ISSN 2229-5518

Carbon Stock Estimation in Tidal Flats of Eastern Niger Delta, Nigeria

[1]Nwankwo, C., [2]Tse, A.C. and [3]Nwankwoala, H.O.

[1]University Port Harcourt, Nigeria
[2]Department of Geosciences, University of Namibia
[3]Department of Geology, Rivers State University, Port Harcourt, Nigeria
[Corresponding author's E-mail: nwankwochukwukere@gmail.com]

Abstract

Carbon stock estimation in tidal flats of Eastern Niger Delta, Nigeria was carried out. The study aimed at determining the sediment bulk density (SBD), organic carbon concentration (%C) and the organic carbon stock of sediments. A total of 312 sediment samples were collected from 24 equally spaced sampling points at seven locations using a locally fabricated 1-m, open-cylindrical gouge auger. The field measurement, laboratory tests, data analysis, presentation and interpretation followed the procedures outlined for the National Forest Carbon Measurement, Monitoring and Reporting. The lithologies are typical of mangroves which included peats and clays with pockets of sands. All the parameters significantly varied with depth and lithology. The values of SBD and %C varied between 0.95 and 1.97 g/cm^3 (mean value of 1.30 g/cm^3) and between 0.9 and 33.6 % (mean value of 12.50 %) respectively. Organic carbon stocks per hectare varied between 38.85 ± 15.18 and 3,245.76 ± 15.18 Mg C ha^{-1} (with mean value of 622.12 Mg C ha^{-1}). The total carbon stock was summed up to 194,102.24 Mg C ha^{-1} (equivalent to 712,355.22 ± 53.57 Mg CO_2 ha^{-1}) and scaled to the entire study area to obtain at 921.50 ± 53.57 Gg C, equivalent to 3,096.57 ± 53.57 Gg CO_2. This value is about 0.048 % of the total global mangrove carbon storage in sediments

Keywords: Carbon stock estimation, Tidal flats, Organic carbon concentration, Niger Delta mangroves

1. Introduction

Mangroves are defined as large and extensive tree types which grow in coastal sediments with ability to tolerate saline water and are usually found within the tropical and subtropical intertidal areas such as lagoons, creeks, bays and estuaries (Mitsch and Gosselink, 2007). This vegetation type which occurs at the land-sea transition zone occupies about half of the global coastal area but has a high production rate of organic carbon ranging from 92 Tg C y^{-1} to 280 Tg C y^{-1} and contributing about 15 % of the total carbon accumulation within marine sediments (Kusumaningtyas *et al.,* 2019; Alongi, 2014; Bouillon *et al.,* 2008; Jennerjahn and Ittekkot, 2002; Twilley *et al.,* 1992).

The amount of carbon of carbon stored in any carbon pool say sediment is referred to as carbon stock. It is an estimate which tracks the changes in the amount of carbon resulting from land use and/or land cover change, and measured in mass per unit area (t ha^{-1} and Mg C ha^{-1}, Kauffman and Donato, 2012). Carbon management strategy such as Reducing Emissions from Deforestation and Forest Degradation and Enhancing Forest Carbon Stocks in Developing Countries ($REDD^{+}$) has made carbon stock estimation of mangroves of great interest especially due to mangroves' potential for carbon sequestration (Sanderman *et al.,* 2018; Alongi, 2012; Kauffman and Donato, 2012). Estimation of carbon stock is needed to determine the amount of carbon that are emitted and/or sequestered over time.

Following a change in land use and/or land cover such as deforestation, conversion, degradation, afforestation, the entire belowground carbon pool of tidal wetland sediments may become susceptible to loss (Kauffman and Donato, 2012). The mangrove forests of Niger Delta are under threats and therefore require restoration, protection and conservation. Agreeably, Numbere (2018) and Nwobi *et al.,* (2020) concurred that deforestation and degradation caused by oil and gas exploration/exploitation, developmental projects in coastal communities, unregulated lumbering for construction and wood carving are some of the major threats to the mangrove forests in Niger Delta of Nigeria. Consequently, water and soil are polluted, vegetation is altered while the amount of carbon stored in the tidal flats of the mangroves is released back to the atmosphere (Nwobi *et al.,* 2020; Numbere, 2018). Consequent to the enormous values provided by mangrove forest especially carbon sequestration and storage, and the alarming threat to mangrove forest existence and survival, research to describe and quantify their carbon stock is necessary. In Niger Delta Nigeria, researches on carbon stock estimation have focussed on aboveground carbon pool. This study therefore assessed the carbon stock in belowground carbon pool (sediments collected from tidal flats). The objectives were to determine sediment bulk density, analyse spatial variation of organic carbon concentration and estimate the carbo stock of mangrove sediments. The finding would facilitate the effort of Nigeria's government in prioritizing the mangrove forest of Niger Delta for management, expansion, restoration, protection and conservation.

2. Study Area

The study was carried in the tidal flat terrain of Kibani, Eastern Niger Delta in Nigeria, West Africa (Figure 1). The area which lies between Latitude 4^0 33' to 4^0 35'N and Longitude 7^0 16' to $7^0$17'E is located within the Mangrove Swamp Forest and bounded with the Atlantic Ocean in the south. It is characterized by a humid tropical climate of annual mean rainfall which peaked at 4000 mm during the rainy season of July to September. A break in rainfall amount commonly referred to as 'August break'' occurs around August. The monthly temperature varies from 26^0 C to 30^0 C (Asuk *et al.,* 2018). The soils are commonly referred to as 'Chikoko mud' and contain dark grey sandy, clayey and muddy. The mangroves are the dominant vegetation types with the *Rhizophora* genus is very common (Asuk *et al.,* 2018). Exotic and invasive plant species (*Nypa fruticans)* are colonizing areas where deforestation and other forms of forest degradation are well-pronounced (Numbere, 2020;

Nwobi *et al.,* 2020). The Niger Delta region of Nigeria has an estimated surface area of 112,110 km^2 and has the largest mangrove cover in Africa and fourth largest in the world (Essen, 2020; Nwobi *et al.,* 2020; Asuk *et al.,* 2018; Taillardat *et al.,* 2018; Numbere, 2018).

In terms of geology, there are five major depositional belts within the Niger Delta basin namely Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp and Offshore (Obaje, 2009). They represent a successive phase of delta growth with bands of thick sediments bounded by faults. The thickness of the sediments in the Niger Delta basin has been estimated to be about 12,000 m (Evamy *et al.,* 1978). These units of deposition are grouped into Benin Formation, Agbada Formation and Akata Formation (Short and Stauble, 1967). They are now overlain by recent coastal sands and clays. There are three most striking structural features that have been identified in the basin. These structures include growth faults, rollover anticlines and shale diapirs (Obaje, 2009). Akata Formation as a basal marine shale unit deposited in prodelta environments. The formation consists of clays and shales with minor intercalation of sands which is usually less than 30 % in composition. Agbada Formation is a coastal marine sediment consisting of alternating sands and shales while the percentage of sand ranges from 30 % to 70 %. Benin Formation is the top layer of the depositional sequence with a very high percentage of sand which ranges from 70 % to 100 % (Obaje, 2009).

ISSN 2229-5518

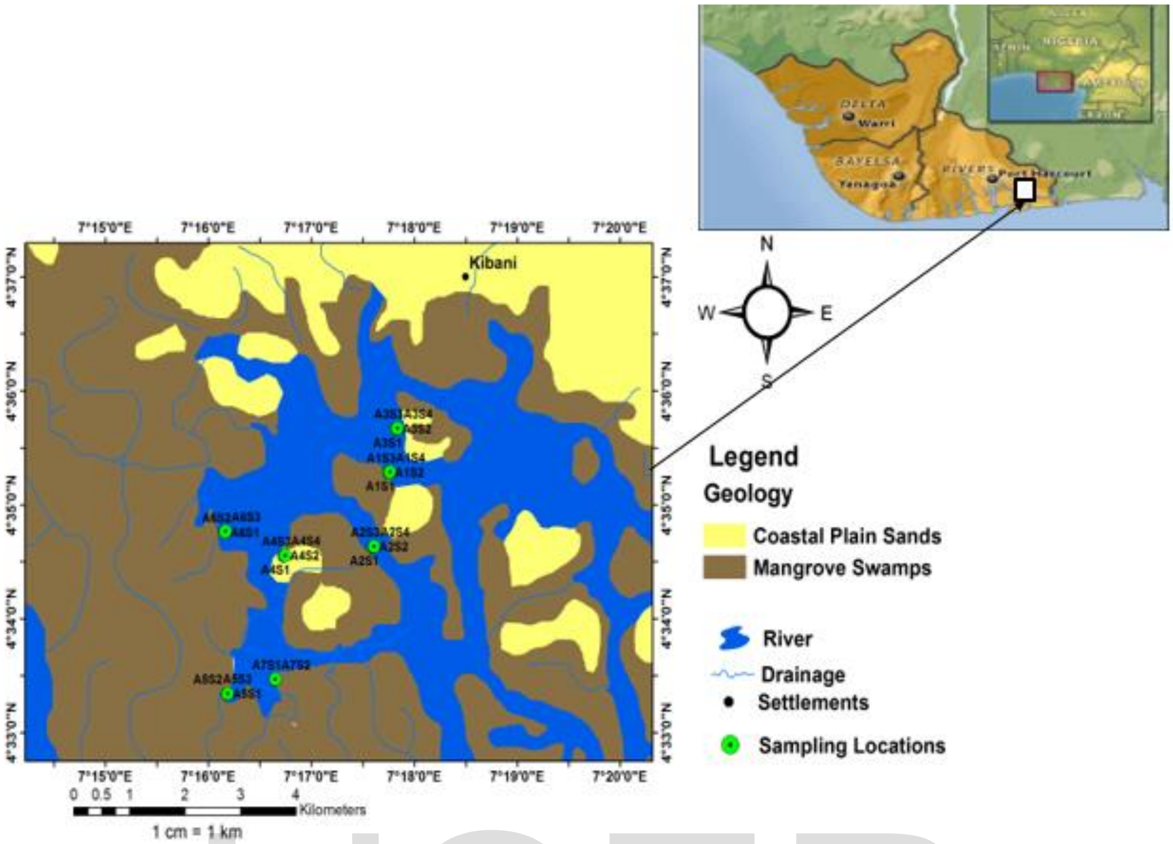

Figure 1: The Map of the Study Area

3. Materials and Methods

A total of 312 samples of sediment was obtained from 24 sampling points at seven locations of the tidal flats labelled L1, L2, L3, L4, L5, L6 and L7 respectively. A 1-m open-cylindrical sediment sampler (gouge auger) specially designed for environmental research purposes, was locally fabricated and used in sample collection (Plate 1**).** Also used were three wooden core-boxes with six compartments, aluminium foils, nylon, measuring tape, spatula knife, a Global Positioning System (GPS), a digital camera, field notebook, datasheet, pen and pencil (Table 1). The field work lasted for three weeks.

In the field, a rectangular plot of dimension 10 m by 5 m was mapped out at each location along the creek. Sampling points were established at the centre of the rectangular plot. The number of sampling points and the size of plot depended on the size of the tidal flat. At each sampling point, an open-cylindrical gouge auger assembled together, litters removed from the ground surface while the auger was gently pushed into the ground until the top of the auger got to the level of the ground surface. The auger was pulled out and samples retrieved were measured with tape and split into 13 subsamples with varying depth intervals of 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm, 25-30 cm, 30-40 cm, 40-50 cm, 50-60 cm, 60-70 cm, 70-80 cm, 80-90 cm and 90-100 cm and sealed in aluminium foils and kept in core boxes. The samples were transported to the Engineering Geology Laboratory of the Department of Geology at University of Port Harcourt for analysis. The sampling date, coordinates, depth intervals, plot number and sample number/foil identification number were all recorded in the field notebook and later transferred to the field datasheet.

Plate 1: Sediment Sampling in the Field using Gouge Auger

Table 1: The Materials and Tools used in the Study

Item	Materials/Methods	Equipment
Sediment sampling	Gouge auger, core boxes,	
Bulk density	BS 1377; Part 1: 1990	Cutter, spatula, weighing balance
Organic carbon content	Loss-On-Ignition (ASTM D 2974; 2000)	Lenton Furnace
Modelling	Software	SPSS

BS = British Standard, ASTM = American Standard for Testing Materials, SPSS = Statistical Package for the Social Sciences

4. Data Analysis

The three parameters required to estimate organic carbon stock are sediment depth interval, bulk density and organic carbon concentration (Winrock, 2016; USAID 2015; Kauffman and Donato, 2012; Pearson *et al.*, 2007). The bulk density was determined using a standard density formula of mass by density. The dimensions of the mould (height, diameter and radius) were first determined and the volume of the mould calculated. Sediment bulk density was determined using equation 1.

$$SBD = \frac{[\text{mass of sample}]}{volume} \quad 1$$

(where SBD is Sediment bulk density)

The organic matter content was determined using the loss-on-ignition (LOI), a semi-quantitative method as described by Schumacher, 2002; ASTM, 2000; Nelson and Sommers, 1996 in equation 2.

$$\left[\frac{Ds - Mign}{Ds}\right] * 100\% \quad 2$$

Where Ds is mass of dry sample, Mign is mass of ignition

A conventional conversion factor of 0.58 was used to convert organic matter content to total organic carbon content as described by Paulsen, 2020; Kauffman and Donato, 2012; Schumacher, 2002; Nelson and Sommers, 1996 in equation 3 on the bases that organic matter contains 58% of organic carbon.

$$\%C = LOI * 0.58 \quad 3$$

The organic carbon stocks of sediments were estimated for each depth interval per sampling point. This was done using equation 4vmodified after Diesing *et al*., (2020), Malunguja *et al.*, (2020), Scheffold & Hense (2020), Shaltout *et al.*, (2020), Eid *et al.*, (2019), Kusumaningtyas *et al.*, (2019), Almahasheer *et al.*, (2017), Avelar *et al.*, (2017), Diesing *et al.*, (2017), Eid and Shaltout (2016), Kauffman and Donato (2012), Han *et al.*, (2016), Meersmans *et al.*, (2008) and Pearson *et al.*, (2007).

$$Carbon\ Stock\ (Mg\ C\ ha^{-1}) = SBD * \%C * D \quad 4$$

where C_{org} Stock = organic carbon stock in Mg ha^{-1}, SBD = sediment bulk density in g cm^{-3}, %C = organic carbon concentration in % and D= sediment depth interval in cm

The total carbon stock of the study area was obtained from equation 5 modified from Scheffold and Hense (2020), Siraj (2019), Rumengan *et al.*, (2018), Shunyang *et al.*, (2018), Iticha, (2017), Kauffman and Donato (2012).

$$\text{Total Carbon Stock(Mg C)} = \text{Carbon Stock} * \text{Project Area} \quad 5$$

Statistical analysis: One-way analysis of variance (ANOVA) was used to determine the statistically significant variation between the dependent variables (bulk density, organic carbon concentration and carbon stock) and independent variable (sediment depth). The 95-% confidence interval was determined from equation 6.

$$95\%\ CI = 1.96 * \frac{SD}{\sqrt{n}} \quad 6$$

5. Result and Discussion

Soil Description: The lithologies identified in the study area are typical of mangrove sediments and included peat, clay, peaty clay, clayey peat, sandy clay, clayey sand, peaty clayey sand, sandy peat and peaty sand. The sediment type played a significant role in the spatial distribution of organic carbon and together with bulk density, controlled the organic carbon stock in the study area. About 90.7 % of the lithologies are peaty layers whereas about 9.3 % are clayey layers. The peaty and clayey layers decrease with depth whereas sandy layer increase with increasing depth (Figure 2).

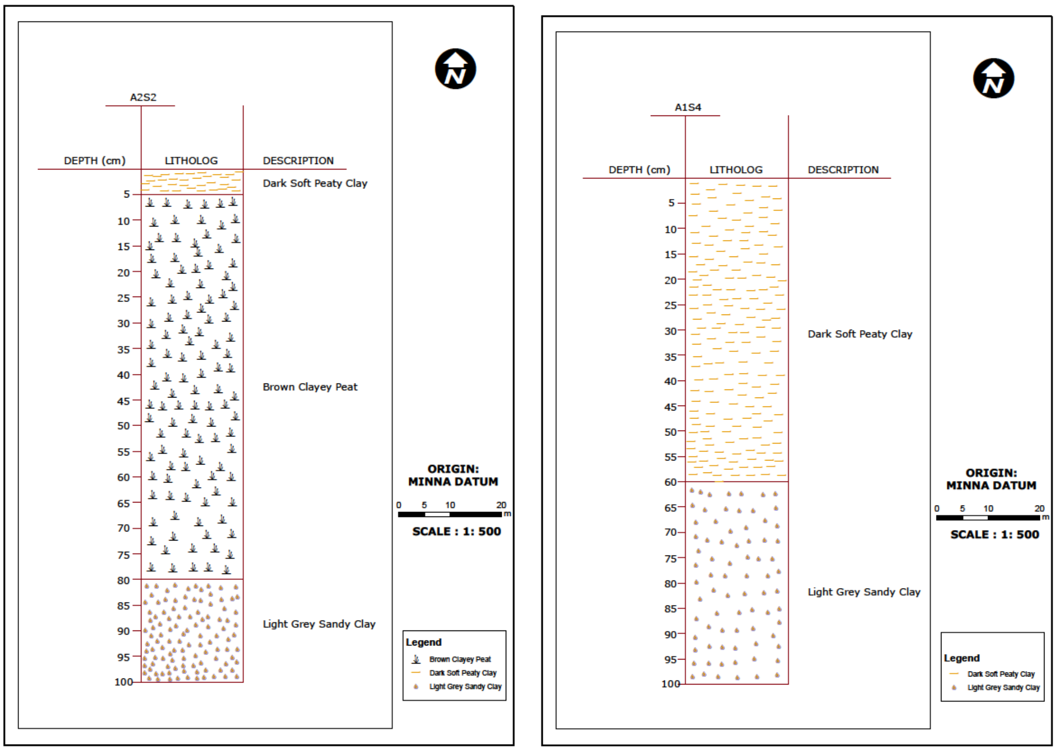

Figure 2: Identified Soils in the Study Area

Sediment Bulk Density (SBD): SBD values were highly affected by soil type. Sandy clay recorded the highest SBD value of 1.97 g cm^{-3} while peat recorded the lowest SBD value of 0.95 g cm^{-3}**.** Although the values of SBD seemed to increase with depth, lithology is the main control. This variation was reported by Donato *et al.*, (2011).

Generally, the SBD values increased significantly with depth except in some areas where lithological control is well-pronounced ($p=0.00$). The values were found to increase from 1.26 g cm^{-3}, 1.25 g cm^{-3} and 1.05 g cm^{-3} at 0-10 cm depth interval to 1.48 g cm^{-3}, 1.65 g cm^{-3} and 1.36 g cm^{-3} at 90-100 cm depth interval in L3, L4 and L5 respectively. The increase of SBD values with increasing depth is consistent with the findings of Trettin *et al.*, (2021), Arshad *et al.*, (2018) and Eid *et al.*, (2016) whose works demonstrated that the values of SBD increased with increasing depth. Arshad *et al.*, (2018) in a comparative analysis, found that the SBD values increased from 1.27 g cm^{-3} at a depth interval of 0-5 cm to 1.94 g cm^{-3} at a depth interval of 45-50 cm for a polluted mangrove site along the southern Red Sea coast of Saudi Arabia while the values increased from 1.19 g cm^{-3} at a depth of 0-5 cm to 1.83 g cm^{-3} at a depth of

45-50 cm for a non-polluted mangrove site. Eid *et al.,* (2016) determined the SBD values at the *Avicennia marina* locations within the mangrove forest of Farasan Islands, Saudi Arabia and found that SBD values increased from 1.10 g cm^{-3} at the depth interval of 0-5 cm to 1.99 g cm^{-3} at the depth interval of 45-50 cm. In addition to the observed variation, Trettin *et al.,* (2021) carried a research in the mangroves within the Pongara National Park, Gabon and found that SBD values increased with an increase in soil depth from 0.24 g cm^{-3} at 0-15 cm depth interval to 0.40 g cm^{-3} at 180-200 cm depth interval.

Ansa & Francis (2007) showed that some variables including SBD are dependent on the sandy and muddy nature of sediments. The result of the research showed that SBD value in muddy sediment was 0.46 g cm^{-3} while the value varied between 1.36 g cm^{-3} and 1.41 g cm^{-3} in sandy sediment. The mean SBD value obtained in this study was 1.30 g cm^{-3}. This is similar to SBD value of 1.36 g cm^{-3} reported in similar samples obtained at Andoni flats, a mangrove location about 20 km away from the present location by Ansa and Francis (2007) and shows no wide variations from SBD value of 1.4 g cm^{-3} reported by Eid and Shaltout (2016).

Organic Carbon Concentration (%C): %C varied significantly with lithology and depth ($p=0.030$) (Figures 3 and 4). The values %C were low in soil layers with sandy fractions but high in soil layers with peaty and clayey fractions. About 80 % of %C of the study area occurred in sediment layers with clay fraction. This agrees with Diesing *et al.,* (2017) whose research reported mud content as a strong factor that controls %C distribution in mangrove sediments. Ansa and Francis (2007) in a research carried out within a location in eastern Niger Delta of Nigeria revealed that the values of %C ranged from 0.17 % to 0.35 % in the sandy soil and from 2.76 % to 3.26 % in the muddy soil.

The decrease of %C values with depth observed in this study is in agreement with the findings of many researchers (Trettin *et al.,* 2021; Malunguja *et al.,* 2020; Gao *et al.,* 2019; Arshad *et al.,* 2018; Stringer *et al.,* 2015;). Trettin *et al.,* (2021) observed that the mean %C within the mangroves of the Pongara National Park, Gabon decreased from 17.04 % at 0-15 cm depth interval to 7.05 % at 180-200 cm depth interval. Malunguja *et al.,* (2020) investigated the climate change mitigation potential in north-western Tanzania through carbon dioxide sequestration and confirmed the variation of soil organic carbon across the sampled depth intervals as the value decreased with depth. In support of the observed variation of %C with depth, Arshad *et al.,* (2018) reported that the values %C dropped from 20.8 g C kg^{-1} at a depth interval of 0-5 cm to 8.1 g C kg^{-1} at a depth interval of 45-50 cm. Additionally, Gao *et al.,* (2019) showed significant variation of %C contents across the sampling sites of different mangrove forests which decreased with increasing depth. The study showed that the organic carbon in the soil pool contributed most significantly to the total carbon stock, with the top 30 cm containing the largest carbon concentration in all soil profiles. In a separate research conducted within the mangroves of Zambezi River Delta in Mozambique, Stringer *et al.,* (2015) showed that the soil carbon concentration was highest in the top layer of 0-15 cm but decreased with increasing depth.

In the study area, the significant variation of %C with depth can be attributed to pollution (resulting from artisanal refining of crude oil), deforestation and other forms of mangrove forest degradation whose effects are affecting the organic carbon accumulation within the top soil. Arshad *et al.,* (2018) demonstrated that pollution of mangrove forest strongly affects %C. The research obtained %C value of 20.8 g C kg^{-1} at a depth of 0-5 cm in a polluted site and %C value of 22.4 g C kg^{-1} in a non-polluted site at the same depth interval along the southern Red Sea coast of Saudi Arabia. This shows that pollution reduces the %C value of mangrove forests.

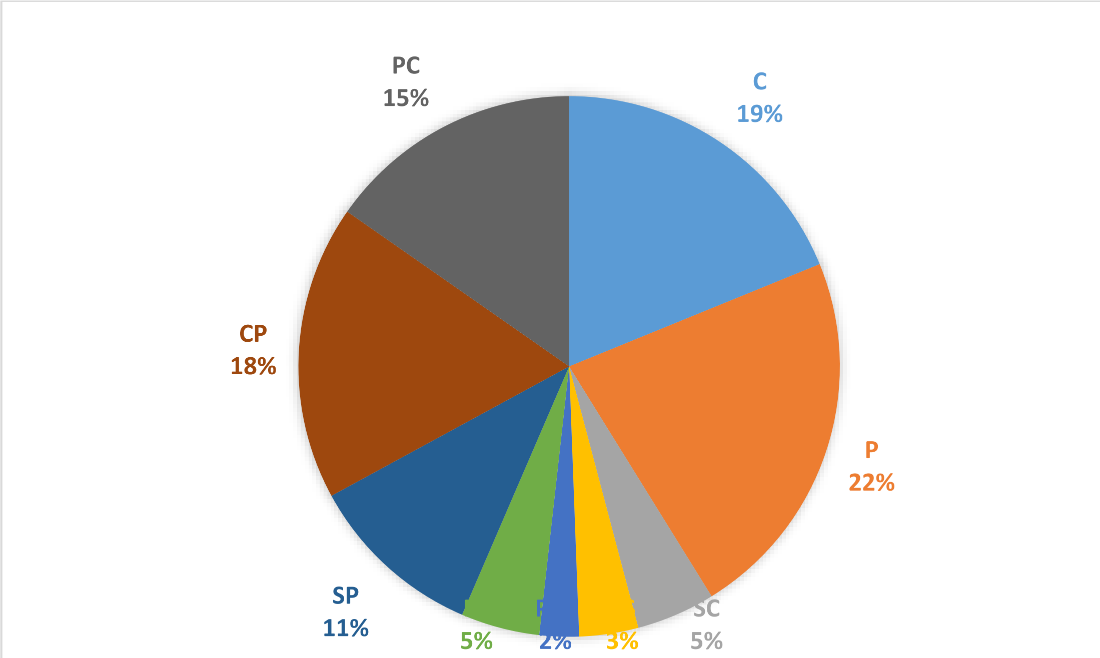

Figure 2: Variation of Total Average Organic Carbon Concentration (%C) with Lithology (C=clay, P=peat, SC=sandy clay, CS=clayey sand, PCS=peaty clayey sand, PS=peaty sand, SP=sandy peat, CP=clayey peat, PC=peaty clay).

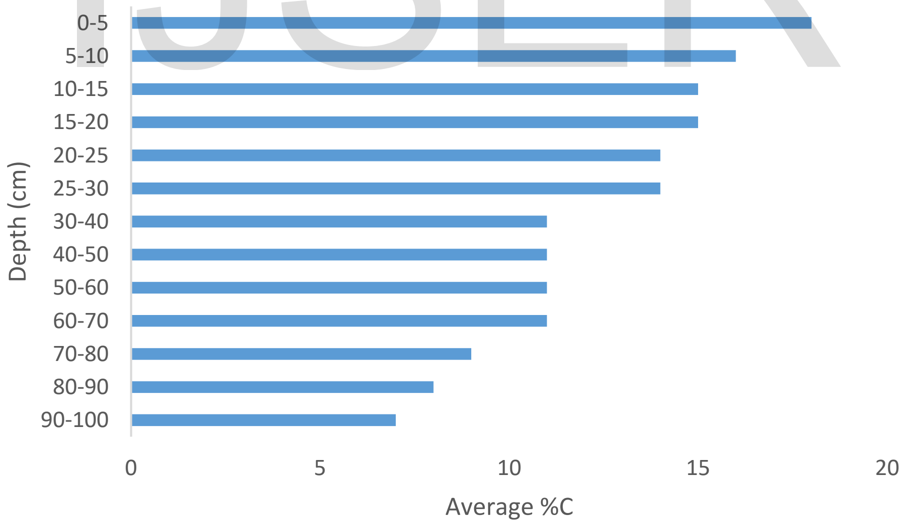

Figure 3: Variation of Total Average Organic Carbon Concentration (%C) with Depth

Carbon Stock: In this study, there is significant variation between carbon stock and depth ($p=0.007$) (Figures 4 and 5). Variation of organic carbon stock with depth is in line with other researches and can be attributed to the both increasing bulk density and depth. Perera and Amarasinghe (2019), Komolafe *et al.,* (2020), Suhaili *et al.*, (2020) and Arshad *et al.*, (2018) agreeably posited that carbon stock increases with depth. Perera & Amarasinghe (2019) demonstrated that organic carbon stocks increased with depth with values ranging from 316.29 Mg C ha^{-1} at the surface (0-15 cm) to 580.84 Mg C ha^{-1} at the depth interval of 31-45 cm. In another research carried out within the Sulaman Lake Forest Reserve, Sabah in Malaysia, Suhaili *et al.*, (2020), the highest organic carbon stock (178.37 ± 28.56 Mg C ha^{-1}) was obtained at the depth interval of 50-100 cm while the lowest organic carbon stock (52.12 ± 8.90 Mg C ha^{-1}) was obtained at the depth interval of 0-15 cm. Komolafe *et al.*, (2020) reported that the values of carbon stock in Ibodi Monkey Forest in Atakumosa, Osun state, Nigeria ranged from 21.7 t C ha^{-1} at the depth interval of 0-15 cm to 40.0 t C ha^{-1} at the depth interval of 45-60 cm. Arshad *et al.*, (2018) revealed that the value of carbon stock increased from 26.6 kg C m^{-3} at a depth of 5-10 cm to 17.5 kg C m^{-3} at a depth of 45-50 cm in non-polluted sediments while in polluted sediments, it ranged from 15.4 kg C m^{-3} at depth of 45-50cm to 26.7 kg C m m^{-3} at a depth of 5-10cm.

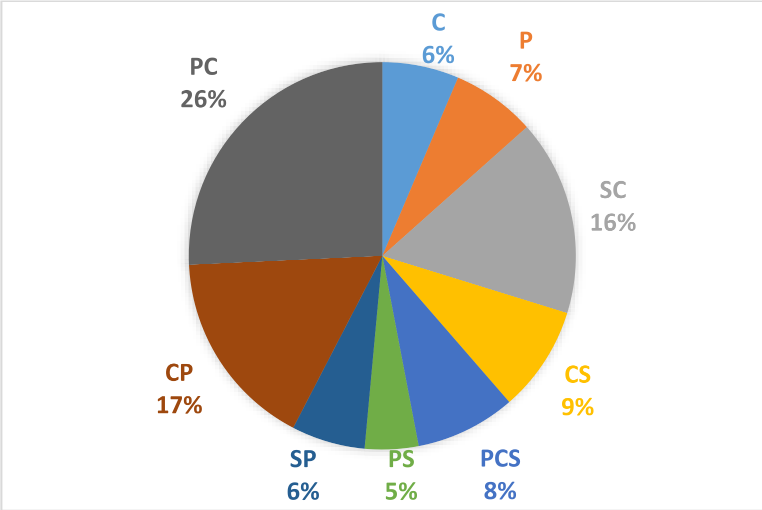

Figure 4: Variation of Total Average Carbon Stock with Lithology (C=clay, P=peat, SC=sandy clay, CS=clayey sand, PCS=peaty clayey sand, PS=peaty sand, SP=sandy peat, CP=clayey peat, PC=peaty clay).

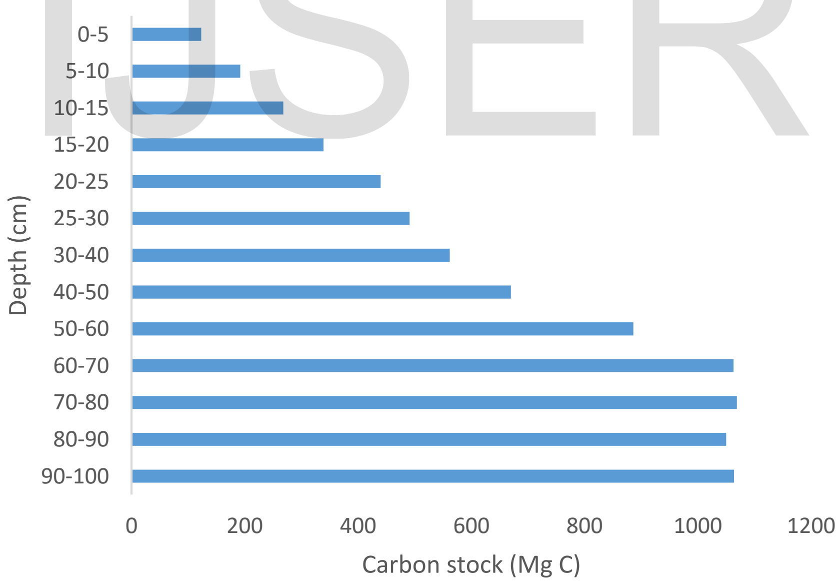

Figure 5: Variation of Total Average Carbon Stock with Depth

According to Kauffman and Donato (2012), carbon stock increases with increasing depth to a depth of 2-3 m where organic carbon begins to decrease. At this depth, %C starts to diminish and tend toward zero. The slight decrease in the value of carbon stock from 640.60 (70-80 cm) to 575.90 (80-90 cm) and to 503.75 (90-100 cm) in L4, and from 1215.00 (80-90 cm) to 1244.10 (90-100 cm) in L7 is a pointer that at this depth (100 cm) in the study area, organic carbon may begin to drop drastically.

The mean value of carbon stock (622.12 Mg C ha^{-1}) was about 1.54 times less than the global mean mangrove carbon stock of 956 Mg C ha^{-1} reported by Alongi (2014). This might have resulted from the degradation of the mangroves through deforestation and the destruction of vegetation from fires caused by illegal artisanal refining of crude oil within the study area.

Apart from SBD and %C which are determinant variables, the values of carbon stock were influenced slightly by sediment type. This result is consistent with the findings of Shaltout *et al.,* (2020) and Sanderman *et al.,* (2018). Highest value was obtained in peaty clay while the lowest value was obtained in sandy peat. Widespread occurrence of a particular sediment type plays a key role. Peaty clay has the highest mean value of carbon stock (948.95 Mg C ha^{-1}) while peaty sand has the lowest value (164.85 Mg C ha^{-1}).

6. Conclusions

All the variables including bulk density, organic matter content, organic carbon concentration and carbon stock vary significantly with sediment type and depth. The values of sediment bulk density vary significantly with depth and sediment type. The values were low and influenced by peaty fractions. Organic carbon concentration was found to decrease with depth. The values were high. The values of organic carbon stock were high. The mass of organic carbon in the top 100-cm of mangrove sediments in the study area was summed up to obtain the value of 194,102.24 ± 53.57 Mg C. This value was scaled up to cover the entire study area from which the total carbon storage was estimated at 921 ± 53.57 Gg C (about 0.048 % of the total global mangrove carbon storage in sediments). Therefore, mangrove forest restoration, protection and conservation should be pursued to reduce the rate of deforestation and other forms of forest degradation in the study area in order to enhance its carbon storage.

References

Almahasheer, H., Serrano, O., Duarte, C.M., Arias-Ortiz, A., Masque, P. & Irigoien, X. (2017). Low Carbon Sink Capacity of Red Sea Mangroves. *Scientific Reports*, *7*, 97-100. DOI:10.1038/s41598-017-10424-9

Alongi, D.M. (2012). Carbon Sequestration in Mangrove Forests. *Carbon Balance and Management*, *3*, 313-322.

Alongi, D.M. (2014). Carbon Cycling and Storage in Mangrove Forests. *Annual Review of Marine Science*, *6*, 195-219.

American Society of Testing and Materials, ASTM D 2974-87 (2000). *Standard Methods for Moisture, Ash and Organic Matter of Peat and other Organic Soils*. Race Street, Philadelphia: Author.

Ansa, E.J. & Francis, A. (2007). Sediment Characteristics of the Andoni Flats, Niger Delta, Nigeria. *Journal of Applied Science and Environmental Management*, *11*(3), 21-25.

Arshad, M., Alrumman, S. & Eid, E.M. (2018). Evaluation of Carbon Sequestration in the Sediment of Polluted and Non-Polluted Locations of Mangroves in Jazan Economic City along Red Sea Coastline, Saudi Arabia. *Fundamental Applied Limnology*, *192*(1), 53-64.

Asuk, S.A., Offiong, E.E., Ifebueme, N.M. & Akpaso, E.O. (2018). Species Composition and Diversity of Mangrove Swamp Forest in Southern Nigeria. *International journal of Avian and Wildlife Biology*, *3*(2), 159-164.

Avelar, S., van der Voort, T.S. & Eglinton, T.I. (2017). Relevance of Carbon Stocks of Marine Sediments for National Greenhouse Gas Inventories of Maritime Nations. *Carbon Balance and Management*, *12*(10), 1-10.

Bouillon, S., Borges, A., Casteneda-Moya, E., Diele, T. & Dittmar, T. (2008). Mangrove Production and Carbon Sinks: A Revision of Global Budget Estimates. *Global Biogeochemistry Cycle*, *22*(2), 15-24. doi:https://doi.org/10.1029/2007GB003052

Diesing, M., Kroger, S., Parker, R., Jenkins, C., Mason, C. & Weston, K. (2017). Predicting the Standing Stock of Organic Carbon in Surface Sediments of the North-West European Continental Shelf. *Biogeochemistry*, *135*, 183-200. doi:10.1002/2016JG003510

Diesing, M. Thorsnes, T. & Bjarnadottir, L.R. (2020). Organic Carbon in Surface Sediments of the North Sea and Skagerrak. *Biogeosciences*, *6*(20), 352-379.

Donato, D., Kauffman, J., Murdiyarso, D., Kurnianto, S., Stidham, M. & Kanninen, M. (2011). Mangroves among the most Carbon-Rich Forests in the Tropics. *Natural Geosciences, 4*(5), 293-297. doi:https://doi.org/10.1038/ngeo1123

Eid, E.M. & Shaltout, K.H. (2016). Distribution of Soil Organic Carbon in the Mangrove *Avicennia marina* (Forssk Vierh) along the Egyptian Red Sea Coast. *Regional Studies in Marine Science*, *3*, 76-82.

Eid, E.M., El-Bebany, A.F. & Alrumman, S.A. (2016). Distribution of Soil Organic Carbon in the Mangrove Forests along the Southern Saudi Arabian Red Sea Coast. *Rendiconti Lincei*, *27*, 629-637. Retrieved from https://doi.org/10.1007/s12210-016-0542-6

Eid, E. M., Arshad, M., Shaltout, K.H., El-Sheikh, M.A., Alfarhan, A.H., Picó, Y. & Barcelo, D. (2019). Evaluation of Carbon Stock in the Sediment of Two Mangrove Species, *Avicennia marina* and *Rhizophora mucronata*, growing in the Farasan Islands, Saudi Arabia. *Environmental Resources, 176,* 20-31. doi:https://doi.org/10.1016/j.envres.2019.108536

Essen, C. (2020, August 3). Government Plans Niger Delta Mangrove Restoration Project. *The Guardian*, *18*.

Evamy, B.D., Harembourne, J., Kamerling, W.A., Knapp, W.A., Molloy, F.A. & Rowlands, P.H. (1978). Hydrocarbon Habitat of Tertiary Niger Delta. *Bulletin of American Association of Petroleum Geology*, *62*, 1-39.

Gao, Y., Zhou, J., Wang, L., Guo, J., Feng, J., Wu, H. & Lin, G. (2019). Distribution Patterns and Controlling Factors for the Soil Organic Carbon in Four Mangrove Forests of China. *Global Ecology and Conservation*, *17*(2019), 12-26.

Han, Y., Zhang, J., Mattson, K.G., Zhang, W. & Weber, T.A. (2016). Sample Sizes to Control Error Estimates in Determining Soil Bulk Density in California Forest Soils. *Soil Science and Sociology of American Journal*, *80*(3), 756-764.
DOI: 10.2136/sssaj2015.12.0422.

Iticha, B. (2017). Ecosystem Carbon Storage and Partitioning in Chato Afro-montane Forest: Its Climate Change Mitigation and Economic Potential. *International Journal of Environment, Agriculture and Biotechnology*, *2*(4), 1785-1794.

Jennerjahn, T. C., & Ittekot, V. (2002). Relevance of Mangroves for the Production and Deposition of Organic Matter along Tropical Continental Margins. *Nature wise*, *89*(1), 23-30.
doi:https://doi.org/10.1007/s00114-001-0283-x

Kauffman, J.B. & Donato, D.C. (2012). *Protocols for the Measurement, Monitoring and Reporting of Structure, Biomass and Carbon Stocks in Mangrove Forests*. Bogor, Indonesia: Center for International Forestry Research.
Retrieved from www.cifor.org

Komolafe, E.T., Chukwuka, K.S., Obiakara, M.C. & Osonubi, O. (2020). Carbon Stock and Sequestration Potential of Ibodi Monkey Forest in Atakumosa, Osun State, Nigeria. *Trees, Forests and People*, *2*(2020), 100-107.

Kusumaningtas, M.A., Hutahaan, A.A., Fischer, H.W., Prez-Mao, M., Ransb, D. & Jennerjahn, T.C. (2019). Variability in the Organic Carbon Stocks, Sources and Accumulation Rates of Indonesian Mangrove Ecosystems. *Estuarine, Coastal and Shelf science*, *218*(2019), 310-323.

Malunguja, G.K., Devi, A., Kilonzo, M. & Rubanza, C.D.K. (2020). Climate Change Mitigation through Carbon dioxide (CO2) Sequestration in Community Reserved Forests of Northwest Tanzania. *Archives of Agriculture and Environmental Science*, *5*(3), 231-240.

Meersmans, J., De Ridder, F., Canters, F., De Baets, S. & Van Molle, M. (2008). A Multiple Regression Approach to Assess the Spatial Distribution of Soil Organic Carbon (SOC) at the Regional Scale (Flanders Belgium). *Geoderma*, *143*(1-2), 1-13. http://dx.doi.org/10.1016/j.geoderma.2007.08.025.

Mitsch, W.J. & Gosselink, J.G. (2007). *Wetlands* (4^{th} ed.). New York, USA: John Wiley and Sons, Inc.

Nelson, D.W. & Sommers, L.E. (1996). *Total Carbon, Organic Carbon, and Organic Matter*. In Sparks, D.L. (Ed.), *Methods of Soil Analysis*. Madison: SSSA Book Series.

Numbere, A.O. (2018). Mangrove species Distribution and Composition, Adaptive Strategies and Ecosystem Services in the Niger Delta, Nigeria. *Mangrove Ecosystem ecology and Function* (open access database).
Retrieved from DOI:10.5772/intchopen

Nwobi, C., Williams, M. & Mitchard, E.T. (2020). Rapid Mangrove Forest Loss and Nipa Palm (*Nypa fruticans*) Expansion in the Niger Delta, 2007-2017. *Remote sensing*,*12*(4), 23-44.

Obaje, N.G. (2009). *Geology and Mineral Resources of Nigeria*. New York: Springer.

Paulsen, H.M. (Ed.) (2020). *Inventory of Techniques for Carbon Sequestration in Agricultural Soils*. North Sea Region: Thunen Institute of Organic Farming. http://:www.northsearegion.eu/carbon-farming

Pearson, T.R.H., Brown, S.L. & Birdsey, R.A. (2007). *Measurement Guidelines for the Sequestration of Forest Carbon*. Newtown Square, Pennsylvania: USDA Forest Service.

Perera, R. & Amarasinghe, M. (2019). Carbon Sequestration Capacity of Mangrove Soils in Micro Tidal Estuaries and Lagoons: A Case Study from Sri Lanka. *Geoderma, 347*(2), 80-89.

Rumengan, A.P., Mantiri, D.M H., Rompas, R., Hutahaean, A., Kepel, T.L., Parunt, C.P., Kepel, R.C. & Gerung, G.S. (2018). Carbon Stock Assessment of Mangrove Ecosystem in Totok Bay, Southeast Minahasa Regency, North Sulawesi, Indonesia. *Bioflux, 11*(4), 1280-1288.

Sanderman, J., Hengl, T., Fiske, G., Solvik, K., Adame, M., Benson, L., Bukoski, J. & Carnell, P. (2018). A Global Map of Mangrove Forest Soil Carbon at 30 m Spatial Resolution. *Environmental Resource Letter, 13*(5), 12-25. doi:https://doi.org/10.1088/1748-9326/aabe1c

Scheffold, M.I.E. & Hense, I. (2020). Quantifying contemporary organic carbon stock of the Baltic Sea ecosystem. *Frontiers in Marine Science*, *7*(57), 1-19.

Schumacher, B.A. (2002). *Methods for the Determination of Total Organic Carbon (TOC) in Soils and Sediments.* Las Vegas, USA: US Environmental Protection Agency.

Shaltout, K.H., Ahmed, M.T., Sulaiman A. Alrumman, S.A., Dalia A. Ahmed, D.A. & Eid, E.M. (2020). Evaluation of the Carbon Sequestration Capacity of arid Mangroves Along Nutrient Availability and Salinity Gradients Along the Red Sea Coastline of Saudi Arabia. *Oceanologia*, *62*(2020); 56-69.

Short, K. & Stauble, A. (1967). Outline of Geology of Niger Delta. *AAPG Bulletin, 51*(5), 761-779.

Shunyang, C., Bin, C., Pramudji, S., Eka, D.I.W., Danyun, O.O. Xijie, Y. Weiwei, Y.U. & Guangcheng, C. (2018). Ecosystem Carbon Stock of a Tropical Mangrove Forest in North Sulawesi, Indonesia. *Acta Oceanologica Sinica*, *37*(12), 85-91. doi: 10.1007/s13131- 018-1290-5

Siraj, M. (2019). Forest Carbon Stocks in Woody Plants of Chilimo-Gaji Forest, Ethiopia: Implications of Managing Forests for Climate Change Mitigation. *South African Journal of Botany, 127*, 213-219 http://doi.org/10.1016/j.sajb.2019.09.003

Stringer, C.E., Tretin, C.C. & Zarnoch, S.J. (2015). Carbon Stock of Mangrove within the Zambezi River Delta Mozambique. *Forests Ecology and Management*, *354,* 139-148.

Suhaili, N.S., Fei, J.L.J., Sha'ari, F.W., Idris, M.I., Hatta, S.M., Kodoh, J. & Besar, N.A. (2020). Carbon Stock Estimation of Mangrove Forest in Sulaman Lake Forest Reserve, Sabah, Malaysia. *Biodiversitas*, *21*(12), 5657-5664. DOI: 10.13057/biodiv/d211223

Taillardat, P., Friess, D.A. & M. Lupascu, M. (2018). Mangrove Blue Carbon Strategies for Climate Change Mitigation are most Effective at the National Scale. *Biological Letter, 14*(10), 1-14. doi:https://doi.org/10.1098/rsbl.2018.0251

Trettin, C.C., Dai, Z., Tang, W., Lagomasino, D., Thomas, N., Lee, S.K., Simard, M., Ebanega, M.O., Stoval., A. & Fatoyinbo, T.E. (2021). Mangrove Carbon Stock in Pongara National Park, Gabon. *Estuarine Coastal Shelf Science, 9*(2021), 107-114.

Twilley, R.R., Chen, R.H. & Hargis, T. (1992). Carbon Sinks in Mangroves and their Implications to Carbon Budget of Tropical Coastal Ecosystems. *Water, Air and Soil Pollution, 64*, 265-288.

United State Agency for International Development, USAID (2015). *USAID Lowering Emissions in Asia Forests Program (USAID LEAF): USAID LEAF's Climate Change Curriculum*. Bangkok, Thailand: Winrock International and US Forest Service.

Winrock International (2016). *USAID's Climate-Resilient Ecosystems and Livelihoods (CREL)*. Dhaka, Bangladesh: Winrock International.
Retrieved from www.winrock.org