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# A cross-section analysis of sedimentary organic matter in a mangrove ecosystem under dry climate conditions: The Somone estuary, Senegal

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## Abstract

Mangrove sediments are an important organic matter (OM) reservoir and play a major role in the carbon cycle. Since the 1990s, these ecosystems were subjected to numerous studies, in order to quantify the sedimentary sink for organic carbon (OC) and to characterize the organic matter sources, but remain poorly studied in Western Africa. The aim of our study is to quantify the organic carbon content and to identify the OM origin stored in the Somone mangrove sediments. Studied area is characterized by a (i) dry climate conditions with a higher rate of evaporation, (ii) lack of freshwater input by river, and (iii) tide dominated system. Here, we focus on physico-chemical properties of sediments (temperature, pH and redox), sediment grain size, water content, particulate organic carbon and dissolved organic carbon from a series of 40 cm-deep cores in four tidal contexts: mudflat, *Rhizophora*, and *Avicennia* mangroves and barren area. Results show that total organic carbon (TOC) contents range between 0.34 and 3.92 wt.% and are higher in sediments from mudflat and *Rhizophora* mangrove than in sediments from *Avicennia* mangrove and barren area. Indeed, sediments stored under *Avicennia* is subjected to suboxic conditions initiated by roots system and crabs bioturbation; while under *Rhizophora* and mudflat, local anoxic conditions are prevalent as suggest the negative Eh values and the occurrence of framboidal pyrites. Mangrove sediments of the Somone estuary contain an autochthonous lignocellulosic-derived organic matter. The youngest and stunted form of the Somone mangrove explains the low organic carbon content of sediments; where dry climate conditions limit the organic matter production by the mangrove forest.

The shallow depth at which the organic matter of the former mudflat was found confirms that the Somone mangrove is subjected to a low sedimentation rate. This suggests that organic carbon burial depends on others processes than sedimentation. Then, in the Somone mangrove ecosystem, both of pneumatophores and burrowing crab activities are the main factors that control OM degradation (*Avicennia* station) while anaerobic conditions (mudflat and *Rhizophora*) promote OM preservation.

**Keywords :** Mangrove sediments; Organic carbon; pH/redox; Bioturbation; Tide; Somone estuary

## 1. Introduction

75% of world's tropical coasts (>150,000 km<sup>2</sup>) are covered by mangroves forests considered as one of the major transitional ecosystems between terrestrial and marine environments (Spalding et al., 1997). Mangroves are present throughout the West African coast, and particularly from Senegal to Sierra Leone where they cover an area of about 3 millions hectares (Marius and Lucas, 1991). Mangrove ecosystems are highly productive, rich in biodiversity and support numerous ecological functions (Chong et al., 1996, Schaffelke et al., 2005, Wolanski, 2007, Alongi, 2008, Nagelkerken et al., 2008 and Comeaux et al., 2012) and human services (Rönnbäck et al., 2007, Walters et al., 2008, Alongi, 2011 and Badola et al., 2012). Despite its importance, a reduction of surface area occupied by mangroves forests is observed worldwide, and is related as much to natural as to anthropogenic causes (Spalding et al., 1997, Ellison, 1999 and Sakho et al., 2011). However, reforestation policy was developed in order to restore and protect mangrove ecosystems (Sakho et al., 2011 and Monsef et al., 2013).

Mangroves forests are characterized by a total net primary production of  $218 \pm 72$  Tg C/yr (Twilley et al., 1992 and Bouillon et al., 2008), making them one of the most productive natural ecosystems of the world (FAO, 2007). Due to their high productivity and transitional position, mangroves play an important role in the C, N, P biogeochemical cycles in coastal environments (Singh et al., 2005 and Kristensen et al., 2008). Hence, such environments play also a significant role in the global organic carbon budget (Chmura et al., 2003, Duarte et al., 2005 and Bouillon et al., 2008). OC in mangrove sediments can be autochthonous (mangrove detritus, litters, benthic vegetation) and/or allochthonous (coastal ecosystems vegetation, riverine transport of eroded soils, freshwater and marine phytoplankton, tidally suspended OM e.g. Goni et al., 2006, Mesnage et al., 2007, Kristensen et al., 2008 and Ranjan et al., 2011). They are both an important sink and source of OC (Twilley et al., 1992, Sanders et al., 2010, Sanders et al., 2012, Tue et al., 2011 and Donato et al., 2011). However, at global scale, particulate OC storage within mangrove sediments is variable as attests the wide range of TOC content measured in sediments varying between <2.00 and <40.00 wt.%, with a median particulate OC of 2.20 wt.% (Kristensen et al., 2008). Accordingly, improve our knowledge in the OC storage and OM dynamics in mangroves require to address to the parameters acting on these two processes in a considered mangrove ecosystem (Tue et al., 2012). Unfortunately, mangrove sediments were very seldom investigated at global scale (Marchand et al., 2008, Bouillon et al., 2008 and Sanders et al., 2010) and even more seldom at the African continent scale. Scientific investigations on African mangroves, as in Kenya (Middelburg et al., 1996) and Nigeria (Ukpong, 1995, Ukpong, 1997 and Effiong and Ayolagha, 2010) clearly were highlighted the fact that the biogeochemical characteristics of sediments – particulate and dissolved OC contents, interstitial water nutrients concentrations, redox potential, salinity – are the main indicators showing that sediment biogeochemistry influences the way of mangroves development (*Rhizophora*, *Avicennia*). In Senegal, researches have mainly focused on how Saloum's and Casamance's mangrove surfaces have evolved with climate variations ( Sall, 1982, Marius, 1995 and Diop et al., 1997), but only a few and ancient studies have focused on sediment geochemistry ( Viellefon, 1969 and Marius and Lucas, 1982). The sediment colonized by the mangroves is relatively homogenous. In the mineralogical point of

view, they are dominated by quartz and clays associated to halite, pyrite and jarosite. The clays suite is mainly composed of smectite and kaolinite ( Marius and Lucas, 1991).

In this work, we examine the bulk OM coupled with porewater chemistry in order to discuss (i) the OM sources, (ii) the OM degradation processes, (iii) the impact of bioturbation on the OM dynamics (preservation or degradation), and (iv) the impact of tidal dynamics on porewater chemistry.

## **2. Materials and methods**

### **2.1. Study area**

The Somone estuarine mangrove located on the Petite Côte in Senegal is a 7 km<sup>2</sup> surface tropical ecosystem (Fig. 1A). It extends at the end of a 350 m length sand spit, stretches parallel to the coast (Sakho et al., 2010). This ecosystem comprises of habitats, including mangroves (*Rhizophora* and *Avicennia*), intertidal mudflats, barren area (locally named tannes), sand banks and sand spit ( Fig. 1B). The mangrove forest and the mudflats are located in the intertidal zone whereas the barren areas are in the supratidal zone ( Fig. 1C). They are submerged by exceptional tides and/or rainfall during the wet season (June to October). The mouth area ( Fig. 1B) is relatively deep (>4 m), its width varies depending on the dynamics of the distal part of the sand spit (7 m in January 2010, at the time of the study).

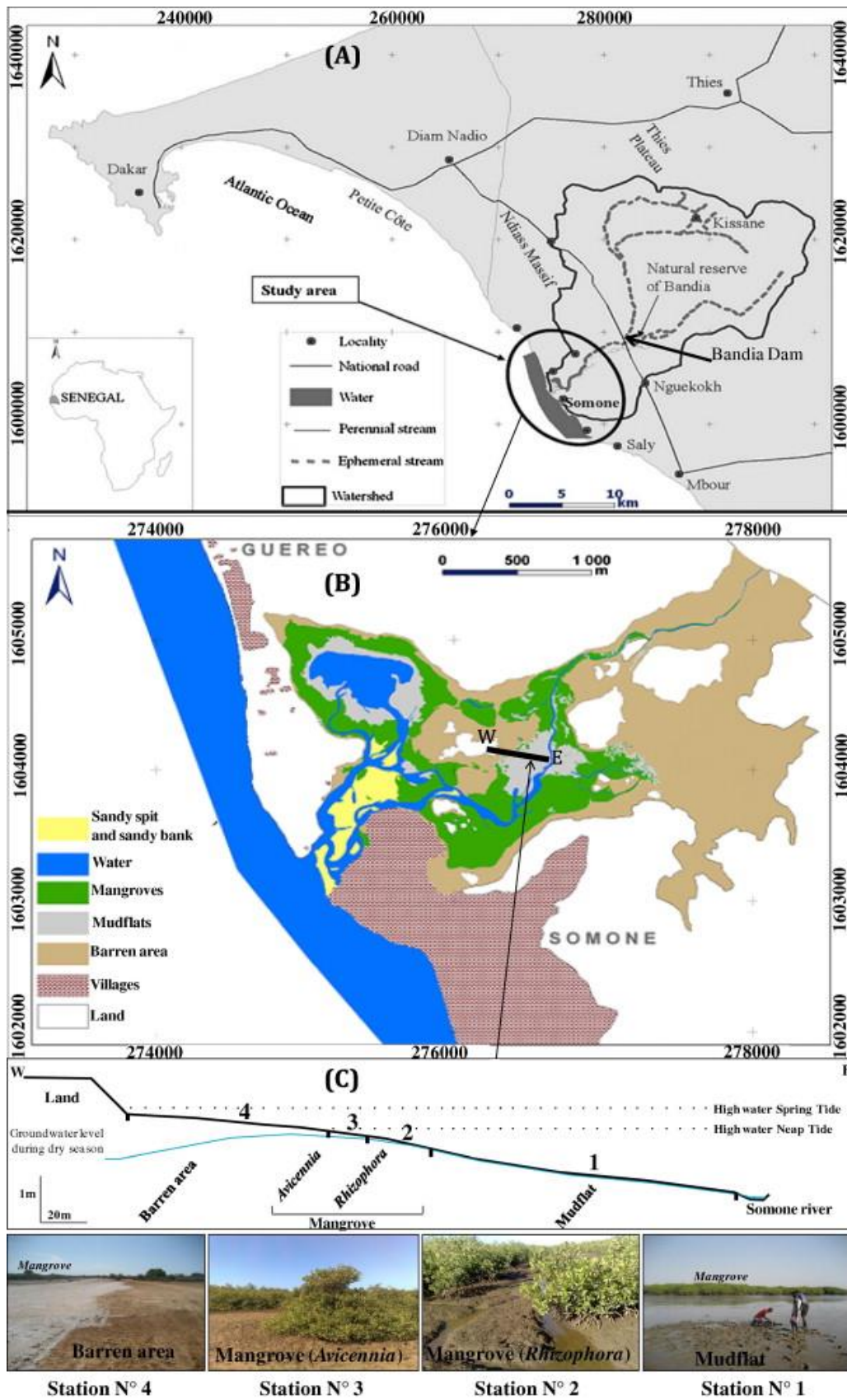


Fig. 1. : Study site localization (Somone River correspond to the Channel).

The Somone region lies within the Atlantic Soudanian climatic zone characterized by two contrasted seasons (Leroux and Sagna, 2000). The dry season lasts approximately eight months – from November to June – and is characterized by warm and dry winds while the short rainy season lasts 3 to 4 months – from June/July to October – and is mainly ruled by monsoonal flows.

The hydrographic network of the Somone region drains a 420 km<sup>2</sup> watershed and has little hierarchical organization. It is formed by the confluence of two ephemeral streams that meet at the Bandia reserve (Fig. 1A). Most of the flow occurs in August and September, when the maximum precipitation occurs. Since 1975 at the Bandia station, the maximum discharge has never exceeded 10 m<sup>3</sup> s<sup>-1</sup> with an annual average of 4 m<sup>3</sup> s<sup>-1</sup>. The mangrove forest is located in a microtidal zone – tidal range <2 m at the mouth- with a semi-diurnal tide regime. In this ecosystem, salinity is highly correlated to rainfall with rather important seasonal variations. 70% of the time, it increases when going upstream leading to a reverse estuary context. This increase in salinity from the ocean is enhanced by their location in the Northern latitude and the watershed geometry (Diop, 1990).

## 2.2. Field sampling

We have investigate a cross-section of bulk sediment along a downstream-upstream transect that respectively defines the intertidal mudflat (station 1), the *Rhizophora* mangrove (station 2), the *Avicennia* mangrove (station 3) and the barren area (station 4) corresponding to a hypersaline zone with salt efflorescence ( Fig. 1C). This transect was selected according to a salinity and a flooding-dessication gradient. Indeed, stations 1 and 2 are located in the intertidal zone and are therefore submerged at high tide. The tanne is located in the supratidal zone and is only submerged at spring tide. The *Avicennia* mangrove is located at the limit of these two tidal zones.

Field works were conducted during the dry season (January 2010). A set of 42 cm-deep sediment cores was collected at the four stations with some 10 cm-diameter PVC corers. Cores were immediately cut-off into sections from the top to the bottom (0–2 cm/10–12 cm/20–22 cm/40–42 cm); samples were then stored at –20 °C until their analysis.

By using a transparent pierced-PVC corer, the temperature, salinity, pH and redox profiles were carried out in-situ with pH-KCl-saturated glass electrode and Pt/Pt-Ag/Ag-Cl redox electrodes.

## 2.3. Laboratory analysis

The grain size distribution (sand to clay fractions) was performed with a micro-granulometric laser Bechman-Coulter L230.

The sediment porewater was extracted by centrifugation (3000 R/mn, during 25 mn). The concentrations in anions (Cl<sup>-</sup> and SO<sub>4</sub><sup>2-</sup>) and cations (K<sup>+</sup>, Ca<sup>2+</sup>, Na<sup>+</sup>, Mg<sup>2+</sup>) were determined using ionic chromatography equipped with anions and cations specific columns (Metrohm IC 732, IC 733).

The dissolved organic carbon (DOC, measurement uncertainty <5%) was analyzed with a “TOC Shimadzu 5050” carbon analyser.

Pyrite in sediments has been observed using Scanning electronic microscopy – Zeiss Evo40 Ep.

Sediments were air-dried at room temperature and sieved to <2 mm. TOC was analyzed using the Rock-Eval 6 pyrolyser (Lafargue et al., 1998). This apparatus is now applied to quickly characterize the global geochemistry of recent OM of sediments (e.g. Disnar and Trichet, 1984 and Marchand et al., 2008), of soils (e.g. Di-Giovanni et al., 1998), or of suspended load in river (e.g. Copard et al., 2006). Between 50 and 100 mg of dry sample are first pyrolyzed under inert atmosphere (N<sub>2</sub>) according to a linear temperature programming (25 °C/min from 250 to 650 °C). This first phase releases signals S<sub>1</sub> and S<sub>2</sub> delivered by an FID detector and corresponding respectively to the release of free hydrocarbon (already present in the sample) following by the hydrocarbon release due to the progressive OM cracking. The signal S<sub>3</sub> and S<sub>3'</sub> that are recorded concurrently by an IR cell, come respectively from the release of CO<sub>2</sub> and CO emitted during this step. The pyrolysis residue is then submitted to heating under O<sub>2</sub> with a linear temperature programming from 300 to 750 °C. An IR cell records the signals S<sub>4</sub> and S<sub>4'</sub> corresponding respectively to CO<sub>2</sub> and to CO produced by the combustion of the carbonaceous material.

The usual parameters of this analysis method come from the signal integration. Hydrogen Index (HI in mg HC/g TOC), calculated from signal S<sub>2</sub>, corresponds to the hydrogen richness of the sample whereas OI RE6 (OI in mg O<sub>2</sub>/g TOC) reveals the oxygenation degree of OM. Tmax (in °C) corresponding to the pyrolysis temperature at which the maximum quantity of HC compounds are released informs on the ability for recent OM to be processed (i.e. hydrolysis, bacterial consumption, oxidation). RE6 pyrolysis also provides the total organic carbon content (TOC expressed in weight%) corresponding to the sum of organic carbon (OC) calculated during the pyrolysis (PC, wt%) and combustion stages (RC, wt%). On the basis of the analyses performed with a standard from the Institut Français du Pétrole, measurements uncertainty does not exceed 3% (Noël et al., 2001).

### 3. Results

#### 3.1. Grain size distribution

Sediments in the four stations were composed of sand, silt and clay (Table 1). Considering the two first centimeters of sediment (0–2 cm), the mudflat (station 1) is characterized by 32% of sand, 63% of silts and 5% of clay. *Rhizophora* (station 2) is characterized by 30% of sand, 66% of silts and 4% of clay. The sediments of *Avicennia* (station 3) were composed by 34% of sand, 63% of silts and 3% of clay whereas the barren area (station 4) is composed by 75.5% of sand, 23% of silts and only 1.5% of clay (Table 1). Thus, at station 4 sediment grain size (0–2 cm) is dominated by sand fractions (76%) whereas, the others stations (1, 2, 3) it represents only 30% (Table 1). This pattern in the grain size distribution is the same whatever the depth. The intertidal zones (*Avicennia*, *Rhizophora* and mudflat) are mainly dominated by silt fraction. It ranges between 59% and 79% without any vertical gradient. With the exception of a maximum value of 20% at 40–42 cm depth, the clay fraction ranges between 2% and 7%, without any gradient with depth or the tidal stations (Table 1).

Table 1. Sediment grain size and porewater chemistry through a tidal cross-section.

Stations		Mangrove			Mudflat
Parameters	Depth/units	Barren area			(%)
		(Tanne) (%)	<i>Avicennia</i> (%)	<i>Rhizophora</i> (%)	
63 $\mu\text{m}$ < Sand < 2 mm	0–2 cm	76	34	30	32
	10–12	69	26	27	21
	20–22	79	35	30	30
	40–42	74	0.3	30	30
2 $\mu\text{m}$ < Silts < 63 $\mu\text{m}$	0–2 cm	22	63	66	63
	10–12	28	67	68	74
	20–22	19	59	67	65
	40–42	21	79.8	64	67
Clay < 2 $\mu\text{m}$	0–2 cm	2	3	4	5
	10–12	3	7	5	5
	20–22	2	6	3	5
	40–42	5	19.9	6	3
Water content (%)	0–10 cm	17	27	55	49
Salinity (g/L)	0–10 cm	>70	53	47	38

The water content remains of the same order of magnitude for the first 40 cm of the sedimentary column. But over the cross-section, the water content of sediments shows also an increasing gradient with 17%, 27%, 55% and 49%, in the tanne, *Avicennia*, *Rhizophora* and mudflat respectively ( Table 1).

This relative drying out can be explained by the flooding time that decreases toward the barren area (supratidal zone) to the mudflat (intertidal zone).

### 3.2. Porewater physicochemical properties

Concentrations in cations ( $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ) measured in interstitial waters exhibit the same trend that those of anions ( $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ ); the concentrations are always higher in the barren area (Fig. 2A). As an example,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$  and  $\text{Mg}^{2+}$  reach 0.5, 0.6, 12.0 and 1.5 g/L respectively in the mudflat while in the barren area, concentrations of these cations reach 1, 1, 22 and 2.5 g/L respectively. This trend can also be observed for anion concentrations in interstitial waters ( $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ ) showing a steadily increase from the tideway toward the barren area (Fig. 2A). As an example, chloride ( $\text{Cl}^-$ ) varies from 20.0 g/L in the channel to 22.5 g/L in the mudflat and to roughly 51.5 g/L in the barren area (Fig. 2A). This hyper salinity of barren area sediments is attested by salinity values, which gradually increase from the mudflat (station 1) toward the barren area (station 4) profiles, respectively 38.0 to



>70.0 g/L at sediment surface (Table. 1).  $\text{SO}_4^{2-}$  varies from 3 g/L in the mudflat to 3 g/L in *Rhizophora*, 4.0 g/L in the *Avicennia* and to 8.0 g/L in the barren area.

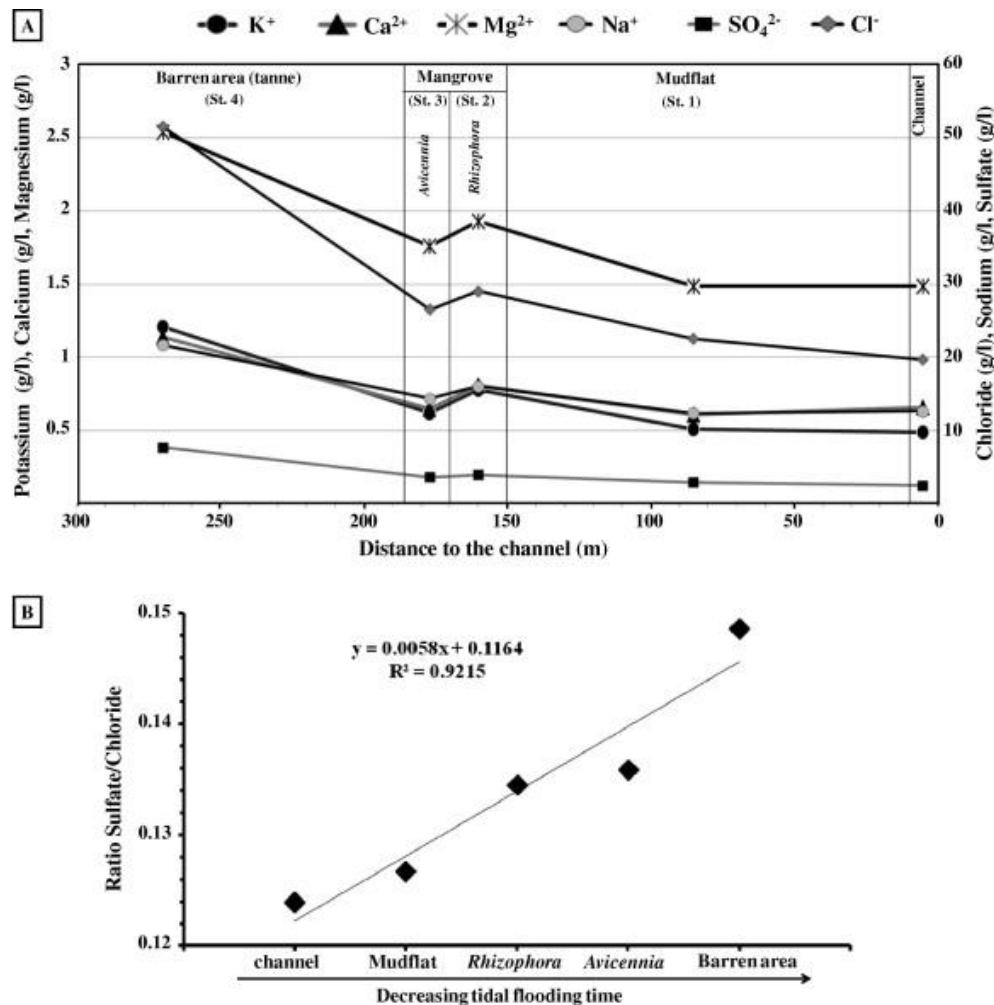
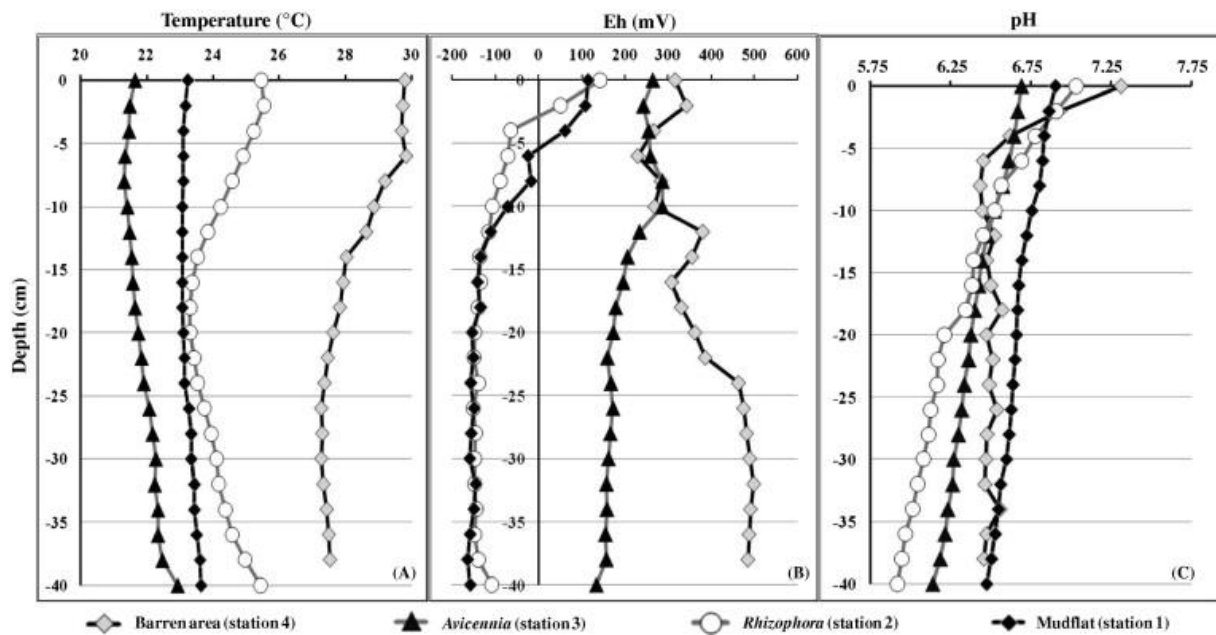


Fig. 2. : Sediment porewater chemistry (A) and ratio Sulfate/Chloride (B) variations through a tidal cross-section (st. = station).

The ratio sulfate/chloride shows also the same trend. Values range from 0.12 to 0.15 g/L, respectively for the mudflat and the barren area (Fig 2B). The lower values of the  $\text{SO}_4^{2-}/\text{Cl}^-$  ratio correspond to area mostly influenced by marine input. Then, these ions concentrations increasing toward the barren area are well correlated to the tidal flooding time, which decrease from the mudflat to the barren area. At station 1 (mudflat facies, Fig. 3A) temperature profile exhibits a value of 23.0 °C at the sediment surface and remains constant until – 40 cm depth (Fig 3A). In contrast, at station 2 (*Rhizophora* facies, Fig. 3A), the temperature values are not constant with depth. Indeed, at the top 2 cm of sediment, the temperature profile exhibit a value of 25.5 °C, then 24.0 °C at 10 cm depth, then 23.0 °C at 20 cm depth, 24.0 °C at 30 cm depth and finally 25.0 °C at 40 cm depth ( Fig. 3A). At station 3 (*Avicennia* facies, Fig. 3A), the temperature profile is quite vertical with some temperatures reaching 22.0 °C ± 0.5 °C. At station 4 (Barren area, Fig. 3A), the temperature values are higher than the three others stations ( Fig. 3A). Temperature values range from 27.2 to 29.8 °C all along the profile. At the 6 top cm of sediment, the temperatures reach values of 30.0 °C ( Fig. 3A) then, the temperature values

slightly decrease to to 27.0 °C at 25 cm depth and remain constant until the bottom of the profile ( Fig 3A)



. Fig. 3.

#### Physico-chemical properties of sediments.

At station 1 (mudflat facies, Fig. 3B), redox profiles present some positive values, (+100 mV) on the first 4 cm sediment (0–4 cm), the redox potential values decrease to reach – 25 mV at 5 cm depth. Deeper, the redox potential values are always negative with –70 mV at 10 cm and –150 mV at 15 cm depth, and remain constant toward the bottom of the profile. At station 2 (*Rhizophora* facies, Fig 3B), redox potential values remain positive (100 mV) at the top 2 cm of sediment, then the values become negative (–70 mV) at –5 cm depth. The Redox potential remains negative at –10 cm (–100 mV), –15 cm (150 mV) and until 40 cm depth. So, the sediment remains reduced for these two facies “mudflat” and “*Rhizophora*” (station 1 and 2) with the same redox potential profiles from 15 to 40 cm depth. These anoxic conditions in sediment at *Rhizophora* and mudflat stations have been pointed out by the occurrence of framboïdal pyrite ( Fig. 4).

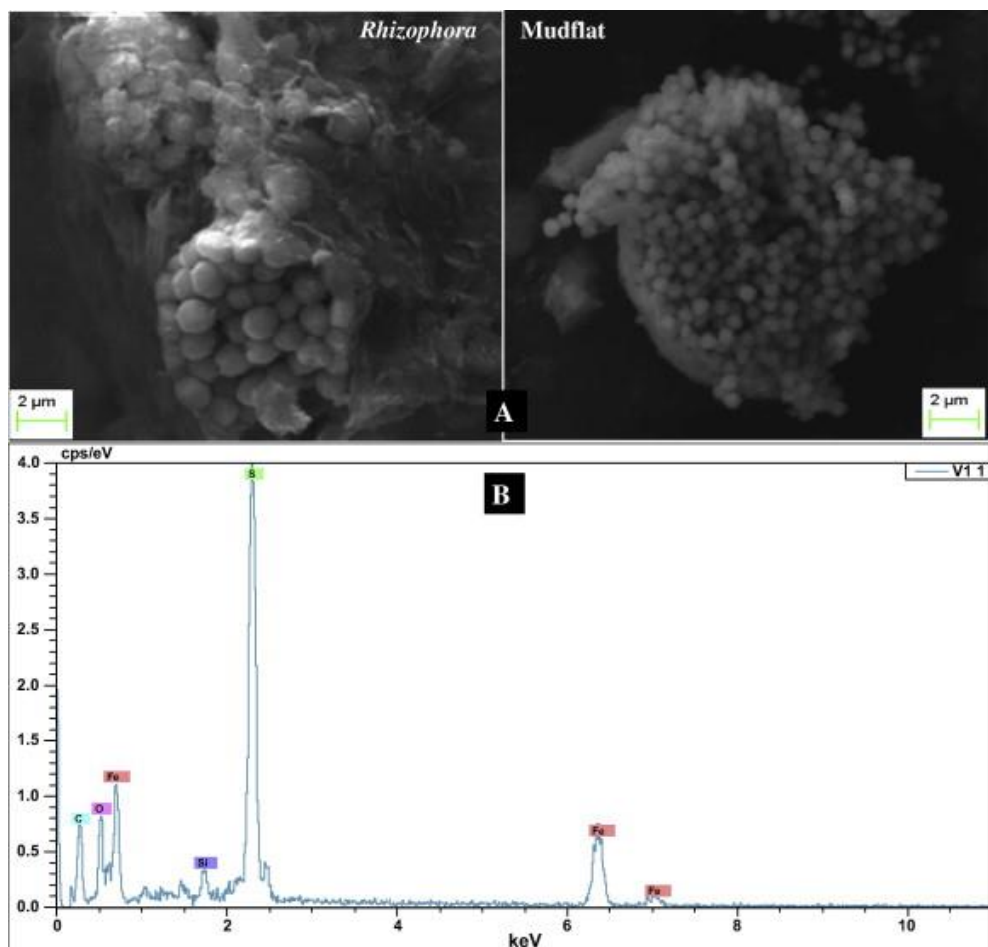


Fig. 4.

Spectrum of the pyrite in the Somone mangrove sediments (B: at the mudflat).

These pyrites are observed at 20 cm depth (Fig. 4). In contrast, at station 3 (*Avicennia* facies, Fig 3B) the redox potential profile is oxidized on the whole sedimentary column. At the sediment surface (0–5 cm) redox potential is 288 mV and decreases slightly to a value of 250 mV at 10 cm depth, reaches 200 mV at 15 cm depth, decreases at 150 mV at 20 cm depth, and remains stable deeper. At station 4 (Barren area), redox potential profile reveals also an oxidized sediment column. Indeed, redox potential values reach 300 mV at the 2 first sediment (0–2 cm), then decrease at 250 mV between 2 and 10 cm depth and between 15 and 40 cm depth, the values increase gradually from 250 mV to 450 mV.

At station 1 (Mudflat facies – Fig 3C), sediment surface exhibit a pH value of 7, then the pH values decrease slightly all along the sediment column to reach a value of 6.75. At station 2 (*Rhizophora* facies, Fig 3C), surface sediments exhibit a pH value of 7, then the pH values decrease to 6.75 at 5 cm depth and continue to decrease until 6.25 at 20 cm depth. Between 20 and 40 cm depth, pH values gradually decrease until 6. At station 3 (*Avicennia* facies, Fig 3C), pH profile varies from 6.75 at the surface sediment to 6.25 pH unit at 40 cm depth, pointing out the acidic character of sediment for this facies. At station 4 (Barren area), pH values of top sediments (0–5 cm) vary from 7.25 to 6.25, then the pH profile remains quite vertical with values around 6.5. The pH profiles of the 4 facies (stations 1, 2, 3, 4, Fig. 3C) exhibit acidic sediment all over the sedimentary column. The sediment is more acid in the first 10 cm depth (pH from 6.4 to 7.3) whatever the facies. pH is more acid under *Rhizophora*

(station 2) followed by *Avicennia* (station 3), then the Barren area (station 4) and finally the mudflat (station 1) – ( Fig. 3C).

### 3.3. Particulate and dissolved organic matter of sediments

On the whole, POC values (i.e. TOC contents) vary between 0.34 and 3.92 wt.% (Fig. 5). In the first 11 cm, the mudflat sediments are characterized by a TOC content around 1.50 wt.% increasing downward to reach 3.92 wt.%. For *Rhizophora*, the TOC values vary between 1.66 and 2.14 wt.%. TOC values for *Avicennia* decrease with depth (0.56–0.34 wt.%) increasing to 0.63 wt.% at the base of the profile ( Fig. 5). With TOC values always below 0.08 wt.%, tanne sediments are considered as devoid of organic matter. The hydrogen and oxygen richness of OM can respectively be expressed by the values of the hydrogen index (HI) and oxygen index (OI). In the mudflat facies, HI values rise up to 31 cm (230 mg HC/g TOC) and then decrease at the base of the profile (177 mg HC/g TOC at 41 cm depth). There is an opposite trend for the evolution of OI values which drop when measuring down from the surface (188 mg O<sub>2</sub>/g TOC) up to 21 cm depth (111 mg O<sub>2</sub>/g TOC) to then increase again at the base of the profile, 154 mg O<sub>2</sub>/g TOC. The recalcitrant character of recent OM toward further degradations can be assessed with Tmax values. Generally, this resistance to any OM processes as hydrolysis, (photo)-oxidation and biodegradation increases with increasing Tmax values ( Copard et al., 2006). Evolution of Tmax within the mudflat profile follows that of the HI values (i.e. value of 421 °C on the surface, 431 °C at 21 cm depth and 425 °C at 40 cm depth). The measured Tmax within the profile under *Rhizophora* are constant between 0 and 21 cm (420 °C) and decrease toward bottom core (406 °C). Between 0 and 11 cm depth, Tmax values under *Avicennia* tend to decrease from 417 to 409 °C and then remain unchanged at around 415 °C between 21 and 41 cm.

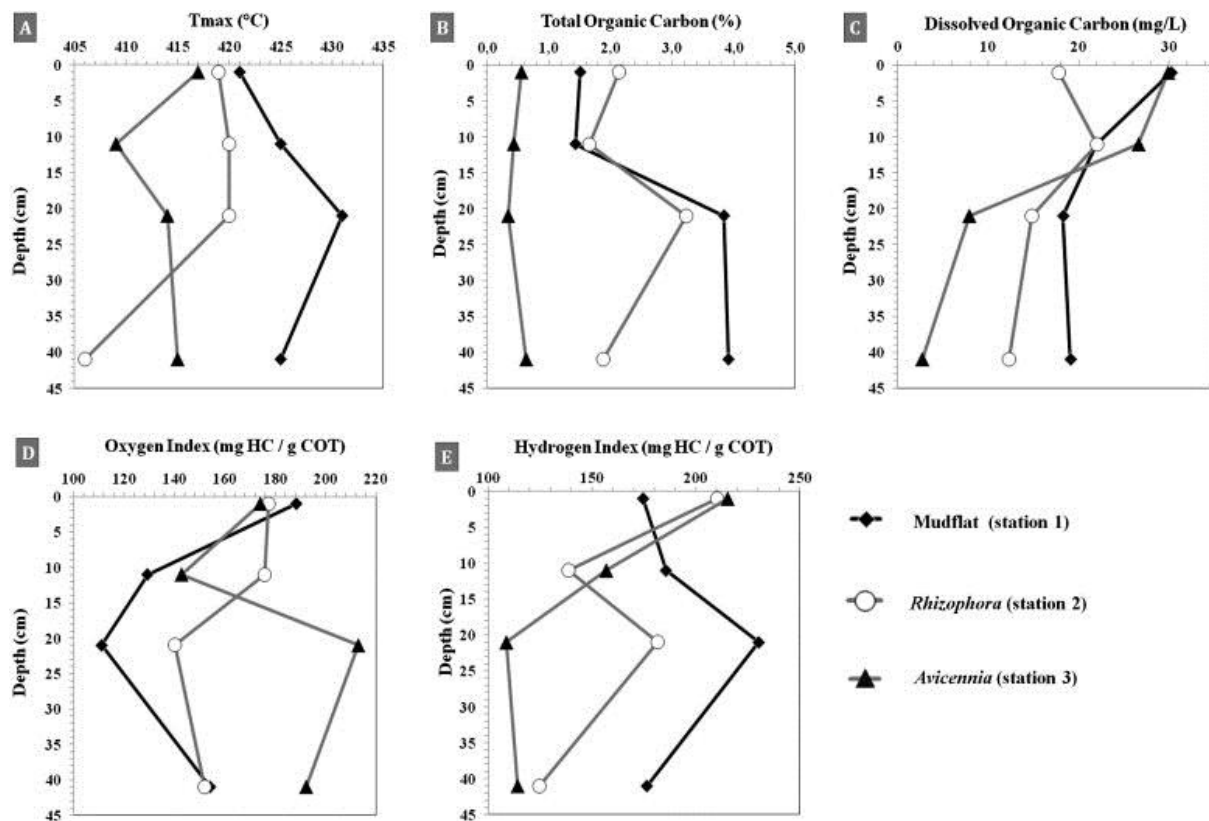


Fig. 5. : Characterization of sedimentary organic matter through Rock-Eval pyrolysis.

Both surface sediment (0–10 cm) from mudflat and *Avicennia* profiles present a DOC concentration close to 30 mg/L. Then concentrations decrease afterward with depth down to 20 mg/l. For *Rhizophora*, the concentrations of surface sediment are lower, approximating 20 mg/L. For tanne profile, DOC values are very low, always <1 mg/L in surface sediments.

## 4. Discussion

### 4.1. Sedimentary organic matter sources

The origin of OM can be deciphered in a HI–OI Van Krevelen pseudo-diagram initially designed to characterize the origin (i.e. lacustrine, marine, terrestrial) of source rocks releasing oil and gas (Espitalié et al., 1985 and Lafargue et al., 1998). For recent OM characterization, this diagram highlights the nature of OM, from a lignocellulosic, pollen/spore origin to a lipid-rich wax or microorganisms origin (Meyers and Lallier-Verges, 1999). On the whole, OM of lignocellulosic type presents some low HI values (<250 mg HC/g TOC) associated to high OI values (>100 mg O<sub>2</sub>/g TOC) whereas aquatic OM presents higher HI values (>400 mg HC/g TOC) associated to lower OI values (<100 mg O<sub>2</sub>/g TOC) (Marchand et al., 2008). Contrary to a previous extensive research that has shown the role of microbial or algal mats (Kristensen et al., 2008), such an influence was not observed for this study. This absence of algal mats, yet frequently observed in sediment surface of mangrove environment, can be related to the high biodegradability of this OM during early diagenesis; a very important processes in such environments (Patience et al., 1995 and Marchand et al., 2003). This limited input of aquatic OM in the sedimentary columns would be related to the very low sedimentation rates (2 mm/year) measured on the mudflat (Sakho et al., 2011) increasing the exposure duration of aquatic OM to the biodegradation process in surface sediments.

If OM has a lignocellulosic origin, it can however be at least partly allochthonous and may originate from the watershed. In such case, OM is conveyed with the suspended load by the drainage network as already observed in Kenya (Bouillon et al., 2007). However, (i) the Somone river dries out nine months out of twelve, (ii) shows a very low average annual flow of around 4 m<sup>3</sup>/s and (iii) sediment load mainly stored at the foot of Bandia dam since 1999 (Fig. 1A). In addition, over the 2007/2010 period, no hydric fluxes were observed downstream the dam. This terrestrial OM should therefore be minor, or even inexistent compared to the mangrove productivity. However, terrestrial OM could also be carried out by the sea currents coming from a river with a high sediment load and located near the study site.

This situation that prevails only when the sea currents are favorable, was already observed in mangroves of French Guinea's that accumulate strongly altered terrestrial OM originated from Amazonia's mouth (Marchand et al., 2008). Yet, this allochthonous terrestrial OM would show HI values inferior to 150 mg HC/g TOC and extremely high OI, comprised between 200 and 800 mg O<sub>2</sub>/g TOC (Marchand et al., 2008) (Fig. 6A) but this was not observed here. Regarding all these features, sedimentary OM may probably come from a unique lignocellulosic source from the local root production (Twilley et al., 1992, Chen and Twilley, 1999 and Otero et al., 2006). This hypothesis is reinforced by the high determination coefficient ( $R^2 > 0.90$ ) between S2 and TOC parameters ( Fig. 6B) indicating a homogeneous OM ( Noël et al., 2001) whatever the studied profile.

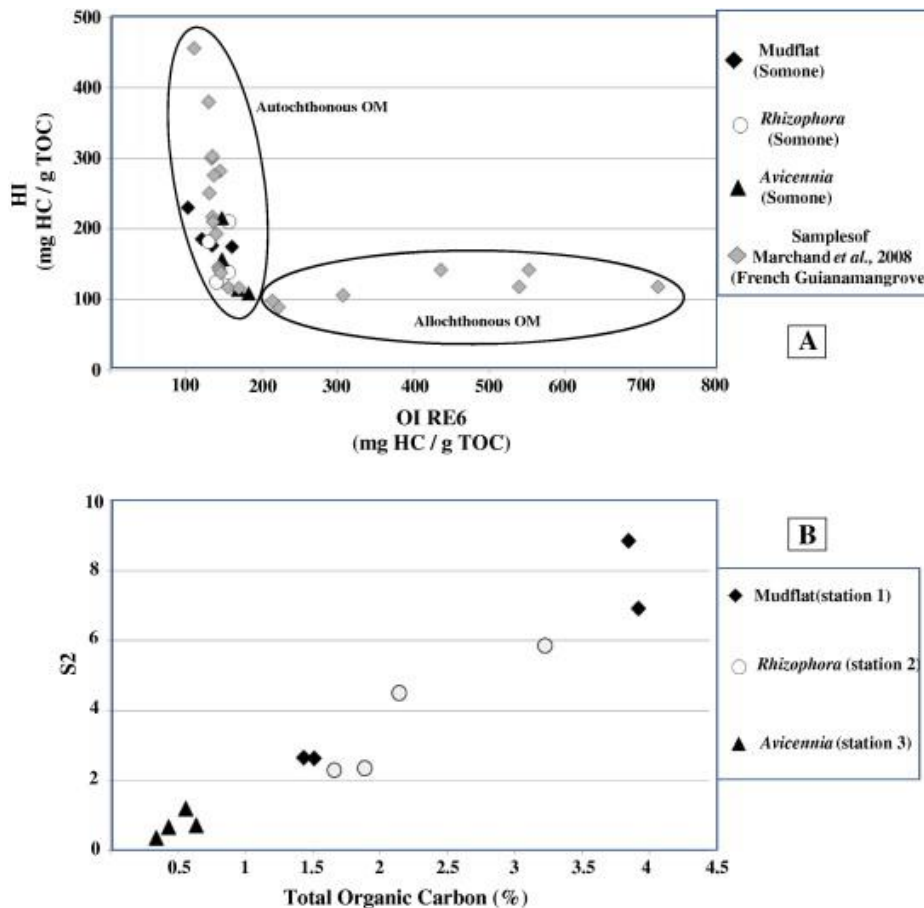


Fig. 6. : Organic matter sources in the Somone mangrove sediments.

#### 4.2. Sedimentary organic carbon dynamics: storage (preservation) or degradation

Organic matter (OM) degradation in mangrove surface sediments is well described in literature as an acidification process within the sedimentary column (Marius and Lucas, 1982). This process corresponds to an intense sulfate reduction activity leading to the degradation of the OM, which produces organic acids acidifying the sediment. The pH values of surface sediments, varying from 6.75 to 7.25, are consistent with literature on the mangrove surface sediments as in Senegal, especially in the Casamance and Sine-Saloum (Marius and Lucas, 1982), in Belize (Feller et al., 2002), in French Guiana (Marchand et al., 2004) and in Tanzania (Lyimo and Mushi, 2005 and Sjöling et al., 2005).

OM processes are also controlled by redox-potential conditions in sediment. Indeed anaerobic reactions, performed by the sulfate reducing bacteria, consume the whole oxygen contained in the sediment. Via their roots, *Rhizophora* enhance pyrite precipitation and promote dominant reduction conditions. Pyrite formation (framboidal pyrite) occurs through the reduction of sulfates that are directly brought by seawater. Anaerobic environment preserved in the deposit from the sediment interface to -40 cm depth, was already described for mangroves in the Casamance and the Saloum regions (Marius and Lucas, 1982 and Marius, 1995), in Columbia (Cardona and Botero, 1998), in Mexico (Giani et al., 1996). The POC content is evaluated with the total organic carbon (TOC) values that were measured on the sediment column, ranging from 0.34 to 3.92 wt.% for the four profiles. All these values are low but range within the average generally accepted for mangroves sediments (Kristensen et al., 2008). In West

Africa, data on the storage capacity of organic carbon in sediments are scarce. Only average values of OC, from 3.60 to 9.20 wt.%, were measured along a 40 cm depth on different vegetal units of Nigeria's mangrove forests ( Ukpong, 1995 and Ukpong, 1997). Other investigations at the South of Senegal (Basse Casamance, Vieillefon, 1977) have shown approximately similar values to those we obtained on the Somone's transect.

However, TOC contents of surface sediments are low compared to surface sediment sampled in some mature mangroves where TOC can frequently reach 15.00 wt.% (Lallier-Vergès et al., 1998 and Marchand et al., 2003). Globally, sedimentary OC content increases according to mangrove ageing (Marchand et al., 2003). This can be explained by litter production that, in early development stages of the mangrove, is only sufficient to compensate the loss of OC due to OM processes at the surface sediments. Accordingly, OC storage is necessarily less important for the Somone's mangrove which can be qualified as a "young mangrove". Indeed a work on this same study site has shown that, between 1946 and 1978, 85% of the mangrove surface disappeared to the benefit of mudflats because of concomitant effects of anthropogenic and natural factors: domestic use of mangrove woods, drought developed in 1970 and sand barrier migrated (1974) thus isolating the ecosystem and leading to a hypersaline environment. However, reforestation efforts were carried out at the beginning of the 1990s, and the area was changed into a natural reserve of common interests in 1999. Mangrove surfaces have increased with factor 5 during 15 years and have thus highlighted the capacity of vegetal recovery over a decade. This is the reason why this mangrove forest is young (two decades) with a low sedimentation rate, around 2 mm/year (Sakho et al., 2011). Thus, the production of autochthonous OC due to the fall of the mangrove leaves and stems occurring since two decades, justifies the small amount of TOC contained in the sediments. Moreover, in the intertidal zone, the mangrove undergoes the tide energy level; this allows part of the litter (autochthonous OM) to be exported at each tide, thus limiting the accumulation and degradation of this autochthonous OM to the same extent.

OC storage which can be seen as an OM accumulation/preservation in the sediment varies according to the studied profiles. For the mudflat profile (station 1) and *Rhizophora* (station 2), OC storage clearly appears 10 cm below the surface where TOC values increase up to 20 cm to then stabilize on the remaining part of the investigated sedimentary column. OM is subjected to a mineralization process and becomes much more resistant as evidenced by the abrupt drop of the C ratio (24.38 down to 18.40). Variability of TOC contents in this cross-section is obviously related to the grain size of sediment (i.e. fine sediment associated to higher TOC content). Nonetheless, other factors as bioturbation activity, mangrove forest age, physiological activities of the root system, the extent of water logging and intensity of faunal burrowing activities can influence the OC preservation in these coastal environment ( Kristensen et al., 2008, Perry and Berkeley, 2009, Tue et al., 2012, Donato et al., 2011, Fanjul et al., in press and Andretta et al., 2014).

#### **4.3. How bioturbation contribute to OM dynamic?**

Bioturbation refers to the biological reworking of soils and sediments and impacts sediment texture, bio-irrigational transport of solutes and the dispersal of solid particles (Meysman et al., 2006). In mangrove coastal systems, crabs are one of the most abundant macrobenthos that affect sedimentary compartment by their activities. Field investigations in many coastal studies have shown the relationship between crabs burrowing activities and the organic carbon dynamic and sediment oxygenation processes. According to Robertson, 1986 and Twilley et al., 1997, some crabs reduce carbon export from mangrove forest by an

important burying litter through their burrows. Same observations are noticed in many recent studies, where authors show that crab burrows activities increase zones of detritus retention and can locally increase sediment OM content by trapping detritus and OM rich sediments (Escapa et al., 2008 and Montemayor et al., 2011). More recently, Luppi et al. (2013) conclude that this pattern could particularly be important in systems characterize by low OM content, such as Mar Chiquita (3.8%) and Bahia San Antonio (1.8%) in SW Atlantic intertidal zones. Our results in the Somone mangrove ecosystem, which is characterized by low OC sediment content (range from 0.30 to 3.90 wt%), are in contrast to these conclusions. Two sediment types characterize the Somone mangrove coastal system: bioturbated and non-bioturbated sediment, linked to our four-studied stations. The non-bioturbated sediment at mudflat and *Rhizophora* stations, are characterized by a higher % OC content than the bioturbated sediment at *Avicennia* station, which is marked by the most higher DOC content in the first 15 cm sediment depth. The Barren area (stations 4) is a bioturbated zone but without any sedimentary OM, due to lack of vegetation and mangrove detritus retention. This result is in accordance to those of Otani et al. (2010), which give a burrow depth ranges from 3.3 to 16.5 cm. However, ours results is in accordance with those recently published ( Fanjul et al., in press and Andretta et al., 2014) showing the highest OC contents in non-bioturbated superficial sediment than in bioturbated sediment. Results of Wilson et al. (2012) indicate also the same conclusions: crab borrowing activity increase oxidized conditions in the upper of 10–15 cm of the sediment, which significantly lead to OM degradation. Thus, these results suggest that crab bioturbation increases sediment permeability, water percolation, and subsequently increases aerobic condition, which caused mineralization of sedimentary OM.

This explains the fact that, DOC is higher in *Avicennia* than in *Rhizophora* or mudflat. According to Benner et al. (1991), substantial quantities of DOC are produced during OM decomposition; which increase with aerobic condition. Koo et al., 2005, Xin et al., 2009 and Thomas and Blum, 2010 have shown that burrows structures of crab increase oxygen exchanges from both the atmosphere and tidal waters. This pattern is observed in the *Avicennia* station (bioturbated sediment), which is characterized by a most positive Eh at the first 15 cm depth (between +200 and +300 mV). However, a second factor that participates in sediment oxidation is linked to the physiology of the *Avicennia* species that introduces oxygen along a 15–20 cm depth via their specific roots system (pneumatophores) and thus maintaining suboxic conditions ( Thibodeau and Nickerson, 1986, Marchand et al., 2003 and Otero et al., 2006). The roots network activity on the first half of the profile clearly explains the drop in TOC and HI values while OI values increase. This oxidizing environment increases the DOC concentration at sediment surface (30 mg/L); such a process has already been observed for mangrove forests in French Guyana ( Marchand et al., 2004).

Nonetheless, the context of non-bioturbated sediment and the dominated anoxic conditions at the mudflat and *Rhizophora* station, attested by negative Eh value from 5 cm depth and the framboidal pyrite occurrence, are favorable conditions to OM storage processes and lead to protect it from further OM processes and in such cases, TOC values can exceed 3.00 wt.%. The shallow depth at which such old organic matter was found ( Sakho et al., 2011) confirms that the Somone mangrove is characterized by a low sedimentation rate. This suggests that OC burial depends on others processes than sedimentation. Then, in the Somone mangrove ecosystem, both of pneumatophores and crab burrowing activities are the main factors that control OM degradation (*Avicennia* station) whereas anaerobic conditions (mudflat and *Rhizophora*) promote OM preservation.



#### 4.4. Impact of tidal dynamic on porewater chemistry

A salinity gradient is well marked, with the formation of salt efflorescence on the tanne facies (supratidal zone), as a consequence of the over-concentration in chlorides and sulfates. Indeed at high tide, the mudflat and mangrove *Rhizophora* in the intertidal zone are recovered by seawater that provides concentration of chloride and sulfate ions close to those of the seawater. On the contrary, the tanne facies located in the supratidal zone is only submerged during the strongest high tides. High temperatures and absence of vegetation involve a severe evaporation of seawater explaining high concentrations in chlorides and sulfates. In hot and dry climatic contexts as in Sahel, processes of over-concentration have been described in literature on other Senegalese estuaries ( Viellefon, 1969 and Marius, 1995) but also in Mexico ( Day et al., 1996), in Australia ( Ridd and Stieglitz, 2002). Impact of the deficient in the annual hydrologic budget has also been pointed out, associated with a shallow groundwater, the phenomenon of salt concentrate through capillary-driven can well explain salt efflorescence characterizing the ascending saline profile ( Bouteyre and Loyer, 1992).

Other authors have demonstrated a clear tidal signature with water column nutrients concentration (DOC, phosphate and nitrogen) covaried with salinity controlling the sediment porewater chemistry (Lara and Dittmar, 1999 and Dittmar and Lara, 2001). Otherwise, at the sediment surface, the impact of tidal dynamic can be deciphered with pH values fluctuation. The regular input of seawater of basic pH (pH > 8) on the mudflat and mangrove *Rhizophora* facies explains the less acid pH values as for the *Avicennia* facies. However, sediment acidification can result from OM decomposition, but also from sulfur oxidation ( Marchand et al., 2003). Mangrove sediments are subjected to an alternation of oxic and anoxic decay processes, which can lead to a production of sulfur and then to their dissolution. Our results show that the biogeochemistry of mangrove sediments is strongly influenced by local environmental conditions (tidal flooding, duration of inundation, without freshwater input, seasonality of precipitation and temperature, bioturbation, etc.). These findings were evidenced in other mangroves area ( Luther et al., 1991 and Attri et al., 2011).

### 5. Conclusion

Organic geochemical signature of sediments suggests that sedimentary OM is mainly ligno-cellulosic-derived. Absence of algal mat is linked to the low sedimentation rate increasing the duration exposure of this OM to the biodegradation process. The low TOC content in sediments, reflect the low organic matter production of the mangrove as it is a young and stunted mangrove. Youth of mangrove, coupled to the low sedimentation rate and the drastic conditions (i.e. drought, absence of fluvial freshwater input, high evaporation rate, hypersalinisation) and bioturbation are the main limiting factors preventing the sedimentary OC preservation in this mangrove sediments. Our result show that the redox conditions in mangrove ecosystem depend mainly to the mangrove genus e.g. the physiology of *Avicennia* permits the introduction of oxygen via their pneumatophores, maintaining suboxic conditions. In the first 15 cm of the sedimentary column, such conditions are also enhanced by the burrowing crabs activities, which cause OM degradation. The tidal flooding time, which decrease toward the barren area (supratidal zone) to the mudflat (intertidal zone) is the main factor that control the drying out and the porewater chemistry of the sedimentary facies along this intertidal-supratidal cross-section.

The shallow depth at which the organic matter of the former mudflat was found confirms that the Somone mangrove is characterized by a low sedimentation rate. This suggests that OC

burial depends on others processes than sedimentation. Then, in the Somone mangrove ecosystem, both of pneumatophores and crab burrowing activities are the main factors that control OM degradation (*Avicennia* station) whereas anaerobic conditions (mudflat and *Rhizophora*) aim to OM preservation.

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