Open Journal of Forestry, 2024, 14, 127-140
https://www.scirp.org/journal/ojf
ISSN Online: 2163-0437
ISSN Print: 2163-0429

National Soil Organic Carbon Stocks Inventories under Different Mangrove Forest Types in Gabon

Rolf Gaël Mabicka Obame[1], Neil-Yohan Musadji[2], Jean Hervé Mve Beh[3], Lydie-Stella Koutika[4], Jean Aubin Ondo[5], Farrel Nzigou Boucka[6], Michel Mbina Mounguengui[7], Claude Geffroy[8]

[1]Département de Phytotechnologie, Institut National d'Agronomie et de Biotechnologies, Université des Sciences et Techniques de Masuku, Franceville, Gabon
[2]Département des Sciences Fondamentales de l'Ingénieur, Institut National d'Agronomie et de Biotechnologies, Université des Sciences et Techniques de Masuku, Franceville, Gabon
[3]Institut Agronomiques et Forestières, Centre National des Recherches Scientifiques et Technologiques, Libreville, Gabon
[4]Research Centre on the Durability and the Productivity of Industrial Plantations (CRDPI), Pointe Noire, Republic of Congo
[5]Laboratoire Pluridisciplinaire des Sciences, École Normale Supérieure, Libreville, Gabon
[6]Agence Gabonaise d'Étude et d'Observation Spatiale, Immeuble les Arcades, Libreville, Gabon
[7]Département de Géologie, Faculte des Sciences, Université des Sciences et Techniques de Masuku, Franceville, Gabon
[8]Institut de Chimie des Milieux et Matériaux de Poitiers (IC2MP), Université de Poitiers, Poitiers, France
Email: *rolfmabicka@gmail.com, nyohan1@gmail.com, mormyre69@gmail.com, ls_koutika@yahoo.fr, ondo.jean-aubin@laplus-ens.ga, Boucka:farrelboucka@gmail.com, michelmbina@gmail.com, claude.geffroy@univ-poitiers.fr

How to cite this paper: Obame, R. G. M., Musadji, N. -Y., Beh, J. H. M., Koutika, L. -S., Ondo, J. A., Boucka, F. N., Mounguengui, M. M., & Geffroy, C. (2024). National Soil Organic Carbon Stocks Inventories under Different Mangrove Forest Types in Gabon. *Open Journal of Forestry, 14,* 127-140.
https://doi.org/10.4236/ojf.2024.142009

Received: March 6, 2024
Accepted: April 23, 2024
Published: April 26, 2024

Copyright © 2024 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

Abstract

Gabonese's estuary is an important coastal mangrove setting and soil plays a key role in mangrove carbon storage in mangrove forests. However, the spatial variation in soil organic carbon (SOC) storage remain unclear. To address this gap, determining the SOC spatial variation in Gabonese's estuarine is essential for better understanding the global carbon cycle. The present study compared soil organic carbon between northern and southern sites in different mangrove forest, *Rhizophora racemosa* and *Avicennia germinans*. The results showed that the mean SOC stocks at 1 m depth were 256.28 ± 127.29 MgC ha^{-1}. Among the different regions, SOC in northern zone was significantly ($p < 0.001$) higher (232.45 ± 120.81 MgC ha^{-1}) than that in the southern zone (143.19 ± 44 MgC ha^{-1}). At all sites, SOC stocks were significantly higher in Rhizophora racemose (192.2 ± 114.17 MgC ha^{-1}) than in Avicenia germinans (130.12 ± 161.16 MgC ha^{-1}) ($p < 0.001$). The deeper layers contained higher SOC stocks (254.62 ± 128.09 MgC ha^{-1}) than upper layers (55.42 ± 25.37 MgC ha^{-1}). The study highlights that low deforestation rate have led to less CO_2 (705.3 Mg CO_2e ha^{-1} - 922.62 Mg CO_2e ha^{-1}) emissions than most sediment carbon-rich mangroves in the world. These results highlight the influence of soil texture and mangrove forest types on the mangrove SOC stocks. The first national comparison of soil organic carbon stocks between mangroves and upland tropical forests indicated SOC stocks were two times more in mangroves soils (51.21 ± 45.00 MgC ha^{-1}) than primary (20.33 ± 12.7 MgC ha^{-1}), savanna and cropland (21.71 ± 15.10 MgC ha^{-1}). We find that mangroves in this study emit lower dioxide-carbon equivalent emissions. This study highlights the importance of national inventories of soil organic carbon and can be used as a baseline on the role of mangroves in carbon sequestration and climate change mitigation but the variation in SOC stocks indicates the need for further national data.

Keywords

Mangroves Forest, Soil Organic Carbon Stocks, Rizophora Racemose, *Avicenia germinans*, Gabon

1. Introduction

The Paris Climate Agreement recommends an increase in soil capacity to store carbon and protection of those carbon rich (Rumpel et al., 2018). Coastal organic carbon, named "blue carbon", is stored in above and belowground and soils (Donato et al., 2011; Siikamäki et al., 2012) and removed dioxide carbon from atmosphere contributing to mitigate climate change (Laffoley & Grimsdith, 2009; Nellemann et al., 2009). Submerged ecosystems like mangrove are recognized to be the most carbon-rich forests in the tropics (Donato et al., 2011; Sanders et al., 2016; Macreadie et al., 2019) and soil are important as a pool stored organic carbon (Donato et al., 2011; Alongi, 2018; Serrano et al., 2019; Kauffman et al., 2020). The mangrove soils store about 76.5% of the total ecosystems (Alongi, 2020). Mangroves play a vital role in mitigating climate change by transferring dioxide carbon (CO_2) from atmosphere into aboveground biomass, belowground, non-living and soil (Donato et al., 2011; Sanders et al., 2016; Feher et al., 2017). Despite their importance, mangroves ecosystems continue to be lost across the globe driven primarily by anthropogenic activities (Sippo et al., 2018). Their continued loss and degradation have significant implications for established carbon stocks and rates of burial (de Oliveira Gomes et al., 2021 These activities could have impacted the effects of climate change, such as El Niño Southern Oscillation events (Kulp & Strauss, 2019), sea level rise (Jevrejeva et al., 2012; Saintilan et al., 2020), and more frequent, intense hurricane events (Krauss & Osland, 2020; Emanuel, 2021; Vecchi et al., 2021). Alongi (2012) indicated that mangrove loss leads to the emission of carbon dioxide to the atmosphere, resulting in global warming.

The study of the spatial distribution of mangrove soils organic carbon stocks can help to assess climate change and human pressure impacts on mangrove ecosystems. Africa is home to 19% of the world's mangroves and several studies have estimated the carbon stocks of mangrove ecosystems. Studies have compared the carbon stocks of African mangrove ecosystems with those of other regions (Fatoyinbo & Simard, 2013; Trettin et al., 2021; Kauffman et al., 2020). However, soil carbon stocks can significantly vary across and within the same mangrove ecosystems (Jardine and Siikamäki, 2014; Kauffman et al., 2018; Sahu and Kathiresan, 2019, Kauffman & Bhomia, 2017). mangrove soil organic carbon varies according to land cover and soil type (Kauffman & Bhomia, 2017).

In Gabon, mangroves occupy approximately 5.6% of total mangrove area in Africa (Giri et al., 2011; Fatoyinbo & Simard, 2013) and are located within the coastal region of Atlantic Ocean. So it can play an important role in reducing carbon dioxide emission from deforestation and industrial activities. Recently, Gabon was certified for Carbon credit by the United Nations Framework Convention on Climate Change's (UNFCCC, 2022). So that baselines can be set for country to participate in future climate-change strategies such as reduced emissions from deforestation and degradation (REDD$^+$ 23). Despite this recognition, studies revealed an increasing degradation of mangroves ecosystems along Gabonese coastal due to fishing activities (FAO, 2007). The evaluation of carbon stock and storage potentials of mangrove soils is crucial to determining the amount of CO_2 released to the atmosphere which alters the equilibrium in carbon dioxide distribution amongst the reservoirs of the carbon cycle (Bindoff et al., 2019; Nwankwo et al., 2023). In Gabon, several studies on above and mangrove soil carbon stocks have already been conducted in Gabon (Ajonina et al., 2014; Trettin et al., 2021; Kauffman & Bhomia, 2017). However, uncertainties remain about spatial distribution of mangrove soils organic carbon stocks across country. Trettin et al. (2021) reported that SOC stocks in the top-meter soil in Pongara National Park in Gabon were 369 MgC ha^{-1}. Ajonina et al. (2014) reported SOC stocks of 345 MgC ha^{-1} in Akanda National Park, however, spatial variation of SOC stocks remain unclear. Soil organic carbon stocks may vary on a national scale, understanding the distribution mangrove soil organic carbon at nationwide is thus crucial to increase national carbon storage and will mitigate climate change (Jardine & Siikamäki, 2014; Sanderman et al., 2018; Bindoff et al., 2019). In order to provide data on spatial mangrove soil organic carbon nationally, this study aimed to assess 1) soil organic carbon stocks profile distribution under two mangrove forests *Rhizophora racemosa* L. (Rhizophoraceae) and *Avicennia germinans* (L.), 2) to estimate SOC stocks in relation to geographical locations (northern sites vs southern sites), in estuary of Gabon. 3) in order to assess the role of mangrove soils in organic carbon sequestration, carbon stocks in mangrove soils were compared to those of soils under primary and secondary forests, 4) carbon dioxide concentrations have also been estimated. We hypothesized that SOC stocks differ among mangrove forests and localization.

2. Methods

The study area as shown in Figure 1 is located along the coast of Gabon which is part of the Congo Basin. The climate is humid wet tropical with an average rainfall between 2400 on the eastern to 2830 mm on western side (Ajonina et al., 2014). At all sites, the main mangrove vegetation was *Rhizophora racemosa* L. (Rhizophoraceae) and *Avicennia germinans* (L.) The data used for this study were mainly taken from the Center for International Forestry Research (CIFOR): Sustainable Wetlands Adaptation and Mitigation Program (SWAMP) database of tropical wetlands carbon survey: soil, Swamp Dataset-Mangrove soil carbon-Gabon South and North-2014 and Swamp Dataset-Mangrove biomass

Figure 1. Map showing the location of soil samples.

vegetation-Gabon South and North-2014 (Kauffman & Bhomia, 2017, 2020). Datasets were collected in northern and southern Gabon. For SOC stocks assessments 17 soil cores were collected: 10 in the southern and 7 in northern part following the approach of (Donato et al., 2011; Kauffman & Donato, 2012). Soil core was divided into depth intervals of 0 - 15 cm, 15 - 30 cm, 30 - 50 cm, 50 - 100 cm (Kauffman & Bhomia, 2017). In laboratory several parameters such as organic carbon content and bulk density were determined by Kauffman and Bhomia (2017). Mangrove soil organic carbon stocks in layer was determined following Equation (1)

$$\text{Soil organic carbon stocks} = \text{SOC concentration} \times h \times BD \quad (1)$$

where SOC concentration is organic carbon concentration (%), h is the layer thickness (cm) and BD is the bulk density ($g \cdot cm^{-3}$). The carbon of the soil profile is calculated by summing up the carbon stored per unit area over le depth. For this study, only carbon stock data for the upper meter of sediment were used to compare relative storage per unit area on a global scale.

To convert carbon to carbon dioxide, the organic carbon stock is multiplied by 3.67 using the formula proposed by Iticha (Hamilton & Casey, 2016) and Kauffman and Donato (2012) expressed Equation (2)

$$CO_2e(MgCO_2) = 3.67 \times \text{Total Carbon Stock} \quad (2).$$

To assess the carbon sink capacity of mangrove ecosystems and to further clarify this ecosystem's carbon sink capacity, we made the comparison of mangrove SOC stock with upland (forest primary and secondary), savannas, cropland and fallow forest. The database was compiled from (Mabicka Obame et al., 2021). We only used data from the top 0 - 30 cm.

3. Results

The general trend in SOC stocks, C: N ration and bulk density are presented in **Table 1**. The mean SOC stocks at 1 m depth were 256.28 ± 127.29 MgC ha^{-1} (**Figure 2(a)**). Among the different regions, SOC in Zthe northern zone was significantly ($p < 0.001$) higher (232.45 ± 120.81 MgC ha^{-1}) than that in the southern

Table 1. Bulk density, organic carbon content and stocks and equivalent dioxide carbon of mangrove soil for 1 m depth in *Avicennia germinans* and *Rhizophora racemose*.

	BD ($g \cdot cm^{-3}$)		C/N		CO_2 Mg ($eqCO_2e$)		SOC (MgC ha^{-1})		SOCS (%)	
	n	Mean (Sd)	*n*	Mean (Sd)	*n*	Mean (Sd)	*n*	Mean (Sd)	*n*	Mean (Sd)
0 - 30*	77	0.52 (0.41)	96	24.60 (6.12)	102	379.13 (262.74)	102	23.02 (15.71)	102	105.31 (72.98)
0 - 100	77	0.66 (0.45)	-	-	102	927.08 (490.39)	102	35.07 (23.90)	102	257.52 (136.22)
Ag	28	1.27 (0.19)	19	19.56 (4.18)	40	457.35 (585.35)	40	6.97 (8.86)	40	127.04 (162.60)
Rr	126	0.44 (0.31)	82	25.77 (6.02)	164	700.85 (438.23)	164	34.42 (19.62)	164	194.68 (121.73)
North	84	0.30 (0.07)	42	27.92 (6.01)	84	859.97 (476.27)	84	42.36 (14.97)	84	238.88 (132.30)
South	70	0.95 (0.42)	59	22.23 (5.21)	120	508.30 (426.39)	120	19.72 (19.68)	120	141.20 (118.44)

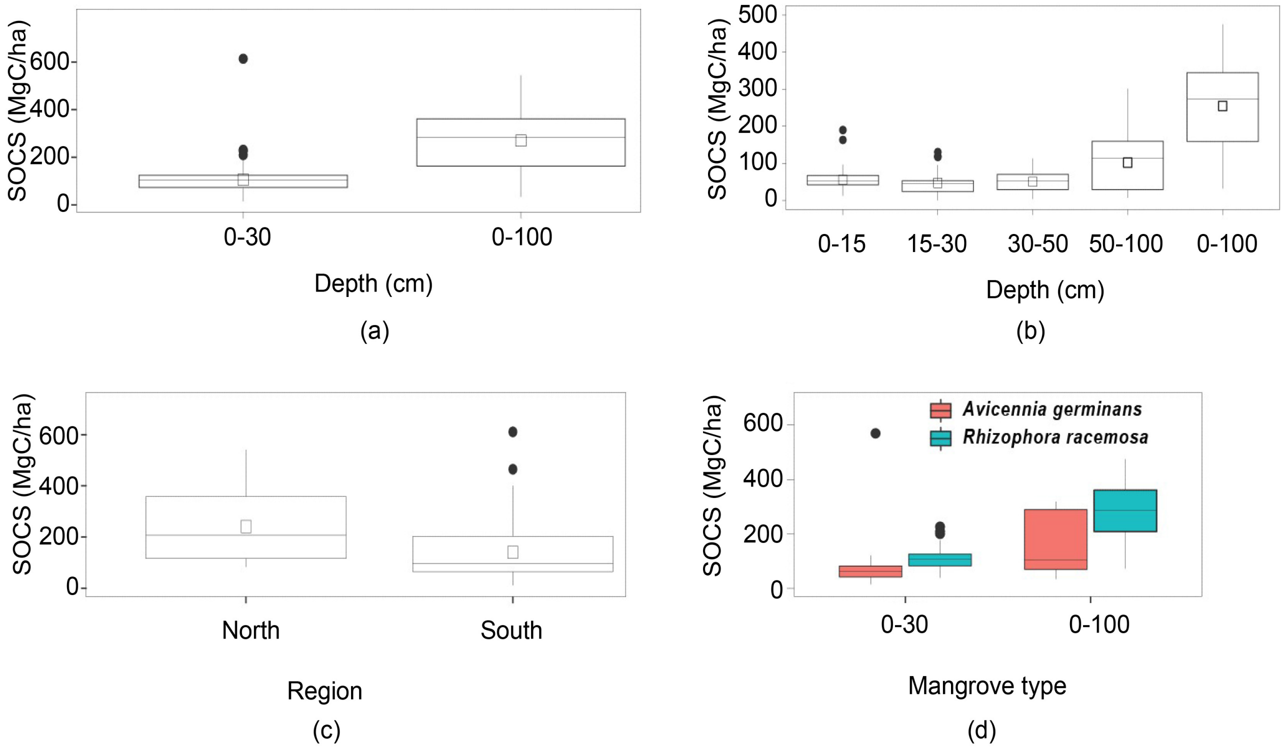

Figure 2. Mangrove soil organic carbon stocks. (a): Soil organic carbon stocks between 0 - 30 cm and 1 m depth; (b): soil organic carbon stocks distribution with depth; (c): comparison of soil organic carbon between northern and southern sites, (d): soil organic carbon among mangroves; and e: soil organic carbon stocks among mangrove forests stature. Error bars denote standard deviation.

zone (143.19 ± 44 MgC ha^{-1}) (Figure 2(c)). Mangrove SOC stocks were significantly higher in *Rhizophora racemose* (192.2 ± 114.17 MgC ha^{-1}) than in *Avicenia germinans* (130.12 ± 161.16 MgC ha^{-1}) ($p < 0.001$) (Figure 2(d)).

The lowest mangroves SOC stocks occurred at the depth of 0 - 15 (55.42 ± 25.37 MgC ha^{-1} to 47.00 ± 58.23 MgC ha^{-1}) whereas the highest SOC occurred between 15 and 100 cm depth (47.00 ± 58.23 MgC ha^{-1} to 254.62 ± 128.09 MgC ha^{-1}) (Table 2, Figure 2(b)) in all sites indicating carbon storage in deep horizons.

3.1. Comparison of Mangrove with Rainforest of Gabon

There were high differences in SOC ($p < 0.00$) between mangrove soil and rainforest (Table 3). The mean soil organic carbon stocks in mangrove in the upper 30 cm were two times higher (51.21 ± 45.00 MgC ha^{-1}) than in primary forest (20.33 ± 12.7 MgC ha^{-1}), savanna (23.21 ± 12.15 MgC ha^{-1}), and cropland (21.71 ± 15.10 MgC ha^{-1}). The mangrove SOC stocks were higher by 39.7%, 45.3% and 42.4% compared to primary forest, savanna and cropland respectively (Figure 3).

3.2. Potential Carbon Dioxide Emission

Our emissions estimates, based upon our actual measurements, ranged from

Table 2. Evolution of bulk density, organic carbon content and stocks of mangrove soil with depth.

	BD		C/N		SOC		SOCS	
	n	Mean (Sd)	n	Mean (Sd)	n	Mean (Sd)	n	Mean (Sd)
0 - 15	77	0.47 (0.40)^{a}	100	23.20 (6.95)^{ab}	102	13.13 (8.92)^{c}	102	55.56 (25.60)^{a}
15 - 30	77	0.57 (0.48)^{ab}	91	26.90 (7.90)^{c}	102	9.85 (8.38)^{b}	102	47.00 (58.23)^{a}
30 - 50	77	0.72 (0.51)^{bc}	83	24.78 (5.98)^{bc}	102	7.66 (6.56)^{b}	102	50.34 (26.06)^{a}
50 - 100	77	0.86 (0.53)^{c}	69	21.83 (6.72)^{a}	102	4.44 (4.25)^{a}	102	101.61 (68.70)^{b}

Table 3. Comparison of soil organic carbon stocks between and main Gabonese's land cover (rainforest, savannah, cropland and fallow).

LULC	Type	System	SOCS		CO_2
			n	Mean (Sd)	Mean (Sd)
Land use		Cropland	180	21.71 (15.09)^{a}	78.15 (54.32)^{a}
		Follow Forest	42	16.70 (13.65)^{a}	60.11 (49.12)^{a}
Land cover	Mangrove	Avicennia germinans	20	84.68 (127.98)^{b}	304.84 (460.73)^{b}
		Rhizophora racemosa	82	110.35 (51.66)^{c}	397.25 (185.98)^{c}
	Forest	Primary forest	190	21.44 (13.11)^{a}	77.17 (47.23)^{a}
		Secondary forest	288	19.66 (12.33)^{a}	70.79 (44.39)^{a}
	Savanna	Shrub savanna	123	23.20 (13.53)^{a}	83.52 (48.72)^{a}
		Herbaceous savanna	236	23.26 (11.47)^{a}	83.72 (41.31)^{a}

371.83 Mg CO_2e ha^{-1} in upper layers (0 - 30 cm) mangrove to 922.62 Mg CO_2e ha^{-1} at 1m depth. CO_2 concentrations were significantly higher (*705.3* Mg CO_2e ha^{-1}) in *Rhizophora racemose* than those of in *Avicenia germinans* (477.54 Mg CO_2e).

4. Discussion

4.1. Soil Carbon in Function of Locations and Mangrove Forests Types

The mean Soil C stocks in the upper 1 m depth were 256.28 ± 127.29 MgC ha^{-1}. Similar findings were reported by previous studies indicating that mangroves soils are a major reservoir of organic carbon (Donato et al., 2011; Sanders et al.,

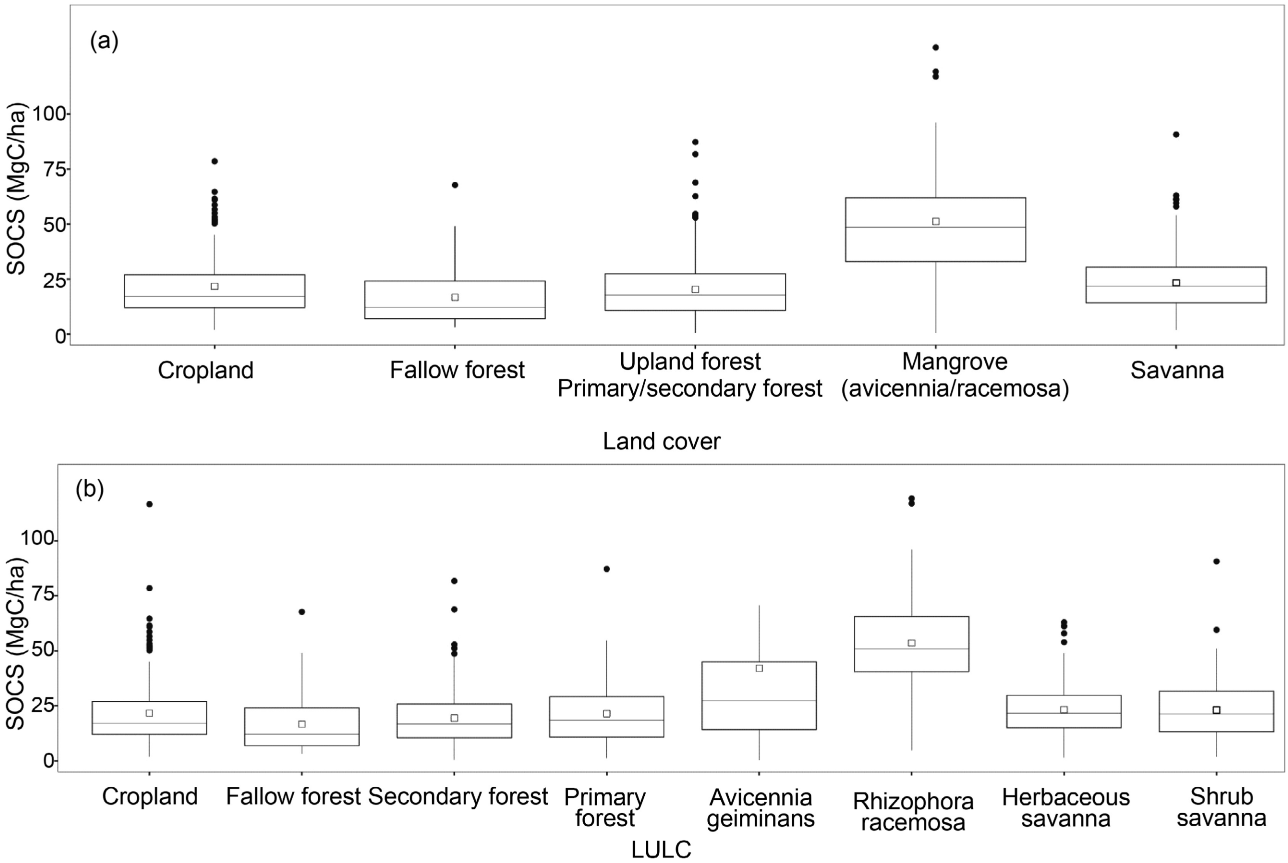

Figure 3. Comparison of soils organic carbon stocks between mangrove forest and upland forest in coastal of Gabon. (a): comparison between mangrove forest and others land cover/land uses; (b): comparison between mangrove forest type and upland land cover.

2016). The findings matched the global median value for SOC in mangrove (237 MgC ha^{-1}) reported by Ouyang and Lee (2020), but were lower than the values obtained by Ajonina et al. (2014) in Akanda National Park (345 MgC ha^{-1}) by Trettin et al. (2021) in the Pongara National Park (369 MgC ha^{-1}) and at global scale (504.3 MgC ha^{-1}) by Alongi (2020). These results can be explained by several factors such as high productivity and anoxic conditions reducing organic carbon mineralization of mangroves ecosystems (Donato et al., 2011; Alongi, 2012). Mangroves properties are variable on small spatial scales in particular soil organic carbon storage (Alongi, 2009; Jennerjahn, 2020). Our results also showed that soil organic carbon stocks varied from northern to southern sites. This trend is in line with Chou et al. (2022) who reported variation in SOC stock among sites in the same region in China's mangroves. Soil particle size control soil organic carbon (Kathiresan et al., 2014; Kauffman et al., 2018). This is in agreement with our results, the northern site had finer textures and high SOC stocks, while in southern, soils were composed of coarse sand texture (Kauffman & Bhomia, 2017) with the lowest SOC stocks. Organic matter in sandy soil would be more susceptible to decomposition and less likely to be sequestered (Schmidt et al., 2011; Kathiresan et al., 2014; Kauffman et al., 2018; Sahu &

Kathiresan, 2019) which is consistent with our results whose indicated that C/N ratios were significantly ($p < 0.001$) higher (28.15 ± 5.77 MgC ha^{-1}) in northern than in southern (22.38 ± 5.22 MgC ha^{-1}) (**Table 1**). This study also indicated that SOC stocks varied among mangroves forest. In this study, mean SOC was highest in *Rhizophora racemose* compared to *Avicenia germinans*. This in agreement with Yang et al. (2014) who reported that vegetation type affects soil carbon storage. The variation in mangrove land cover was also observed by Daud et al. (2022) in Zanzibar, Githaiga (2013) in Kenya, Dung et al. (2016) in Can Gio (Vietnam) mangroves forest, which is consistent with global data (Jardine & Siikamäki, 2014). The differences in SOC stocks among forests can be explained by differences in density and aerial root type (Xiong et al., 2018). Studies have shown that *Rhizophora spp* are associated with higher mean total ecosystems carbon stocks than *Avicennia spp* (Kauffman et al., 2020).

Regarding the variability of SOC stocks, this study showed that the average SOC stocks were higher in the deeper layers and lowest in upper sediments. These results are in agreement with Trevathan-Tackett et al. (2018) who showed that microbial activities decreased with sediment depth. In mangroves forest subsoils (below 50 cm depth) store higher organic carbon (Adame et al., 2013; Tue et al., 2014).

4.2. Comparison of Mangrove with Rainforest of Gabon

No studies SOC stocks comparing mangrove soils and rainforest soils have been conducted in Gabon. We found that soil organic carbon stocks of mangrove were two times higher than those of primary, savanna and cropland. This result is in agreement with numerous studies, which report that soil carbon stocks of mangrove ecosystems are five times higher than those of tropical terrestrial forests (Bouillon, 2011; Donato et al., 2011; Malhi et al., 2011; Alongi, 2012). Mangrove forest had highest belowground carbon compared to upland forest, suggesting higher rates of C accumulation in soil due to the oxygen-limited decomposition of soil organic matter (Lovelock, 2008; Donato et al., 2011; Alongi, 2012; Hapsari et al., 2020).

4.3. Potential Carbon Dioxide Emission

Mangrove ecosystems are recognized as climate solution removing carbon dioxide from the atmosphere (Laffoley & Grimsditch, 2009; Nellemann et al., 2009). However, anthropogenic activities lead to carbon losses from mangroves ecosystems (Sippo et al., 2018). Following the stock-change approach, we estimated the first mangrove soil carbon dioxide potential emission. Mangrove soil located in northern and southern of Gabon absorbed significantly higher CO_2e. Our findings have a highest CO_2e potential absorption than from mangroves forests in the tropics (411 Mg CO_2e, Donato et al., 2011), but are lower than those given by Kauffman et al. (2014) and Pendleton et al. (2012). Using a stock-change approach the potential emission from the degradation of mangrove between 2000-2014 was calculated. The degraded mangroves are estimated to emit around 278.88 $MgCO_2e$ which is much lower than the emission in the tropics (Donato et al., 2011; Kauffman et al., 2014). Although the intensity of mangroves degradation is still low in Gabon, the impact of this degradation on soil carbon stocks must be evaluated to ensure accurate national carbon inventories.

4.4. Policies and Management Strategies to Protect and Enhance the SOC Storage Capacity of Mangroves

At the global scale, because their role as ecosystem services, many initiatives relating to the protection and restoration of mangroves have been taken and implemented (Murdiyarso et al., 2015). Given the importance of mangroves ecosystems in the global carbon cycle, some Sustainable Development Goals (SDG) of the Agenda 2030 of the United Nations are directly and indirectly associated with the ecosystem services. They are for instance SDG1 "No Poverty", SDG2 "Zeo Hunger", SDG 8 "Inclusive and Sustainable Economic Growth", SDG13 "Climate Action", SDG 14 "Conservation and Sustainable use marine's resources" and SDG 15 "Sustainable use of terrestrial ecosystems". Many international initiatives (REDD+, carbon credit) ratified by ratified by the Gabonese government are taken to support and encourage countries to protect and conserve forest ecosystems. At local scale, Recently the United Nations Framework Convention on Climate Change certified Gabon for Carbon credit. This certification involves rigorous Sustainable management of different ecosystems (upland, peatland, mangroves and oceans).

5. Conclusion

Despite their role in mitigating climate change Gabonese soil mangroves remain little studied. We estimated mangrove soil organic carbon in northern and southern sites under *Rhizophora racemose* and *Avicenia germinans.* Our study showed that mangroves soils stored high SOC stocks in belowground compared to the surface. Within national spatial, our results showed variability in SOC stocks among sites and vegetation types. Mean mangroves SOC stocks were highest in *Rhizophora racemose* compared to *Avicenia germinans*. Our results also showed that soil organic carbon stocks varied from northern to southern sites. We found that soil texture and vegetation types controlled SOC stocks. The mangrove SOC stocks were two times higher than those of upland forest. Our study showed in country with low deforestation rate such Gabon, the potential storage of carbon into the soil remain high and therefore need to be preserved and managed sustainably, to retain along with the increase in carbon storage. Our study highlights the importance of national inventories of soil organic carbon and can be used as a baseline on the role of mangrove in carbon sequestration and climate change mitigation but the variation in SOC stocks indicates the need for further national data.

Conflicts of Interest

The authors declare no conflict of interest.

References

Adame, M. F., Kauffman, J. B., Medina, I., Gamboa, J. N., Torres, O., Caamal, J., Reza, M., & Herrera-Silveira, J. A. (2013). Carbon Stocks of Tropical Coastal Wetlands within the Karstic Landscape of the Mexican Caribbean. *PLOS ONE, 8,* e56569. https://doi.org/10.1371/journal.pone.0056569

Ajonina, G. N., Kairo, J., Grimsditch, G., Sembres, T., Chuyong, G., & Diyouke, E. (2014). Assessment of Mangrove Carbon Stocks in Cameroon, Gabon, the Republic of Congo (RoC) and the Democratic Republic of Congo (DRC) Including Their Potential for Reducing Emissions from Deforestation and Forest Degradation (REDD+). In S. Diop, J. P. Barusseau, & C. Descamps (Eds.), *The Land/Ocean Interactions in the Coastal Zone of West and Central Africa, Estuaries of the World* (pp. 177-189). Springer International Publishing. https://doi.org/10.1007/978-3-319-06388-1_15

Alongi, D. M. (2009). *The Energetics of Mangrove Forests*. Springer.

Alongi, D. M. (2012). Carbon Sequestration in Mangrove Forests. *Carbon Management, 3,* 313-322. https://doi.org/10.4155/cmt.12.20

Alongi, D. M. (2020). Global Significance of Mangrove Blue Carbon in Climate Change Mitigation. *Science, 2,* 67. https://doi.org/10.3390/sci2030057

Alongi, D. M. (Ed.) (2018). Mangrove Forests. In *Blue Carbon* (pp. 23-36). Springer. https://doi.org/10.1007/978-3-319-91698-9_3

Bindoff, N. L., Cheung, W. W., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R. et al. (2019). Changing Ocean, Marine Ecosystems, and Dependent Communities. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska et al. (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (pp. 447-587). Cambridge University Press.

Bouillon, S. (2011). Storage beneath Mangroves. *Nature Geoscience, 4,* 282-283. https://doi.org/10.1038/ngeo1130

Chou, M.-Q., Lin, W.-J., Lin, C.-W., Wu, H.-H., & Lin, H.-J. (2022). Allometric Equations May Underestimate the Contribution of Fine Roots to Mangrove Carbon Sequestration. *Science of the Total Environment, 833,* Article 155032. https://doi.org/10.1016/j.scitotenv.2022.155032

Daud, Z. O., Mchenga Islam, S. S, & Ali Abdalla, I. (2022). Blue Carbon Stock of the Dominant Mangrove Species in Zanzibar-Tanzania. *International Journal of Science and Research (IJSR), 11,* 720-725.

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

Dung, L. V., Tue, N. T., Nhuan, M. T., & Omori, K. (2016). Carbon Storage in a Restored Mangrove Forest in Can Gio Mangrove Forest Park, Mekong Delta, Vietnam. *Forest Ecology and Management, 380,* 3-40. https://doi.org/10.1016/j.foreco.2016.08.032

Emanuel, K. (2021). Atlantic Tropical Cyclones Downscaled from Climate Reanalyses Show Increasingactivity over Past 150 Years. *Nature Communications, 12,* Article No. 7027. https://doi.org/10.1038/s41467-021-27364-8

FAO (2007). *The World's Mangroves 1980 746-2005*. Food and Agriculture Organization of the United Nations.

Fatoyinbo, T. E., & Simard, M. (2013). Height and Biomass of Mangroves in Africa from ICESat/GLAS and SRTM. *International Journal of Remote Sensing, 34,* 668-681. https://doi.org/10.1080/01431161.2012.712224

Feher, L. C., Osland, M. J., Griffith, K. T., Grace, J. B., Howard, R. J, Stagg, C. L. et al.

(2017). Linear and Nonlinear Effects of Temperature and Precipitation on Ecosystem Properties in Tidal Saline Wetlands. *Ecosphere, 8,* e01956. https://doi.org/10.1002/ecs2.1956

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., Masek, J., & Duke, N. (2011). Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data. *Global Ecology and Biogeography, 20,* 154-159. https://doi.org/10.1111/j.1466-8238.2010.00584.x

Githaiga, M. (2013). *Structure and Biomass Accumulation of Natural Mangrove Forest at Gazi Bay, Kenya*. I56/CE/15321/08.

Hamilton, S., & Casey, D. (2016). Creation of a High Spatiotemporal Resolution Global Database of Continuous Mangrove Forest Cover. *Global Ecology and Biogeography, 25,* 729-738. https://doi.org/10.1111/geb.12449

Hapsari, K. A., Jennerjahn, T. C., Lukas, M. C., Karius, V., & Behling, H. (2020). Intertwined Effects of Climate and Land Use Change on Environmental Dynamics and Carbon Accumulation in a Mangrove-Fringed Coastal Lagoon in Java, Indonesia. *Global Change Biology, 26,* 1414-1431. https://doi.org/10.1111/gcb.14926

Jardine, S. L., & Siikamäki, J. V. (2014). A Global Predictive Model of Carbon in Mangrove Soils. *Environmental Research Letters, 9,* Article 104013. https://doi.org/10.1088/1748-9326/9/10/104013

Jennerjahn, T. C. (2020). Relevance and Magnitude of Blue Carbon Storage in Mangrove Sediments: Carbon Accumulation Rates vs. Stocks, Sources vs. Sinks. *Estuarine, Costal and Shelf Science, 247,* Article 107027. https://doi.org/10.1016/j.ecss.2020.107027

Jevrejeva, S., Moore, J. C., & Grinsted, A. (2012). Sea Level Projections to AD2500 with a New Generation of Climate Change Scenarios. *Global and Planetary Change, 80-81,* 14-20. https://doi.org/10.1016/j.gloplacha.2011.09.006

Kathiresan, K., Gomathi, V., Anburaj, R., & Saravanakumar, K. (2014). Impact of Mangrove Vegetation on Seasonal Carbon Burial and Other Sediment Characteristics in the Vellar-Coleroon Estuary, India. *Journal of Forest Research, 25,* 787-794. https://doi.org/10.1007/s11676-014-0526-2

Kauffman, J. B., & Bhomia, R. K. (2017). Ecosystem Carbon Stocks of Mangroves across Broad Environmental Gradients in West-Central Africa: Global and Regional Comparisons. *PLOS ONE, 12,* e0187749. https://doi.org/10.1371/journal.pone.0187749

Kauffman, J. B., & Bhomia, R. K. (2020). *SWAMP Dataset-Mangrove Necromass-Gabon South-2014*. Center for International Forestry Research (CIFOR).

Kauffman, J. B., & Donato, D. (2012). *Protocols for the Measurement, Monitoring and Reporting of Structure, Biomass and Carbon Stocks in Mangrove Forests*. Center for International Forestry Research Center (CIFOR) Working Paper 86.

Kauffman, J. B., Adame, M. F., Arifanti, V. B., Schile-Beers, L. M., Bernardino, A. F., Bhomia, R. K. et al. (2020). Total Ecosystem Carbon Stocks of Mangroves across Broad Global Environmental and Physical Gradients. *Ecological Monographs, 90,* e01405. https://doi.org/10.1002/ecm.1405

Kauffman, J. B., Bernardino, A. F., Ferreira, T. O., Giovannoni, L. R., De Gomes, L. E. O., Romero, D. J. et al. (2018). Carbon Stocks of Mangroves and Salt Marshes of the Amazon Region, Brazil. *Biology Letters, 14,* Article 20180208. https://doi.org/10.1098/rsbl.2018.0208

Kauffman, J. B., Heider, C., Norfolk, J., & Payton, F. (2014). Carbon Stocks of Intact Mangroves and Carbon Emissions Arising from Their Conversion in the Dominican Republic. *Ecological Applications, 24,* 518-527. https://doi.org/10.1890/13-0640.1

Krauss, K. W., & Osland, M. J. (2020). Tropical Cyclones and the Organization of Man-

grove Forests: A Review. *Annals of Botany, 125,* 213-234.
https://doi.org/10.1093/aob/mcz161

Kulp, S. A., & Strauss, B. H. (2019). New Elevation Data Triple Estimates of Global Vulnerability to Sea-Level Rise and Coastal Flooding. *Nature Communications 10,* Article No. 4844. https://doi.org/10.1038/s41467-019-12808-z

Laffoley, D., & Grimsditch, G. (Eds.) (2009). *The Management of Natural Coastal Carbon Sinks*. IUCN, 53 p.

Lovelock C. E. (2008). Soil Respiration and Belowground Carbon Allocation in Mangrove Forests. *Ecosystems, 11,* 342-354. https://doi.org/10.1007/s10021-008-9125-4

Mabicka Obame, R. G., Musadji, N. Y., Ndongo, A., Soumaho, J., Mouha Edou, D. L., Abaker Madi, G. et al. (2021). Carbon and Nitrogen Stocks under Various Land Cover in Gabon. *Geoderma Regional, 25,* e00363.
https://doi.org/10.1016/j.geodrs.2021.e00363

Macreadie, P. I., Anton, A., Raven, J. A., Beaumont, N., Connolly, R. M., Friess, D. A. et al. (2019). The Future of Blue Carbon Science. *Nature Communications, 10,* Article No. 3998. https://doi.org/10.1038/s41467-019-11693-w

Malhi, Y., Doughty, C., & Galbraith, D. (2011). The Allocation of Ecosystem Net Primary Productivity in Tropical Forests. *Philosophical Transactions of the Royal Society B: Biological Sciences, 366,* 3225-3245. https://doi.org/10.1098/rstb.2011.0062

Murdiyarso, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., Donato, D. C. et al. (2015). The Potential of Indonesian Mangrove Forests for Global Climate Change Mitigation. *Nature Climate Change, 5,* 1089-1092.
https://doi.org/10.1038/nclimate2734

Nellemann, C., Corcoran, E., Duarte, C. M., Valdés, L., De Young, C., Fonseca, L., & Grimsditch, G. (Eds.) (2009). *Blue Carbon. A Rapid Response Assessment*. United Nations Environment Programme, GRID-Arendal. https://www.grida.no

Nwankwo, C., Tse, A. C., Nwankwoala, H. O., Giadom, F. D., & Acra, E. J. (2023). Below Ground Carbon Stock and Carbon Sequestration Potentials of Mangroves Sediments in Eastern Niger Delta, Nigeria: Implication for Climate Change. *Scientific African, 22,* e01898. https://doi.org/10.1016/j.sciaf.2023.e01898

Ouyang, X., & Lee, S. Y. (2020). Improved Estimates on Global Carbon Stock and Carbon Pools in Tidal Wetlands. *Nature Communications, 11,* Article No. 317.
https://doi.org/10.1038/s41467-019-14120-2

Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S. et al. (2012). Estimating Global "Blue Carbon" Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems. *PLOS ONE, 7,* e43542.
https://doi.org/10.1371/journal.pone.0043542

Rumpel, C., Amiraslani, F., Koutika, L.-S., Smith, P., Whitehead, D., & Wollenberg, E. (2018). Put More Carbon in Soils to Meet Paris Climate Pledges. *Nature, 564,* 32-34.
https://doi.org/10.1038/d41586-018-07587-4

Sahu, S. K., & Kathiresan, K. (2019). The Age and Species Composition of Mangroves Forest Directly Influence the Net Primary Productivity and Carbon Sequestration Potential. *Biocatalysis and Agricultural Biotechnology, 20,* Article 101235.
https://doi.org/10.1016/j.bcab.2019.101235

Saintilan, N., Khan, N. S., Kelleway, J. J., Rogers, K., Woodroffe, C. D., & Horton, B. P. (2020). Thresholds of Mangrove Survival under Rapid Sea Level Rise. *Science, 368,* 1118-1121. https://doi.org/10.1126/science.aba2656

Sanderman, J., Hengl, T., Fiske, G., Solvik, K., Adame, M., Benson, L. et al. (2018). A

Global Map of Mangrove Forest Soil Carbon at 30 M Spatial Resolution. *Environmental Research Letters, 13,* Article No. 055002. https://doi.org/10.1088/1748-9326/aabe1c

Sanders, C. J., Mather, D. T., Tait, D. R., Williams, D., Holloway, C., Sippo, J. Z., & Santos, I. R. (2016). Are Global Mangrove Carbon Stocks Driven By Rainfall? *Journal of Geophysical Research: Biogeosciences, 121,* 2600-2609. https://doi.org/10.1002/2016JG003510

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A. et al. (2011). Persistence of Soil Organic Matter as an Ecosystem Property. *Nature, 478,* 49-56. https://doi.org/10.1038/nature10386

Serrano, O., Kelleway, J. J., Lovelock, C., & Lavery, P. S. (2019). Chapter 28. Conservation of Blue Carbon Ecosystems for Climate Change Mitigation and Adaptation. In G. M. E. Perillo et al. (Eds.), *Coastal Wetlands* (2nd ed., pp. 965-996). Elsevier. https://doi.org/10.1016/B978-0-444-63893-9.00028-9

Siikamäki, J. Sanchirico, J. N., & Jardine, S. L. (2012). Global Economic Potential for Reducing Carbon Dioxide Emissions from Mangrove Loss. *Proceedings of the National Academy of Sciences of the United States of America, 109,* 14369-14374. https://doi.org/10.1073/pnas.1200519109

Sippo, J. Z., Lovelock, C. E., Santo, I. R., Sanders, C. J., & Maher, D. T. (2018). Mangrove Mortality in Changing Climate: An Overview. *Science, 215,* 241-249. https://doi.org/10.1016/j.ecss.2018.10.011

Trettin, C. C., Dai, Z., Tang, W., Lagomasino, D., Thomas, N., Lee, S. K. et al. (2021). Mangrove Carbon Stocks in Pongara National Park, Gabon. *Estuarine, Coastal and Shelf Science, 259,* Article 107432. https://doi.org/10.1016/j.ecss.2021.107432

Tue, N. T., Dung, L. V., Trong, N. M., & Omori, K. (2014). Carbon Storage of a Tropical Mangrove Forest in Mui Ca Mau National Park, Vietnam. *CATENA, 121,* 119-126. https://doi.org/10.1016/j.catena.2014.05.008

UNFCCC (United Nations Framework Convention on Climate Change) (2022). *Technical Report on the Technical Analysis of the Technical Annex to the First Biennial Update Report of Gabon Submitted in Accordance with Decision 14/CP.19, paragraph 7, on 29 December 2021*. United Nations.

Vecchi, G. A., Landsea, C., Zhang, W., Villarini, G., & Knutson, T. (2021). Changes in Atlantic Major Hurricane Frequency Since the Late-19th Century. *Nature Communications, 12,* Article No. 4054. https://doi.org/10.1038/s41467-021-24268-5

Xiong, Y., Liao, B., & Wang, F. (2018). Mangrove Vegetation Enhances Soil Carbon Storage Primarily Through in Situ Inputs Rather than Increasing Allochthonous Sediments. *Marine Pollution Bulletin, 138,* 378-385. https://doi.org/10.1016/j.marpolbul.2018.04.043

Yang, G., Chen, H., Wu, N., Tian, J., Peng, C., Zhu, Q., Zhu, D., He, Y., Zheng, Q., & Zhang, C. (2014). Effects of Soil Warming, Rainfall Reduction and Water Table Level on CH4 Emissions from the Zoige Peatland in China. *Soil Biology and Biochemistry, 78,* 83-89. https://doi.org/10.1016/j.soilbio.2014.07.013