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

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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.

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 eco-

systems. 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)

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

where SOC concentration is organic carbon concentration (%), h is the layer thickness (cm) and BD is the bulk density (g·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)

$$\text{CO}_2\text{e(MgCO}_2) = 3.67 \times \text{Total Carbon Stock} \tag{2}.$$

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·cm^{-3})		C/N		CO$_2$ Mg (eqCO$_2$e)		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)
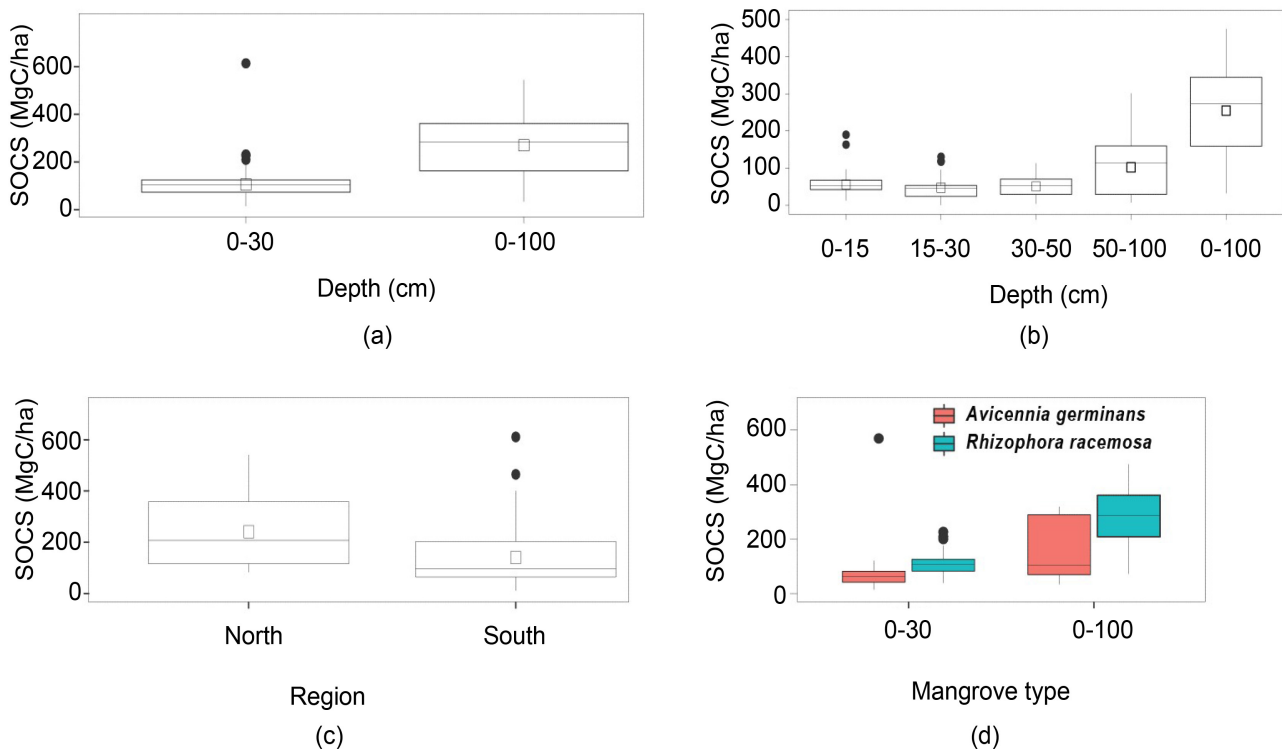
Figure 2. Mangrove soil organic carbon stocks. (a): Soil organic carbon stocks between 0 - 30 cm and 1 m depth; (b): soil organic carbon stocks distribution with depth; (c): comparison of soil organic carbon between northern and southern sites, (d): soil organic carbon among mangroves; and e: soil organic 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.,
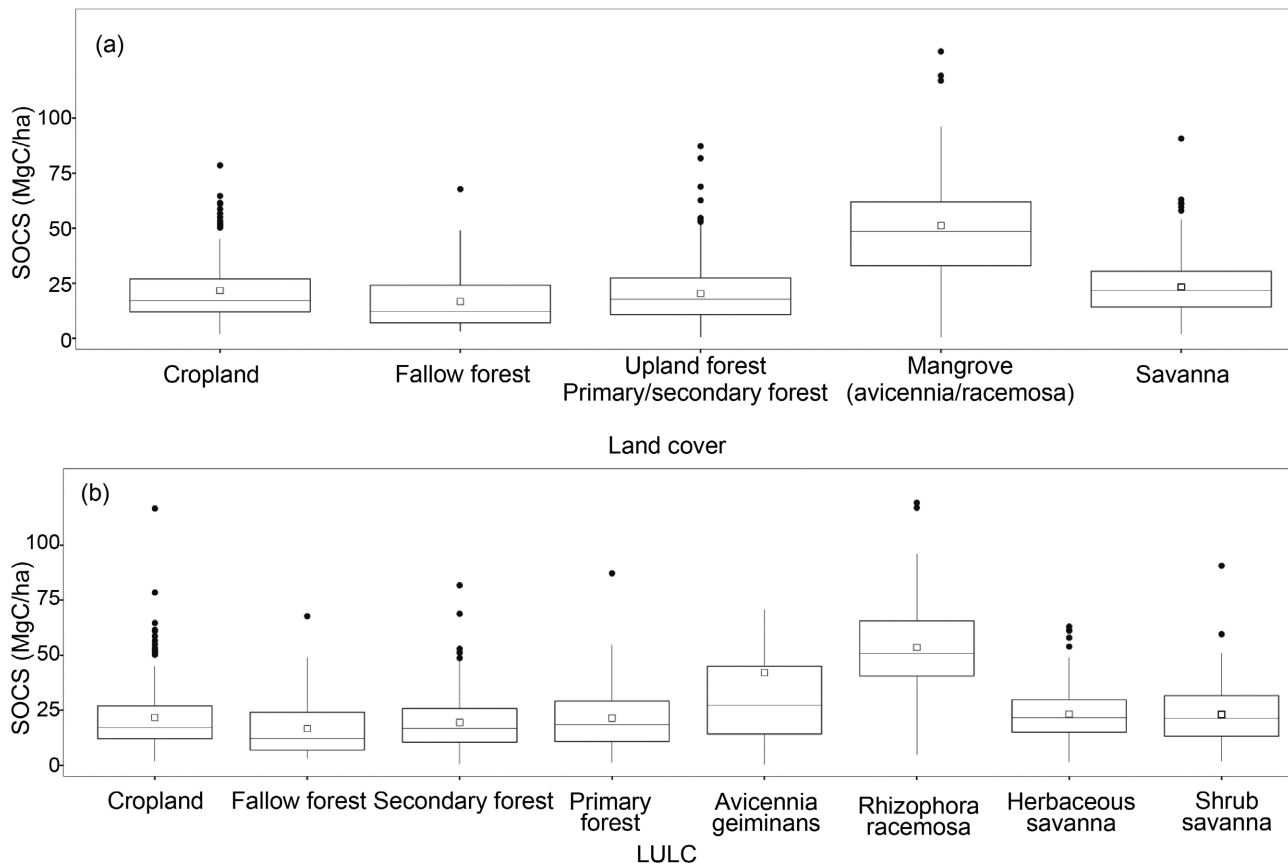
Figure 3. Comparison of soils organic carbon stocks between mangrove forest and upland forest in coastal of Gabon. (a): comparison between mangrove forest and others land cover/land uses; (b): comparison between mangrove forest type and upland land cover.

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 & Ka-

thiresan, 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$_2$e. Our findings have a highest CO$_2$e potential absorption than from mangroves forests in the tropics (411 Mg CO$_2$e, 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.

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