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Structural plasticity and species distribution in a peri-urban mangrove of Southeastern Brazil

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The goal of this study was to evaluate the structural plasticity and distribution of mangrove species in the Estuarine System of Greater *Vitória* (ESGV). Four areas distributed along the estuary were analyzed. Fringe and basin forests were sampled in each station. Concomitantly to the forest sampling, interstitial salinity was measured in the field, and sediment was collected for analysis of organic matter (OM) content. There was variation in species distribution along the ESGV. Regarding the structural variables, comparative analysis between physiographic types indicated that basin forests were more mature than fringe forests. OM content values were higher in basin forests. There was an inverse relationship between values of mean DBH (Diameter at Breast Height) and live trunk density (R^2 = 0.8795, p <0.0001), and a positive relationship between OM content in the sediment and mean DBH (R^2 = 0.3215, p = 0.00593). Multivariate analysis evidenced the formation of three groups: The first with higher structural development and dominated by *Rhizophora mangle*, in areas with higher OM content; the second dominated by *Laguncularia racemosa* with more impoverished soils; and third group, which aggregated plots subjected to environmental and anthropic stress (like tree cutting), restricted to more urbanized areas.

Key words: Forest maturity, organic matter, multivariate analysis.

INTRODUCTION

Mangroves are among the most productive ecosystems on the planet (Alongi, 2009); however, when compared to other tropical forests, they have a low number of plant species (Kantharajan et al., 2018). Nevertheless, the plants of these forests display a wide range of structural and functional attributes that promote their survival in relatively severe conditions of the intertidal zone (Lugo et al., 2014). Thus, evaluation of the mangrove ecosystem diversity should consider not only the species richness but also the structural and functional heterogeneity of the environment.

The structural and functional plasticity of the mangrove is related to environmental factors that interact at different scales. This ecosystem is globally limited by climate, with

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elements like solar radiation and temperature setting the limit of maximum forest development (Walsh, 1974; Alongi, 2009; Soares et al., 2012). At a regional scale, the mangrove development depends on the sediment origin, tidal energy, waves, and currents to which it is subjected. Differences in the magnitudes of these forces originate the geomorphological environments that will condition the processes of mangrove colonization, development, and succession (Thom, 1984). Besides, the water balance should be considered at the regional scale (Schaeffer-Novelli et al., 1990, 2000) since, together with geological patterns, it contributes to the habitat diversity of the environment.

Locally, the flood frequency, as determined by microtopography and the continental water supply control the mangrove structure and function. These two environmental parameters act on other variables, including salinity, redox potential, dissolved oxygen concentration, and nutrient availability, resulting in the control and distribution of species as a function of their optimal ecological tolerance (Semeniuk, 1983; Estrada et al., 2013).

Lugo and Snedaker (1974) divided mangroves into six physiographic types according to the flood regime. This classification was later modified by Schaeffer-Novelli et al. (2000), who reduced the physiographic types for fringe and basin. Fringe forests develop along protected coastlines and into sheltered estuaries and bays, often flooded by tides. The basin forests are located in sites that are less frequently washed by tides, and in many cases present water stagnation. Besides the environmental factors previously cited, anthropic factors like changes in water flow, sediment retention by river dams, metal contamination, eutrophication, and tree cutting also influence the species structure, functioning, and composition (Lovelock et al., 2009; Gupta et al., 2012; Souza et al., 2015; Scales and Friess, 2019). Thus, several studies have reported the characteristics of peri-urban mangroves (Dahdouh-Guebas et al., 2002; Branoff, 2017; Kantharajan et al., 2018; Santos et al., 2018), resulting in monitoring that contributes to the management of water and coastal resources.

The spatial distribution of mangrove species responds to flood frequency, salinity, redox potential, concentration of organic matter (OM), nutrients, and sediment granulometry (Lovelock et al., 2006; Estrada et al., 2013; Barreto et al., 2016; Soares et al., 2017), as well as biotic factors (Smith III et al., 1989) of the ecosystem. Therefore, each estuary may display a different species composition, depending on the range of these variables.

Studies on the mangrove structure and its species composition can expose the structural plasticity of the ecosystem. The evaluation of vegetation structure can elucidate the patterns of species zonation and succession, forest development, forest maturity, and anthropic tensors acting on the vegetation, and is also the basis for managing the ecosystem (Estrada et al., 2013; Kiruba-Sankar et al., 2018; Sreelekshmi et al., 2018). On the other hand, the structure data has been still little explored to understand such management.

The mangrove of the Estuarine System of Greater Vitória (ESGV) is structurally heterogeneous due to abiotic factors and anthropic pressures. Its forests can be classified as being from intermediate to mature developed, and the most preserved portions are those far from urbanization (Zamprogno et al., 2016).

In this context, this study aims to (1) evaluate the structural plasticity of the ESGV; and (2) assess the species distribution along the ESGV. The researchers expect that the findings on the structure of mangrove forests will contribute to the identification of environmental functions, like carbon sink (by trapping OM) and carbon stock (through plant biomass).

MATERIALS AND METHODS

Study area

The study was conducted in the ESGV mangroves (Figure 1), located in the central region of the Eastern Brazilian coast (20°10’44,0’’S and 20°16’31,1’’S – 040°15’11.0’’W and 040°20’44.0’’W). The climate of the region is classified as 'tropical monsoon' (Am) according to the Köppen’s climate classification map for Brazil (Alvares et al., 2013). The annual rainfall for the municipality of Vitória, with a historical series between 1984 and 2014, is approximately 1,350 mm. The rainiest months are between October and April and the driest ones are between May and September (Alvares et al., 2013; INCAPER, 2018).

The region has water deficiency in almost all months of the year and water surplus > 100 mm in November and December (Rebello et al., 2011). The Santa Maria da Vitória River is the primary freshwater source of the ESGV (Teubner Jr. et al., 2018), and Station 2 is the closest to the river (Figure 1).

Four mangrove species occur in the Espírito Santo State: *Avicennia germinans* L., *A. schaueriana* Stapf & Leechman ex Moldenke, *Laguncularia racemosa* (L.) Gaertn, and *Rhizophora mangle* L.

Delimitation of the studied stations

Four stations were delimited in the ESGV mangroves (E1, E2, E3 and E4) according to their location in the bay, in the counterclockwise from the north to the south opening (Figure 1). The selected stations depict the extremes of the ESGV mangroves. Each station was divided by physiographic type, that is, fringe (F) and basin (B), totaling eight sampling points (E1F, E1B, E2F, E2B, E3F, E3B, E4F and E4B) with three replicates (= plots) each, except for the E1 and E2 basins, which had two replicates each. The classification of forests into physiographic types was based on Schaeffer-Novelli et al. (2000).

Abiotic variable

In the field, the OM sampling and measurement of interstitial salinity were performed concomitantly with the forest sampling. The sampling of interstitial salinity was performed using three polyvinyl

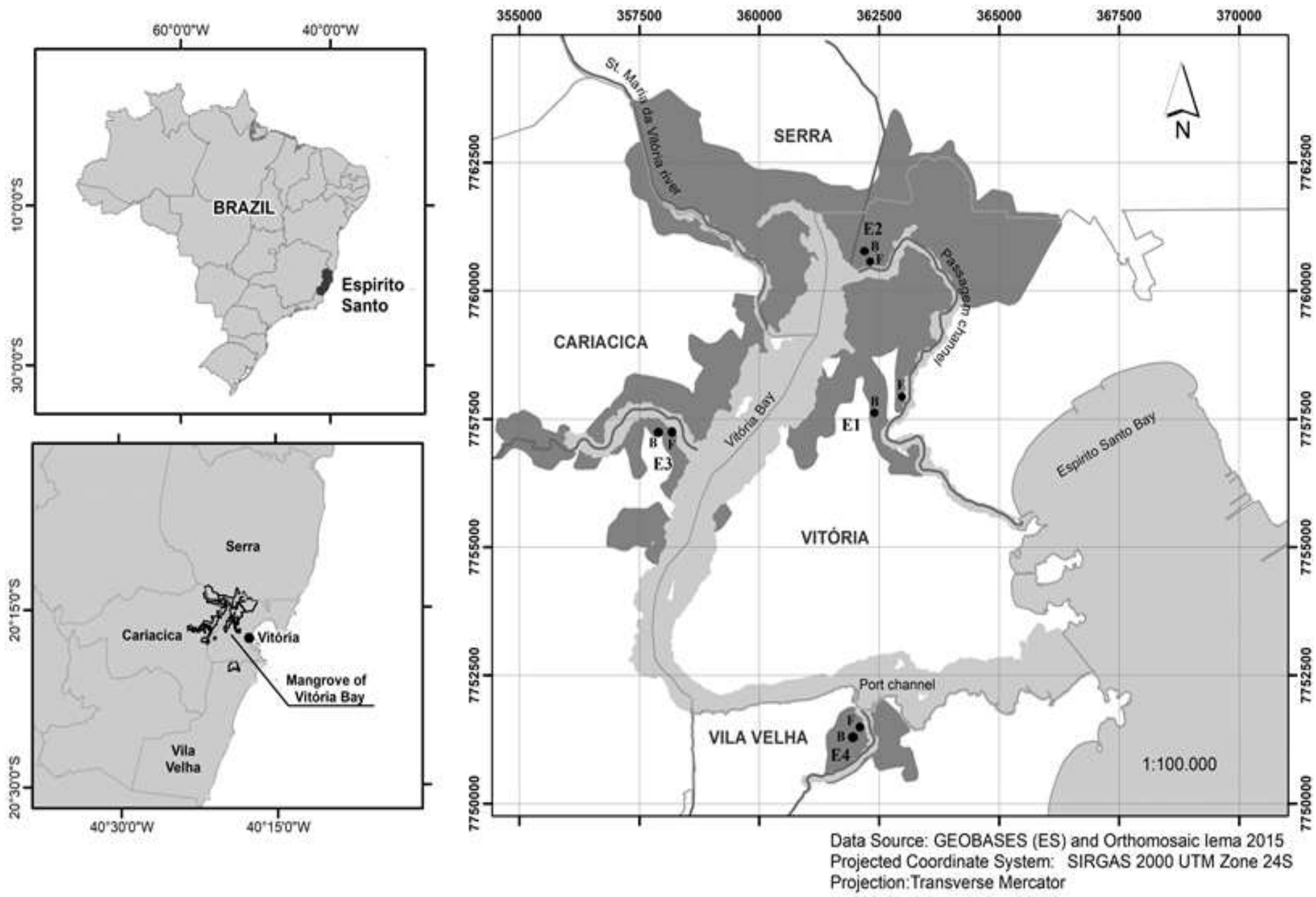

Figure 1. Location of the study stations in the Estuarine System of Greater Vitória (ESGV), Espírito Santo State, Brazil, counter-clockwise from the northern opening (E1) towards the southern opening (E4). F = Fringe; B = Basin. Organized by Elizabeth Del'Orto e Silva.

chloride (PVC) tubes with 5 cm in diameter and 50 cm in depth, which were inserted in each plot to reach at least 45 cm of the sediment. After percolation of the water retained in the sediment, which was available to the plants, the salinity value was measured using a multiparameter (Hach) calibrated with standard solution. Samples of shallow sediment (the first 2 cm) were collected for OM analysis, after removing the deposited macroscopic material, and kept frozen until the sampling procedures per plot in the study stations. The OM content was determined by its dry weight, after ignition in a muffle for 4 h at 550°C. The samples were lyophilized before ignition. The samples were treated individually, with three samples per plot.

Structural characterization

The vegetation structure was carried out according to the methodology proposed by Schaeffer-Novelli and Cintrón (1986), with the plot method adopted. The samplings were performed between August and Decemberm 2015. The plot area ranged from 100 to 693 m², depending on the structural development of the forest, as proposed by Estrada (2009).

The structural parameters measured were tree height (m) and diameter at breast height (DBH), with measuring tape in π units (Forestry Suppliers). The diameter (cm) was obtained from trees higher than 1.0 m and measured at the height of 1.30 m. Following Soares (1999), the diameter was measured below the first branch in shorter individuals. The counting of the number of trunks per individual, the description of the alive or dead condition of the plant and the species identification were also conducted.

In the laboratory, structure records were used to obtain community structure parameters, as follows: Total live and dead basal area (m^2/ha), mean DBH (cm), mean height of all individuals (m), density of live and dead trunks (trunk/ha), species dominance (%), and relative density and dominance per diameter class (%), according to the methodology proposed by Schaeffer-Novelli and Cintrón (1986), with modifications.

The mean DBH was calculated using the following formula:

$$\text{Mean DBH} = \sqrt{\text{BA x } 12{,}732.39\ /\ \text{N}} \qquad (1)$$

Where BA = sum of the live basal area, and N = the total number of live trunks.

The relative basal area was used to define the dominant species in each plot. The dominant species was considered the one with the highest value of the median and with the statistical difference

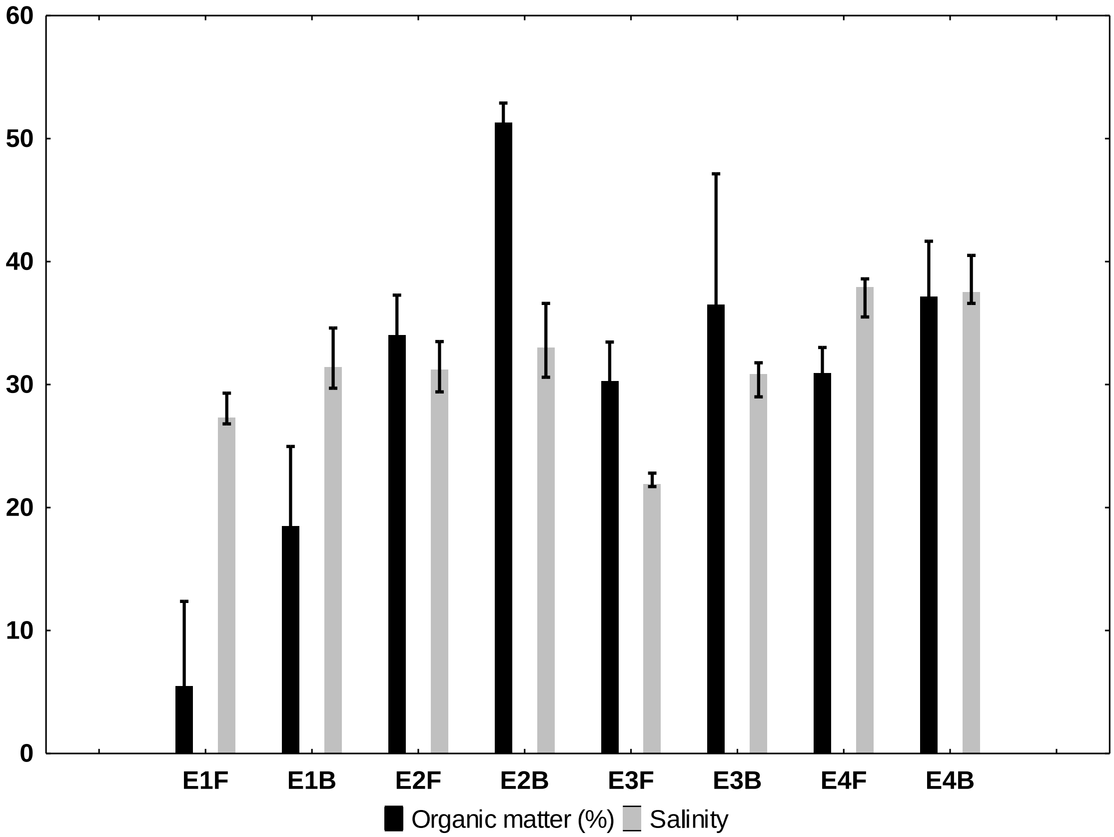

Figure 2. Median (histogram), maximum and minimal (bars) values for organic matter (OM) content (%) and interstitial salinity of the sampling stations (E1 to E4) and physiographic types per station (F, fringe; B, basin) at the Estuarine System of Greater Vitória (ESGV), Espírito Santo State, Brazil.

compared to other species; if the species was not identified as dominant in a station or physiographic type, it was considered mixed.

Data analysis

The abiotic and structure data were not normal, and thus the non-parametric Kruskal-Wallis test was used for comparisons between study stations, together with the multiple comparison test *a posteriori*. In this test, the plots sampled at each station were considered as replicates, independently of the physiographic type. The comparison between fringe and basin was performed using the Mann-Witney test, in which the plots sampled in each physiographic type were analyzed as replicates (Zar, 1996).

In the principal components analysis (PCA), transformed biotic data (mean height, relative basal area ≥ 10 cm, mean DBH, live trunk density, relative dead trunk density, trunk per individual ratio) were considered, using the correlation matrix of data (Hair Jr et al., 2009). The canonical correspondence analysis (CCA) and the corresponding permutation test (Legendre and Legendre, 1994) were generated from the biotic data mentioned previously, together with the relative basal area for each species and the abiotic data. The data were transformed by their division by the Euclidean length of the variable vector. Aiming to verify if the fringe and basin were structurally different from each other, polygons referring to each physiographic type were used.

Forest maturity was determined using simple regression analysis with the mean DBH and trunk density variables (transformed by logarithm); the multiple regression analysis considered the mean DBH, salinity, and OM content variables to test the effect of abiotic factors on forest development. The α value of 0.05 was considered for all tests.

RESULTS

Abiotic variable

The percentage of OM content in the sediment varied between the study stations, with E1 (north opening) presenting statistically the lowest value and the highest recorded values are near the mouth of the rivers (E2 and E3). The interstitial salinity value was relatively higher in the E4 (south opening), where there is marine domain. The highest values for both variables were recorded for the basin forests (Figure 2 and Table 1), regardless of their location in the estuary system. The data did not follow the normality pattern; thus, they were represented by the median obtained between the sample replicates, as well as by the maximum and minimum values

Table 1. Kruskal-Wallis (H) and *a posteriori* multiple comparison tests for abiotic variables across sampling stations and Mann-Whitney's (U) test for physiographic types. Test results are followed by degrees of freedom (D.F.), the number of samples (N), and *p* values.

Variable	Source of variation	D.F.	N	Test value	*p*	Multiple comparison test
OM (%)	Station	3	66	38.20	< 0.0001*	2, 3, 4 > 1
	Type	1	66	231.00	< 0.0001*	B > F
Salinity	Station	3	66	43.37	< 0.0001*	1, 2, 3 < 4
	Type	1	66	281.50	0.0148*	B > F

recorded.

Structural characteristics

The general characteristics of the vegetation structure are shown in Table 2. Since they correspond to the analysis of replicates per station and physiographic types, the values were also represented by the median, maximum and minimum. The highest mean DBH was 20.28 cm in E2B, representing a value 50% above the fringe DBH. In relation to the mean DBH of the fringe and basin forests, the most homogeneous were E1 and E3. The mean height canopy was similar for all forests. The highest trees occur in the basin forests in E2 and E4. Table 3 describes the result of the statistical analysis for the variables that were significantly different between the stations or physiographic types. Higher values of mean DBH and mean height were found for the E2 basin, which had the lowest live trunk density (Table 2). E1 was significantly different from E3 concerning live trunk density values and had the highest median value (Tables 2 and 3). E4 shows the highest values of trunk per individual ratio in comparison to E1 and E3 (Tables 2 and 3).

Regarding the structural variables, there was a higher homogeneity between the stations, with differences observed for the values of live trunk density and trunk per individual ratio (Table 3). On the other hand, the forest types (fringe and basin) did not have significant differences in the values of trunk per individual ratio (Table 3). In the comparative analysis of structural data, the highest values of live and dead trunk density, as well as a higher contribution of trunks, were found in the intermediate diameter class (that is, ≥ 2.5 cm < 10.0 cm) of the fringe forests. The basin forests had the highest values of basal area contribution and trunk density (live + dead) in the DBH class of ≥ 10 cm. The mean DBH explained 87% of the live trunk density variability (R^2 = 0.8795; $p < 0.0001$; degree of freedom = 3; Akaike Information Criterion (AIC) = 4.1065), with an inverse relationship between both variables.

A PCA was performed based on the structural data (live trunk density/ha, mean DBH, mean height, trunk per individual ratio, relative dead trunk density, relative basal area ≥ 10 cm) (Figure 3). The variables were the same used for diagnosing the forest maturity within the different methods used, with 75% of the information explained by the horizontal (52%) and vertical (23%) axes. The variables with the highest positive weight in component 1 (horizontal axis) were mean DBH (0.93, PCA correlation value), mean height (0.82), and relative basal area ≥ 10 cm (0.70); the live trunk density/ha (-0.93) had negative weight. On the other hand, the plots positively correlated with this axis were E2B2 (3.94), E3B3 (2.81), E2B1 (2.32), and E3F1 (1.66); the negatively correlated were E2F3 (-2.79), E1F3 (-1.98), E1F2 (-1.93), E2F2 (-1.90), E3F2 (-1.68), E1F1 (-1.47) and E1B2 (-1.46).

The variables with higher weight in component 2 (vertical axis) were relative dead trunk density (0.71) and trunk per individual ratio (0.60). The plots positively correlated with the axis were those of the station 4 and E2F1 plot; the E1B1, E3B1, E3B2, and E3F3 plots were negatively correlated (Figure 3).

The frequency distribution per DBH class for each station is shown in Figure 4. Most of the studied forests showed the "inverted J" pattern (negative exponential distribution), except for the E2 basin and the E3F1 plot, which had a wider distribution. A higher mean DBH value was observed in these plots in comparison to the others.

E2B2 contributed with living individuals in the last diameter class sampled (44.1 to 46.0 cm), differently from E1F3 and E4B1 that had a distribution of trunks with smaller diameters, reaching the class of 16.1 to 18.0 cm. Both E2B2 and E3F1 had pulsed colonization.

A higher contribution of dead trunks was observed in the smallest diameter classes. Cut

Table 2. Median (Med), maximum (Max) and minimal (Min) values for structural parameters of sampling stations (E1 to E4) and physiographic types per station (F, fringe; B, basin) at Estuarine System of Greater Vitória (ESGV), Espírito Santo State, Brazil.

Station	Forest	Mean DBH (cm)			Height (m)			Dens. (tr.lives.ha^{-1})			Dens. (tr.dead.ha^{-1})			Trunk/individual			BA ≥ 10 cm (%)			Dens. ≥ 2.5 cm (%)			Dens. ≥10.0 cm (%)		
		Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max
1	F	7.57	7.35	8.35	5.8	5.65	7.17	5200	4933	5800	889	600	1600	1.17	1.09	1.22	67.26	53.61	72.99	58.78	44.82	59.45	24.14	16.21	25.19
	B	7.83	7.19	8.47	4.1	4.03	4.25	4054	4000	4108	289	179	400	1.03	1.03	1.04	90.35	88.37	92.33	14.00	10.83	17.17	22.6	20.2	25.00
	Overall	7.57	7.19	8.47	5.6	4.03	7.17	4933	4000	5800	600	179	1600	1.09	1.03	1.22	72.99	53.61	92.33	44.82	10.83	59.45	24.13	10.83	59.45
2	F	7.35	5.73	12.23	5.49	4.34	8.26	4489	1375	6545	606	356	1333	1.07	1.04	1.18	75.74	68.05	82.01	52.29	25.42	56.92	9.32	9.17	21.53
	B	20.28	18.42	22.15	8.95	7.45	10.45	653	606	699	78	70	87	1.42	1.25	1.6	98.44	97.53	99.35	14.39	8.33	20.45	76.51	61.36	91.66
	Overall	12.23	5.73	22.15	7.45	4.34	10.45	1375	606	6545	356	70	1333	1.18	1.04	1.6	82	68.05	99.35	25.42	8.33	56.92	21.53	9.17	91.66
3	F	10.33	7.53	15.26	6.07	4.42	7.34	2667	1778	3644	222	89	356	1.03	1.03	1.45	86.37	77.82	93.31	41.53	39.58	44.04	23.07	11.9	56.25
	B	10.35	10.18	18	5.22	4.57	8.93	1981	607	2566	346	89	373	1.3	1.07	1.34	92.39	90.31	97.08	17.94	15.87	28.09	31.74	25.61	76.92
	Overall	10.34	7.53	18	5.65	4.42	8.93	2273	607	3644	284	89	373	1.18	1.03	1.45	91.35	77.82	97.08	33.84	15.87	44.04	28.68	11.9	76.92
4	F	10.37	8	12.15	6.82	6.61	8.14	2815	2604	3022	578	407	710	1.97	1.81	2.13	86.71	72.78	87.02	58.02	41.37	58.92	27.58	20.98	41.07
	B	8.47	7.89	10.84	6.5	6.06	6.98	2711	2625	2773	533	508	708	2.16	2.14	2.47	74.12	70.43	88.71	48.8	43.75	54.79	28.76	26.19	43.7
	Overall	9.62	7.89	12.15	6.72	6.06	8.14	2742	2604	3022	571	407	710	2.13	1.81	2.47	80.42	70.43	88.71	51.8	41.37	58.92	28.17	20.98	43.75
Tipo	F	8.17	5.73	15.26	6.34	4.34	8.26	3333	1375	6545	589	89	1600	1.17	1.03	2.13	76.79	53.61	93.31	48.56	25.42	59.45	22.3	25.42	59.45
	B	10.27	7.19	22.15	6.28	4.03	10.45	2595	606	4108	360	70	708	1.32	1.03	2.47	91.32	70.43	99.35	19.2	8.33	54.79	30.25	20.2	91.66

Table 3. Statistical comparisons of structural parameters across the sampling stations (E1 to E4) and physiographic types per station (F, fringe; B, basin) using Kruskal-Wallis followed by *a posteriori* multiple comparisons and Mann-Whitney's test. Test results are followed by degrees of freedom (D.F.), the number of samples (N), and *p* values.

Variable	Source of variation	D. F.	N	Test value	*p*	Multiple comparison test
Dens. (v.tr.ha^{-1})	Station	3	22	8.69	0.0336*	1 ≠ 3
	Type	1	22	29.00	0.0409*	F > B
Dens. (m.tr.ha^{-1})	Station	3	22	7.18	0.0661	-
	Type	1	22	30.00	0.0479*	F > B
Tr.ind^{-1}	Station	3	22	13.18	0.0043*	4 ≠ 1, 3
	Type	1	22	45.00	0.3226	-
BA ≥ 10.0 cm	Station	3	22	4.59	0.2037	-
	Type	1	22	21.00	0.0101*	B > F

Table 3. Cont'd

Dens. ≥ 2.5 cm	Station	3	22	4.57	0.2057	-
	Type	1	22	18.00	0.0056*	F > B
Dens. ≥ 10.0 cm	Station	3	22	2.93	0.4015	-
	Type	1	22	23.00	0.0147	B > F

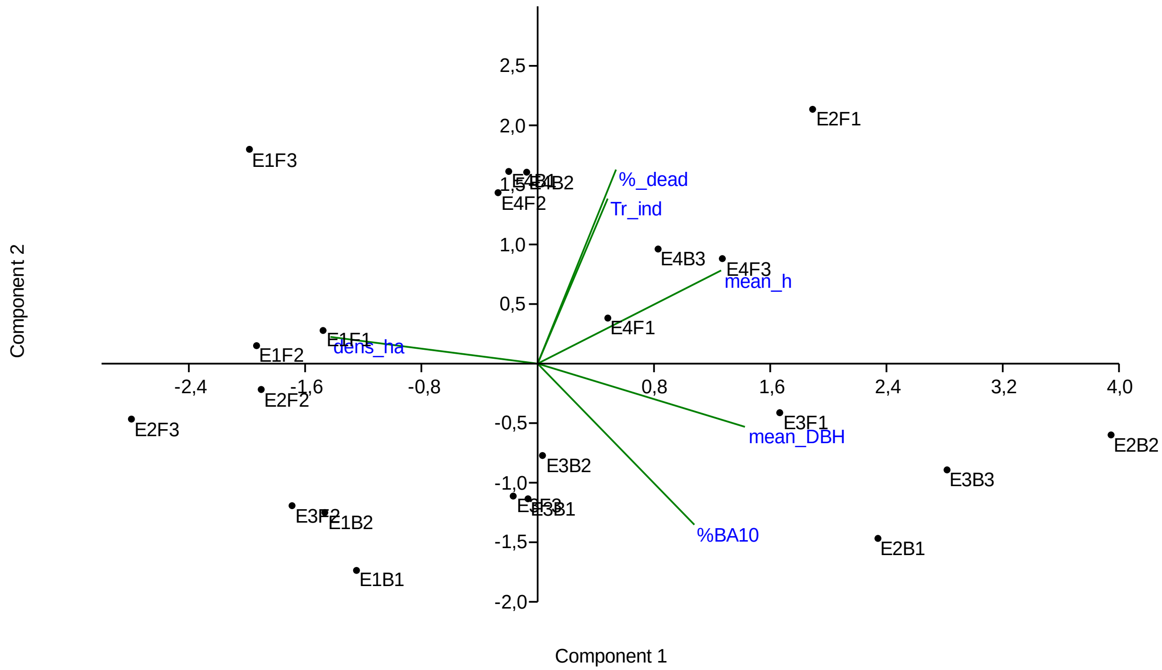

Figure 3. Principal component analysis of vegetation structure of mean height (mean_h); relative basal area ≥ 10 cm (%BA10); mean DBH (mean_DBH); the live trunk density (dens_ha); the relative dead trunk density (%_dead); and the trunk per individual ratio (Tr_ind).

trunks were detected in some sampled areas, contributing 43 and 69% of the dead trunks in the E1F1 and E2F1 plots, respectively.

The cut target species were *L. racemosa* (E1F1) and *R. mangle* (E2F1); the diameter class 2.1 to 4.0 cm in E2F1 concentrates more than 20% of dead trunks (Figure 4). The E1 area is intensely urbanized and in E2F1 the cut was for a pathway.

In Brazil, *L. racemosa* is used as firewood and

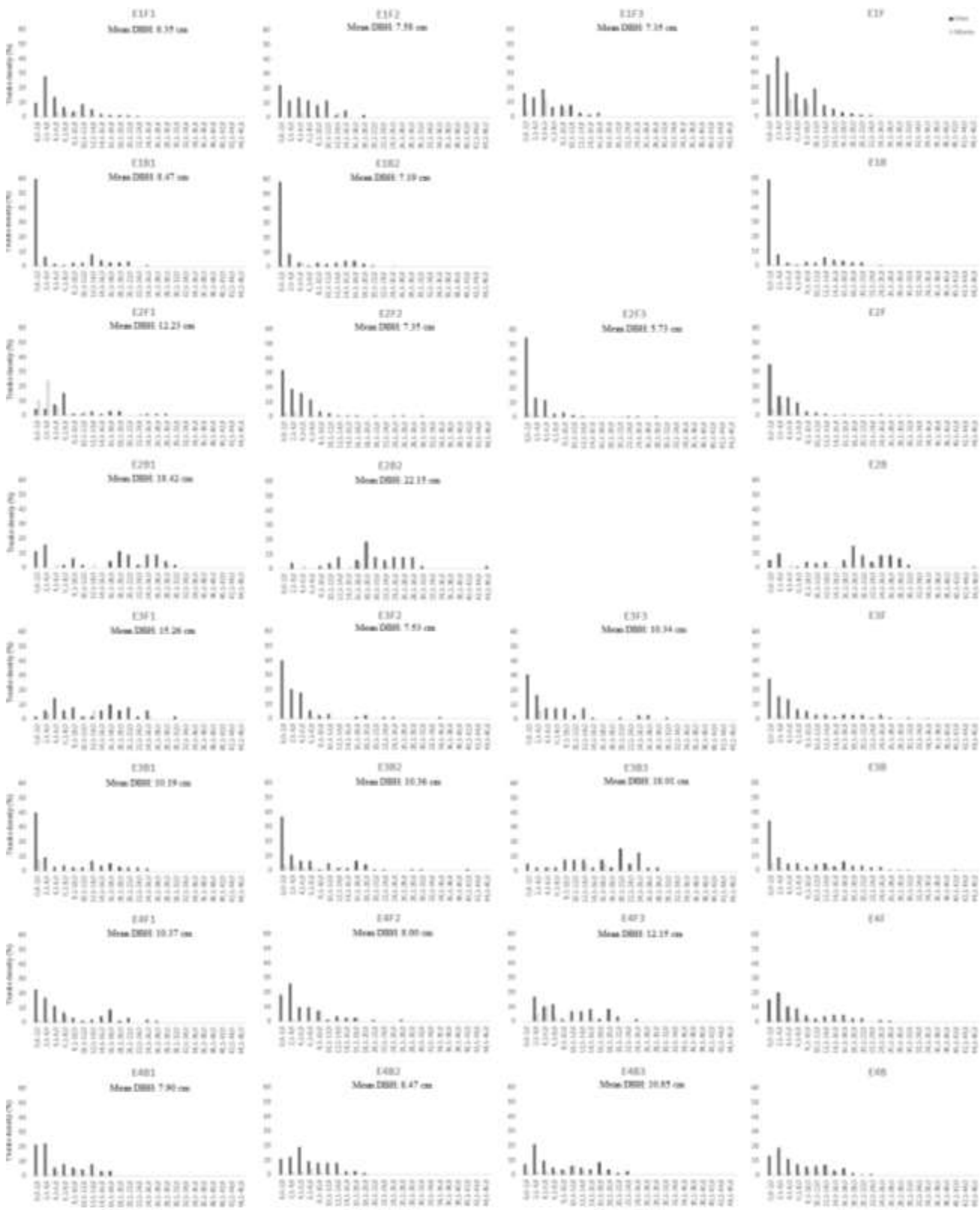

Figure 4. Distribution (relative values) of live and dead trunks in study area plots in the Estuarine System of the Greater Vitória (ESGV), Espírito Santo State, Brazil.

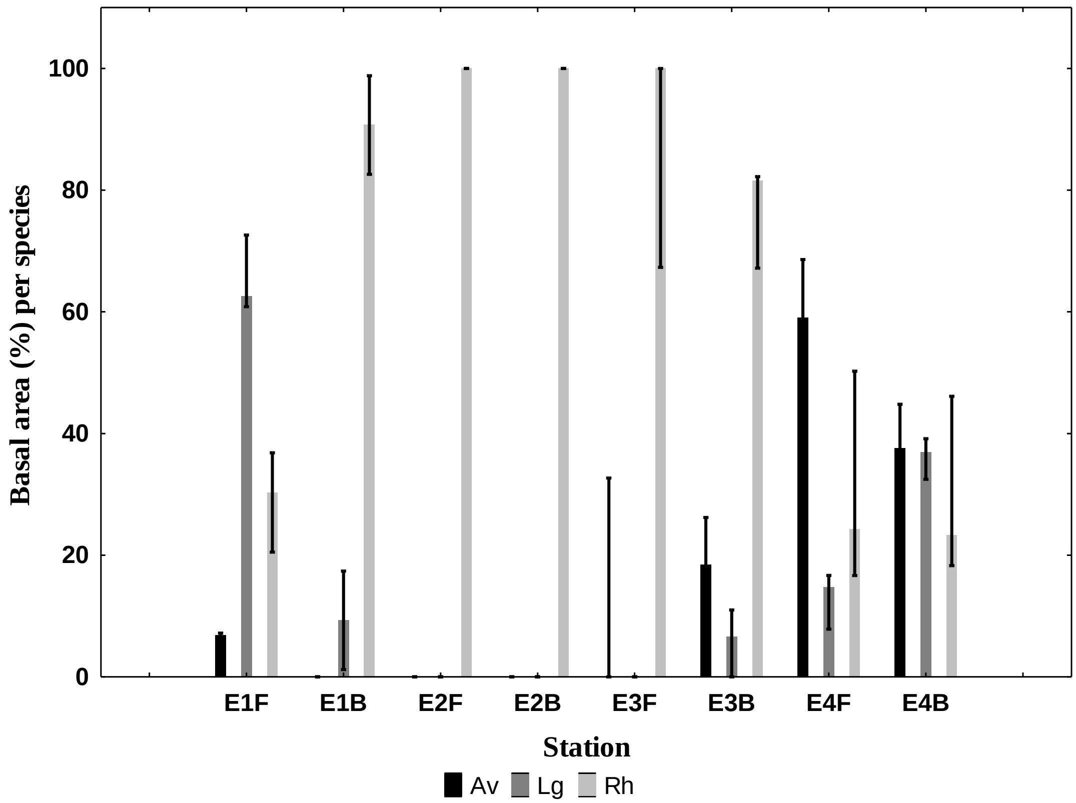

Figure 5. Median (histogram), maximum and minimum (bars) values for the basal area (%) per species for each sampling station (E1 to E4) and physiographic type per station (F, fringe; B, basin) at the Estuarine System of Greater Vitória (ESGV), Espírito Santo State, Brazil.

posts.

Species distribution

Figure 5 shows a histogram with the median, minimum and maximum values obtained for the relative basal area of the species recorded in the stations and physiographic types. It is observed that at the extremes of the estuarine system there is greater diversity of species, with *L. racemosa* and *A. schaueriana* showing higher median in the north and south opening, respectively. Higher data variability is observed in E3F and E4. In E3F, this dispersion is the result of the presence of *A. schaueriana* in only one of the replicas and absence of *L. racemosa* for the station. In E4, *R. mangle* displays maximum value distant from the median increasing the data variation. Statistical difference was observed in species dominance in the stations in the Kruskal-Wallis test; the exception was E2, whose forests are monospecific for *R. mangle*. Concerning *L. racemosa*, the median of the basal area indicated dominance >50% in E1; however, in the Kruskal-Wallis test, the species was considered statistically similar to *R. mangle*. *R. mangle* was dominant in E3; on the other hand, in E4, there was no statistical difference between species dominance (Figure 5 and Tables 4). Considering the physiographic types, *R. mangle* had the highest median value of the relative basal area concerning the other species, both in the fringe and in the basin forests (Figure 5 and Table 4).

Regression analysis - abiotic and biotic components

Initially, multiple regressions were performed between the mean DBH as a function of the OM and salinity variables; however, this last parameter was removed from the model since it was not significant. Subsequently, a positive relationship was found between the OM content and mean DBH (R^2 = 0.3215; p = 0.00593), that is, the OM content explained 32% of the variability of the mean DBH data.

Canonical correspondence analysis

The CCA (Figure 6) separated the majority of the polygons of the fringe and basin stations and mainly of the plots,

Table 4. Statistical comparisons of the basal area (%) per species for each sampling station (E1 to E4) and each physiographic type per station (F, fringe; B, bay) at the Estuarine System of Greater Vitória (ESGV), Espírito Santo State, Brazil, using Kruskal-Wallis followed by *a posteriori* multiple comparisons test. Test results are followed by degrees of freedom (D.F.), the number of samples (N), and *p* values.

Source of variation	D.F.	N	Test value	*P*	Multiple comparison test
E1	2	15	7.77	0.0205*	Lg, Rh > Av
E2	2	15	14.00	0.0009*	Rh
E3	2	18	12.79	0.0017*	Rh > Av, Lg
E4	2	18	4.99	0.0823	-
F	2	36	12.08	0.0024*	Rh > Av, Lg
B	2	30	14.50	0.0007*	Rh > Av, Lg

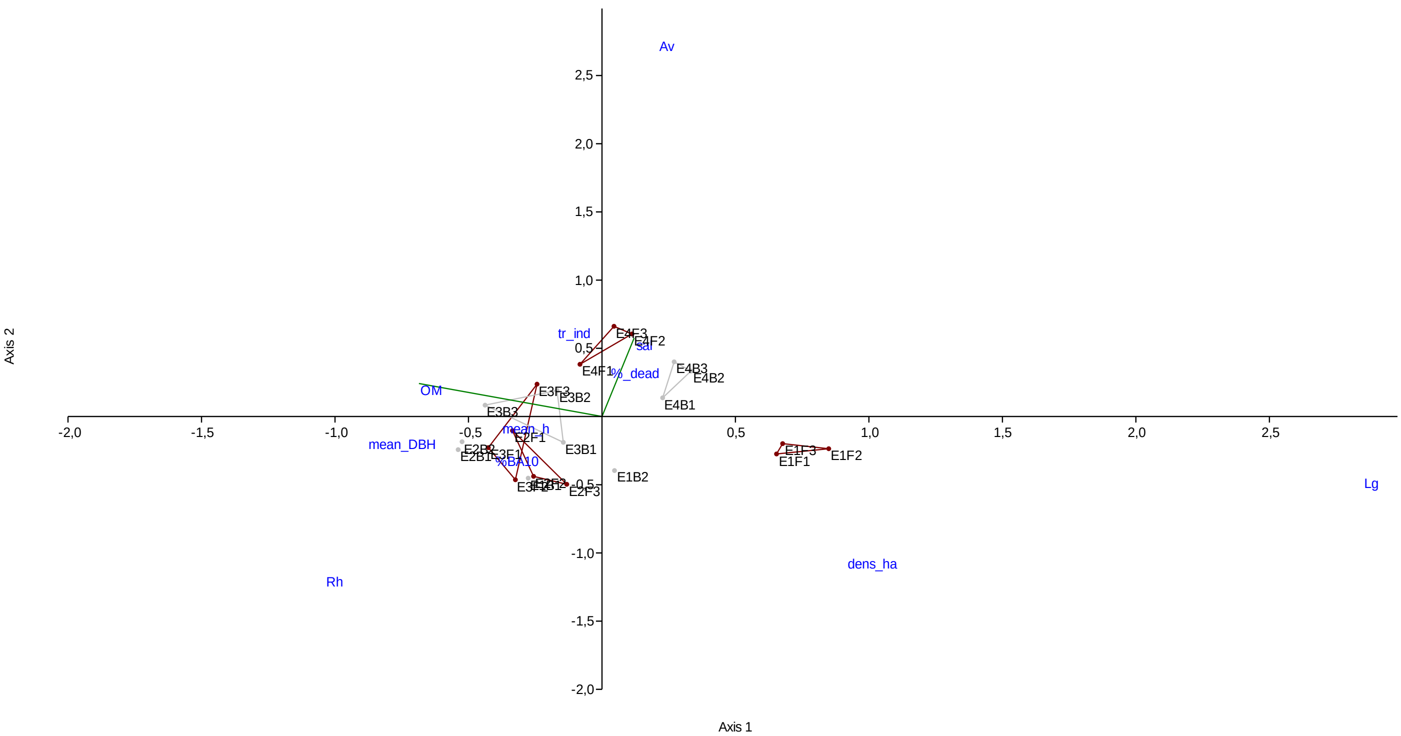

Figure 6. Canonical Correspondence Analysis using vegetation structure biological data, mean height (mean_h); relative basal area ≥ 10 cm (%BA10); mean DBH (mean_DBH), live trunk density (dens_ha); relative dead trunk density (%_dead); trunk per individual ratio (Tr_ind); relative basal area of *A. schaueriana* (Av); relative basal area of *L. racemosa* (Lg); and relative basal area of *R. mangle* (Rh) – and abiotic variables, salinity (sal); and organic matter (OM) content.

according to the dominant species. Concerning the permutation test, axis 1 was significant ($p = 0.009901$) and explained 99.95% of the environmental and biological data. Axis 2 was also significant ($p = 0.009901$) and explained 0.05% of the data variability.

The OM content was negatively related to the axis 1 (correlation value = -0.68). The vegetation structure variables related negatively to this axis were the mean DBH (-0.88), basal area > 10 cm (-0.40), and mean height (-0.38). Salinity was positively related to axis 2 (0.56); the biological variables positively related to this axis were trunk per individual ratio (0.57) and relative dead trunk density (0.30). On the other hand, live trunk density (-0.99) was negatively related to axis 2 (Figure 6).

A. schaueriana and *L. racemosa* dominated the upper and lower right quadrants, respectively. *A. schaueriana* was regulated by salinity, and *R. mangle* predominated in the lower left quadrant, in more developed forests.

The E1 fringe was regulated by the live trunk density, mainly of *L. racemosa*. E2 and E3 were both influenced by the OM content and, respectively, mean DBH and tree height. E4 was regulated by salinity and higher values of relative dead trunk density and trunk per individual ratio.

DISCUSSION

Mangrove forests are globally subjected to different regulating factors influencing their structural plasticity (Lovelock et al., 2006; Alongi, 2009; Suwa et al., 2009; Estrada et al., 2013; Madi et al., 2016). The structural development of the ESGV mangroves is affected by several local environmental variables, such as pH, salinity, OM content, and granulometry, besides anthropic influences that can modify these variables and/or change land use (Almeida, 2007; PMV, 2008a, b; Zamprogno et al., 2016; Teubner Jr. et al., 2018). The areas near the mouth of the Santa Maria da Vitoria River (RSMV) receive a higher freshwater supply than the areas located in the southern opening of the basin. By their turn, they can present differences in growth and development due to changes in freshwater flow.

A statistical approach was used to compare sampling stations and physiographic types, as recommended by Lovelock et al. (2006), Cavalcanti et al. (2009), Estrada et al. (2013), and Madi et al. (2016). The use of several plots as replicates in the same station allowed us to compare forests statistically since structural patterns of spatial form were identified in the ESGV mangrove.

There were statistical differences between the sampling stations for the biological variables live trunk density and trunk per individual ratio and for the abiotic variables OM and salinity. E1 showed a higher live trunk density and the lowest OM content; this station has a significant occurrence of *L. racemosa,* which forms degraded monospecific stands (Soares et al., 2003) and sandy patches (Cintron and Schaeffer-Novelli, 1983), with lower OM content in the sediment. These sediment characteristics have also been recorded by other studies carried out in the proximities of E1, both in forest patches (Zamprogno et al., 2016) and estuary (Grilo et al., 2016).

Salinity and the trunk per individual ratio were higher in E4. The water scarcity caused by salinity apparently does not restrict tree growth, although it can influence the increase in branching. Changes in the architecture of arboreous plants follow an increase in disturbance intensity (Bellingham, 2000). This behavior has been observed in mangroves in previous studies (Pellegrine et al., 2009; Estrada et al., 2013). Moreover, the sediment around E4 had a higher content of heavy metals compared to the natural sediments of the system (mangrove + estuary), due to industrial and urban effluents (Jesus et al., 2004; Zamprogno, 2015). The three species sampled in this study were observed in this locality: *A. schaueriana*, *L. racemosa*, and *R. mangle*; the first two are traditionally considered as more tolerant to salinity than the latter one (Ball, 1988; Sobrado, 2000; Parida and Jha, 2010). Ball (1988) and Sobrado (2000) observed a conservative behavior of *A. schaueriana* and *L. racemosa* regarding characteristics of water use for increased tolerance to salinity. However, some new studies recorded the dominance of *R. mangle* in areas with salinity close to the seawater (Estrada et al., 2013; Bompy et al., 2014). In this study, it is likely that salinity affects species composition, given the predominance of *R. mangle* in other areas, differently from E4, where salinity values are closer to the optimum for this species (Ball, 1988).

Mangroves show a reduction of their structure in response to environmental gradients of salinity, flood frequency, and nutrient concentration (Lovelock et al., 2006; Estrada et al., 2013; Soares et al. 2017). Schaeffer-Novelli et al. (1990) described similar values of rainfall and potential evapotranspiration for the Vitória Bay. Usually, mangrove structure has a reduction from fringe to basin forest, as a result of the increase in salinity (and consequent water restriction). In Setiba Bay, Rio de Janeiro, there is a marked reduction in the structural gradient from the fringe to the basin, with basin forests exhibiting lower mean DBH and height, associated with higher tree density (Estrada et al., 2013). However, the opposite of this was observed, that is, the relative density of trunks and the basal area of individuals > 10.0 cm increased from the fringe towards the basin which contains the smallest relative density of trunks between 2.5 and 10.0 cm.

Mangroves tend to colonize depositional environments and, as the sediment is deposited, more individuals are recruited. Vitória Bay suffers erosion in several areas caused by both natural and anthropic changes in its central channel (Veronez et al., 2009) and compromise in sediment supply to the estuarian system (Teubner Jr. et al., 2018); the mangrove fringe areas in the ESGV are more fragile in comparison with basin areas, in the extent that the dead trunks density is higher in this physiographic type. Besides, most of the fringe areas evaluated by Zamprogno (2015) present a particular erosive sediment profile, and therefore the forest is expected to exhibit lower structural development and forest degradation. Kantharajan et al. (2018) and Santos et al. (2019) reported structural reduction in areas with anthropogenic interference and marine erosion (like the fringe forests sampled here), including reduction in basal area, higher tree density and smaller diameter, not allowing forest to reach maturity. In a climate change scenario, the balance between sedimentation, erosion and vegetation growth will dictate the maintenance of the ecosystem in certain locations. One of the problems reported by Willemsen et al. (2016) for mangroves under anthropic influence is the reduction in sediment supply to the ecosystem, which decreases their capture capacity.

Thus, restoring sediment supply increases the resilience of the system, with fringe forests depositing fines sediments first and most intensely.

The OM content accumulated in the mangrove sediment is associated with litter production and OM degradation processes, as well as species composition, forest age, and flood frequency (Lacerda et al., 1995; Chen and Twilley, 1999; Middleton and Mckee, 2001; Marchand et al., 2003; Barreto et al., 2016; Chaikaew and Chavanih, 2017). This work shows evidence of a relationship between forest maturity and OM content in the sediment. Several studies suggested that the maturity of mangroves is related to a negative regression of forest density, as a function of the mean DBH (Jimenez et al., 1985; Schaeffer-Novelli and Cintrón, 1986; Estrada et al., 2013). One could follow this reasoning, considering the regression established between the OM content in the sediment and mean DBH.

Alongi (2009, 2011) and Lovelock et al. (2010) reported that older forests could be associated with increased concentration of organic carbon in the sediment. Therefore, forest age may be an important factor in sediment maturity, especially in the OM accumulation through agglomeration of dead roots. OM accumulation in the sediment are complex and depend on numerous factors, like flood frequency, allochthonous contribution, microorganisms, and physical-chemical characteristics of the sediment (Marchand et al., 2003; Alongi, 2009); therefore, this pattern might not be universally the same for mangroves. E2B was the station with the highest OM content (~50%) in the sediment, and its forest had higher structural development. Besides, this physiographic type is characterized by a lower frequency of flooding, decreasing OM removal by tides (Schaeffer-Novelli et al., 2000).

Although salinity is considered the main abiotic factor in the analysis of mangroves (Ball, 1988; Parida and Jha, 2010), it should be pointed out that this variable did not reach a level that would prevent the species occurrence in this sampled region, considering the analysis between the physiographic types (Parida and Jha, 2010; Bompy et al., 2014). The salinity values obtained along the estuary were different from the expected, based on literature data and the geographic position within the estuary (Jesus et al., 2004; Sterza and Fernandes, 2006; Grilo et al., 2016). This was the case of the plots closer to the RSMV mouth: the salinity values were above the expected for the area, most likely due to the low rainfall during the sampling period (INCAPER, 2018). Leite (2018) also found a negative correlation between the RSMV flow and estuarine salinity and reported estuarine salinization during the same sampling period than our study. Two dams regulate the RSMV flow in the middle course of the river, the hydroelectric plants of Rio Bonito and Cachoeira Suiça, as well as the leveling dam of the State water and sewage company (Companhia Espírito Santense de Saneamento - CESAN) in the lower course of the river (AGERH, 2016; Teubner Jr. et al., 2018). Both structures can cause a reduction in the river flow, in addition to the rain scarcity. This may have contributed to the exclusion of salinity from the multiple regression analysis.

Climatic variability, expressed by the variation in the average conditions or other climate statistics at spatial and temporal scales, as well as isolate weather events (IPCC, 2001), are known to affect humid areas, including mangroves (Ward et al., 2016). These variations occur as a result of natural internal processes within the climatic system or due to natural external variations and/or anthropogenic factors (IPCC, 2001). Changes in the rainfall patterns, marked by periods of prolonged drought, together with the alteration of the river flow through the installation of dams, affect the salinity of estuaries. Consequently, they act in the mangroves by increasing or reducing their area, modifying species composition, and decreasing their growth. These scenarios will be common in the Anthropocene and clearly illustrate the link between terrestrial and coastal ecosystems (Lugo et al., 2014; Ward et al., 2016; Ghosh et al., 2017). Thus, changes in land use along the RSMV, like the replacement of natural forests by agriculture and livestock (Teubner Jr. et al., 2018) can affect mangroves in the ESGV.

When describing species composition, species dominance was considered based on the data for the relative basal area (Estrada et al., 2013; Kiruba-Sankar et al., 2018). Parcial et al. (2014) note that species dominance can be assessed through the basal area since there is a strong correlation between the crown and stem diameter. In this context, *L. racemosa* and *R. mangle* are codominant in E1; E2 is monospecific with *R. mangle* and E3 is dominated by *R.* mangle; and E4 has a mixed forest.

The mortality rate was a relevant variable in this study. Mortality tends to be high at the beginning of colonization and decreases as maturity progresses (Jímenez et al., 1985). On the other hand, massive mortality is characterized by the death of countless individuals, affecting all diameter classes as a result of pressures like extreme weather (Servino et al., 2018), fertilizers, changes in sedimentation processes, and flood pattern and frequency (Jímenez et al., 1985; Lovelock et al., 2009; Duke et al., 2017). Several studies interpret mortality as a result of anthropic pressure acting on vegetation, even if there is no massive mortality (Soares, 1999; Cavalcanti et al., 2009; Sinfuego and Buot Jr., 2014). Mortality in E4 could be associated to stress due to chemical contamination, as Zamprogno (2015) recorded higher concentrations of polyaromatic hydrocarbons and polychlorinated biphenyls in the vicinities of E4 and Jesus et al. (2004) recorded heavy metal concentrations. The trunk per individual ratio seems to support such inference since this variable had a higher value in this area compared to others. Tree branching can also be associated to soil characteristics, variations in the flood regime, tide energy, wind, and anthropic stress (Bellingham, 2000; Estrada et al., 2013; Scales and Friess, 2019).

Studies have reported the effects of small-scale selective cutting on the mangrove structure. This pressure can lead to cumulative effects on the structure, species composition, and succession, as well as change sediment characteristics (Alongi and Carvalho, 2008; Chagas et al., 2015; Scales and Friess, 2019). The multivariate analyses showed that cutting was a relevant factor for separating the groups, affecting the relative dead trunk density such that E2F1 was grouped with the E4 plots.

In this study, multivariate analyses were relevant for a better understanding of the structural patterns, anthropic pressures, and colonization characteristics of the species. This approach highlights the role of structural patterns and species composition of mangroves and has been employed by Sinfuego and Buot Jr. (2014), Kiruba-Sankar et al. (2018) and Sreelekshmi et al. (2018). OM content was an important variable to separate the groups and, along with regression data, indicated that the most structurally developed areas of the ESGV mangroves are associated with higher OM contents. The coefficient of determination obtained here for OM and mean DBH may represent the effect of anthropic stress, since dead trunks are not accounted for in the calculation of mean DBH, and species composition; observing the CCA, it is clear that *R. mangle* dominated forests are associated with the OM content in the sediment and the inverse occurs for *L. racemosa*, whereas E4 deviates from this pattern, despite showing relatively mature forests. The E4 has OM content and salinity compatible with the appropriate levels for the development of the three species, allowing competition between them for the same habitat. OM trapping in sediments of mangrove forests has contributed to the reduction of suspended particles in the water body from the several basins that drain into the estuarine system and allows maintaining the critical ecosystem function provided by oysters, which purify the estuarine water (Leite et al., unpublished data).

Mangroves colonize different coastal environments, where the variables have different levels depending on the hydrological domain (Thom, 1984; Woodroffe, 2000) the urban areas surrounding the ecosystem, that is, besides environmental characteristics; they are subject to the different kinds and intensity of land use in the drainage basin. This interferes with the processes of forests colonization and development, highlighting the importance of a more detailed assessment of the structure for coastal environmental management. Thus, analyses of the relationship between structural aspects and species composition with environmental variables like salinity, OM, rainfall, river flow, and estuary changes are critical for the study of peri-urban mangroves.

Conclusion

Information from environmental data such as precipitation, salinity and OM content is essential for the management of mangrove ecosystems, helping to understand habitat mosaics (or habitat complexity), which structural data alone could not clarify. In this study, the fragility of the fringe in comparison to the basin of the ESGV mangroves was observed. The fringe is less developed structurally, with evidence of forest degradation given the higher density of dead trunks.

Drought periods and the presence of dams affect estuarine salinity and can affect mangrove dynamics in the mid to long-term. Sediment retention by dams alters erosion and sedimentation patterns, which should be considered in mangrove studies since, in a sea level rise scenario, maintaining the ecosystem depends on the accretion of sediment.

Structural variability was observed across the analyzed stations regarding live trunk density, trunk per individual ratio, and particularly species composition. Species distribution accompanies their ecological optima, especially for OM content in the sediment and interstitial salinity, both for *L. racemosa* and *R. mangle*. These species were co-dominant in E1, which was the station with the lowest OM content. The presence of *R. mangle* in that area could be due to the flood frequency and environmental changes. The Aribiri River mangrove (E4), a mixed forest area, is known for suffering anthropic pressures regarding chemical contamination and higher salinity in the estuary. This study associated OM content in the sediment to forest maturity and the predominance of *R. mangle* in mature mangrove forests.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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