Journal of Integrated Coastal Zone Management / Revista da Gestão Costeira Integrada 18(1):41-48 (2018)
http://www.aprh.pt/rgci/pdf/rgci-n119_Sampaio.pdf | DOI:10.5894/rgci-n119

GESTÃO COSTEIRA INTEGRADA
Journal of Integrated Coastal Zone Management

Leaf area index and vegetation cover of the Paripe river mangrove, Pernambuco, Brazil, in 1997 and 2017

Índice de área foliar e cobertura vegetal no manguezal do rio Paripe, Pernambuco, Brasil, em 1997 e 2017

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ABSTRACT: The leaf area index (LAI) was estimated for *Rhizophora mangle*, *Laguncularia racemosa* and *Avicennia schaueriana*, based on the average leaf size, number of leaves in each growth apex, number of apices per plant and number of plants per hectare. Crown projection areas were also determined. The number, size and biomass of leaves per growth apex varied little among plant stem diameter classes and were higher in *R. mangle* than in *L. racemosa* and *A. schaueriana*. The number of apices and the crown projection area increased greatly in plants with larger stem diameters. *R. mangle* contributed (82%) to most of the total leaf area index (3.96), due to the combination of high plant densities, large plants, many apices and large leaves. The leaf areas corresponded to normalized difference vegetation indices (NDVI) from 0.68 to 0.77 in 1997 and from 0.74 to 0.80 in 2017. Therefore, contrary to many other mangroves in the world, the vegetation of the Paripe river has been relatively protected from human impact in the last twenty years.

Keywords: leaf size and mass; crown area; species; *Rhizophora mangle*; NDVI change

RESUMO: O índice de área foliar (IAF) foi estimado para Rhizophora mangle, Laguncularia racemosa e Avicennia schaueriana, baseado na área média das folhas, no número de folhas por ápice de crescimento, no número de ápices por planta e no número de plantas por ha. Também foi determinada a área de projeção das copas. O número, tamanho e biomassa das folhas em cada ápice de crescimento variou pouco com a classe de diâmetro do caule das plantas e foram maiores em R. mangle que em L. racemosa e A. schaueriana. O número de ápices e as projeções

** Submission: 5 JUN 2017; Peer review: 1 OCT 2017; Revised: 6 NOV 2017; Accepted: 6 NOV 2017; Available on-line: 2 JUL 2018*

das copas aumentaram muito em plantas com maiores diâmetros de caule. R. mangle é o que mais contribui (82%) para o índice de área foliar do manguezal (3.96), pela combinação de alta densidade de plantas e plantas grandes, com muitas e grandes folhas. As áreas foliares corresponderam a índices de vegetação (NDVI) de 0.68 a 0.77, em 1997, e de 0.74 a 0.80, em 2017. Portanto, ao contrário do que tem acontecido com muitos manguezais no mundo, a vegetação do rio Paripe tem sido relativamente protegida dos impactos humanos nos últimos 20 anos.

Palavras-chave: tamanho e biomassa de folhas, área de copa, espécies, Rhizophora mangle, mudanças de NDVI

1. INTRODUCTION

Mangroves occur along the coasts of tropical and subtropical areas, forming dense forests wherever climatic and geomorphological conditions are appropriate (Kuenzer *et al.*, 2011). They provide important ecological and economic services and, concomitantly, are one of the most threatened ecosystems worldwide, with dramatic declines in cover area in the last half century (Kuenzer *et al.*, 2011; Cougo *et al.*, 2015). From the landward they are threatened by growing populations and from seaward by climate change (Walters *et al.*, 2008), in a way that more than one third of the total mangrove area was lost in the last two decades (Kuenzer *et al.*, 2011). Therefore, there is an increasing interest in studying mangroves from different points of view (Kovacs *et al.*, 2009; Zhu *et al.*, 2015).

One of the more meaningful parameters in mangrove studies is its leaf area index (LAI). It is an indicator of ecological processes, such as photosynthesis, plant and soil respiration (Lovelock 2008) and evapotranspiration rates, of net primary productivity and of energy exchange rates between plants and atmosphere (Kamal *et al.*, 2016). It can be used to predict future growth and changes in canopy structure, fundamental aspects of environmental management.

Leaf area index can be determined by different methodologies. There is a growing tendency to make measurements based on satellite images, that are easily available and can cover large areas (Kamal *et al.*, 2016), but local measurements using portable sensors are also used (Kovacs *et al.*, 2005). Ultimately, all these indirect methods have to be validated by labor consuming determinations of leaf areas in all plants of specific plots (Kamal *et al.*, 2016).

In Brazil, there are very few published studies on mangrove LAI determinations (Lima *et al.*, 2013). In fact, studies are scarce in relation to any mangrove leaf characteristics (Lima *et al.*, 2013; Medeiros & Sampaio 2013; Arrivabene *et al.*, 2014). Satellite data have been correlated to plant density and mangrove basal area and biomass in the Brazilian northern region (Cougo *et al.*, 2015) but not LAI, and they have been used more often to map mangrove areas and their uses, particularly in this region (Rodrigues & Souza Filho, 2011; Tenório *et al.*, 2015) but also in other Brazilian regions (Pereira *et al.*, 2012; Santos *et al.*, 2014). Considering the necessity to fill the gap in knowledge of Brazilian mangrove leaf characteristics, the objectives of this study were: 1) to determine LAI indices for the tree species that compose the mangrove vegetation of the Paripe river, in Itamaracá municipality, Pernambuco state, Brazil; 2) to relate these LAI indices to normalized difference vegetation indices (NDVI) obtained from satellite images; and 3) to compare NDVI values for this mangrove with a 20-year interval to detect changes in vegetation cover and possible indications of human impact.

2. MATERIAL AND METHODS

2.1 Study area

The study was conducted in the estuary of the Paripe river (07° 41’ 39” to 07° 48’54” latitude south and 34° 49’12” to 34° 53’13” longitude west), in Itamaracá island, Pernambuco state, Brazil (Figure 1). The Paripe river is 4.5 km long and belongs to the group of small coastal basins of Pernambuco, its basin extending for 37.3 ha, 29.4 of them covered by mangroves. The estuary is classified as type 2, according to the Tom (1982) classification, since it has a predominance of sea over river water, an almost flat topography and shallow channels, remaining flooded for 25 to 75% of the day (Medeiros & Sampaio 2008). The tides are semidiurnal, with a 12.4-hour periodicity and amplitude that vary from 1.35 to 1.90 m in the syzygy and 0.90 to 1.32 m in the quadrature.

The climate is AS´, according to the Köppen classification, characterized as hot and humid with autumn-winter rains, rainiest months being May to July and driest months November and December (Figure 1). Average temperatures are around 25°C, with absolute maxima of 30.1°C and absolute minima of 19.6°C. The salinity regime is classified as marine polyhyaline; salinity being higher during high tides of the dry season, when it reached a 32.6‰ in the superficial waters of the river mouth and 30.7‰ upriver. Soils are sandy to loamy, those of the river mouth composed of 80 to 85% sand, 8 to 12% silt and 5 to 10% clay (Medeiros & Sampaio, 2008).

The mangrove belongs to the riverine type, according to the Lugo & Snedaker (1974) physiographic classification. *Rhizophora mangle* L., *Laguncularia racemosa* Gaertn. and *Avicennia schaueriana* Stapf & Leechman are the tree component species, with average density of 3487 plant ha^{-1}, diameter of 7.2 cm, height of 5.2 m, and basal area of 14.1 m^2 ha^{-1} (Medeiros & Sampaio, 2008). Anthropic movement within the mangrove is high, to capture crabs, oysters, fishes and other animals.

2.2 Plant and mangrove characteristics

The leaf area index of the mangrove was calculated, in 1997, based on the density and leaf area of plants of the three species, divided into five stem-diameter-at-breast-height (DBH) (1.3 m) classes (2.5 to 5 cm; >5 to 10 cm; >10 to 20 cm; >20 to 30 cm; and >30 to 40 cm DBH). None of the three species had plants in all classes: only *L. racemosa* had plants in the >30 to 40 cm DBH class but had no plant in the two previous classes; and *A. schaueriana* also had no plant in the >20 to 30 cm class. Trees representing each class were chosen, had their canopy projection area determined, were cut and had their masses of leaves determined. Twenty-two trees of *R. mangle* were cut, 23 of *L. racemosa* and 16 of *A. schaueriana*, at least four trees in each class, except in the class of largest size, in which only one tree was cut. The canopy projection area was determined measuring the two largest orthogonal diameters and assuming an ellipsoid shape (Schaeffer-Novelli & Cintron, 1986). All leaves were collected, weighed and sampled to determine dry weight after oven-dried at 65°C. One hundred shot tips (apices) of each diameter class and species were randomly selected and had their leaves counted, weighted and each one leaf had its area determined. The growth apex is the terminal structure of each branch

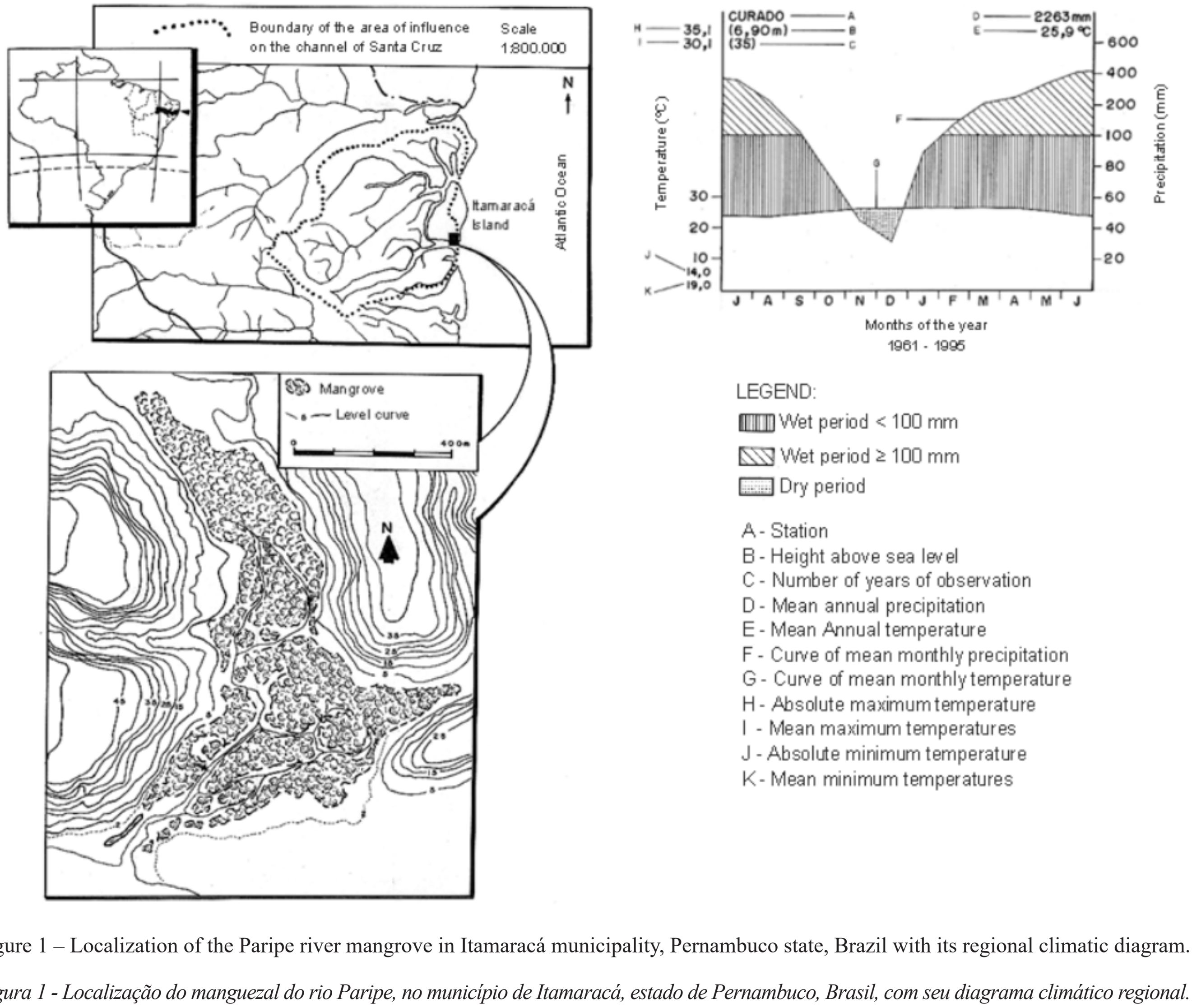

Figure 1 – Localization of the Paripe river mangrove in Itamaracá municipality, Pernambuco state, Brazil with its regional climatic diagram.

Figura 1 - Localização do manguezal do rio Paripe, no município de Itamaracá, estado de Pernambuco, Brasil, com seu diagrama climático regional.

where leaves, flowers, fruits and new apices are formed (Medeiros & Sampaio, 2013). The number of apices of each cut tree was estimated dividing its total leaf mass by the average leaf mass of one apex. The leaf area of each plant was estimated multiplying its number of apices by the average apex leaf area of its diameter class and species. The plant leaf area index was estimated dividing the plant leaf area by its canopy projection area. The leaf area of each species in the mangrove was estimated multiplying the average leaf area of each diameter class by the plant density in each class, previously determined (Medeiros & Sampaio, 2008). The leaf index of the mangrove was calculated as the sum of the leaf areas of the different species.

The mangrove area was determined based on the vectorization, in a computer screen, of images obtained from the Google Earth software, version 7.1.8.3036 (32-bit). The mangrove vegetation was differentiated from other land covers (water, urban, agriculture and others) based on visual observation. Based on images from the TM sensor of the Landsat 5 satellite, with a spatial resolution of 30 m, dated from September 18, 1997, the normalized difference vegetation indices (NDVI) were calculated. The same vegetation index was calculated from the Sentinel 2A satellite, with a resolution of 10 m, dated January 3, 2017.

3. RESULTS

The number of leaves per growth apex (including young, mature and senescent ones) and their size and biomass varied little among plant stem diameter classes. This was expected since these morphological variables are little affected by the size of the plants. Therefore, only the general averages are presented (Table 1). Since the size and biomass of the leaves and the number of leaves per apex were higher in *R. mangle*, the area and biomass of leaves per apex were more than double in this species than in *L. racemosa* and *A. schaueriana*.

The number of apices per plant increased as the size of the plants increased (Tables 2 to 4). A linear increase in the stem diameter class corresponded to a more than proportional increase in the number of apices because the diameter is a one-dimension unit and the apices are distributed in the whole tridimensional crown volume. In *R. mangle*, there was a 45-fold increase in the number of apices from the 2.5-5 cm to the >20-30 cm diameter class (Table 2). In *L. racemosa* (Table 3), the increase was higher (114-fold) because some of the plants of this species that occupied the fringe of the mangrove attained the largest size among all trees in the vegetation (>30-40 cm diameter class). Apart from this border area, the trees of *L. racemosa* were much smaller, none belonging to the >20-30 cm diameter class. Also smaller were the *A. schaueriana* plants, reaching at the most the >10-20 cm diameter class, with only a 4-fold increase in the number of growth apices (Table 4). Since the leaf area and biomass of the average apex was statistically similar for all plant sizes, within each species, the total leaf area and leaf biomass per plant increased proportionally to number of apices per plant.

Table 1 - Leaf characteristics in growth apices of *Rhizophora mangle*, *Laguncularia racemosa* and *Avicennia schaueriana* in the Paripe river, Pernambuco.

Tabela 1 - Características das folhas nos ápices de crescimento de Rhizophora mangle, Laguncularia racemosa e Avicenia shaueriana no rio Paripe, Pernambuco.

Characteristic	*R. mangle*	*L. racemosa*	*A. schaueriana*
Leaf length (cm)	10.2 ± 0.27	7.5 ± 0.14	6.9 ± 0.15
Leaf width (cm)	4.5 ± 0.1	3.8 ± 0.1	3.9 ± 0.1
Leaf area (cm^2)	32.4 ± 1.4	21.0 ± 0.8	18.4 ± 0.8
Leaf biomass (g)	0.75 ± 0.04	0.53 ± 0.02	0.37 ± 0.02
Leaf mass per area (g cm^{-2})	0.023	0.025	0.020
Number of leaves per apex	9.74	6.62	8.11
Apex leaf area (cm^2 $apice^{-1}$)	315.8	138.9	149.4
Apex leaf biomass (g $apice^{-1}$)	7.3	3.5	3.0

The crown projection area, as a two-dimensional unit, also increased with the increase in stem diameter, being 25-, 19- and 3.5-fold higher from the class of the smallest to the class of the largest diameters, in *R. mangle*, *L. racemosa* and *A. schaueriana*, respectively (Tables 2 to 4). The leaf area index (LAI) of the average plant in each stem diameter class, as the ratio of the plant leaf area and its crown projection area, varied in an irregular pattern with plant size. In *R. mangle* and *A. schaueriana*, the largest LAI (2.0 and 1.8) were estimated for the <5-10 cm diameter class while in *L. racemosa* the LAI increased until the class of largest diameters (3.0 in the >30-40 cm class), which corresponded to the largest trees in the mangrove.

Considering the plant densities of each diameter class and species and their leaf areas, their contribution to the leaf area of the whole mangrove vegetation can be estimated (Tables 2 to 4). *R. mangle* contributed the most (3.26 of the total 3.96, 82%) due to the combination of high plant densities, large plants, many apices and large leaves, while *A. schaueriana* contributed the least (0.15, 4%), mainly as a result of few and small plants. The contribution of *L. racemosa* (0.55, 14%) was levered by the large plants of the border area.

Table 2 - Characteristics of *Rhizophora mangle* plants of different stem diameter and their contribution to mangrove leaf and crown areas in the Paripe river, Pernambuco.

Tabela 2 - Características das plantas de Rhizophora mangle com diferentes diâmetros de caule e suas contribuições para as áreas foliares e de copas no rio Paripe, Pernambuco, Brasil.

Characteristic	Stem diameter class (cm)			
	2.5 – 5	>5 – 10	>10 – 20	>20 – 30
Growth apices (apex plant^{-1})	77	647	2022	3479
Plant leaf area (m^2 plant^{-1})	2.4	20.4	63.9	109.9
Plant leaf biomass (kg plant^{-1})	0.6	4.7	14.8	25.4
Crown projection area (m^2 plant^{-1})	3.1	10.2	41.2	79.0
Plant leaf area index (m^2 m^{-2})	0.8	2.0	1.6	1.4
Plant density (plant ha^{-1})	1722	651	188	29
Mangrove leaf area (m^2 ha^{-1})	4133	13280	12013	3187
Mangrove crown area (m^2 ha^{-1})	5338	6640	7746	2291

Table 4 - Characteristics of *Avicennia schaueriana* plants of different stem diameter and their contribution to mangrove leaf and crown areas in the Paripe river, Pernambuco.

Tabela 4 - Características das plantas de Avicenia shaueriana com diferentes diâmetros de caule e suas contribuições para as áreas foliares e de copas no rio Paripe, Pernambuco, Brasil.

Characteristic	Stem diameter classes (cm)		
	2.5 – 5	>5 – 10	>10 – 20
Growth apices (apex plant^{-1})	232	516	852
Plant leaf area (m^2 plant^{-1})	3.5	7.7	12.7
Plant leaf biomass (kg plant^{-1})	0.7	1.5	2.6
Crown projection area (m^2 plant^{-1})	3.0	4.3	16.5
Plant leaf area index (m^2 m^{-2})	1.2	1.8	0.8
Plant density (plant ha^{-1})	29	159	14
Mangrove leaf area (m^2 ha^{-1})	102	1224	178
Mangrove crown area (m^2 ha^{-1})	87	684	231

Table 3 - Characteristics of *Laguncularia racemosa* plants of different stem diameter and their contribution to mangrove leaf and crown areas in the Paripe river, Pernambuco.

Tabela 3 - Características das plantas de Laguncularia racemosa com diferentes diâmetros de caule e suas contribuições para as áreas foliares e de copas no rio Paripe, Pernambuco, Brasil.

Characteristic	Stem diameter class (cm)			
	2.5 – 5	>5 – 10	>10 – 20	>30 – 40
Growth apices (apex plant^{-1})	132	283	1155	15085
Plant leaf area (m^2 plant^{-1})	1.8	3.9	16.0	209.0
Plant leaf biomass (kg plant^{-1})	0.5	1.0	4.1	52.9
Crown projection area (m^2 plant^{-1})	3.6	8.7	18.9	70.1
Plant leaf area index (m^2 m^{-2})	0.5	0.4	0.8	3.0
Plant density (plant ha^{-1})	202	448	29	14
Mangrove leaf area (m^2 ha^{-1})	364	1747	464	2926
Mangrove crown area (m^2 ha^{-1})	727	3898	548	981

The mangrove area could be divided into five different sectors based on their NDVI indices obtained from images of 1997 (Figure 2). The indices varied from 0.68, in the lower left mangrove limit, to 0.77, in the upper right mangrove limit. Twenty years later, four of the five sectors had higher indices (0.77 to 0.80) and only one had a lower index (0.74), and this sector was the one with the highest index in 1997.

4. DISCUSSION

The average areas of the leaves of all three species were similar to those reported by Lima *et al.* (2013) but lower than those reported by Arrivabene *et al.* (2014), both in mangroves at higher latitudes in Brazil (Paraná and Espírito Santo states), while the biomasses were in the same range; thus, the leaf mass per area (LMA) was higher at the Paripe river mangrove (Table 1). This indicates that they have higher sclerophylly indices and may have higher longevity (Lima *et al.*, 2013). Their longevities were discussed in another article (Medeiros & Sampaio, 2013) and were longer than those in Venezuelan (Suárez, 2003) and one Northern Brazilian (Menezes *et al.*, 2008) mangroves but in the same range as those in Florida (Ross *et al.*, 2001) and another Northern Brazilian (Mehlig, 2006) mangroves. The absence of data on leaf number, area and biomass per apex in South American

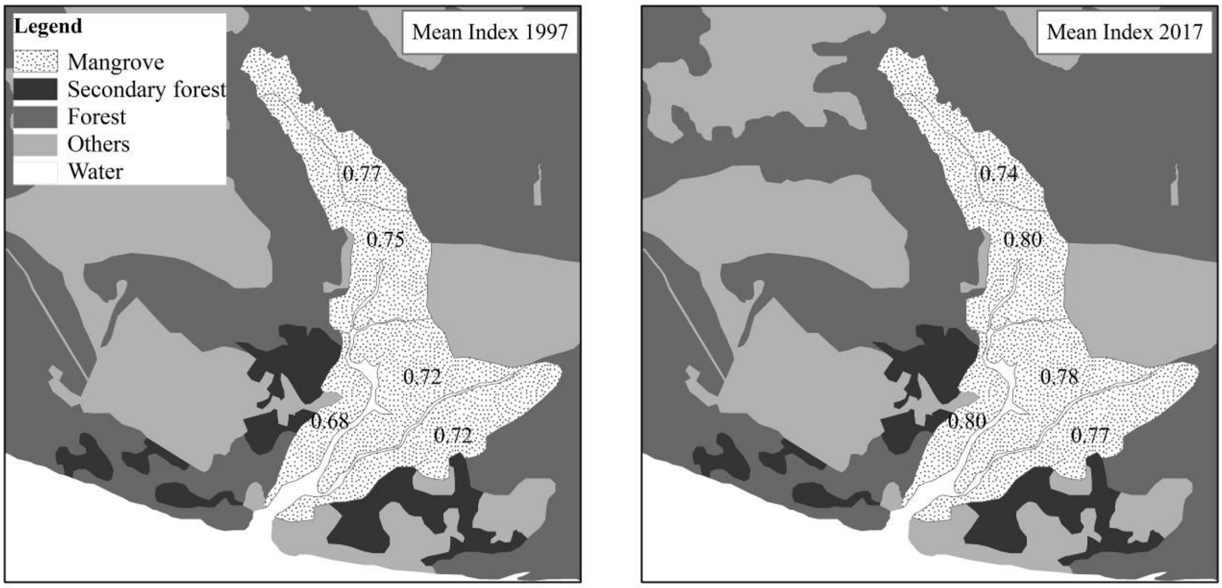

Figure 2 - Normalized difference vegetation index (NDVI) values in 1997 and 2017 in the Paripe river mangrove in Itamaracá municipality, Pernambuco state, Brazil.

Figura 2 - Valores de Índice de Vegetação da Diferença Normalizada (NDVI) em 1997 e 2017 no manguezal do rio Paripe, município de Itamaracá, estado de Pernambuco, Brasil.

Atlantic mangroves, except those reported for the same mangrove area (Medeiros & Sampaio, 2013), prevents further discussion on the subject. In Asia, leaf longevity and the number of leaves per shoot are greater in higher latitudes (Wilson & Saintilan, 2012) but the species are not the same present in Brazilian mangroves.

As the plants grew bigger, their numbers of apices, leaf areas, leaf biomasses and crown projection areas increased, as expected. However, the leaf area indices of individual trees peaked in the >5-10 (*R. mangle* and *A. schaueriana*) or >10-20 cm (*L. racemosa*) diameter classes. Therefore, plants at intermediate sizes had more layers of leaves in crowns that seemed to be squeezed by larger plants that are more able to compete for light. Once the plants reach the top of the canopy, they can spread their crowns and may do without some of the leaves in the lower layers, which receive less light and may have a worse balance of photosynthesis and construction and/or maintenance costs (Suárez, 2003; Suárez & Medina, 2005; Li *et al.*, 2011).

This stacking of leaf layers is reflected in the overall leaf area index (LAI) of the mangrove (3.96), which is higher than those of all species and size classes, independently considered. This LAI is also composed of the overlapping of the crowns. The sum of all crown projection areas (2.92 ha ha^{-1} = *R. mangle*, 2.20 + *L. racemosa*, 0.62 + *A. schaueriana*, 0.10) indicates an overlapping of almost three crown layers occupying the same space.

This overlapping is responsible for the relatively high LAI of the Paripe river mangrove. It is higher than those of mangroves in São Paulo state (1.17 to 1.48; Lima *et al.*, 2013), but still higher values can be reached in different areas: 5.33 in heterogeneous mangroves in Australia and Indonesia (Kamal *et al.*, 2016); 5.6 in the Dominican Republic (Sherman *et al.*, 2003); 5.7 in large mangroves in the United States of America (Araújo *et al.*, 1997; Lagomasino *et al.*, 2014); and up to 7.53 in mangroves in Mexico (Kovaks *et al.*, 2009). Values similar or slightly below that of the Paripe river have been reported for many places (Cintron & Schaeffer-Novelli, 1985; Clough, 1998; Sherman *et al.*, 2003; Kovacs *et al.*, 2005). The high LAI in the Paripe river mangrove is consistent with the high leaf production along the year: 13.96 Mg ha^{-1} (Medeiros & Sampaio 2013).

The NDVI indices of the different mangrove sectors varied from 0.68 to 0.77, in 1997, and from 0.74 to 0.84, in 2017. Those are relatively short ranges and all quite high, close to the saturation values (Mutanga *et al.*, 2012) where the indices do not respond linearly to increases in vegetation cover (Kamal *et al.*, 2016). Mangroves that occupy larger areas, with higher variation in vegetation cover, may have larger NDVI ranges. Kamal *et al.* (2016) reported Landsat TM based NDVI values varying from 0.40 to 0.65 for a mangrove in Australia where the LAI varied from 0.26 to 3.23 and averaged 1.27 and NDVI values varying from 0.45 to 0.69 for a mangrove in Indonesia, where the LAI varied from 0.88 to 5.33 and averaged 2.98. In both areas, higher NDVI values occurred where the vegetation had higher density canopy cover with overlapping leaves, independently of the mangrove structure and species composition. Mangroves dominated by *R. mangle* in Florida, USA, had NDVI values ranging from 0.61 to 0.86, with LAI of up to 5.7 (Lagomasino *et al.*, 2014). A larger variation was observed in the Mexican Pacific mangroves (Kovacs *et al.*, 2009) where the NDVI varied from less than 0.1 to close to 0.60, with LAI from 0.11 to 7.53. The Paripe river mangrove NDVI and LAI values are higher than those in Australia and Indonesia and similar to those in the USA, indicating a vegetation with a high canopy cover. The higher NDVI values in the Paripe river than in Mexico and the similarity with NDVI values in Florida mangroves, in spite of the higher LAI in the North American mangroves, can be attributed to the saturation of the optical index (Kuenzer *et al.*, 2011) and the different vegetation structures, having the taller North American mangroves more overlapping leaf layers.

The fact that 20 years later the NDVI values were even higher in four of the sectors indicates that the mangrove may still be accumulating leaf layers, and possibly still growing and accumulating more biomass. In 1997, the aboveground biomass was estimated to be 105 Mg ha^{-1}, (Medeiros & Sampaio, 2008) below that of mangroves of the same species in other northern and northeastern Brazilian states (Souza & Sampaio, 2001; Deus *et al.*, 2003; Cougo *et al.*, 2015). However, the plants were bigger than those in other southern Brazilian mangroves (Soares 1999; Bernini & Rezende 2004; Soares & Schaeffer-Novelli, 2005). The slight NDVI decrease in the upper right sector corresponds to some human interference from the neighboring agricultural field. A similar trend of higher NDVI indices, after these 20 years, was observed in the images of other mangrove areas along the border of Itmaracá island (data not shown). Therefore, as an overall picture, the increases in the NDVI indices imply that, contrary to many other mangroves in the world, the vegetation of the Paripe river has been relatively protected from human impact.

5. CONCLUSIONS

The number, size and biomass of leaves per growth apex varied little among plant stem diameter classes and were higher in *R. mangle* than in *L. racemosa* and *A. schaueriana*. Their leaf mass per area (LMA) and sclerophylly indices were higher than in southern Brazilian mangroves. The number of apices and the crown projection area increased significantly in plants with larger stem diameters. The mangrove leaf area index (3.96) was higher than those of southern Brazilian mangroves. *R. mangle* contributed (82%) to most of the total leaf area index, due to the combination of high plant densities, large plants, many apices and large leaves.

The leaf areas corresponded to normalized difference vegetation indices (NDVI) from 0.68 to 0.77 in 1997 and from 0.74 to 0.80 in 2017. Therefore, contrary to many other mangroves in the world, the vegetation of the Paripe river has been relatively protected from human impact in the last twenty years.

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