrove areas with the greatest chance of survival, that is, those in which upward migration is viable.
- Application of techniques that allow the creation of new mangrove areas.
- Public policies with the poorest people that value the importance of mangroves, creating housing, sanitation, and education conditions without invasions in the areas of this biome.
- Effective application of the concept of green ports, aimed at preserving the environment, as an awareness that the port itself may suffer the consequences of a predatory occupation.

To take measures is not only responsibility of the port and industrial stakeholders, but also from the government authorities. Therefore the accountability has to come from both sides. If people are aware of possible threats, it is easier to convince them in taking preventive measures. The government authorities of the involved municipalities in the Baixada Santista must deal with that prospect. New mangrove areas are of great importance for that people, however not all areas are suited for mangrove growth and to make certain areas suitable will be an expensive undertaking.

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