

Research Article

Dendrometrical Structure and Physicochemical Analysis of Mangrove Sediments from the Nyong River Estuary (Cameroon, Atlantic Coast)

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Abstract

Mangrove estuaries are not immune to the threats posed by climate and anthropogenic constraints on aquatic environments. In the Nyong River estuary, mangrove ecotone has capital importance for biodiversity conservation due to its localization in the Douala-Edea protected area. For this study, seven quadrats were delimited in aim to evaluate mangrove structure and assessed his interplay with sediment and water physicochemical characteristics. The study revealed a total of 120 individuals of 4 regularly encountered species over a distance of 14 km: *Rhizophora racemosa*, *Avicennia germinans*, *Rhizophora harrisonii* and *Phoenix reclinata* palms. The marshy soils under the mangrove have Total Nitrogen percentages varying between 0.04 and 0.68%. Total Organic Carbon (from 2.20 to 8.61%) and Total Organic Matter (from 3.66 to 14.64%) contents have a similar pattern. The ratios of Carbon and Nitrogen (C/N) reflect the presence of organic matter and plant debris over a large proportion of the estuary. The ratio of Nitrogen and Phosphate (N/P) reflects the low availability of nitrogen in relation to phosphorus. The cation elements evolve on average in the order $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$. This study provides information that would help explore linkages for future research on biogeochemical balance in mangrove sediment and their implementation.

Keywords

Mangroves, Physicochemical Parameters, Sedimentary Physics, Nyong Estuary, National Park Douala-Edea

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1. Introduction

Both estuary beds and the seabed are the deposition sites for a more or less important fraction of the organic material produced in the water column, as well as for (detrital) material of continental origin transiting mainly via rivers. The weight of the pelagic input to the benthic environment is related to the modalities and intensity of organic production processes for a given coastal marine area [1-3].

Many environmental factors regulate the structure and function of mangrove ecosystems, including climate, geomorphology, hydrodynamics and physicochemical parameters of sediments [4-6]. Several authors have studied the physical and chemical characteristics of soils in mangrove ecosystems. These parameters are regulated by the river and tidal currents, sediment texture, redox status, microbial activities, litter production and decomposition [7, 8]. The degradation of organic matter started in water, and proceeds when it is in contact with sediments in different ways depending on its nature, its stage of evolution and the characteristics of the environment [9-11]. Sedimentary particles are indeed a privileged site of fixation for microorganisms, but the conditions prevailing in this environment will evolve during burial, particularly with regard to oxygenation, pH and redox potential [12]. As a result, most biological processes will be limited to the most superficial levels of sediment. This biological activity will result in the release or consumption of elements dissolved in the pore waters that circulate more or less freely between the grains, thus making possible a series of reactions (adsorption, desorption, group exchanges, etc.) that will determine the evolution of certain compounds during burial [13]. These different edaphic factors (pH, organic matter, exchangeable cations, soil texture and water chemistry) are deeply influenced by the physical phenomena of the soil and the behaviour of water appears to be fundamental [14, 15]. Mangrove sediments are generally characterized by high concentrations of organic matter, exchangeable cations or bases compared to non-mangrove environments [16-18]. These physical and chemical parameters of sediments influence the development of mangrove tree species in terms of structure and growth [19]. Macronutrients such as exchangeable cations, i.e. calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}), vary according to the tide and pore water saturation indicating good soil fertility [20].

Mangroves are plant formations specific to coastal ecosystems such as estuaries and deltas in tropical regions, which are subject to daily tidal action [21-25]. The plant species that characterise mangroves are known as paletuvia, of which the two most important, if not exclusive, genera on the

Atlantic coast are: *Rhizophora* and *Avicennia* [26].

Mangroves or swamp forests are among the most important tropical forest ecosystems that provide several essential resources and services. They generate rich plant litter with abundant microorganisms that provide important food for the living organisms found there [27]. Each year, they protect millions of people from flooding and billions of dollars worth of goods worldwide, and they are a source of food for the areas in which they occur. If these mangroves were to disappear, the number of people suffering from flooding each year would increase by 18 million, or 39%. Material damage would increase by 82 billion dollars or 16% [28].

In Africa in general and Cameroon in particular, the oceans are responsible for the presence of brackish water when they come in contact with the rivers of the latter. The lower reaches of the Nyong River catchment are located in the southern part of the Douala-Edéa National Marine and Terrestrial Park. This maritime reach is a mangrove estuary that provides several ecological and socio-economic services for the riparian populations and the surrounding departments or administrative divisions of this locality [29]. Moreover, this mangrove is partially attacked by anthropic activities that modify its natural functioning. It is therefore necessary to know the ecological structure of this ecotone in terms of vegetation and soil in relation to the gradient of mineralisation from the ocean and that of organic matter from streams and rivers [30].

People living near the Nyong estuary use wood from this mangrove for smoking fish and for various other practices [31]. This activity is likely to change the health of this mangrove, which is very beneficial to the organisms living there and to humans. Information on this estuary in general is still insufficient, although some work have been done on water quality and micro-algal biodiversity [32, 33]. Various factors can contribute to mangrove zonation, such as, an expression of plant succession, a response to geomorphic change, a physiological response to tide gradients and differential tree dispersal. As mangroves are very important because of the ecological and socio-economic services they provide, the Nyong estuary is even more important because it is part of the Douala-Edéa National Park, which could be subject to anthropogenic pressures. To contribute to the understanding of the biogeochemical functioning of the Nyong River mangrove estuary, it appears important to carry out a study on the ecological structure of the mangrove system associated with the evaluation of the physicochemical parameters of the sediments and water of this ecosystem.

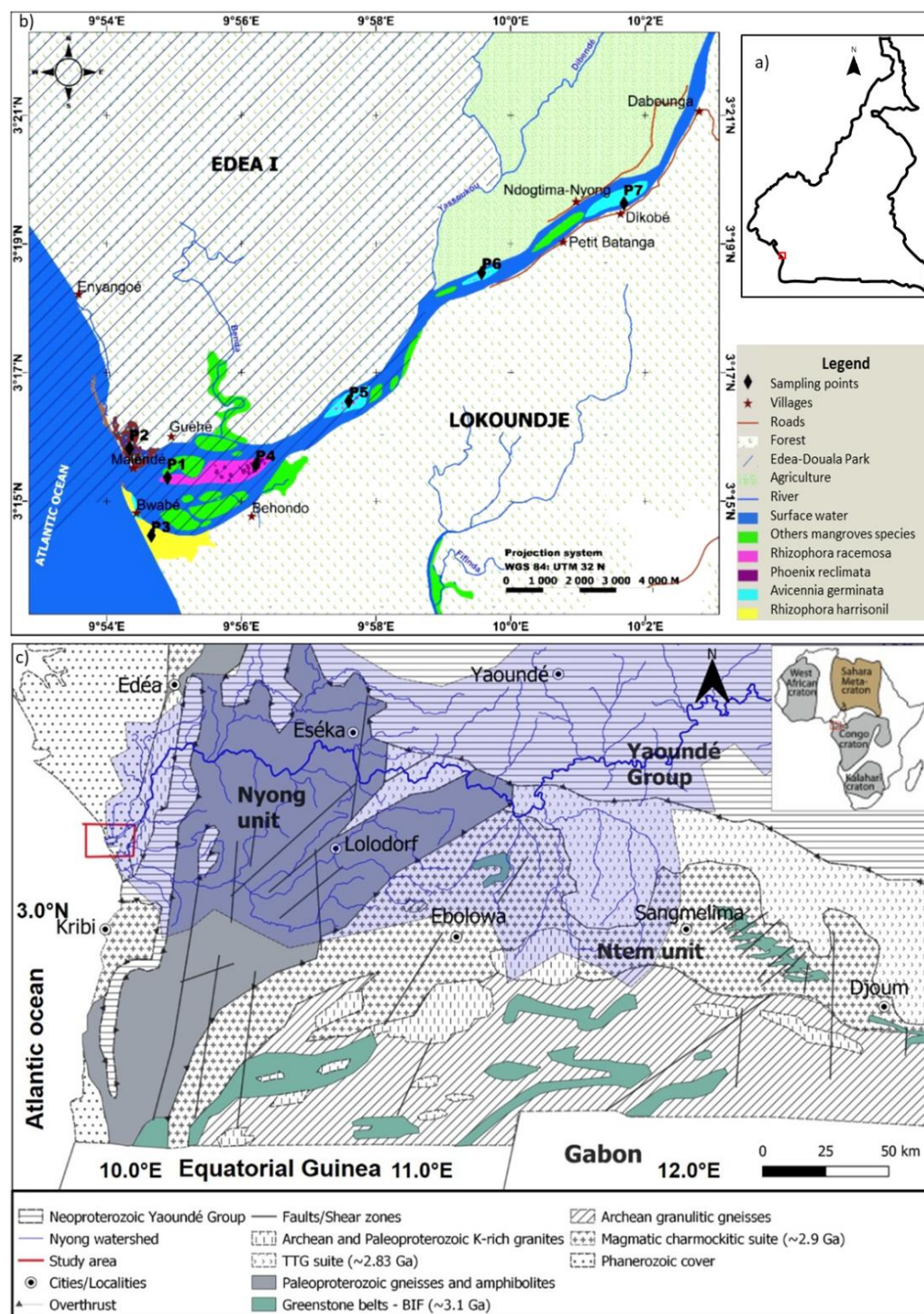


Figure 1. (a) Study area location in Cameroon map (b) Thematic mapping of the mangrove in study area (c) Geological map of the South Cameroon [41].

2. Materials and Methods

2.1. Study Area

The Nyong estuary is located at the southern end of the Douala-Edea National Marine and Terrestrial Park. It is

located in the downstream part of the Dধানé village falls (Littoral region) to the Atlantic Ocean between 3°13.413' and 3°18.331' North latitude and 9°54.286' and 9°57.541' East longitude (Figure 1b). Located in the climatic zone of Equatorial Guinea, the Nyong estuary occupies the lower sub-basin of a watershed that drains its waters over an area of 27800 km². The average flow in the flood period at Dধানé, about 40 km from the mouth, is about 1349 m³/s. It

is influenced by the southwest monsoon winds, limited to an average of 10 km/h due to the high annual rainfall (2919 mm/year) and the highly developed tropical forest on the southern plateau [33, 34]. The study area is a shallow estuary with an average depth of 6 m. The average water temperature varies seasonally between 23.57 and 28.70 °C [29, 30]. The tidal ranges are relatively modest on the straight and more or less rocky coast of the southern part of the Cameroonian plateau: during spring tides, they reach 1.8 m at Kribi and 1.5 m at Petit-Batanga, located 20 km upstream from the mouth of the Nyong [35]. Salinity is mainly influenced by the tide, which is semidiurnal. With values between 0 and 25 PSU along the estuary, it shows a space effect during both tidal cycles, with an average of 10.81 and 10.31 PSU at high and low tide respectively in the lower part, while in the upstream, the average salinity evolves from 0 to 5 PSU [33]. This is an area less affected by anthropogenic influence. It is a dense evergreen forest of low and medium altitudes, one of the main components of which is the mangrove, a rainforest under essentially maritime influence. The geological formations of the catchment area of the Nyong belong to both the Pan-African belt and the Ntem complex. In its coastal part, the lithological and structural units encountered are the Archean basement of the Ntem made up of Granodiorites, gneiss, basic and ultrabasic intrusion of dolerites on the one hand, and sedimentary formations on the other hand, made up of alluvial deposits and sandy coastal strips (Figure 1c). Two types of soil are identified in this area. Ferralitic soils distinguished by a brown humus layer, followed by a clay layer, with ferruginous concretions at the base (pH between 4.7 and 5.10). Hydromorphic soils of 2 types, firstly organic hydromorphic soils which are found on the banks of rivers and in marshy areas. Secondly mineral hydromorphic soils specific to mangrove areas, rich in gleys and evolving towards the marine environment [36-40].

2.2. Data and Method

2.2.1. Field Sampling

In this study frame, a field campaign and monitoring of the estuary was conducted from 9th to 20th March 2020. This campaign consisted of observations and identification of trees from downstream to upstream of the estuary, followed by sediment cores sampling at seven (07) points; this was done during low tides to facilitate access to the site (Figure 1).

Firstly, the mapping of the study area was necessary to characterize the mangrove of the Nyong estuary in a global way. Data characterizing the mangrove were collected in such a way that those relating to the density, height and circumference of mangroves were recorded and plots, selected on the field during low tide and according to accessibility. The method of permanent plots (10 X 10 m) along transects has been classically used between the downstream estuary (Quadrats 1, 2, 3, 4) and the upstream estuary (Quadrats 7) via

the intermediate (Quadrats 5, 6) [42-44]. In a second step, sediments were collected from the 07 selected sampling points using a 1.30 m long, 100 mm diameter PVC core barrel. Once the core was collected, it was immediately covered with a plastic film and aluminium foil according to the method described by Marchand *et al.* [45]. This preserves the sediments from drying out and limits gas exchange with the atmosphere. The height of the water table and the physico-chemical parameters (pH, salinity, electrical conductivity, redox potential) were measured in-situ in the residual hole of the sample using a HANNA HI 9829 multiparameter according to Marchand *et al.* [45].

2.2.2. Laboratory Analysis

After the fieldwork, the cores were transported to the laboratory of the IRAD Marine Ecosystem Research Station in Kribi, Cameroon. The cores were carefully placed on a specially designed cutting rack (in 10 cm slices) [46]. For this first step, each core was described in detail based on the length and distinction of different parts, in terms of color and texture of the sediments according to the methods of Hussenot *et al.* and Raimbault *et al.* [47, 48]. All traces of plants and other organisms as well as any remarks useful for the digitization of these cores and the interpretation of the analytical results were also noted. In this study, only the 0-10 cm and 10-20 cm slices were analyzed after air-drying and storage in aluminium foil to limit exchange with the atmosphere [46, 49]. The recovered dry samples were transported to the soil laboratory of the Faculty of Agronomy and Agricultural Sciences (FASA) in Dschang for various analyses. Total phosphorus (TP), total nitrogen (TN), total organic carbon (TOC), sodium (Na⁺), potassium (K⁺), magnesium (Mg²⁺), calcium (Ca²⁺) and sulfates (S) were determined according to the methods described in Chougong *et al.* [46]. The particle size distribution (sand, silt and clay content) was determined using the standard pipette method described by Singh *et al.* and Ekoa Bessa *et al.* [50, 51].

2.2.3. Data Analysis

(i). Dendrometric Analysis of the Mangrove

The parameters studied are the types of mangrove species found in the plot carried out, their genus, family and the nature of the canopy are found there. As well as the number of trees found per plot, their representative percentage in the mangrove, their different circumferences and their different heights were also studied. The average diameter (D_m) of the trees is the average of the diameters of the different individuals, i.e. the sum of the diameters of the trees over the number of trees. It is calculated by the following formula.

$$D_m = \sum \frac{d}{n} \quad (1)$$

With D_m = average diameter, d = diameter of a tree, n =

number of trees measured.

The average tree height is the average of the tree heights as indicated.

$$H_m = \sum \frac{h}{n} \quad (2)$$

With H_m = average tree height, h = height of a tree, n number of measured trees.

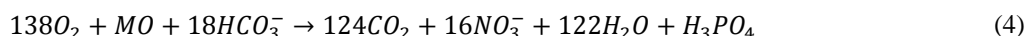
(ii). Physical Parameters of the Sediment

The studied parameters are the lithofacies (type, thickness, arrangement and texture), the composition (plants debris, biogenic fragments, etc), the colour determined by the Munsell chart [52]. The determination of the water content of the sediments is calculated by the following formula.

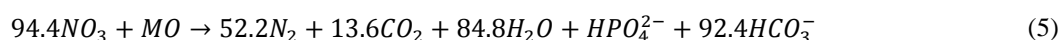
$$W = \frac{\text{Mass of the wet sediment} - \text{Mass of the dry sediment}}{\text{Mass of the wet sediment}} \times 100 \quad (3)$$

(iii). Chemical Parameters of the Sediment

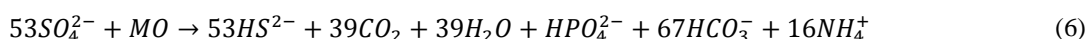
The studied parameters were analysed in the laboratory, in order to determine the concentration of TP (mg/kg), TN (%), TOC (%), S (mg/kg) and TOM (%) found in the sediments of the mangrove from the Nyong estuary, according to the method described by Raimbault et al. [48]. These are the oxidising elements used for bacterial degradation processes. Their successive use controls their distribution within the dissolved and solid phase of the sediment column according to the chemical equations of Froelich et al., then of Postma and Jakobsen [53, 54]. Some equations are established according to the stoichiometry for one mole of organic matter proposed by Redfield (1963) (C106/N16/P) and the C39/S53 ratio [55, 56].



Oxidation of Organic Matter (OM) by oxygen (4)



Denitrification (5)



Oxidation by sulphates (6)

The analysis of absorbed cations or exchangeable bases requires a double determination of the soluble salts and the cations of the non-desalted complex, due to the presence of the soluble salts. According to the standard method of Viellafon, improved by Pauwels et al. for air-dried sediment samples, the salts were determined on the 1:10 extract and recorded in milliequivalents per 100 g [57, 58].

(iv). Statistical Analysis

The basic statistical treatment of each measured variable started with the estimation of some classical statistical parameters such as: means, minimum values, maximum values, standard deviations and variances. To test the effect of space represented by the stations, seven (7) ordinal analysis of variance with a classification criterion (ANOVA 1) was used for each physicochemical parameters and sediment core slices.

3. Results

3.1. Structural Characterisation of the Mangrove

3.1.1. Overall Characterisation of the Study Area

In the Nyong estuary, from downstream to upstream, the mangrove forest extends over about 14 km. Four species and 120 individuals were identified during this study (Figure 1). The general configuration of the mangrove is mainly made up of the genus *Rhizophora racemosa*, of which 40 individuals have been identified along the marine frontage representing approximately 33.33% of the surface area of the formations. The genus *Avicennia germinans* has been recorded downstream, in the intermediate zone and upstream of the estuary. These species occupy about 40% of the total area. The genus *Rhizophora harrisonii* (8 individuals) is located only downstream of the estuary and represents the minority with a percentage of 6.67% of the total area. Palms are also represented with 24 individuals of *Phoenix recinata*. Unidentified seagrass beds and other invasive plants were quantified on 20% of the area (Table 1).

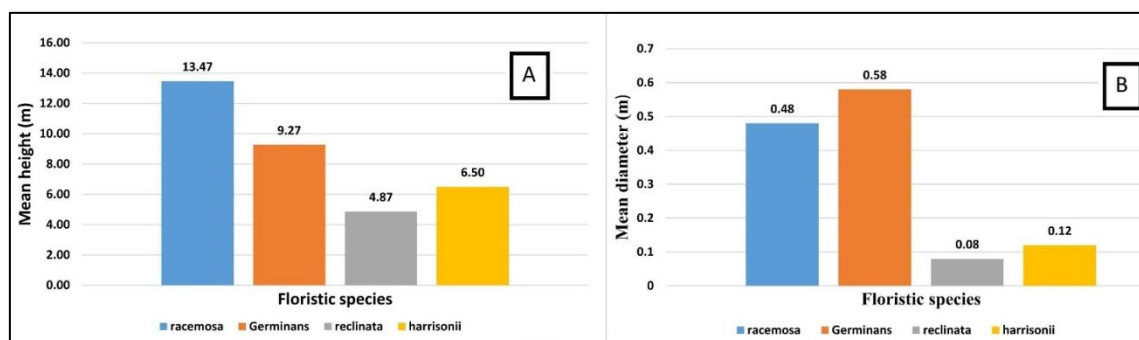
Table 1. Characteristics of the plots sampled in the mangrove.

Quadrats	Sample points	Species (number of specimens)	Observations made
Q1	P1 (3°15'37"N; 9°54'47"E)	<i>Avicennia germinans</i> (2) <i>Rhizophora harrisonii</i> (8)	Presence of stump sprouts Slightly open canopy
Q2	P2 (3°15'45"N; 9°54'7"E)	<i>Avicennia germinans</i> (4) <i>Phoenix reclinata</i> (13)	Pneumatophores covered by sea grass and silting
Q3	P3 (3°15'03"N; 9°54'3"E)	<i>Rhizophora racemosa</i> (17)	Full mangrove Closed canopy
Q4	P4 (3°15'55"N; 9°56'11"E)	<i>Phoenix reclinata</i> (11) <i>Rhizophora racemosa</i> (12)	Canopy completely open Presence of invasive species containing stilt roots
Q5	P5 (3°16'36"N; 9°57'32"E)	<i>Avicennia germinans</i> (11) <i>Rhizophora racemosa</i> (7)	Open canopy Roots and invasive species
Q6	P6 (3°18'31"N; 9°59'33"E)	<i>Avicennia germinans</i> (13) <i>Rhizophora racemosa</i> (4)	Closed canopy Presence of discharge
Q7	P7 (3°19'32"N; 10°01'23"E)	<i>Avicennia germinans</i> (18)	Scoured earth. Closed canopy Sandy and clayey soil Presence of stump sprouts

3.1.2. Vertical Stratification of the Mangrove

The species *Rhizophora racemosa* has the highest average height on the Nyong estuary with a value of 13.46 m, followed respectively by the species *Avicennia germinans* (9.26 m), then *Rhizophora harrisonii* (6.52 m) and *Phoenix reclinata*

(4.86 m) (Figure 2A). The floristic species *Avicennia germinans* has a dominant average diameter of 0.58 m, followed by *Rhizophora racemosa* (0.48 m), *Rhizophora harrisonii* (0.12 m) and *Phoenix reclinata* (0.08 m) (Figure 2B).

**Figure 2.** Variation in mean height (A) and mean diameter (B) according to mangrove species.

3.2. Physicochemical Characterization of Sediments and Pore Waters

3.2.1. Description of the Cores

The seven cores taken in this mangrove have heights ranging from 56 to 91 cm and consist of sediments containing stems of milli-metric diameter and roots of centimetric diameter. The lithofacies and resulting texture, presence of

figured elements, color and water content differed from one core to another.

P1 core is 64 cm long and consists of alternating medium to fine yellow-brown to grey sands with the presence of bi-valves in the upper layer (Figure 3). It is sandy in texture and its water content varies from 14.20 to 27.22% by weight (Figure 4 and Figure 5).

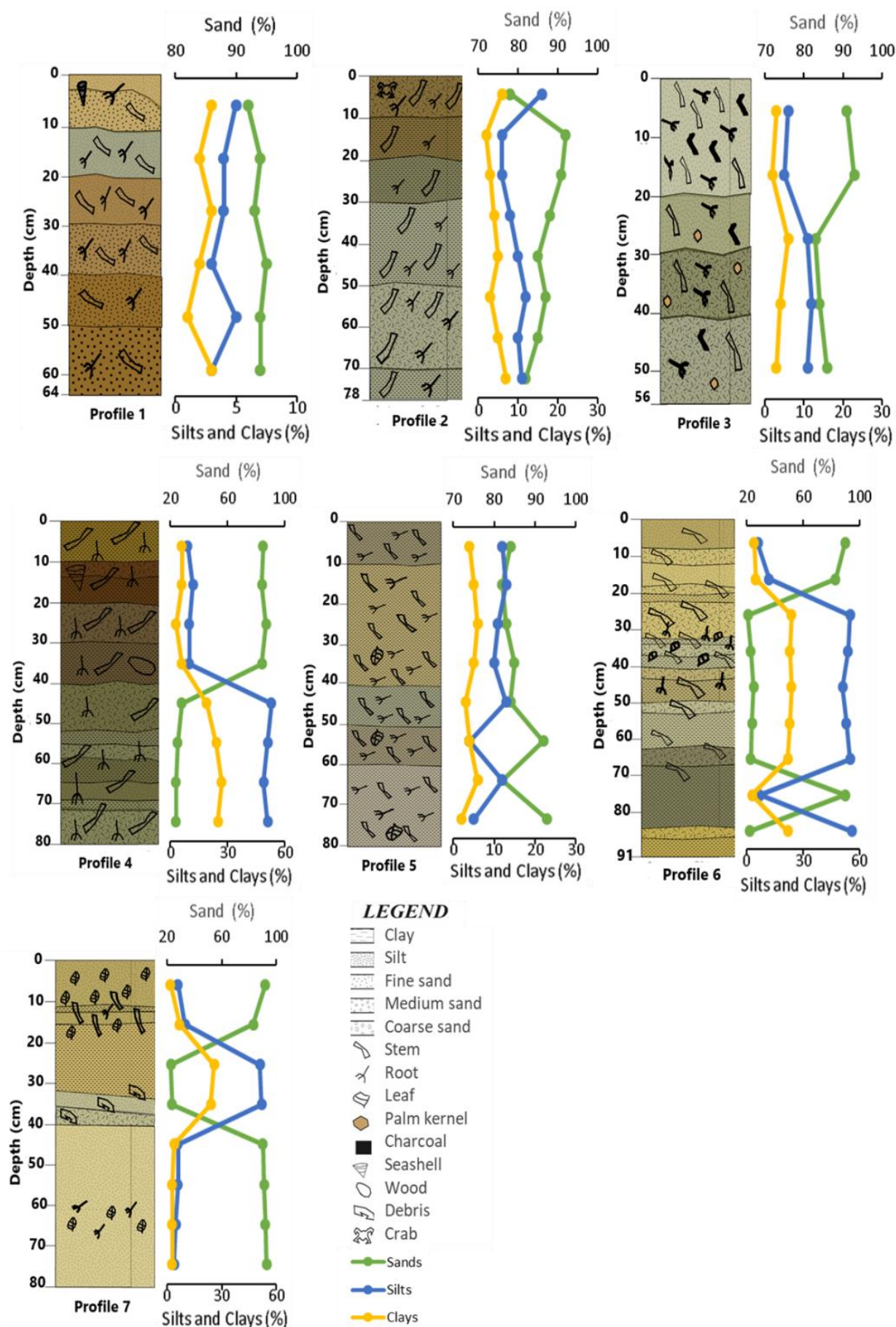


Figure 3. Vertical profile of cores sediment from Nyong estuary and their variation in grain size distribution.

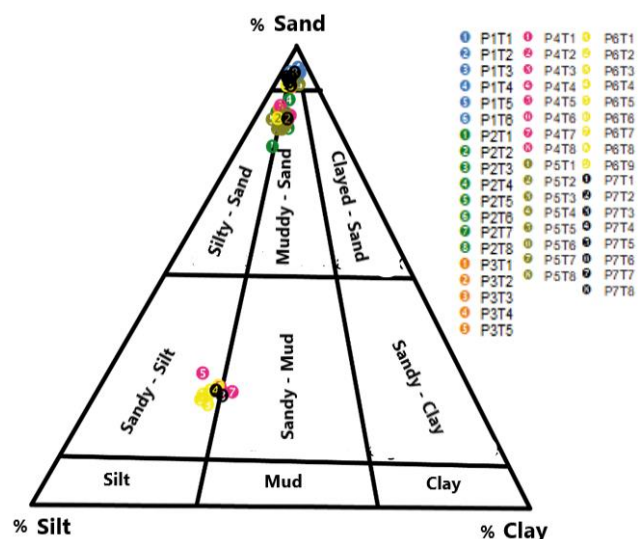


Figure 4. Sediments of the Nyong Estuary in the Folk Diagram (1954).

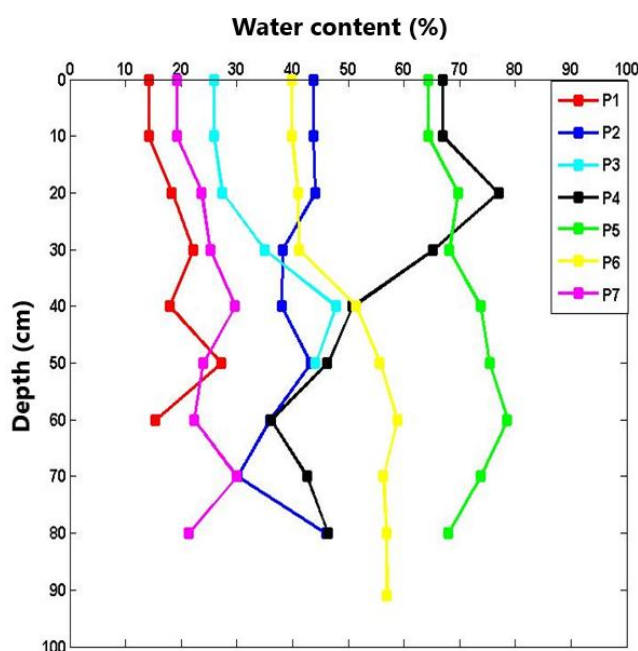


Figure 5. Water content variation curve along the Nyong estuary.

Core P2 is 78 cm long and consists of alternating sandy, silty and clay layers of brown to grey color, where living organisms (crabs) were identified in its upper layer (Figure 3). The resulting texture of this core is that of silty to muddy sands with water contents between 30.10 and 45.97% (Figure 4 and Figure 5).

Core P3 is 56 cm long and consists of fine sand in the upper part and silt in the lower part, where coals and palm nuts are

encountered (Figure 3). The resulting textures are sand and silty sand. The water contents range from 25.89 to 47.78% and these layers are grey to brown (Figure 3 to Figure 5).

Core P4 is 80 cm long consisting of sandy, silty and clayey layers, greyish brown to yellow in color, and contains gastropods and pieces of bark (Figure 3). The resulting textures are: silty and muddy sand, sandy silt and sandy mud; water contents vary from 36.10 to 76.95% (Figure 4 and Figure 5).

Core P5, 80 cm long essentially made up of grey-brown to light-colored clays, containing dead leaves (Figure 3). The water contents vary from 64.37 to 78.56% and the texture is that of muddy sands (Figure 4 and Figure 5).

Core P6 is 91 cm long and consists of alternating sandy, silty and clayey layers, grey-brown to light in color, containing dead leaves (Figure 3). The resulting textures here are sandy, silty sand and sandy silt and the water contents vary from 39.92 to 58.82% (Figure 4 and Figure 5).

Core P7 is 80 cm long and consists of brown and grey sand and clay with dead leaves and animal and plant debris (Figure 3). The resulting textures are sand, muddy sand and sandy mud, and the water contents are between 19.20 and 29.98% (Figure 4 and Figure 5).

Overall, the mangrove sediments of the Nyong estuary are predominantly sands (74.08%). These are respectively followed by silt (17.72%) and clay (8.2%). The water content of these sediments ranged from 14.20 to 78.56%. The water content of cores P1, P2, P3 and P7, ranging from 14.20 to 47.78%, was less than 50% and that of cores P4, P5 and P6, ranging from 36.10 to 78.56%, was greater than 50%.

3.2.2. Physicochemical Characteristics of Pore Waters

The salinity of waters of the mangrove sediments varies in a decreasing manner from the downstream estuary (19.88 PSU at P1) to the upstream estuary (0.01 PSU at P7) (Figure 6A). Dissolved oxygen in different cores varies from 0.51 (P2) to 2.17 mg/l (P6), with an average of 1.24 mg/l (Figure 6B). There is a significant difference between the values in the lower estuary (P1, P2 and P3) and those in the upper zone (P6 and P7) ($P < 0.05$). The lowest value of electrical conductivity is 0.022 $\mu\text{S}/\text{cm}$ in core P7 and the highest value 32.05 $\mu\text{S}/\text{cm}$ in P1 (Figure 6C). The TDS, presents a similar pattern with salinity and conductivity, but varies between 0.01 mg/l in P7 and 16.03 mg/l in P1 (Figure 6D). The redox potentials (Eh) range from -82.8 mV in P1 to 160.5 mV in P2 (figure 6E). The soils regularly exposed to the air are well oxidized as show at P2, P3, P4, P7 (Figure 6E).

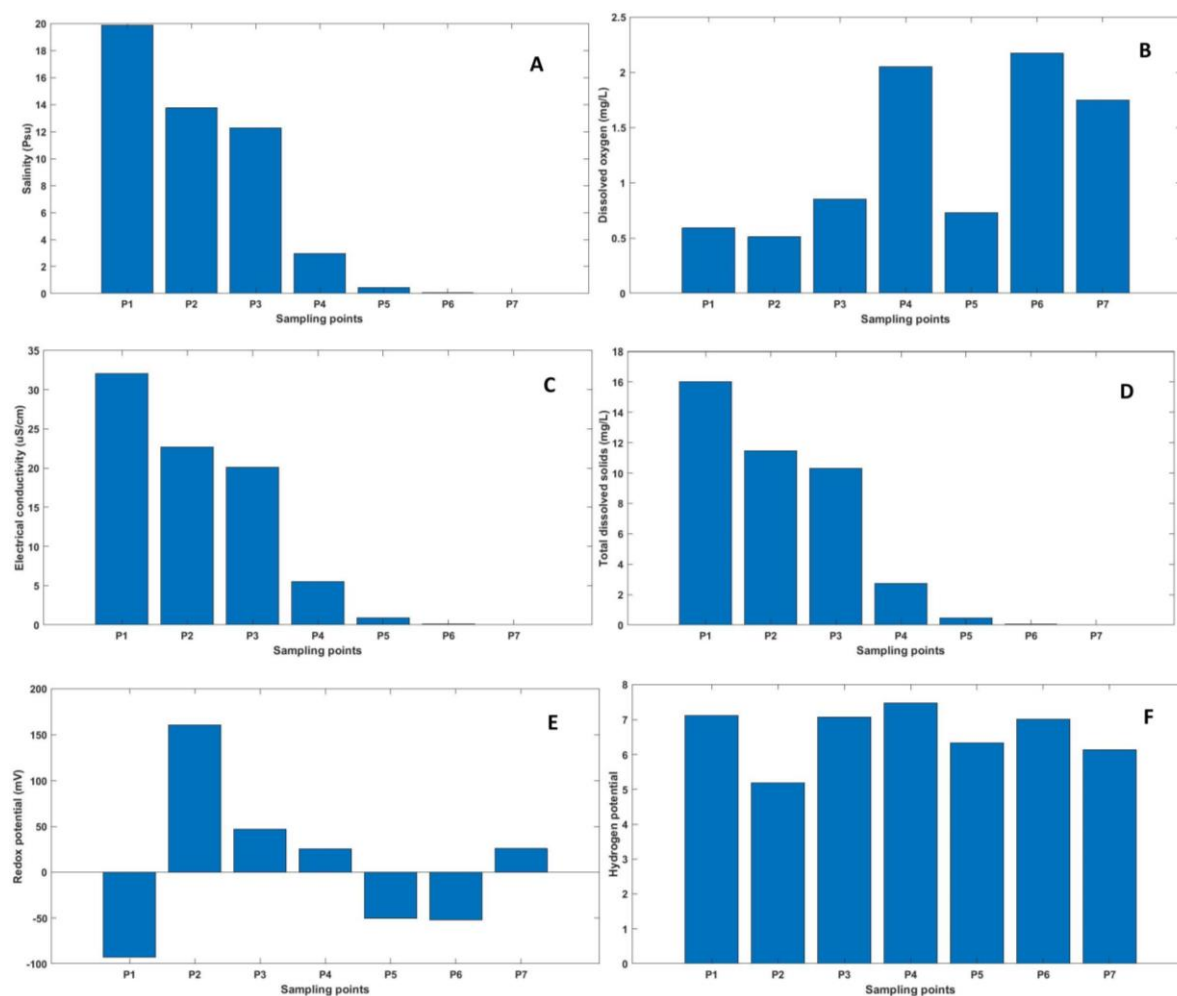


Figure 6. Evolution of the physicochemical characteristics of the pore water of the mangrove soil according to the sampling point, (A) Salinity, (B) Dissolved Oxygen, (C) Electrical Conductivity, (D) Total Dissolved Solids, (E) Redox potential, (F) Hydrogen potential.

3.2.3. Chemical Characteristics of Sediments

The range of variation of chemical parameters of the sediments at all the stations of this study is presented in [table 2](#).

Table 2. Range of variation of some chemical parameters in sediments (SD = Standard Deviation, Min = Minimum, Max = Maximum).

Parameters	Range (cm)					
	0-10cm			10-20cm		
	mean \pm SD	Min	Max	mean \pm SD	Min	Max
TP (mg/kg)	648.71 \pm 122	514	823	625.14 \pm 144.14	485	856
TN (%)	0.33 \pm 0.24	0.04	0.68	0.31 \pm 0.24	0.04	0.65
S (mg/kg)	5.20 \pm 3.70	0.68	10.56	5.48 \pm 4.67	0.65	12.83
TOC (%)	4.78 \pm 2.50	2.20	8.05	4.89 \pm 2.86	1.80	8.61
TOM (%)	8.27 \pm 4.47	3.66	14.05	8.428 \pm 4.92	3.10	14.64

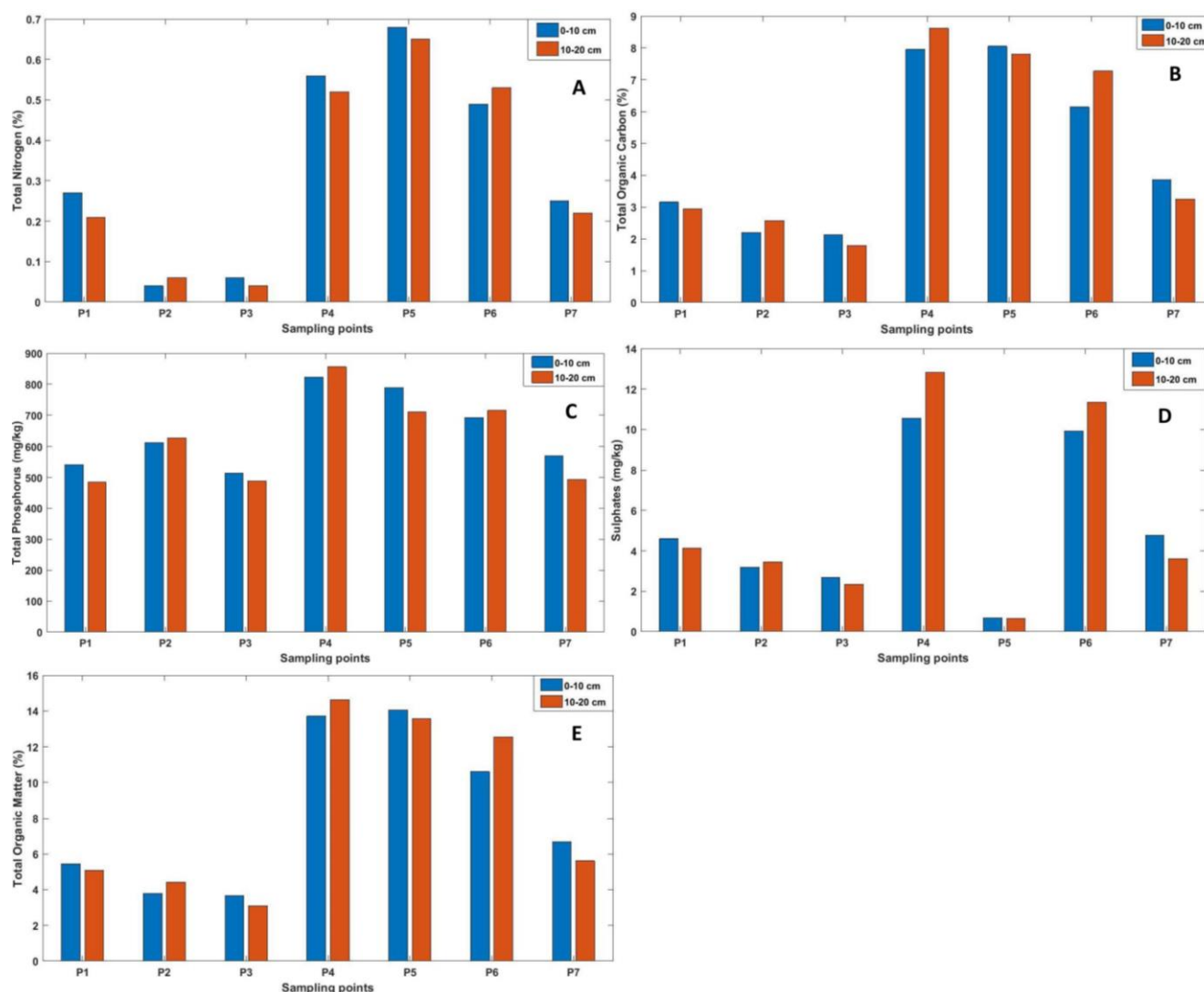


Figure 7. Evolution of nutrient concentrations in mangrove sediments, (A) Total Nitrogen, (B) Total Organic Carbon, (C) Total Phosphorus, (D) Sulphate, (E) Total Organic Matter.

(i). Total Nitrogen

The TN contents varied from 0.04 (P2) to 0.68% (P5) with an average of 0.336% in the 0-10 cm depth and between 0.04 (P3) and 0.65% (P5) with an average of 0.316% (10-20 cm) (Figure 7A). Between the stations, the TN content shows a very significant difference ($P < 0.01$). The highest values are observed in the stations of the intermediate zone (P4, P5, P6). For each station, there is a significant difference ($P < 0.05$) between the values along the vertical profile.

(ii). Total Organic Carbon

The TOC contents varied from 2.13 (P3) to 8.05% (P5) with an average of 4.78% (0-10 cm) and between 1.80 (P3) and 8.61% (P4) with an average of 4.89% (10-20 cm). Total Organic Carbon levels appear high in the Nyong estuary, but the highest contributions are observed in the intermediate zone (Figure 7B). Stations P4, P5 and P6 show significantly

different TOC contents than those observed in P1, P2, P3 and P7 ($P < 0.05$). The TOM content of the cores in the solid phase of the sediments shows a similar pattern with the TOC content. Its percentages vary between 3.10 (P3) and 14.64% (P4) with an average of 8.28% (0-10 cm) and between 3.66 (P3) and 14.05% (P5) with an average of 8.43% (10-20 cm) (Figure 7E).

(iii). Total Phosphorus

The TP contents obtained in the samples taken at the different sampling points varied from 514 (P3) to 823 mg/kg (P4) with an average of 648.72 mg/kg (0-10 cm) and between 485 (P1) and 856 mg/kg (P4) with an average of 625.14 mg/kg (10-20 cm) (Figure 7C). TP showed a significant difference ($P < 0.05$) between the stations.

(iv). Sulphates

In the 0-10 cm depth range sulphates varied from 0.68 (P5)

to 10.5 mg/kg (P4) with an average of 5.201 mg/kg. Then from 0.65 (P5) to 12.83 mg/kg (P4) with an average of 5.48 mg/kg (10-20cm) (Figure 7D).

3.2.4. Exchangeable Bases (Potassium, Sodium, Calcium and Magnesium)

As presented in Table 3, the exchangeable bases have decreasing average concentrations following the order $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$. The difference between stations and slices

is not significant when combining the concentrations of these elements.

The Na^+ contents varied globally from 0.39 (10 - 20 cm) to 4.17 cmol+/kg (10 - 20 cm), the highest values are observed in the intermediate estuary at P4 with 3.82 and 4.17 cmol+/kg respectively in the surface and deep sediment slices (Figure 8A). For both core slices the difference is significant between the two stations ($p < 0.05$).

Table 3. Range of exchangeable bases in mangrove sediment (SD = Standard Deviation, Min = Minimum, Max = Maximum).

Parameters	Range (cm)					
	0-10cm			10-20cm		
	mean \pm SD	Min	Max	mean \pm SD	Min	Max
Ca^{2+} (cmol+/kg)	5.98 \pm 5.33	1.96	15.66	6.261 \pm 6.16	0.96	18.24
Mg^{2+} (cmol+/kg)	2.46 \pm 2.22	0.46	5.95	2.581 \pm 2.48	0.46	7.15
K^+ (cmol+/kg)	0.68 \pm 0.42	0.31	1.25	0.72 \pm 0.596	0.22	1.58
Na^+ (cmol+/kg)	1.86 \pm 1.28	0.48	3.82	1.887 \pm 1.479	0.39	4.17

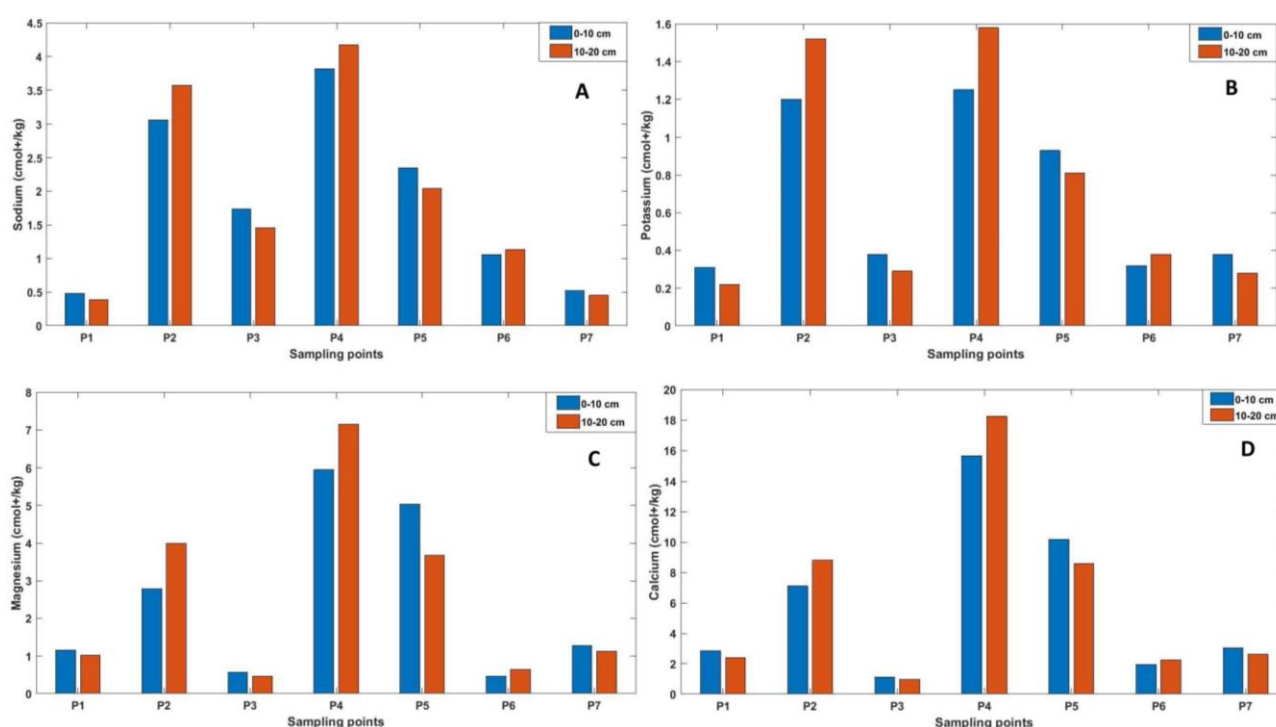


Figure 8. Evolution of exchangeable bases in mangrove sediments, (A) Total Nitrogen, (B) Total Organic Carbon, (C) Total Phosphorus, (D) Sulphate, (E) Total Organic Matter.

The K^+ values varied from 0.31 to 1.25 cmol+/kg in the slice (0 - 10 cm), then from 0.22 to 1.58 cmol+/kg (10 - 20 cm). The highest concentrations are observed in P4 followed by P2

and P5 (Figure 8B). An average of Exchangeable Potassium was 0.68 ± 0.40 and 0.72 ± 0.50 cmol+/kg respectively for 0 - 10 cm and for 10 - 20 cm, from one point to another the difference

is significant ($p < 0.05$).

The mean values of Mg^{2+} (surface slice) were 2.58 ± 2.40 cmol+/kg (next slice). The lowest levels were obtained at P3 with 0.46 (10-20 cm) and 0.56 cmol+/kg (0-10 cm), while the highest levels were observed at P4, i.e. 5.95 cmol+/kg at the surface and 7.15 cmol+/kg at depth (Figure 8C). The difference was significant ($p < 0.05$) between stations in the cores from downstream to upstream.

The overall means of the exchangeable Ca^{2+} base was 5.98 ± 5.30 (0-10 cm) and 6.26 ± 6.16 cmol+/kg. The maximum Ca^{2+} contents, 18.24 and 15.66 cmol+/kg were observed in P4 at the base and the superficial sediment slice respectively (Figure 8D). The minimum values 0.96 and 1.12 cmol+/kg are observed in P3 at the base and the surface layer respectively.

3.2.5. Nutrient Ratios (N/P; C/SO₄; C/N; C/P)

These are among others: N/P, C/SO₄, C/N and C/P (Figure 9). The values obtained in this study for N/P are between 0.65

(P2) and 8.61 (P5) (0-10 cm) and between 0.81 (P3) and 9.14 (P5) (10-20 cm). Thus, for values of this ratio ($N/P < 16$), it can be seen that nitrogen is the limiting element for the optimal growth of the plant species (Figure 9A).

The Figure 9D shows the evolution of the C/SO₄ ratio in the sediment along the estuary. The values obtained in this study range from 0.19 (P1) to 11.83 (P5) (0-10 cm) and from 0.40 (P6) to 1.2 (P5) (10-20 cm).

The Figure 9C shows the evolution of the C/N ratio. The values obtained in this study are between 11.70 (P5) and 55 (P2) (0-10 cm) and between 13.72 (P6) and 45 (P3) (10-20 cm). These values are higher than the classical Redfield yield $C/N = 106/6 = 6.625$. The variation of the ratio shown in Figure 9B is the C/P ratio. The values obtained in this study range from 35.889 (P2) to 102.03 (P5) with an average of 70.16 (0-10 cm) and from 36.88 (P3) to 109.70 (P5) with an average of 73.82 (10-20 cm).

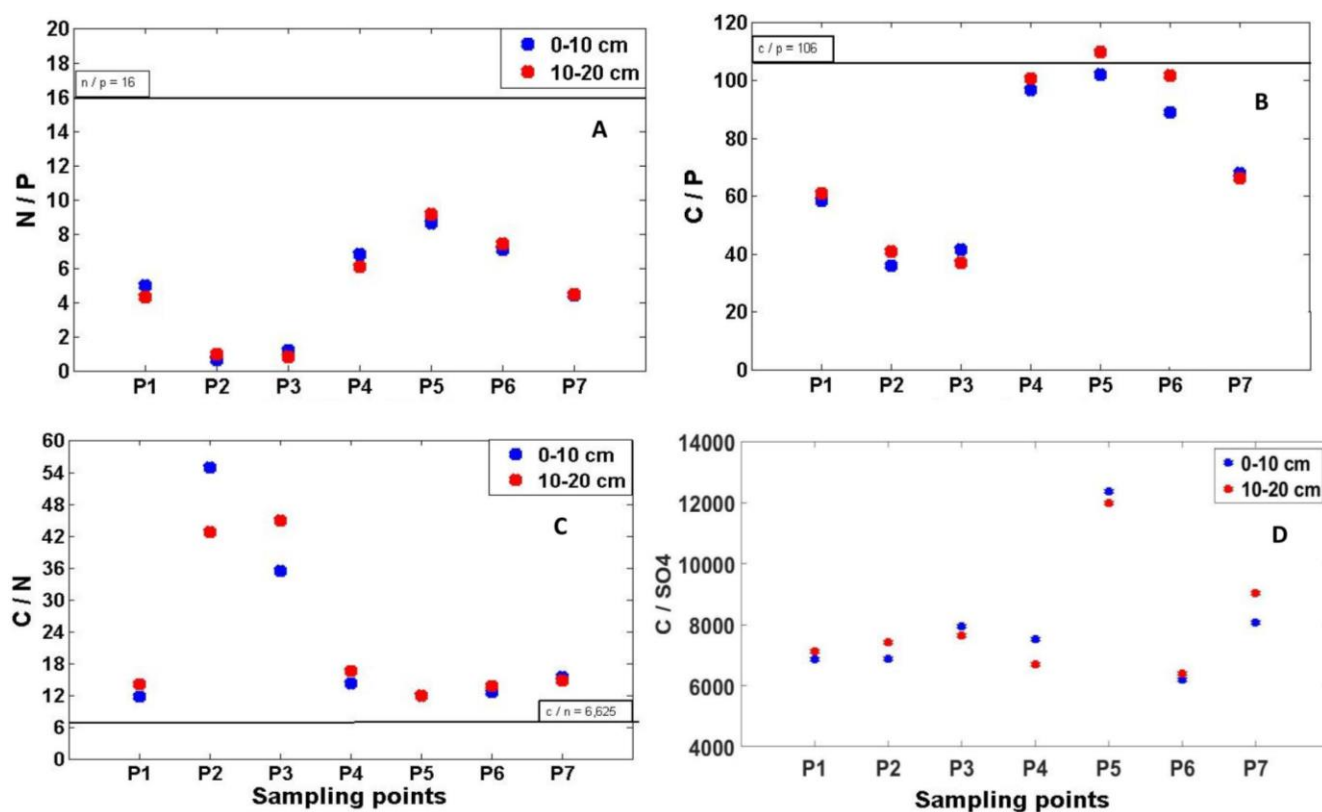


Figure 9. Diagram showing the nutrients ratio in mangrove sediments, (A) ratio N/P, (B) ratio C/P, (C) ratio C/N, (D) ratio C/SO₄.

4. Discussion

4.1. Dendrometrical Structure of the Estuary Mangrove

The dominant plant formations in the Nyong estuary man-

grove sample quadrats are *Avicennia germinans* and *Rhizophora racemosa*. The height of the trees found there is between 4.86 m and 13.46 m and the circumference is between 0.08 and 0.58 m. These dimensions are close to those recorded in the Shark River estuary in Florida in the USA, which has a rainfall (2000 mm/year) close to the coastal zone through which the Nyong estuary passes [59-61]. The dimensions of the Nyong vegetation are even smaller than those

found in the Bamosso mangrove (southwest coast of Cameroon) where the average height is equal to 20.20 m and the average diameter to 2.65 m [62]. This difference is due to the fact that the south-western region of Cameroon has an oceanic climate on the west coast and an equatorial coastal climate characterized by two seasons with a long rainy season (March to November) [60]. Secondly, in Bamosso, they develop on soils that are rich in water and uncrystallised minerals due to the large amount of organic matter. These soils also have an abundance of humus and are well oxygenated [60-64]. The forest vegetation of the Nyong estuary is evergreen, dominated by mangroves and interspersed with shrubby grassland in the upstream part of the estuary [65]. The most common species, *Rhizophora racemosa*, is found in the lower estuary and on the banks, while *Rhizophora harrisonii* is mainly found in the middle of the area and other species occur in stunted, shrubby forms such as *Avicennia germinans* and *Phoenix reclinata*. Similar observations to those made in the coastal zone of southwestern Nigeria [66, 67]. The result is all so similar to that of Okanga et al. [68], in the Gabon estuary.

4.2. Assessment of Physical and Chemical Parameters of Mangrove Sediments

The cores collected in the Nyong mangrove consist of heterogeneous sediments. The facies encountered are clays (8.2%), silts (17.72%) and sands (74.08%), generally grey (5/1) and yellow (8/8). This high sand content can be explained by the presence of sandy deposits (terraces, strandplain ridges, chains) that line the entire length of the river downstream from the Džhane Falls. The texture of the sediments based on the average percentages of particle composition revealed that the sediments belong to the sandy-clay and sandy-silt texture, a texture observed in the equatorial sub-climate estuaries as Burutu (Forcados River), Opuama (Benin River) and Kurutie (Escravos River) [67]. Mangrove forests are usually closed and sheltered environments with low energy water, which favours the sedimentation of medium and fine particles [69, 70]. However, sediments containing higher sand particles in about 90 cm as in this study could be attributed to sandy barrier beaches that are sub-actual and modern [71].

Salinity is considered to be one of the factors limiting the growth structure of mangrove trees [72, 73]. Along the estuary, the salinity of waters pore in the mangrove wetland is much lower than 35 PSU. They are below the critical values that influence the complexity of the mangrove [74]. Along the estuary, in the waters of the mangrove sediments, the pH levels ranged from moderately acidic (5.2 - 6.8) to moderately basic (7.1 - 7.5). The pH of waters pore of mangrove wetlands in other tropical environments has shown similar values (acidic or alkaline) to those observed in this study, ranging from 4.87 to 6.40 on the one hand and 7.40 to 8.22 on the other [75-78].

The mangrove sediments of the Nyong are characterised in places as reduced with low redox values and oxidised with

high values. In stations P1 (-82.8 mV), P5 (-50 mV) and P6 (-52.28 mV) the Eh values are relatively low, which would be justified by the position in the intermediate estuary with rhizophora and avicennia showing a high root development [79]. In these sediments, the degradation of organic matter takes place under anaerobic conditions, involving iron or sulphates in the processes. Highly anaerobic conditions can lead to the production of foul smelling sulphides [80, 81]. Sediments regularly exposed to the air are well oxidised (P2, P3, P4, P7). The Malende camp point in the downstream estuary (P2= +160 mV) has strong hydrodynamics. It is a creek outlet, followed by P3 (+48.30 mV), both oxygenated by wave mixing. Point P7 (+30.28 mV) at Donenda has significantly low Eh ($P < 0.005$) compared to P2 and P3 as it is located in the upstream estuary zone with low hydrodynamics due to dynamic tide only [82].

4.3. Variability of Nutrient Content in Mangrove Sediment

Soil nutrients such as nitrogen and phosphorus play a very important role in the photosynthetic yield of mangrove trees [45]. Due to its high biomass production, mangrove ecosystems are rich in organic matter [83]. The low levels of nitrogen with the average of 0.336% (0-10 cm) and of 0.316% (10-20 cm) indicate undisturbed sediment. This is in contrast with the mangrove environment, which is subjected to wastewater discharges from households and industries [84, 85]. This non-perturbed character is also observed in the phosphorus content with local values of 600 and 800 mg/kg that allow the mangrove of the Nyong estuary to be classified as a eutrophic system [86, 87].

In this study, the C/N ratio is between 10 and 15 for sediment layers from 0 to 20 cm at sampling points P4, P5, P6, P7, except for P1, P2 and P3 located on the banks on either side of the mouth. The range of C/N ratio, implies that the organic input does not come completely from marine sources. This reflects a mixture of degraded debris from higher plants and organic matter [88]. This organic matter has moderately high levels (>12%) which is linked to the presence of decomposing mangrove tissues from stems, roots and leaves [18, 89]. This supply of organic matter also explains the high TOC levels (>8%) observed in the middle estuary stations [90]. In this mangrove, the heterotrophic habitat comparisons consist of several species of crabs, molluscs, fauna inhabiting leaf litter and detritus arthropods using this one as a source of food or as shelter, reptiles, birds, bacteria and fungi [91]. These organic carbon contents are also concentrated in the mangrove swamps of the protected area in southwestern Nigeria. The nature of such sediments is considered to be peaty, with potential as a reservoir [82]. At stations P2 and P3, $C/N \geq 40$ with total nitrogen levels close to 0.1% reflecting the nitrogen poverty at these sites. This could be due to the position of these points in an area regularly flooded by waves. Consequently, the litter that could accumulate there is exported by

the waves. These sites are poor in organic matter and organic carbon, and are dominated by sand (at least 74%). This result is similar to that obtained at Yoyo and Manoka in the estuary of Sanaga River in South West Cameroon coastal zone [18].

In general, along the Nyong estuary the N/P < 16 ratio reflects a low availability of nitrogen relative to phosphorus, as the phosphorus is bounded to the stream substrate while nitrogen is bounded to litter that could be leached by the water current [92]. The intermediate estuarine zone and the mouth are sediment deposition environments as suggest by Chen and Twilley [59]. The phenomenon of scavenging could explain this higher concentration of phosphorus in the sediment than nitrogen. This enrichment in phosphate is equally observe in the C/P report which is comprise between 35.88 (P2) and 102.03 (P5) with an average of 70.16 (0-10 cm), then between 36.88 (P3) and 109.70 (P5) with an average of 73.82 (10-20 cm). This reflects the good growth of plant species in the mangrove of the Nyong estuaries [93, 94]. The sediments of the Nyong estuary are both hydromorphic organic and mineral according to Olivry and Oslisly [60, 95]. They are sediments under the *rhizophoras* and *avicennia* mangrove, characteristic of acid sulphate sediments [57]. This would justify the low values of the C/SO₄ ratio indicating high sulphate contents as designated by the FAO classification [96]. Although both organic carbon and organic nitrogen are released during mineralisation, the clearly marked carbon concentrations in the sediment beneath the *rhizophora* sites reflected a different control, with mineralisation probably related to root exudation or fine root degradation on the one hand, and a higher necromass root biomass for *rhizophora*, compared to the higher live root biomass for *avicennia* on the other [97].

Cation exchangeable bases are generally used to assess soil fertility [98]. Indeed, this decomposition of the roots of this mangrove species leads to a high production of sulphide from soil compounds and sulphate from sea water, as shown in the Tiko mangrove on the North Atlantic coast of Cameroon [99, 100]. The Ca²⁺ values were found to be below 4 cmol+/kg in cores P1, P2 in the lower estuary and P6, P7 in the upper estuary, thus revealing a critical level for fertility [18, 101]. Locations where quadrats exhibited lighted canopies with scattered trees and a rather sandy and clayey sediment. The Ca²⁺ and Mg²⁺ cations have higher average values than Na⁺ and K⁺. This decreasing order of macronutrients in mangrove estuary soils is similar to that observed by Andrade et al. [102] in the São Francisco estuary in Brazil. The Na⁺ values evolve in a decreasing way from the mouth to the upstream of the river with a non-significant difference between stations. Sediments in the downstream and intermediate zones with high concentrations P2 (3.06 and 3.57 cmol+/kg), P3 (3.82 and 4.17 cmol+/kg) and P5 (2.35 and 2.04 cmol+/kg), indicate sediments classified as saline sodic where the dominance of *Rhizophora* followed by *Avicennia* has been noted [17].

5. Conclusion

The investigations in this study show that in the Nyong mangrove estuary several factors influence vegetation zonation such as a response to geomorphological changes and a physiological response to tidal gradients. The following conclusions can be drawn from this study:

1. The forest of the Nyong estuary is dominated by mangrove trees in the saline tidal zone. The most common species is *Rhizophora racemosa*, followed by *Rhizophora harrisonii* in the brackish marshlands, and then by shrub species such as *Avicennia germinans* and *Phoenix reclinata*. The dynamic tidal zone is mainly occupied by shrubby grasslands.
2. It appears that, although salinity is a limiting factor for mangrove growth and development, it collaborates with other factors in influencing the mangrove ecosystem.
3. Sediment texture is relevant to mangrove structural development due to the dominance of sandy-clay and sandy-silt textures. Several other factors contributing to mangrove structuring such as pH, redox potential, nutrient salts reveal that it is important to examine in more detail other aspects of the mangrove environment in order to discover the importance of each of the variables on plant structure.
4. Organic carbon and organic nitrogen levels, both of which are released during mineralization, show strong control by *rhizophora* zones where the sediment is rich in carbon. *Rhizophora* had a higher root biomass and root degradation than *avicennia*.
5. Macronutrient concentrations in the sediment evolve in the order Ca²⁺ > Mg²⁺ > Na⁺ > K⁺. The Na⁺ values from downstream to upstream revealed in sediments classified as sodium saline with *rhizophora* dominating followed by *avicennia*. there is a tendency for species zonation according to soil fertility, dominated by *rhizophora* which is strongly present in fertile soils.
6. Variations in salinity, grain size, redox potential and nutrients from downstream to upstream of the estuary could be at the origin of the population structure of the Nyong. It is important and timely to conduct research to improve the understanding of the biogeochemical processes and dynamics of estuarine sediments that support the stability of mangrove ecosystems.

Abbreviations

SERECOMA: Station Expérimentale de Recherche sur les Ecosystèmes Marins

IRAD: Institut de Recherche Agricole pour le Développement

PSU: Practical Salinity Unit

ANOVA 1: One-Way Analysis of Variance

FASA: Faculté d'Agronomie et des Sciences Agricoles (Faculty of Agronomy and Agricultural Sciences)

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Bishop, J. K. B., Ketten, D. R., Edmond, J. M. Chemistry, Biology and Vertical Flux of Particulate Matter from the Upper 400 m of the Cape Basin in the Southeast Atlantic Ocean. *Deep-Sea Research*. 1978, 25(12), 1121-1161. [https://doi.org/10.1016/0146-6291\(78\)90010-3](https://doi.org/10.1016/0146-6291(78)90010-3)
- [2] Gogina, M., Zettler, M. L., Vanaverbeke, J., Dannheim, J., Van Hoey, G., Desroy, N., Wrede, A., Reiss, H., Degraer, S., Van Lancker, V., Foveau, A., Braeckman, U., Fiorentino, D., Holstein, J., Birchenough, S. N. R. Interregional comparison of benthic ecosystem functioning: Community bioturbation potential in four regions along the NE Atlantic shelf, *Ecol. Indic.* 2020, 110: 105945. <https://doi.org/10.1016/j.ecolind.2019.105945>
- [3] Romano, E., Bergamin, L., Parise, M. Benthic Foraminifera as Environmental Indicators in Mediterranean Marine Caves. A Review. *Geosciences*. 2022, 12(42), <https://doi.org/10.3390/geosciences12010042>
- [4] Khan, H., Brush, G. S. Nutrient and metal accumulation in a freshwater tidal marsh. *Estuaries*. 1994, 17(2), 345–360. <https://doi.org/10.2307/1352668>
- [5] Lacerda, L. D., Ittekkotb, V., Patchineelama, S. R. Biogeochemistry of Mangrove Soil N Organic Matter: a Comparison Between Rhizophora and Avicennia Soil Ns in Southeastern Brazil, *Estua. Coast. Shelf Science*. 1995, 40(6), 713-720. <https://doi.org/10.1006/ECSS.1995.0048>
- [6] Murdiyarso, D., Hanggara, B. B., Lubis, A. A. Sedimentation and soil carbon accumulation in degraded mangrove forests of North Sumatra, Indonesia. *BioRxiv*. 2018, 25p. <https://doi.org/10.1101/325191>
- [7] Ataulh, M., Chowdhury, M. R., Hoque, S., Ahmed, A. A. Physico-chemical properties of soils and ecological zonations of soil habitats of Sundarbans of Bangladesh. *Int. J. Pure Appl. Res.* 2017, 1(1), 80 – 93.
- [8] Rajal, P., Lamb, C., Roshan, B., Kamboj, R. D., Harshad, S. Physico-chemical characteristics of mangrove soil in Gulf of Kachchh, Gujarat, India. *Advances in Environmental Research*. 2019, 8(1), 39-54. <https://doi.org/10.12989/aer.2019.8.1.039>
- [9] Dahdouh-Guebas, F. Mangrove forests and tsunami protection. In: McGraw-Hill (éd). *Yearbook of Science & Technology*, New York, USA. 2006, 187-191.
- [10] Alongi, D. M. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine Coastal and Shelf Science*. 2008, 76, 13p. <https://doi.org/10.1016/j.ecss.2007.08.024>
- [11] Howarth, L. M., Waggitt, J. J., Bolam, S. G., Eggleton, J., Somerfield, P. J., Hiddink, J. G. The effects of bottom trawling and primary production on the biological traits composition of benthic assemblages. *Marine Ecology Progress Series*. 2018, 602, 31-48. <https://doi.org/10.3354/meps12690>
- [12] Guesdon, G., De Santiago Mart ín, A., Galvez-Cloutier, R. Restauration du lac La Retenue, l'AngeGardien, Québec. Phase I: Caract érisation des s édiments et qualité de l'eau de surface, Département de génie civil et de génie des eaux. UniversitéLaval, Québec. 2014, 37 p.
- [13] Benon, P., Blanc, F., Bourgade, B., David, P., Kantin, R., Leveau, M., Romano, J. C., Sautriot, D. Distribution of some heavy metals in the Gulf of Fos. *Marine Pollution Bulletin*. 1978, 9(3), 71-75. [https://doi.org/10.1016/0025-326X\(78\)90452-6](https://doi.org/10.1016/0025-326X(78)90452-6)
- [14] Safiur Rahman, M., Khan, M. D. H., Jolly, Y. N., Kabir, J., Akter, S., Salam, A. Assessing risk to human health for heavy metal contamination through street dust in the Southeast Asian Megacity: Dhaka, Bangladesh. *Sci Total Environ*. 2019, 660, 1610–1622. <https://doi.org/10.1016/j.scitotenv.2018.12.425>
- [15] Zhou, Y. W., Zhao, B., Peng, Y. S., Chen, G. Z. Influence of mangrove reforestation on heavy metal accumulation and speciation in intertidal sediments. *Marine Pollution Bulletin*. 2010, 60(8), 1319-1324. <https://doi.org/10.1016/j.marpolbul.2010.03.010>
- [16] Cotnoir, L. J. Marsh soils of the Atlantic coast. In: *Ecology of halophytes*. (eds.) R. J. Reimold, W. H. Queen, Academic press, INC. New York. 1974, 441-448.
- [17] Naidoo, G., Raiman, F. Some physical and chemical properties of mangrove soils at Sipingo and Mgeni, S. Afr. *J. Bot.* 1982, 1(4), 85-90. [https://doi.org/10.1016/S0022-4618\(16\)30155-3](https://doi.org/10.1016/S0022-4618(16)30155-3)
- [18] Mangwa Dongang, C., Nkwatoh, A. F., Asongwe, G. A., Kamah, P. B. An Assessment of the Physico-Chemical Parameters of Mangrove Soils that Support Nypa fruticans and Other Mangrove Species Establishment in the Cameroon Estuary. *Asian Soil Research Journal*. 2021, 5(2), 18 p. <https://doi.org/10.9734/ASRJ/2021/v5i230102>
- [19] Bomfim, M. R., G. Santos, J. A., Costa, O. V., da Conceição, J. N., da Silva, A. A., de Souza Souza, C., de Almeida, M. C. Morphology, Physical and Chemical Characteristics of Mangrove Soil under Riverine and Marine Influence: A Case Study on Subaé River Basin, Bahia, Brazil. *Mangrove Ecosystem Ecology and Function*. 2018, 7, 133 – 162. <https://doi.org/10.5772/intechopen.79142>
- [20] Souza, H. F., Guedes, M. L. S., Oliveira, S. S., Santos, E. S. Alguns aspectos fitossociológicos e nutricionais do manguezal da Ilha de Pati, Bahia, Brasil. *Sitientibus*. 1996, 15(1), 151-165.
- [21] Tomlinson, P. B. The botany of mangroves. Cambridge University Press. 1986, 413p.
- [22] Duke, N. C. Mangrove floristics and biogeography. In: Robertson, A.I., Alongi, D.M., (eds) *Tropical mangrove ecosystems*, Washington DC, American Geophysical Union, USA. 1992, 63– 100.

- [23] Jayatissa, L. P., Dahdouh-Guebas, F., Koedam, N. A review of the floral composition and distribution of mangroves in Sri Lanka. *Botanical Journal of the Linnean Society*. 2002, 138(1), 29-43.
- [24] Cannicci, S., Burrows, D., Fratini, S., Lee, S. Y., Smith III, T. J., Offenberg, J., Dahdouh-Guebas, F. Faunistic impact on vegetation structure and ecosystem function in mangrove forests. *Aquat. Bot.* 2008, 89(2), 186-200.
<https://doi.org/10.1016/j.aquabot.2008.01.009>
- [25] Nagelkerken, I., Blaber, S., Bouillon, S., Green, P., Haywood, M., Kirton, L. G., Meynecke, J. O., Pawlik, J., Penrose, H. M., Sasekumar, A., Somerfield, P. J. The habitat function of mangroves for terrestrial and marina fauna. *Aquat. Bot.* 2008, 89(2), 201-219. <https://doi.org/10.1016/j.aquabot.2007.12.007>
- [26] Nfotabong Atheull, A., Din, N., Longonje, S. N., Koedam, N., Dahdouh-Guebas, F. Commercial activities and subsistence utilization of mangrove forests around the Wouri estuary and the Douala-Edea reserve (Cameroon). *Journal of Ethnobiology and Ethnomedicine*. 2009 5(35), 14 p.
<https://doi.org/10.1186/1746-4269-535>
- [27] Krauss, K. W., Lovelock, C. E., McKee, K. L., Lopez-Hoffman, L., Ewe, S. M., Sousa, W. P. Environmental drivers in mangrove establishment and early development. *Aquat. Bot.* 2008, 89(2), 105-127.
- [28] MINEPDED-RCM. Atlas des mangroves du Cameroun. 2017, 14 p.
- [29] Mama, A. C., Youbouni Ghepdeu, G. F., Ngoupayou Ndam, J. R., Bonga, M. D., Onana Fils, M., Onguene, R. Assessment of water quality in the lower Nyong estuary (Cameroon, Atlantic Coast) from environmental variables and phytoplankton communities' composition. *African Journal of Environmental Science and Technology*. 2018, 12(6), 198 -208.
<https://doi.org/10.5897/AJEST2017.2454>
- [30] Mama, A. C. Structure et dynamique hydrobiogéochimique des estuaires du Cameroun: cas du Nyong et de la Kienkésur la Côte Atlantique méridionale au sud de la Sanaga. Thèse. 2019, 250 p.
- [31] Nfotabong Atheull, A. Utilisation des mangroves par les habitants des zones côtières près de Kribi, du Nyong et de l'estuaire du Cameroun. Mémoire de DEA, Université Libre de Bruxelles-ULB, Bruxelles, Belgique. 2008, 80 p.
- [32] Mama, A. C., Oben, L. M., Dongmo, T. C., Ndam, N. J. R., Motto, I., Ayina, O. L. M. Tidal Variations and its Impacts on the Abundance and Diversity of Phytoplankton in the Nyong Estuary of Cameroon. *J. Multidiscip. Eng. Sci. Technol.* 2016, 3(1), 3667-3675.
- [33] Mama, A. C., Bodo, W. K. A., Ghepdeu, G. F. Y., Ajonina, G. N., Ndam, J. R. N. Understanding Seasonal and Spatial Variation of Water Quality Parameters in Mangrove Estuary of the Nyong River Using Multivariate Analysis (Cameroon Southern Atlantic Coast). *Open Journal of Marine Science*. 2021, 11(3), 103-128.
<https://doi.org/10.4236/ojms.2021.113008>
- [34] Dzana, J. G., Ngoupayou, J. R. N., Tchawa, P. The Sanaga Discharge at the Edea Catchment Outlet (Cameroon): An Example of Hydrologic Responses of a Tropical Rain Fed River System to Changes in Precipitation and Groundwater Inputs and to Flow Regulation. *River Research and Applications*. 2011 27(6), 754-771.
<https://doi.org/10.1002/rra.1392>
- [35] Giresse, P., Megope-Foonde, J. P., G. Ngueutchoua, G., Aloisi, J. C., Kuete, M., Monteillet, J. Carte sédimentologique du plateau continental du Cameroun. Éditions de l'ORSTOM/IRD. 1996, 111, 46 p.
- [36] Boye, M., Baltzer, F., Caratini, C. Mangrove of the Wouri Estuary. *International Symposium of Biology and Management of Mangrove*. Honolulu. 1974, 8(11), 435-455.
- [37] Zogning, A., Kuete, M. L'équilibre écologique du littoral Camerounais: Données géographiques du problème. *Xe Coll. Sepanrit Leget, Cayenne*. 1985, 229-237.
- [38] Morin, S., Kuété M. Le littoral Camerounais: Problèmes morphologiques. *Travaux du Laboratoire de géographie physique appliquée*. 1988, 11, 5-52.
<https://doi.org/10.3406/tlgepa.1988.900>
- [39] Giresse, P., Cahet, G. Organic Fluxes of Cameroon Rivers into the Gulf of Guinea: A Quantitative Approach to Biodegradation in Estuary and Plume. *Oceanologica Acta*. 1997, 20(6), 837-849.
- [40] Chougong, D. T., Mama, A. C., Ekoa, A., Ngualeu Siewe, G. C., Djoumo Nono, S. C., El-Amier, Y. A. Distribution of trace metals and radionuclides contamination in two sections of sediments cores from the Nyong estuary, Cameroon, southern Atlantic coast. *Regional Studies in Marine Science*. 2022, 56, <https://doi.org/10.1016/j.rsma.2022.102675>
- [41] Toteu, S. F., Van Schmus, W. R., Penaye, J., Michard, A. New U-Pb and Sm-Nd data from north-central Cameroon and its bearing on the Pre-Pan-African history of central Africa. *Pre-camb. Res.* 2001, 108, 45-73.
- [42] Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J. L., Cadamuro, L. Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. *Oecologia*. 1998, 115(1-2), 39-53.
<https://doi.org/10.1007/s004420050489>
- [43] Mendoza, A. B., Alura, D. P. Mangrove structure on the Eastern Coast of Samar Island, Philippines. In: D. E. Stott, R. H. Mohtar and G. C. Steinhardt (eds.). 2001, 423-425.
- [44] Kangas, P. Mangrove forest structure on the Sittoung river, Belize. *Natural Resources Management Program*. University of Maryland. 2002, 7 p.
- [45] Marchand, C., Allenbach, M., Lallier-Vergès, E., Sabrina Virly, L. D. P., Rataud, C. Structure écologique et bilan des processus biogéochimiques au sein d'une mangrove. *IRD-Nouvelle Calédonie*. 2008, 131 p.
- [46] Chougong, D., Ekoa, A., Ngueutchoua, G., Yongue, R., Fouateu. Mineralogy and geochemistry of Lobe river sediments, SW Cameroon: Implications for provenance and weathering. *Journal of African Earth Sciences*. 2021, 183(3), 104320, <https://doi.org/10.1016/j.jafrearsci.2021.104320>

- [47] Hussenot, J., Martin, J. L. M. Assessment of the quality of pond sediment in aquaculture using simple, rapid techniques. *Aquaculture International*. 1995, 3(2), 123-133.
- [48] P. Raimbault, Slawyk, G., Coste, B., Fry, J. Feasibility of measuring an automated colorimetric procedure for the determination of seawater nitrate in the 0 to 100 nM range: examples from field and culture. *Mar. Biol.* 1990 104, 347-351.
- [49] Guesdon, G., De Santiago, M. A., Galvez-Cloutier, R., Restauration du lac La Retenue, l'Ange-Gardien, Québec Phase I: Caractérisation des sédiments et qualité de l'eau de surface Département de génie civil et de génie des eaux. Université Laval, Québec. 2014, 37 p.
- [50] Singh, P., Major. trace and REE geochemistry of the Ganga River sediments: influence of provenance and sedimentary processes. *Chem. Geol.* 2009, 266(3-4), 242 – 255. <https://doi.org/10.1016/j.chemgeo.2009.06.013>
- [51] Ekoa Bessa, A. Z., Nguetchoua, G., Ndjigui, P. D. Mineralogy and geochemistry of sediments from Simbock Lake, Yaoundé area (southern Cameroon): provenance and environmental implications. *Arabian Journal of Geosciences*. 2018, 11(22), 710p. <https://doi.org/10.1007/s12517-018-4061-x>
- [52] Munsell. Munsell Soil Color Charts, Revised Washable. GretagMacbeth. 2000, 10p.
- [53] Froelich, P. N., Klinkhammer, G. P., Bender, M. L., Luedtke, N. A., Heath, G. R., Cullen, D., Dauphin, P., Hammond, D., Hartman, B., Maynard, V. Early oxidation of organic-matter in pelagic sediments of the eastern equatorial atlantic - sub-oxic diagenesis. *Geochimica et Cosmochimica Acta*. 1974, 43(7), 1075-1090. [https://doi.org/10.1016/0016-7037\(79\)90095-4](https://doi.org/10.1016/0016-7037(79)90095-4)
- [54] Postma, D., Jakobsen, R. Redox zonation: equilibrium constraints on the Fe (III)/SO₄ reduction interface. *Geochimica et Cosmochimica Acta*. 1996, 60(17), 3169-3175.
- [55] Deborde, J. Processus biogéochimiques des zones intertidales des systèmes lagunaires: le Bassin d'Arcachon (SW, France). Thèse de doctorat de l'Université de Bordeaux 1, Bordeaux. 2007, 210 p.
- [56] Molnar, N. Impact des effluents de la crevetteiculture sur la dynamique de la matière organique benthique et leurs implications sur les processus biogéochimiques dans une mangrove (Nouvelle-Calédonie). Thèse de doctorat. 2012, 288 p.
- [57] Vieillefon, J. Étude des variations du pH et du rH dans les sols de mangroves de Basse-Casamance. *Comm. Vie Conf. West. Afric. Sc. Assoc.*, Abidjan. 1969, 36 p.
- [58] Pauwels, P. M., van Ranst, E., Verloo, M., Mvendo, Z. E. A. Manuel de laboratoire de pédologie. Méthodes d'analyses de sols et de plantes, équipements, gestion de stocks de verrerie et de produits chimiques. AGCD, Publications Agricoles. 1992, 28, 265p.
- [59] Chen, R., Twilley, R. R. Patterns of Mangrove Forest Structure and Soil Nutrient Dynamics Along the Shark River Estuary, Florida. *Estuaries*. 1999, 22(4), 955-970. <https://doi.org/10.2307/1353075>
- [60] Olivry, J. C. Fleuves et Rivières du Cameroun. Hydrologie ORSTOM. Unité de recherche. 1986, 107(9), 733 p.
- [61] Kouogang Tchuenkam, F. C., Mama, A. C., Gah-Muti, S. Y., Araujo, M. Variability of Sea Breezes Over the Cameroonian Coast and Their Interaction with the West African Monsoon. *Front. Earth Sci.* 2022, (10), <https://doi.org/10.3389/feart.2022.848684>
- [62] Ndema, E., Sone Essoh, W., Ajonia, G. N., Etame, J., Din, N., Diyouke Mibog, E. Dynamique de croissance et taux de mortalité de *Rhizophora* spp. dans les mangroves de l'estuaire du Rio del Rey: Site de Bamusso (Sud-Ouest Cameroun). *Journal of Applied Biosciences*. 2015, 85(1), 7824-7837. <https://doi.org/10.4314/jab.v85i1.7>
- [63] Martin, D. Géomorphologie et sols ferrallitiques dans le Centre Cameroun. *Cah. Orstom, s.é. Pédol.* 1967, (2), 189-218.
- [64] Vallerie, M. La pédologie. In *Atlas régional Sud-Cameroun*. ORSTOM éd. 1995, 10(11).
- [65] Ajonina, G. N. Inventory and modelling mangrove forest stand dynamics following different levels of wood exploitation pressures in the Douala- Edea atlantic coast of Cameroon, Central Africa. PhD Thesis. Faculty of forest and environmental sciences, Albert-Ludwigs- Universität Freiburg im Breisgau, Germany. 2008, 232 p.
- [66] FAO, Food and Agricultural Organization. Mangrove Forest Management Guidelines. Rome (RO): FAO Forestry Paper. 1994.
- [67] Efe, U. A. Mangrove growth dynamics and sediment relations in South Western Nigeria. *JPSL*. 2020 10(4), 688-698. <https://doi.org/10.29244/jpsl.10.4.688-698>
- [68] Okanga-Guay, M., Ondo Assoumou, E., Akendengue Aken, I., Mpie Simba, C., Mombo, J. B. Suivi des changements spatiaux et environnementaux dans les mangroves de la province de l'Estuaire du Gabon. Conférence OSFACO: Des images satellites pour la gestion durable des territoires en Afrique, Cotonou, Bénin. (hal-02189534). 2019.
- [69] Cintron, G., Schaeffer-Novelli, Y. Introduction a la Ecologia del Manglar. Rostlac, San Juan, Puerto Rico. 1983, 109 p.
- [70] Wolanski, E., Gibbs, R. J., Spagnol, S., King, B., Brunskill, G. Inorganic sediment budget in the mangrove-fringed Fly River delta, Papua New Guinea. *Mangroves Salt Marshes*. 1998, 2(2), 85-98. <https://doi.org/10.1023/a:1009946600699>
- [71] Ferreira, T. O., Otero, X. L., De Souza, V. S., Vidal-Torrado, P., Macias, F., Firme, L. P. Spatial patterns of soil attributes and components in a mangrove system in Southeast Brazil (Sao Paulo). *J. Soils Sediments*. 2010, 10(6), 995-1006. <https://doi.org/10.1007/s11368-010-0224-4>
- [72] Lugo, A. E., Snedaker, S. C. The ecology of mangroves. *Annual Review of Ecology and Systematics*. 1986, 5, 39-64. <https://doi.org/10.1146/annurev.es.05.110174.000351>
- [73] Cintron, G., Lugo, A. E., Pool, D. J., Morris, G. Mangroves of and environments, in Puerto Rico and adjacent islands. *Biotropica*. 1978, 10(2), 110-121. <https://doi.org/10.2307/2388013>

- [74] Lugo, A. E., Brown, S., Brinson, M. M. Forested wetlands in freshwater and saltwater environments. *Limnology and Oceanography*. 1988, 33(4-2), 894-909.
<https://doi.org/10.4319/lo.1988.33.4part2.0894>
- [75] Barrêdo, J. F., Costa, M. L., Vilhena, M. P. S. P., Santos, J. T. Mineralogia e geoquímica de sedimentos de manguezais da costa amazônica: o exemplo do estuário do rio Marapanim (Pará). *Revista Brasileira de Geociências*, São Paulo. 2008, 38(1), 26-37.
- [76] Rambok, E., Gandaseca, S., Ahmed, O. H., Majid, N. M. A. Comparison of selected soil chemical properties of two different mangrove forests in Sarawak. *Am. J. Environ. Sci.* 2010, 6(5), 438-441. <https://doi.org/10.3844/ajesp.2010.438.441>
- [77] Moreno, A. N. M., Calderon, J. H. M. Quantification of organic matter and physical-chemical characterization of mangrove soil at Hooker Bay, San Andres Island-Colombia. *Proceedings of the Global Conference on Global Warming*, Lisbon, Portugal. 2011, 7 p.
- [78] Das, S., De, M., Ganguly, D., Maiti, T. K., Mukherjee, A., Jana, T. K., De, T. K. Depth integrated microbial community and physico-chemical properties in mangrove soil of Sundarban, India. *Adv. Microbiol.* 2012, 2, 234-240.
<https://doi.org/10.4236/aim.2012.23028>
- [79] Sabrina V. Evaluation de l'impact de l'aquaculture de crevettes sur les mangroves de nouvelle-caledonie. *Zonéco*. 2005, 30913, 125 p.
- [80] Reeburgh, W. S. Rates of biogeochemical processes in anoxic sediments. *Annual review of earth and planetary Sciences*. 1983, 11, 269-298.
<https://doi.org/10.1146/annurev.ea.11.050183.001413>
- [81] Hussenot, J. Les systèmes intégrés en aquaculture marine: une solution durable pour un meilleur respect de l'environnement littoral. *Centre de Recherche sur les Ecosystèmes Marins et Aquacoles, UMR CNRS-IFREMER*. 2004, 44p.
- [82] Hossain, M. D., Nuruddin, A. A. Soil and mangrove: A Review. *J. Environ. Sci. Technol.* 2016, 9(2), 198-207.
<https://doi.org/10.3923/jest.2016.198.207>
- [83] Alongi, D. M. The dynamics of benthic nutrient pools and fluxes in tropical mangrove forests. *Journal of Marine Research*. 1996, 54, 123-148.
- [84] Alongi, D. M. Present state and future of the world's mangrove forests *Environmental Conservation*. CAMBRIDGE university press. 2002, 29(03), 331-349.
<https://doi.org/10.1017/S0376892902000231>
- [85] Virly, S. Atlas cartographique des mangroves de Nouvelle-Calédonie. *Programme ZoNéCo*. 2008, 207p.
- [86] Testa, J. M., Kemp, W. M., Hopkinson, C. S., Smith, S. V. Ecosystem Metabolism. *Estuarine ecology*. 2012, 15, 381-416.
<https://doi.org/10.1002/9781118412787.ch15>
- [87] Akhand, A., Chanda, A., Watanabe, K., Das, S., Tokoro, T., Hazra, S., Kuwae, T. Reduction in riverine freshwater supply changes inorganic and organic carbon dynamics and air-water CO₂ fluxes in a tropical mangrove dominated estuary. *Journal of Geophysical Research: Biogeosciences*. 2021, 126(5), 22 p.
<https://doi.org/10.1029/2020JG006144>
- [88] Meyers, P. A. Organic Geochemical Proxies of Paleoceanographic, Paleolimnologic, and Paleoclimatic Processes. *Organic Geochemistry*. 1997, 27(5-6),
[https://doi.org/10.1016/S0146-6380\(97\)00049-1](https://doi.org/10.1016/S0146-6380(97)00049-1)
- [89] Allotey, D. F. K., Asiamah, R. D., Dedzoe, C. D., Nyamekye, A. L. Physico-chemical properties of three salt-affected soils in the lower volta basin and management strategies for their sustainable utilization. *West African Journal of Applied Ecology*. 2008, 12(1), 14 p.
<https://doi.org/10.4314/wajae.v12i1.45776>
- [90] Hazelton, P., Murphy, B. Interpreting soil test results: what to do all the numbers mean? *CSIRO Publishing*. Collingwood Victoria-Australia. 2007, 631(42), 169 p. ISBN 978 0 64309 225 9. Available: <http://www.publish.CSIRO>.
- [91] Hochard, S., Pringault, O., Pinazo, C., Bourgeois, S., Rochelle-Newall, E. Impact des apports anthropiques sur le fonctionnement biogéochimique et le rôle des sédiments du lagon de Nouvelle-Calédonie. *Programme ZoNéCo*. 2012, 41 p.
- [92] Koch, M. S., Snedaker, S. C. Factors influencing *Rhizophora* mangrove seedling development in Everglades carbonate soils. *Aquatic Botany*. 1997, 59(1-2), 87-98.
[https://doi.org/10.1016/S0304-3770\(97\)00027-2](https://doi.org/10.1016/S0304-3770(97)00027-2)
- [93] Sterner, R. W., Elser, N. B. Carbone, azote et phosphore, stœchiométrie des poissons cyprinidés. *Ecology*. 2000, 81(1), 127-140. [https://doi.org/10.1890/0012-9658\(2000\)081\[0127:CNAPSO\]2.0.CO2](https://doi.org/10.1890/0012-9658(2000)081[0127:CNAPSO]2.0.CO2)
- [94] Anderson, D. M., Glibert, P. M., Burkholder, J. M. Harmful Algal Blooms and Eutrophication: Nutrient Sources, Composition, and Consequences. *Estuaries*. 2002, 25(4), 704-726.
<https://doi.org/10.1007/BF02804901>
- [95] Oslisly, R. The history of human settlement in the middle Ogooué valley (Gabon): implications for the environment. In: Weber, W, White, L. J. T, Vedder, A, Naughton-Treves, L, editors. *African Rain Forest Ecology and Conservation*. New Haven: Yale University Press. 2001, 101-118. Google Scholar.
- [96] FAO, The world's mangroves, 1980- 2005. *FAO Forestry Paper*, Rome. 2007, 153, 89 p.
- [97] Holmer, M., Andersen, F., Holmboe, N., Kristensen, E., Thongtham, N. Transformation and exchange processes in the Brangrong mangrove forest-seagrass bed system, Thailand. Seasonal and spatial variations in benthic metabolism and sulfur biogeochemistry. *Aquatic Microbial Ecology*. 1999, 20, 203-212.
- [98] FAO, Relevance of mangrove forests to African fisheries, Wildlife and Water resources. *Food and Agriculture Organization, regional office for Africa. Nature and Faune Magazine*. 2009, 24(1), 91 p.
- [99] Ranaivoson, J. Etude du schéma d'aménagement de l'aquaculture de crevettes à Madagascar. Phase I: Cas des zones 1, 4. Madagascar, Ministère de la pêche et des ressources halieutiques. *Rapport de l'Union européenne*, Paris. 2001, 78 p.

- [100] Tazo Fopi, R. D., Ngankam Tchamba, M., Nwutih Ajonina G. Caractérisation physico-chimique et dendrométrie dans les traitements de régénération de mangrove de l'Estuaire du Cameroun. *Int. J. Biol. Chem. Sci.* 2021, 15(6), 2701-2714. ISSN 1997-342X (Online), ISSN 1991-8631 (Print).
- [101] Dahdouh-Guebas, F. *World Atlas of Mangroves*: Mark Spalding, Mami Kainuma and Lorna Collins (eds). *Human Ecology*. 2011 39(1), 107–109.
<https://doi.org/10.1007/s10745-010-9366-7>
- [102] Andrade, K. V. S., Holanda, F. S. R., Santos, T. O., Santana, M. B. S., Araújo Filho, R. N. Mangrove Soil in Physiographic Zones in the Sao Francisco River Estuary. *Floresta e Ambiente*. 2018, 25(2), 9 p. e20160638.
<https://doi.org/10.1590/2179-8087.063816>