Oceanic Carbon in Seagrass Ecosystems in Freshwaters of Northern Brazil

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Research Article

Keywords: Seagrass ecosystem, Macapa River, Barra Grande lagoon, Oceanic carbon, Carbon stocks, Carbon financing regime

Posted Date: October 4th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2104804/v1

Abstract

Seagrass ecosystems can sequester and retain considerable amount of oceanic carbon. However, few studies and limited data constrain seagrass carbon stocks on regional and global scales, especially in underreported seagrass region of South America. This study measured and predicted carbon stocks in seagrass beds of the Macapa River and the Barra Grande lagoon, northern Brazil. Aboveground and belowground biomass components were sampled from *Halodule wrightii* seagrass beds of the Macapa River only, while sediment cores were sampled at 50cm depth in the *Halodule wrightii* seagrass beds of the Macapa River. In Barra Grande lagoon, three sediment cores were sampled at 8-30cm depth in *Halodule wrightii* and mixed stands of *Halodule* sp. seagrass beds. The carbon (C) stocks of the seagrass aboveground and belowground biomass of *Halodule wrightii* seagrass beds of the Macapa River were 0.005MgC/ha^{-1} and 0.018MgC/ha^{-1} respectively. The C stock of sediment from seagrass beds in Macapa River averaged 41.8MgC/ha^{-1}, while the C stock of sediment from seagrass beds of Barra Grande lagoon averaged 12.3MgC/ha^{-1}, These findings add to the limited global database on seagrass carbon stocks to support optimization of carbon capture and storage through sustainable global carbon financing regime for vegetated marine ecosystems. The results also contributes to realizing SDG 13 indicator 13.2.2 on reducing the total annual greenhouse gas (GHG) emissions, SDG 14.2 target, namely, “By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans.”

Introduction

Recent studies have shown the capacity of marine ecosystems to capture and bury carbon in their systems. This finding has implications for the management of climate change (Laffoley and Grimsditch, 2009; Lovelock and McAllister, 2013; Maldonad and Zárate Barrera, 2014) and has created new research and ecosystem management opportunity that emphasize the accumulation of considerable quantity of “blue carbon” in marine/coastal ecosystems compared to the dominantly reported quantity of “green carbon” sequestered and buried in terrestrial ecosystems such as grasslands and forests (Agrawal et al., 2011). Essentially, the considerable carbon pool reported in blue systems (mangroves, seagrass and wetlands) has resulted to the need to maintain a system of measurement and reporting of the contribution of marine/coastal ecosystems to carbon capture and storage. Globally, among the three marine/coastal ecosystems, seagrass has remained the least reported, despite being characterized by high species diversity, distribution and primary production values. Seagrass is an angiosperm (flowering plants) growing predominantly in the shallow waters of marine and coastal ecosystems of temperate, sub-tropical and tropical environments. It is a member of the division, Angiospermae, which is sub-divided into three families, namely, Posidoniaceae, Zosteraceae and Hydrocharitaceae or Cymodoceaceae. It grows mainly in the mid to low-tidal zone of seaward area of the shoreline characterised by soft sediments (Beer & Koch 1996) and at a shallow, maximum depth of 50m in marine and estuarine environments, due to decrease in light penetration with depth. Seagrass also colonises soft habitats such as sand or mud, but some species could grow on more rocky substrates e.g. *Phyllospadix* spp. Seagrass species form wide-range of single species stands or zones of diverse species known as seagrass beds or meadows, which create a self-sustaining marine ecosystem or biotope.

Globally, seagrass beds are estimated to bury 27.4 TgCyr-^{1}, amounting to roughly 10% of annual C stock in the oceans (Duarte et al., 2005; Fourqurean et al., 2012). Kennedy et al. (2010) and Duarte et al. (2005b) also observed that seagrass beds contribute to 20% of the overall carbon sink in marine sediments, which can be retained for ages (Mateo et al., 1997, 2006; Orem et al., 1999; Pedersen et al., 2011; Macreadie et al., 2012; Serrano et al., 2012) by preventing remineralisation of carbon. Duarte et al. (2010) reported that the net biological process of conversion

resulting in carbon sequestration by seagrass population yields 9.9 ± 2.22molCm^{-2}yr^{-2}, amounting to above 5 times the carbon burial capacity of North American wetlands. Smith (1981) and Duarte et al. (2005a) demonstrated that the total C buried by seagrass beds may be better estimated by their cumulative net primary productivity and seagrass-derived carbon retained in the sediments, amounting to carbon accumulation rate of 160–186 gCm^{-2} yr^{-1}, while Fourqurean et al. (2012) estimated C accumulation in the seagrass beds of the world to be as much as 19.9 Pg C yr^{-1}, recognizing seagrass beds as global carbon pool. Also the carbon retained by the 10 percent seagrass beds maintaining the largest carbon storage ability is more than the rates of carbon retention in pristine Amazon forests presumed to be the biggest terrestrial carbon store (Duarte et al. 2010). According to Fourqurean et al. (2012), results from 3,640 observations of 946 different seagrass beds across the globe, covering east and west coasts of Australia, the Caribbean, and Mediterranean Sea showed that seagrass beds store 90% of their carbon in the soil which accumulates for ages. He stated, "We found places where seagrass beds have been storing carbon for thousands of years. Seagrass beds can store up to 83,000 metric tons of carbon per square kilometre, mostly in the soils below them. They rival the carbon storage capacity in the extensive peat deposits of mangroves." Effectively, the persistent accumulation of sediment in marine environment over a long time reduces or largely eliminates the oxygen content, resulting in an anoxic condition due to high organic matter content (Kennedy et al. 2010). The sediment high organic matter contains organic carbon pool which accumulates more than a decade to even a millennium in temporal and spatial scales, such that the physical and chemical changes which affect the organic carbon cannot eliminate the consideration of seagrass beds as a carbon sink (Mateo et al. 1997; Orem et al. 1999; McKee et al. 2007). For instance, in Port Lligat, Spain, *P. oceanica* beds have recorded the densest sedimentary carbon pool of 11 m thickness, equivalent to an accumulation of about 0.18 tons C m^2 over 6,000 years. Therefore, the rapid rate of accumulation, inadequate oxygen, low sediment hydraulic conductivity, and slower microbial disintegration rates enhance carbon burial and the accretion of carbon stocks in these coastal sediments (Mateo et al. 2006; Duarte et al. 2010; Duarte et al. 2011). It was further suggested that the high capacity of seagrass beds to sink carbon in the sediment (over a long time scale is a function of high primary production and filtration of particles from the water column displayed by seagrass (Kennedy et al., 2010; Duarte et al., 2011; Hendricks et al., 2007). Other contributing factors include prolonged, slow decay of fallen leaves, rhizome and no fire-induced loss of carbon in the seabed (Mateo et al., 1997; Duarte et al., 2011; Boudouresque et al., 2012). The capacity of seagrass beds to store/bury 10% of annual oceanic C for as long as millennia can be considered as a substantial contribution to climate change mitigation, hence the rationale behind promoting research towards achieving a global carbon financing programme for the conservation and restoration of seagrass ecosystems. As a result, the “blue carbon” sink presents an opportunity for the optimization of carbon pool in seagrass ecosystems through marine/coastal ecosystems management initiatives aimed at mitigating climate change impacts of GHG emissions (Duarte et al. 2005; Bouillon et al. 2008; Lo Iacono et al. 2008; Duarte et al. 2010; Kennedy et al. 2010; Donato et al. 2011; Fourqurean et al. 2012a; Pendleton et al. 2012; Lavery et al., 2013).

This study is the first definitive step to measure and predict carbon stock in the seagrass beds of Brazil, South America in order to fill in the existing gap on seagrass carbon (C) stock in the region. The C stock measurement contributes to expanding the limited global data set of C stock in seagrass beds on the local, regional and global scales. While the available data on seagrass carbon stocks is spatially restricted to only a few geographical regions, data from many locations are still lacking or poorly represented. Most of the regional estimates are dominated by data from seagrass beds of Australia, Mediterranean, Western Europe (North Atlantic) and eastern Indian Ocean (Orem et al., 1999; Duarte et al., 2013; Serrano et al., 2014), with carbon accumulation in *Posidonia oceanica* beds of the Mediterranean Sea being the reported dominant species globally. Among the reported seagrass regions, South America and Africa have been grossly under-represented due to inadequate research and scarcity and/or lack of

data on seagrass area cover and Carbon capture and storage (CCS) capacity. These limitations have contributed to marine/coastal ecosystem management drawbacks on the efforts of the International Blue Carbon Scientific Working Group of the United Nations Framework Convention on Climate Change (UNFCCC) to certify standardised procedures and protocols for measuring and predicting the global carbon stock in seagrass beds (Herr et al., 2012; Macreadie et al., 2013). As a result, carbon stock in seagrass beds has been scarcely measured on a large scale. In aligning the findings of this study in the context of global data on C storage in seagrass beds, some definitive and predictive ecological approximations were applied with respect to the contributing or influencing factors that drive the variations among the parameters analysed. This is because site-specific ecological or environmental predictors that contribute to C stock in seagrass beds were not measured in the studied sites. The objectives of this study are to i) measure carbon stock in seagrass aboveground and belowground biomass, ii) measure the carbon stock buried in seagrass sediment in the seagrass beds of Macapa River and Barra Grande lagoon, northern Brazil, iii) compare carbon stock of the seagrass beds of Macapa River and Barra Grande lagoon, northern Brazil with the stocks found in other regions and the possible influencing factors.

Materials And Methods

Study sites

Macapa River

Macapa River **(fig a)**, located in Amapa State, northern Brazil (0° 2' 8.0664" N 51° 4' 13.9224" W) is associated with an estuarine system, dense intertidal flat and dense seagrass beds dominated by *Halodule wrighti* (**fig b**), associated with macroalgae and epiphytes, at shallow depth of 3–5 m and surrounded by mangroves. The dense intertidal seagrass beds run parallel to the mangrove fringe. The sediment particles is mainly muddy with mixed mud and sand (mixed sand) (Corpetino, personal observation), which is ecologically favourable to the growth of *Halodule wrightii* (Zieman, 1982; Green and Short, 2003). Biomass samples were collected from seagrass bed in this location from 16th to 17th of January, 2014, while sediment samples were collected on 17th of January, 2014 during low tide corresponding to the time of bed exposure twice a day.

Barra Grande Lagoon

Barra Grande lagoon is a marine habitat located in Cajueiro da Praia, Piaui State of northern Brazil (02º55'40" S, 41º20'10"W) (**fig c**). The sampled site is an extensive intertidal flat with shallow water at low tide. It is characterized by mainly muddy and calcareous sediment, with a few sandy particles (Corpetino, personal observation). The seagrass species sampled in this site are monospecies stands of *Halodule wrightii* Ascherson and mixed meadows of *Halodule* sp. (**fig d**) associated with macroalgae, *Hypnea, Acetabularia* and *Padina*. The seagrass beds were located in sheltered reefs and beach. The sampled plots extended from the shallowest to the deepest, up to the drainage channel.

Sampling Techniques

In Macapa River, seagrass beds dominantly populated by *Halodule wrightii* species were sampled, while in Barra Grande lagoon, monospecies stands of *Halodule wrightii* Ascherson and mixed meadows of *Halodule* spp. were sampled using stratified random sampling method. Each sampling site was distinctly divided into sampling fields

(different design per site depending on species distribution) and plots (sampling points) to potentially achieve high level of accuracy and reliability in the carbon stock assessment (Kauffman and Cole, 2010; Kauffman and Donado, 2011). This method also ensures that samples representing the ecological diversities of the two sampled sites were collected to enhance accuracy in carbon accounting (USDA, 2008; Donato et. al, 2011). Samples were collected from the two sites between January 14 and March 14, 2014. The seagrass beds were mapped to determine percentage cover and canopy heights of each species. The sampled plots were randomly selected and demarcated approximately 50m from each other. Seagrass biomass samples were collected from Macapa River only. Sixteen pairs of samples of aboveground and belowground biomass were collected from *Halodule wrightii* seagrass beds of the Macapa River using 50 cm by 50 cm quadrat randomly placed few metres apart from each other. The sediment samples were collected below the seagrass beds within the quadrat limit. Sediment samples were cored in the Macapa River and Barra Grande lagoon. In the *Halodule wrightii* seagrass beds of the Macapa River, sediment samples were collected from three plots (A, B and C) at 50cm (0.5m) length downcore, and sectioned into 5cm sub-samples across the core length. In the Barra Grande lagoon, one sediment core each was sampled from three plots (A, B and C) in seagrass beds dominated by *Halodule wrightii* and mixed stands of *Halodule* sp. The cores were sampled from upper, middle and lower limits of the beds until the maximum penetrable depth. The length of sediment cores varied between 8cm and 30cm downcore. Each core was sectioned into 2cm sub-samples across the core length.

Laboratory Analyses

Estimation of Biomass Carbon stocks

The dry seagrass aboveground and belowground biomass samples were homogenised in a ball mill (Fritsch Pulverisette). A small portion of each homogenized sample was weighed out in silver pans. The samples were acidified with aliquots of 50 µL of 1 M HCl to remove inorganic matter (calcium carbonate, shells and other materials) and dried in a drying oven at a temperature of 50^0C for 24 hours. Acidification and drying were repeated until effervescence effect on samples stopped. The acidified dry biomass samples were placed in a CN analyser to go through the process of combustion in the induction furnace at a high temperature of 1000^0C (Carlo Erba CN analyser, NA1500) to analyze for organic carbon (Fourqurean et al., 2012a). The CN Analyser was calibrated using Acetanilide. In addition, an internal standard protocol was carried out by randomly repeating the analysis of few samples to determine the degree of consistency and reliability of the results. NIST 1515, an international standard was used to test for consistency and accuracy of the analysis in line with the globally accepted procedure. The biomass C stocks were subsequently calculated from the $OC_{measured}$ values, while the dry weight (gDW/m^{-2}) values of the remaining unanalyzed biomass samples were converted to carbon equivalent rating assumed as 35% of dry weight (Fourqurean et al., 2012a) to estimate their C_{org} stocks based on a 1 hectare unit area.

Seagrass Sediment C Stocks

Dry bulk Density (DBD)

DBD is a measure of volumetric content of organic matter in a given volume of sediment. It is inherently determined by the rate of accumulation of organic matter and sediment particle characteristics (Dadey et al., 1991). The sediment sub-samples were dried at 50^0C until constant dry weight was reached. This procedure prevents the loss

of organic matter and oxidation that could result in loss and underestimation of organic carbon from the samples. Sediment Bulk density tends to increase with depth as a result of compaction, which is also a contributing factor to organic matter content.

Using Loss on ignition (LOI) to measure and predict C stock in seagrass sediment

LOI is the method used to measure the amount of organic matter comprising carbon, hydrogen, nitrogen, oxygen, sulphur etc. lost through oxidation reaction that occurs when sediment sample is combusted at high temperature in a muffle furnace (Parker, 1983; Fabiano et al., 1995). According to Dean (1974), Bengtsson and Enell (1986) and Heiri et al. (2001), LOI is a valid method to measure and predict organic matter and carbon storage in marine or terrestrial sediments involving studies on biological, geological and chemical processes that characterise or drive changes in the coastal waters. Fourqurean et al. (2012a) observed a significant relationship between LOI and OC (organic carbon), confirming that LOI could be used to estimate OC in seagrass sediment. This relationship works on the principle that LOI could be used to predict C stock of seagrass sediment where it is not possible to use CN analysis to determine OC (**fig e**). For the reported global data set from 1,748 samples analysed for LOI to determine the seagrass sediment OC, the relationship equation is y = 0.43x%-0.33 for LOI range of 0–100% and y = 0.40x%-0.21for LOI range of 0–20%, where y = OC and x = LOI (Fig. 3). The sediment samples were homogenized in a ball mill (Fritsch Pulverisette). Before determining the LOI on all the sediment samples, seven replicates of approximately 10 g each of two sub-samples from Macapa River were combusted in the muffle furnace at 450^0C for 8 hours until constant weight was reached in order to remove organic matter (Campbell et al., 2014). They were subsequently analyzed for LOI to test the range of reproducibility and comparability of the values. The mean ± SE for Macapa River replicates was 3.71 ± 0.05, indicating low error values. Similar procedure was used to determine the appropriate sample weight for LOI% of sediment sub-samples from Barra Grande lagoon due to limited quantities of subsamples. Approximately 10gDW and 5gDW replicate samples from one subsample were used to determine the reliability of the two replicates to produce similar range of variation or accuracy in LOI% values (for 10gDW, mean ± SE = 0.96 ± 0.03 while 5gDW, mean ± SE = 0.94 ± 0.02). There was no significant difference between the two weights (ANOVA: p = 0.806; df = 5). Loss on ignition (LOI) was subsequently calculated for all the sub-samples using the formula, $\mathbf{LOI\%DryWeight\ (DW)} = \frac{100(\mathbf{initialdryweight - postcombustionweight})}{\mathbf{initialdryweight}}$ according to (Fourqurean et al. 2012a). The $OC_{measured}$ (%DW) from randomly selected seagrass sediment cores from each sampled site was used to determine $OC_{predicted}$ in other cores where OC was not measured to test the confidence level of the linear relationship between LOI and OC as reported by Fourqurean et al. (2012a). This procedure was premised on the conclusion that if the global profile of LOI and OC relationship developed by Fourqurean et al. (2012a) was accurate in predicting OC in sediments of seagrass beds, then the relationship between $OC_{measured}$ and $OC_{predicted}$ will be accurate in measuring and predicting sediment C stock. Figure e Global LOI and OC relationship according to Fourqurean et al. (2012a), where y = 0.43x%-0.33 for LOI range of 0–100% and y = 0.40x-0.21for LOI range of 0–20%, where y = OC and x = LOI

Using Carbon Density To Determine Total Seagrass Sediment C Stock

The sediment C density (g/cm^3) is a measure of the carbon weight (g) of each depth interval (cm) of a sediment core, calculated as DBD (g/cm^3) multiplied by percentage OC (g C/g sediment) of each depth interval e.g. (5cm for the sediment core sampled from Seagrass beds of the Macapa River and 2cm for sediment core sampled from Seagrass beds of the Barra Grande lagoon) in a core divided by 100 (Macreadie et al., 2013).

The C stock of each core section (gC/g sediment) was calculated as Sediment C density (g/cm^3) multiplied by core thickness interval (cm). The C stock in each core was determined by summing the C in each core section or sub-sample (gC/cm^2) of each core interval (cm) up to the entire core length/depth. Using extrapolation method by Fourqurean et al. (2012a), the C stock was then scaled down to 100cm depth (1m), assuming that the stock reported over the measured depth of the core was representative of the unmeasured material down to 1m (100cm) depth. The application of 1m depth was considered based on the assumption that top layer of sediment is usually most affected by remineralisation resulting from seagrass loss (Fourqurean et al, 2012a) expressed in gC/cm^2. This was further converted to MgC/cm^2 by dividing the total gC/cm^2 at 100cm depth with 1,000,000g (1Mg = 1,000,000g). To convert the calculated total gC/cm^2 at 100cm core depth to Mg/hectare, the number (i.e. total gC/cm^2 at 100cm depth) was multiplied by 100,000,000cm^2 (1hectare = 100,000,000cm^2).

Results And Discussion

Biomass C stock calculation

The $OC_{measured}$ (gC/m^{-2}) of aboveground biomass of *Halodule wrightii* seagrass beds of Macapa River was 0.52gC/m^{-2}, while the $OC_{measured}$ (gC/m^{-2}) of the seagrass belowground biomass samples was 1.83gC/m^{-2}. Assuming the Carbon equivalent value of 35% of dry weight, the total $OC_{predicted}$ (gC/m^{-2}) of aboveground biomass of *Halodule wrightii* seagrass beds of the Macapa River was 1.23gC/m^{-2}, while the total $OC_{predicted}$ (gC/m^{-2}) of the seagrass belowground biomass samples was 2.56gC/m^{-2}. In summary, the predicted C stock (MgC/ha^{-1}) of aboveground biomass of *Halodule wrightii* seagrass beds of the Macapa River was 0.012MgC/ha^{-1}, while the predicted C stock (MgC/ha^{-1}) for belowground biomass was 0.026MgC/ha^{-1}. The measured C stock (MgC/ha^{-1}) of aboveground biomass of *Halodule wrightii* seagrass beds of the Macapa River was 0.005MgC/ha^{-1}, while the measured C stock (MgC/ha^{-1}) of the seagrass belowground biomass of seagrass beds of the Macapa River was 0.018MgC/ha^{-1} (see Table 1).

Dry Bulk Density (Dbd)

The DBD of the sediment samples collected from the seagrass beds of the Macapa River ranged from 0.51g dry weight/cm^{-3} to 1.54 g dry weight/cm^{-3} (Mean: 1.03 ± 0.05 g dry weight/cm^{-3}; STD: 0.29 g dry weight/cm^{-3}; Median: 1.06gdry weight/cm^{-3}), while the DBD of the sediment collected from the seagrass beds of the Barra Grande lagoon ranged from 0.19 g dry weight/cm^{-3} to 0.72 g dry weight/cm^{-3} (Mean: 0.49 ± 0.03 g dry weight/cm^{-3}; STD: 0.15 g dry weight/cm^{-3}; Median: g dry weight/cm^{-3}). Comparatively, the DBD range of sediment of seagrass beds of the Macapa River and Barra Grande lagoon was generally within the global DBD range of 0.06-2.35g DW/ cm^{-3}. In the sediment cores of the Macapa River seagrass beds, there was increase in DBD with depth at shallow core followed by inconsistent pattern downcore. In contrast, in the sediments of the Barra Grande lagoon seagrass beds, there was decrease in DBD with depth at shallow core, followed by inconsistent pattern downcore (Figures f1 and f2).

Loss On Ignition (Loi)

The LOI of the sediment samples collected from the seagrass beds of the Macapa River ranged from 1.29wt% to 7.28wt% (Mean: 3.76 ± 0.29wt%; STD: 1.56wt%; Median: 3.70wt%). The LOI of the sediment samples collected from

the seagrass beds of the Barra Grande lagoon ranged from 2.30wt% to 5.70wt% (Mean: 3.61 ± 0.13wt%; STD: 0.73wt%; Median: 3.56wt%). The LOI values of sediments of seagrass beds of the Macapa River and the Barra Grande lagoon were abysmally low compared to the global LOI range of 0.0-100.0wt% compiled by Fourqurean et al. (2012) from studies conducted at 2,783 seagrass beds at different locations.

Sediment Carbon Stock Calculation

The $OC_{predicted}$ stock for the top 1 metre of *Halodule wrightii* seagrass sediment of the Macapa River using global LOI (%DW) and OC (%DW) relationship for the three sampled sediment cores (A, B and C) averaged **118.8MgC/ha^{-1}** (Mean:118.8 ± 3.60MgC/ha^{-1}, STD:19.4MgC/ha^{-1} and Median:127.4MgC/ha^{-1}). The $OC_{predicted}$ stock for the top 1 metre of seagrass sediment of the Macapa River using LOI (%DW) for the three sampled sediment cores averaged **58.8MgC/ha^{-1}** (Mean:58.8 ± 1.31MgC/ha^{-1}, STD:7.07MgC/ha^{-1} and Median:62.3MgC/ha^{-1}). Compared to the $OC_{predicted}$ stock using global relationship between OC (%DW) and LOI (%DW), as well as the $OC_{predicted}$ from LOI (%DW), the $OC_{measured}$ stock for the top 1 metre of seagrass sediment of the Macapa River for the three sampled sediment cores averaged **41.8MgC/ha^{-1}** (Mean:41.8 ± 6.73MgC/ha^{-1}, STD: 36.2MgC/ha^{-1} and Median: 62.0MgC/ha^{-1}) (Table 2). The $OC_{predicted}$ stock for the top 1 metre of *Halodule wrightii* and mixed stand of *Halodule* sp. seagrass sediment of the Barra Grande lagoon using global LOI (%DW) and OC (%DW) relationship for the three sampled sediment cores (A, B and C) averaged **60.7MgC/ha^{-1}** (Mean:60.7 ± 1.12MgC/ha^{-1}, STD:6.32MgC/ha^{-1} and Median:64.3MgC/ha^{-1}). The $OC_{predicted}$ stock for the top 1 metre of seagrass sediment of the Barra Grande lagoon using LOI (%DW) for the three sampled sediment cores averaged **17.4MgC/ha^{-1}** (Mean: 17.4 ± 0.31MgC/ha^{-1}, STD: 1.78MgC/ha^{-1} and Median: 18.0MgC/ha^{-1}). Compared to the $OC_{predicted}$ stock using global relationship between OC (%DW) and LOI (%DW), as well as global relationship using LOI (%DW), the $OC_{measured}$ stock for the top 1 metre of seagrass sediment of the Barra Grande lagoon for the three sediment cores averaged **12.3MgC/ha^{-1}** (Mean:12.3 ± 4.81MgC/ha^{-1}, STD: 27.2MgC/ha^{-1} and Median: 14.8MgC/ha^{-1}) (Table 1).

Table 1
Summary of $OC_{measured}$ and $OC_{predicted}$ used to determine C stock of sediment samples collected from the seagrass beds of the Macapa River and Barra Grande lagon, northern Brazil. C stock for each core was upscaled to top 1m (100cm) core depth to integrate shallow and deep cores

Sampled site	Seagrass species	Mean seagrass cover (%)	Cores	Core depth (cm)	Sub-samples per core (sediment section)	OC stock in top 1 metre core (MgC/ha^{-1})		
						$OC_{predicted}1$	$OC_{predicted}2$	$OC_{measured}$
Macapa River 51° 4' 13.9224" W(long.), 0° 2' 8.0664" N (lat.)	*Halodule wrightii*	62.8%	A	50	10	127.4	62.3	62.0
			B	50	9	96.6	50.7	NM
			C	50	10	132.4	63.5	63.5
Total C Stock						**356.4**	**177.5**	**125.5**
Mean						**118.8**	**58.8**	**41.8**
STD						**19.4**	**7.07**	**36.2**
SEM						**3.60**	**1.31**	**6.73**
Median						**127.4**	**62.3**	**62.0**
Barra Grande lagoon 41°20'10"W (long.), 02°55'40" N (lat.)	*Halodule wrightii* and mixed stands of *Halodule* sp.	41.3%	A	30	15	53.4	15.4	14.8
			B	26	13	64.3	18.8	22.1
			C	8	4	64.4	18.0	NM
Total C Stock						**182.1**	**52.2**	**36.9**
Mean						**60.7**	**17.4**	**12.3**
STD						**6.32**	**1.78**	**27.2**
SEM						**1.12**	**0.31**	**4.81**
Median						**64.3**	**18.0**	**14.8**

Explanatory note: $OC_{predicted}1$: $OC_{predicted}$ from LOI using regression equation for the LOI and OC relationship (y = 0.40x-0.21 for LOI < 20%, where y = OC and x = LOI %) according to Fourqurean et al., (2012) **(OC = 0.4*LOI-0.21). $OC_{predicted}2$**: $OC_{predicted}$ using regression equation from the core-specific LOI to predict OC in the cores where only LOI was measured. **NM**: Not measured

This study measured and predicted C stock in the seagrass beds of the most widely distributed and dominant seagrass species in selected freshwaters of northern Brazil, including *Halodule wrightii* (and mixed stands of *Halodule* sp.). It aims to support the evolving global accounting and standardisation procedures for quantifying carbon capture and burial in seagrass beds [27, 46] in order to achieve a sustainable carbon credit regime for seagrass ecosystem conservation and restoration. The results presented here demonstrate an expansion of the

limited global data set on assessing the C stock of seagrass ecosystem and confirms earlier findings from global scientific domain that seagrass is one of the largest oceanic carbon (blue carbon) pools in the biosphere [17, 18, 16, 26].

Compared to the global ranges of aboveground biomass C stock of 0.001–5.548 MgC/ha^{-1} and belowground biomass C stock of 0.001–17.84 MgC/ha^{-1} from global data set extrapolated from uneven geographically distributed studies of 251 seagrass sites worldwide [7], the total biomass C stock of 0.023 MgC/ha^{-1} of the Macapa River seagrass beds was significantly low, with aboveground biomass C stock having the lowest value of 0.005 MgC/ha^{-1}. Also, the belowground biomass C stock of 0.018MgC/ha^{-1} was significantly low compared to the global belowground biomass C stock. The total biomass C stock of the Macapa River seagrass beds was also significantly low compared to the seagrass biomass C stock range of 0-13MgCO_2eha^{-1} reported by Sifleet et al., [47] from limited studies conducted in 160 seagrass sites. Reports compiled from other locations evidenced that seasonal variability in *Halodule wrightii* biomass peaks in late summer and declines in late winter [48, 49, 50, 51, 52]. Dunton [50, 51] and Oliveira et al. [53] reported evidences of seasonal variation in plant characteristics in *Halodule wrightii.* Primarily, the removal of the associated macroalgae and epiphytes during aboveground samples processing could contribute to low aboveground C stock, as the elimination of associated plant species could lead to loss from the C sinks in their living systems. The reported low C stock of aboveground seagrass biomass of *Halodule wrightii* beds of the Macapa River compared to the C stock of belowground seagrass biomass could be attributable to anthropogenic impacts of artisanal fishing and aquaculture activities around the sampled seagrass beds, which could result in significant loss and damage to the species. Birch and Birch [54] and Reusch et al. [55] identified climate change and damaging fisheries practices as contributors to seagrass loss and damage. Also it was observed that the dense intertidal seagrass beds of the Macapa River were used as soccer field (Corpetino, personal observation), which could exacerbate the degree of species loss and damage. Such loss and damage can cause degradation of seagrass beds with consequent decrease in seagrass biomass. The loss and damage can also lead to release of C into the water column and subsequently into the atmosphere [47], thereby converting the seagrass beds from C sinks to C sources, consequently escalating the extreme climate conditions [56] and [16]. Creed and Amado Filho [57] reported a similar case of anthropogenic impacts due to rapid increase in recreational boating on the *Halodule wrightii* beds in the Abrolhos Marine National Park, Brazil, which led to huge damage and loss of species through anchorage, estimated at 105m^2 in 1993, 125 m^2 in 1994 and 154 m^2 in 1995. High rate of human activities, conversion or damage of coastal ecosystems for other uses e.g. agriculture, aquaculture and burning of compost for fuel [58], can disrupt the carbon capture by seagrass beds and may change the beds from being net carbon sinks to net sources of carbon [59, 60]. According to Fourqurean et al. [26], continuous seagrass loss could lead to the discharge of 299 Tg C into the atmosphere annually, which amounts to 10% of all CO_2 emissions credited to human-induced changes in land use.

In contrast to the low total C stock of aboveground seagrass biomass of the *Halodule wrightii* beds of the Macapa River, the slightly high total C stock of belowground biomass of the *Halodule wrightii* seagrass beds is attributed to the combined contributions of the associated macroalgae and epiphytes to the carbon pool in the seagrass belowground functional system (roots and rhizomes). In addition, the nearness of mangrove ecosystem to the Macapa River seagrass beds may have contributed to the transfer of Carbon dioxide to the seagrass belowground system. Further, the associated macroalgae and epiphytes, as well as the proximity of mangrove ecosystem to the Macapa River seagrass beds may have contributed to the increase in primary productivity in the aboveground and belowground biomass, leading to increase in carbon production especially in belowground biomass [61, 62]. In the Redfish Bay, Texas, USA, Pulich [48] reported that *Halodule wrightii* had 66% of its total biomass belowground which

may account for the slightly high belowground biomass observed in *Halodule wrightii* bed of the Macapa River. This finding is consistent with the positive correlation between high carbon production and primary productivity of the seagrass biomass reported by Walker [61], Hillman and McComb, [62], which may have accounted for the slightly high C stock of belowground seagrass biomass of the *Halodule wrightii* beds.

Although the DBD of sediments from seagrass beds of Macapa River and Barra Grande lagoon was generally within the global DBD range of 0.06-2.35g DW/ cm^{-3}, the DBD of sediments of seagrass beds of the Macapa River was higher than that of seagrass beds of the Barra Grande lagoon. Reports from data extracted from Gonneea et al. [63] indicated that in similar sediments of *Halodule wrightii* beds, as well as *Halodule wrightii* and *Ruppia maritima* seagrass beds of Chelem lagoon, Yucatan, Mexico (DBD range: 0.30–0.64 gDW/cm^3) and Celestun lagoon, Yucatan, Mexico (DBD range: 0.28–0.58 gDW/cm^3) respectively, the DBD range of sediments of the seagrass beds of the Macapa River and Barra Grande lagoon was also higher. However, the DBD range of sediments from seagrass beds of Macapa River and Barra Grande lagoon is slightly consistent with the DBD range reported in other sub-tropical seagrass regions such as the Shark Bay, Western Australia (DBD range: 0.29–1.55 gDW/cm^3) and Florida Bay, USA, (DBD range: 0.24–1.63 gDW/cm^3. The high DBD values in sediments of seagrass beds of the Macapa River (0.51–1.54 gDW/cm^3) could be influenced by the slightly high organic matter (OC) content, which is usually associated with sediment particles characterized by mud, as well as mixed mud and sand (mixed sand) (Corpetino, personal observation). This observation is consistent with the effects of sediment particle composition on sediment density (DBD) and further corroborated by Kennedy et al. [8], who reported that silty and muddy sediments are rich in organic matter, which also contributes to high DBD. In addition, the influence of buried mangrove peats, which is also rich in organic matter, due to the proximity of the seagrass beds to mangrove ecosystem, may have contributed to high DBD values. In contrast, the low DBD values in seagrass beds of the Barra Grande lagoon (0.19–0.72 gDW/cm^3) resulted from low organic matter contents in sand-sized sediments and other associated inorganic/calcareous materials (e.g. molluscs shells) characteristic of the sampled habitat. According to Dadey et al., [38], sediment DBD is influenced by the rate of accumulation of organic matter and sediment particle characteristics.

Generally, patterns of DBD with depth across all the sediment cores of the Macapa River and Barra Grande lagoon seagrass beds were inconsistent (Figs. 3a and 3b). However, in the sediments of the Macapa River seagrass beds, there was increase in DBD with depth at the top to almost midcore followed by inconsistent pattern deepcore (Fig. 3a). In contrast, in the sediments of the Barra Grande lagoon seagrass beds, there was decrease in DBD with depth at the top to almost midcore, followed by inconsistent pattern deepcore (Fig. 3b). High organic matter sediments appeared more exposed to inconsistencies in DBD with depth than sediments characterized by low organic matter content. Core compression effect contributes to increase in DBD with depth and inconsistent depth profile deepcore. Morton and White [64] reported that core compaction results in shortening of core length by 30%, thereby limiting the possibility of general or uniform pattern of DBD with depth. Integrating the findings of Morton and White [64], Berner [65] reported that the scale of core compaction is mainly influenced by sediment deposition rate, weight of overlying soils, chemical composition and size of the sediment particle. The decrease in DBD with depth at the top to almost midcore in the sediment cores of the Barra Grande lagoon seagrass beds is an effect of low compaction of coarser, sand-grained sediments [65] characteristic of the sampled site.

Dean [42], Bengtsson and Enell [43] and Heiri et al. [44] reported that LOI is widely recognised as an uncomplicated technique for measuring and estimating organic matter and carbon content in marine and terrestrial sediments. In contrast, Bengtsson & Enell [43] highlighted that LOI gives a rough suggestion of organic matter and carbon content

of sediments. The weight loss from LOI is usually reported as mostly equal in proportion to the organic matter content of sediments [7]. However, some limitations have been documented on the application of LOI technique as an alternative to estimating C stock due to mass loss on ignition that is unconnected with high organic matter in some sediment samples, particularly samples with high calcium carbonate [66]. For example, in the Shark Bay and Florida Bay, sediment cores collected from seagrass communities dominated by *Thalassia testudinum* with less stands of *Halodule wrightii* and *Syringodium filiforme* showed mass loss on ignition associated with sediment configuration, loss of inorganic materials, sulphide oxidation [67]. In effect, this loss on ignition is unassociated with high organic matter, for which a regression analysis of entire LOI values could account for the application of LOI as an alternative for measuring C stock in sediments with high organic matter content and related to conclusions drawn for an analysis of the LOI values as a means of accurately predicting C stock from a global data compilation and analysis documented by Fourqurean et al. [7]. In this study, the effect of mass loss on ignition in sediments of seagrass beds of the Macapa River and Barra Grande lagoon could be identified from the limitations of the global LOI and OC relationship (regression analysis) to accurately predict C stock in sediment cores A and C of the Macapa River seagrass beds (Table 1), as well as sediment cores A and B of the Barra Grande lagoon seagrass beds (Table 1), showing profiles of OC (%DW) with depth, incorporating global LOI and OC relationship [7], $OC_{measured}$ and $OC_{predicted}$ where only LOI was measured. Consequently, the results shown in Table 1 validate the findings of some authors that sediment C stock estimated from the uniform (global) LOI and OC relationship is approximately twice the OC content [42, 43, 68]. The shortcoming of the global LOI and OC relationship to accurately predict C stock was very predominant in sediment cores A and B of the Barra Grande lagoon seagrass beds (where OC was measured) to a magnitude of approximately three times the OC content of the cores, which could be connected to the effect of mass loss on ignition due to calcareous particles and low organic matter content of the sediments. However, Fourqurean et al. [26] also discovered that the reliability of LOI in estimating/predicting OC in low organic matter sediment is very low due to mass loss on ignition, even when such sediment lacks organic matter. Other LOI tracers in muddy and calcareous sediments such as found in the sediments of seagrass beds of the Macapa River and Barra Grande lagoon include evaporative salts, carbonate minerals [66], and not necessarily high organic matter. Anderson [69] also underlined that the permeation of sediment pore water into the volume of combustible sample greatly limits the likelihood of accurate measurement of organic matter using global (uniform) LOI and OC relationship. Using LOI and $OC_{measured}$ relationship to predict OC in sediment core B of seagrass beds of the Macapa River and sediment core C of the Barra Grande lagoon where only LOI were measured and compared with the global LOI and OC relationship according to Fourqurean et al., [7] proved that LOI was a good predictor of C stock.

Furthermore, other limitations associated with using LOI to determine the organic matter and carbon contents of coastal and marine sediments are technically influenced such as lack of consistent ignition temperature, irregularity of sample exposure time and determination of appropriate sample size. Nonetheless, published report from proxy data generated by physico-chemical and biological information preserved in aquatic sediment profiles indicated a considerable bias in the LOI techniques used. For example sample exposure time in the furnace vary from 1 to 4 h [70, 71] and ignition temperatures from 500 to 550°C e.g. [72, 73]. But the LOI method used in this study includes ignition temperature of 450°C, sample exposure time of 8 hours, as well as sample sizes of 10g and 5gDW respectively (to test reproducibility and comparability of results), which clearly validates the bias in methodology. In an attempt to empirically determine the factors influencing the reliability of LOI method, Heiri et al., [45] conducted series of laboratory experiments to ascertain effects of sample exposure time, position of samples in the furnace, ignition temperature and sample size on LOI results. In testing the effect of sample exposure time, Heiri et al. [45] sent two batches of five samples made up of mixed, high carbonate and high organic matter sediments to 10 different laboratories in Europe. Exposure time for determining organic matter (LOI) and carbon contents varied

from 1 to 6 hours and 0.5 to 8 hours respectively. Relying on results from the time-series experiment, Heiri et al. [45] suggested maximum exposure time of four hours, when the LOI reaction peaked after the initial rapid weight loss. However, for estimation of carbon content, Heiri et al. [45] recommended an exposure time of 2 hours.

In contrast, in an LOI experiment with graphite, Bengtsson & Enell [44] suggested that an exposure time of 2 hours may not be adequate for samples with very high organic matter content. In this context, for mixed sediment as in the case of the Macapa River and Barra Grande lagoon, an exposure time of 4 hours would be adequate. These findings suggest that exposure time for LOI experiment could mainly be sediment-dependent since different sediment samples/types require non uniform exposure times to burn out organic matter usually reported as weight loss. In assessing the effect of position of sample in the furnace using mixed sediment, Heiri et al. [45] discovered that samples in the centre of the furnace consistently recorded the highest LOI at 550°C. In addition, differences in weight loss (LOI) between the innermost and outermost placed samples increased steadily with increase in exposure time, starting with 0.42% until it reached 1.1% after 18 hours exposure time. Also, weight loss (LOI) was highest at 950°C in the middle of the sample tray, with a negligible difference of 0.08% between the innermost and outermost samples. Essentially, higher loss of impregnated sediment pore water, unstable salts or inert carbon due to hotter temperatures in the centre of the furnace and faster heat up of lesser samples are considered the main possible account for the differences in weight loss dependent on position of samples in the furnace and sample size. The impact of ignition temperature on LOI values has been based on laboratory-specific LOI methods. For instance, Virkanen et al. [72]. Korsman et al. [73] recommended furnace/ignition temperatures ranging from 500–550°C, which was also implemented by Fourqurean et al. [7]. In this study, the ignition temperature for LOI was 450°C for sample exposure time of 8 hours, while the ignition temperature for measuring carbon content was 1000°C. However, the ten different European LOI laboratories that analysed first batch of samples sent by Heiri et al. [45] used uniform ignition temperature of 550°C for the first LOI analysis (organic matter content), while six out of the ten laboratories used 950°C and two used 980°C and 925°C respectively for the second LOI analysis (carbon content). Consequently, the differences in ignition temperatures based on laboratory-specific methods suggest that the effects of differences in laboratory equipment and operational methodologies may not be eliminated by standardized LOI procedure. Heiri et al. [45] showed a positive relationship between sample size and sample exposure time coupled with ignition temperature. It has been observed that LOI of 550°C is dependent on sample size [45]. However, these parameters were not measured or covered within the scope of this study to sufficiently unlock their effects on LOI results.

Seagrass sediment C stocks vary widely across diverse, sparsely reported seagrass ecosystems and geographical locations at spatial and temporal scales [7]. This suggests the effects of species composition, abundance and distribution, as well as seagrass habitat-driven characteristics on carbon capture and storage in seagrass beds. The average C stocks in top 1m of seagrass sediment of seagrass beds of the Macapa River (41.8 Mg C/ha^{-1}) and the Barra Grande lagoon (12.3 Mg C/ha^{-1}) were considerably lower than the estimated global average and range of C stock of 194.2 Mg C/ha^{-1} in the top 1m of seagrass sediment (mean: 392.5 ± 55.9 Mg C/ha^{-1}; median: 139.7 Mg C/ha^{-1}) and range of 115.3-829.2 Mg C/ha^{-1} reported by Fourqurean et al. [7]. Specifically, the average C stock in top 1m seagrass sediment of seagrass beds of the Macapa River was 4.64 times (approx. 5 times) lower than and 21.5% of the global average C stock of 194.2 Mg C/ha^{-1} in the top 1m of seagrass sediment, while the average C stock in top 1m seagrass sediment of seagrass beds of the Barra Grande lagoon was 15.78 times (approx. 16 times) lower than and 6.33% of the global average C stock. Integrating this average C stock comparison with the average C stock of 127.7 Mg C/ha^{-1} in top 1m of single sediment core of *Halodule wrightii* seagrass bed of Chelem lagoon, Mexico [digitised data extracted from 63], about the same range of variation in global average C stock was

observed in relation to the average C stocks in top 1m of seagrass sediment of seagrass beds of the Macapa River and the Barra Grande lagoon.

The comparison between the average C stocks in the top 1m of single sediment core of *Halodule wrightii* seagrass bed of Chelem lagoon, Mexico and the *Halodule wrightii* seagrass bed of the Macapa River, as well as the *Halodule wrightii* and mixed stands of *Halodule* sp. seagrass beds of the Barra Grande lagoon suggest that seagrass beds of same species composition may vary in C capture and storage capacities. Campbell et al. [46] suggested that such variation in C stock of same species may be influenced by site characteristics ranging from site depositional and geomorphologic attributes not connected with seagrass biomass and areal cover. Extending the comparison in the direction of geographical locations with similar climatic conditions, the average C stocks in top 1m of seagrass sediment of seagrass beds of the Macapa River and the Barra Grande lagoon were also considerably low. For instance, the average C stocks in top 1m of seagrass sediment of sub-tropical seagrass beds of the Macapa River and the Barra Grande lagoon differ from the average C stocks in top 1m of seagrass sediment of sub-tropical Shark Bay seagrass beds (243.0 Mg C/ha^{-1}) and sub-tropical Florida Bay seagrass beds (163.5 Mg C/ha^{-1}). This suggests the likelihood of variation in C stock in top 1m of seagrass sediments of seagrass beds under similar climatic conditions. In assessing the influence of different climatic regions on C stock buried in top 1m of seagrass sediments, the average C stock of the sub-tropical seagrass beds of the Macapa River and the Barra Grande lagoon differed from the average C stock of the temperate seagrass beds of the Abu Dhabi coastline (49.1 Mg C/ha^{-1}) and North Atlantic (48.7 Mg C/ha^{-1}). Serrano et al. (2014) confirmed that C stock vary across different seagrass species, climatic regions and depths e.g. “C stock in *Posidonia oceanica* seagrass bed in the Mediterranean Sea (at 2m depth) was 21–34 times higher than those in *P. sinuosa* beds in the Indian Ocean (at 2 and 4m depths)”.

Conclusion And Recommendation

The outcome of this study has demonstrated series of analytical procedures to quantitatively measure and predict the C stock in the aboveground and belowground seagrass biomass, as well as the seagrass sediments of the seagrass beds of the Macapa River and Barra Grande lagoon of northern Brazil. The study, signifying the first attempt at quantifying C stock in selected seagrass beds of Brazil, has shown the general low amount of C stock compared to global and regional-based average C stocks. There is indication that the C stocks in seagrass beds of the Macapa River and the Barra Grande lagoon may increase in time and scale depending on implementation of effective and resilient seagrass ecosystem conservation and management strategies. In addressing some of the limitations and future research priorities observed in this study, it is pertinent to consider some key actions. Towards achieving a sustainable carbon financing regime and ecosystem value (economic worth) of seagrass, there is the need to conduct a wide-ranging mapping of all seagrass species in northern Brazil, and estimate the amount of carbon lost through the degradation/damage of seagrass ecosystems e.g. potential damage caused by artisanal fishing, aquaculture activities and sporting activities in the seagrass beds of the Macapa River, as well as the potential impact of water sporting, kitting and beating activities in the seagrass beds of the Barra Grande lagoon. There is limited knowledge in quantifying the contributions of seagrass belowground components (roots, rhizomes and seagrass-dependent epiphytic macroalgae) to seagrass carbon stock. This requires more research to measure the C stock of belowground components on species level to potentially increase the accuracy of C stocks measurements and predictions on temporal and spatial scales. There is also the need to conduct further studies on the possible predictors that influence carbon capture and storage in seagrass beds of northern Brazil to assist in securing carbon credit for the prevention of threats to the sustainability of climate change mitigation strategies through reduction of GHG emissions.

This study, among others, identified the limitations of the global (uniform) LOI and OC relationship to accurately predict C stock in seagrass sediments with low or without organic matter. It was observed from this study that different sediment cores responded differently to the applicability of the global relationship in predicting C stock. This suggests the need to develop LOI and OC relationship that is sediment-specific in terms of the biogeochemical processes that influence sediment accumulation rates. This requires more research into profiling the seagrass sediments of different regions and geographical locations in order to develop a more reliable LOI and OC relationship for C stock predictions.

The inconsistencies in the patterns of DBD with depth found in this research suggests the need to conduct further studies to determine the relationship between measured C and estimated C from LOI in order to achieve more reliable and sustainable C accounting for seagrass globally. In considering the bias resulting from non standardized, laboratory-specific LOI procedures, there is the need to conduct further studies into the relationship between LOI and different predictors such as sample exposure time, position of samples in the furnace, ignition temperature and sample size towards improving the reproducibility and comparability of LOI results. Developing standardized LOI procedures will eliminate the effects of laboratory-specific procedures which contribute to skewed LOI results. Heiri et al. [45] has shown that the uppermost limit of variation from inter-laboratory comparisons of LOI results of different institutes can decrease to error value of 2% LOI based on findings from application of standard LOI method. As a result of this low error value, such minimal difference in LOI results is not sufficient to cause significant bias in LOI procedures. Similar standardization procedures should be extended to measurement of sediment C to resolve the bias in CN analyser furnace/combustion temperature used by different laboratories.

In evaluating the conditions influencing carbon accumulation rate and storage in seagrass functional systems, there are indications of interrelationship and interactions of a combination of biotic and abiotic variables. However, limited research and data on the nature of correlation of these variables still constitute considerable knowledge gaps that require further studies. For instance, Greiner et al. [74] revealed that carbon accumulation rates of stable seagrass beds differ in seagrass density, distinguishing sedimentary attributes and depth range of habitats evidenced by a study conducted at the Virginia Coast Reserve Long Term Ecological Research site (VCR LTER) in the *Zostera marina* seagrass bed on the eastern shore of Virginia, USA. Serrano et al. [15] also predicted that seagrass C stocks could be influenced by light presence, seagrass productivity, bed density, sediment accumulation rate, particle size and DBD. There is therefore, the need to determine the carbon contributing rates of these variables to seagrass C stocks in order to create integrated and sustainable management practices for the maintenance of seagrass ecosystem stability to increase CO_2 sequestration in marine and coastal environments.

Declarations

Financial Interest: No financial or non-financial interest declared

Conflicts of interest: No competing interest to declare relating to the content of this manuscript

Affiliation: No affiliation with or involvement in any organization or entity with any financial interest on the subject matter or materials discussed in this manuscript

The author has no financial or proprietary interest in any material discussed in this article.

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Figures

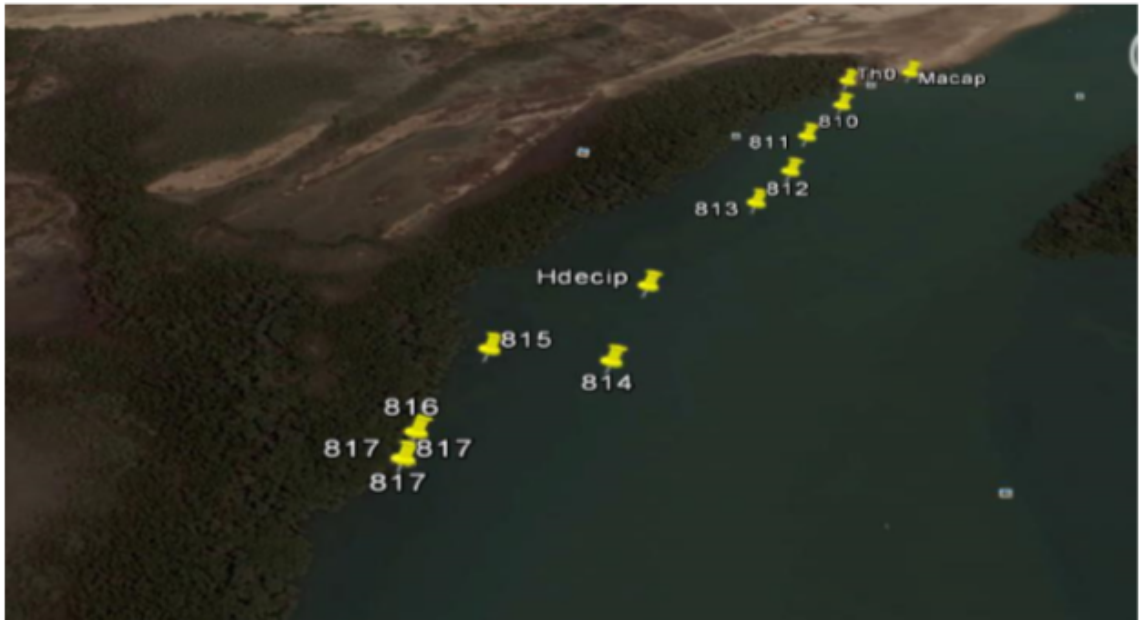

Figure 1

Figure a Macapa River, showing GPS points of seagrass beds sampled between January and March 2014 (Corpetino, 2014)

Figure 2

Figure b sample of *Halodule wrightii*

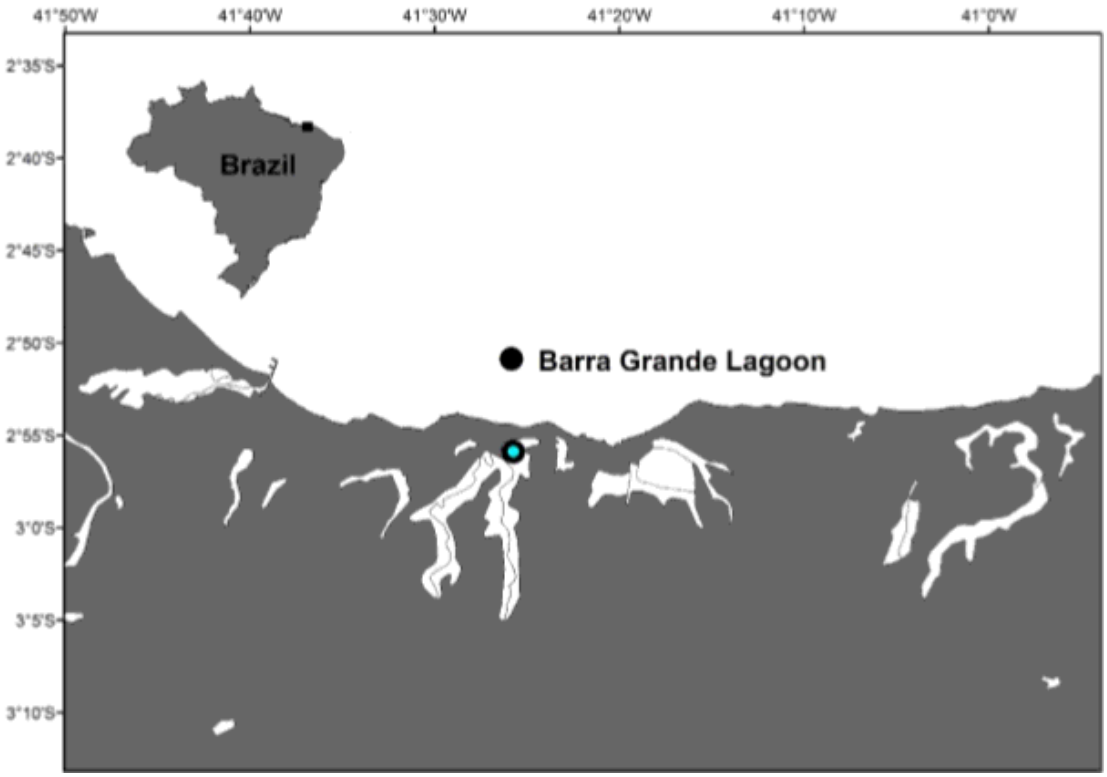

Figure 3

Figure c Barra Grande lagoon, northern Brazil (GIS-designed map) sampled between January and March 2014 (Ogbuka, 2015. Unpublished M.Sc. thesis)

Figure 4

Figure d sample of *Halodule* sp.

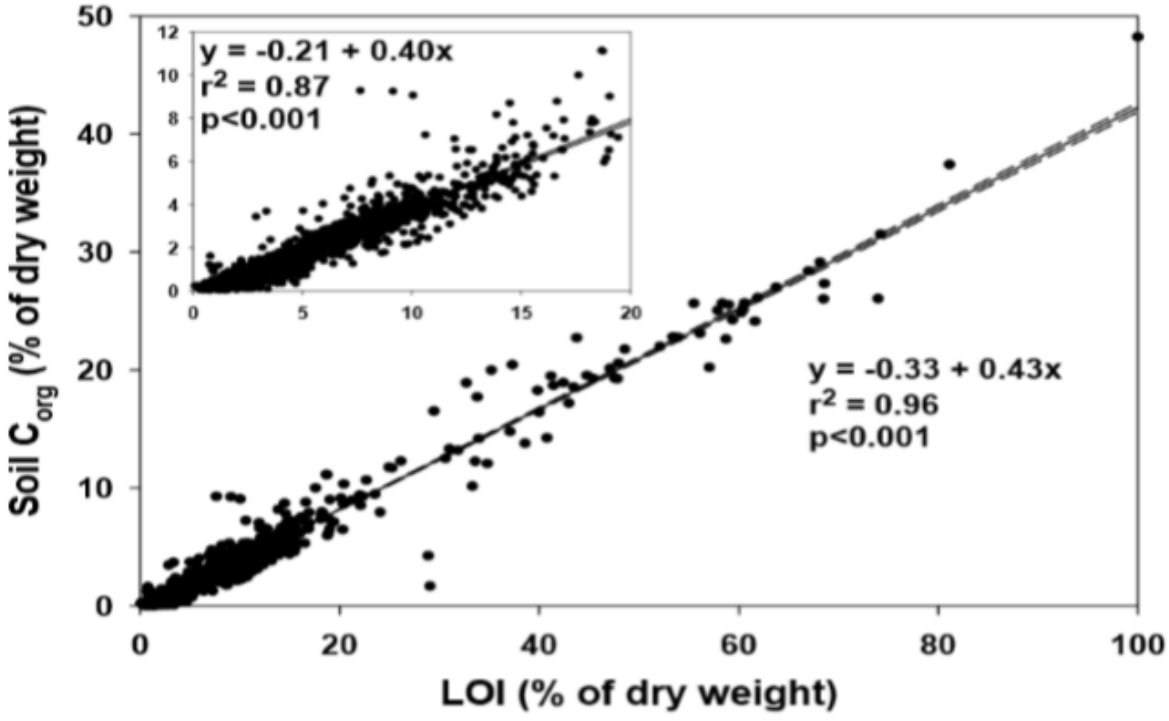

Figure 5

Figure e Global LOI and OC relationship according to Fourqurean et al. (2012a), where y=0.43x%-0.33 for LOI range of 0% to 100% and y=0.40x-0.21for LOI range of 0% to 20%, where y=OC and x=LOI

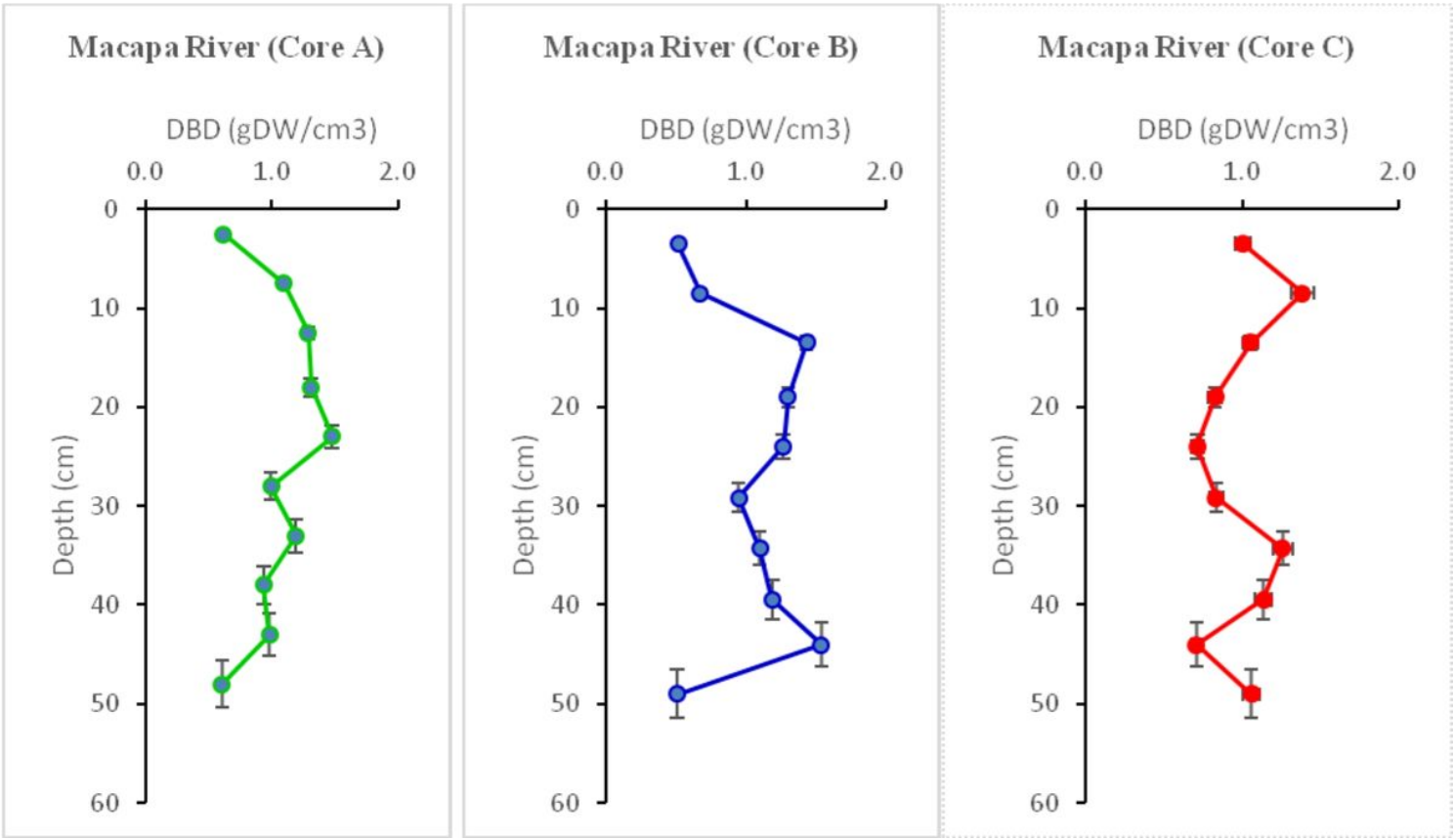

Figure 6

Figure f1 Profile of DBD with depth in sediment cores A, B and C of the Macapa River seagrass beds (Ogbuka, 2015, unpublished M.Sc. thesis

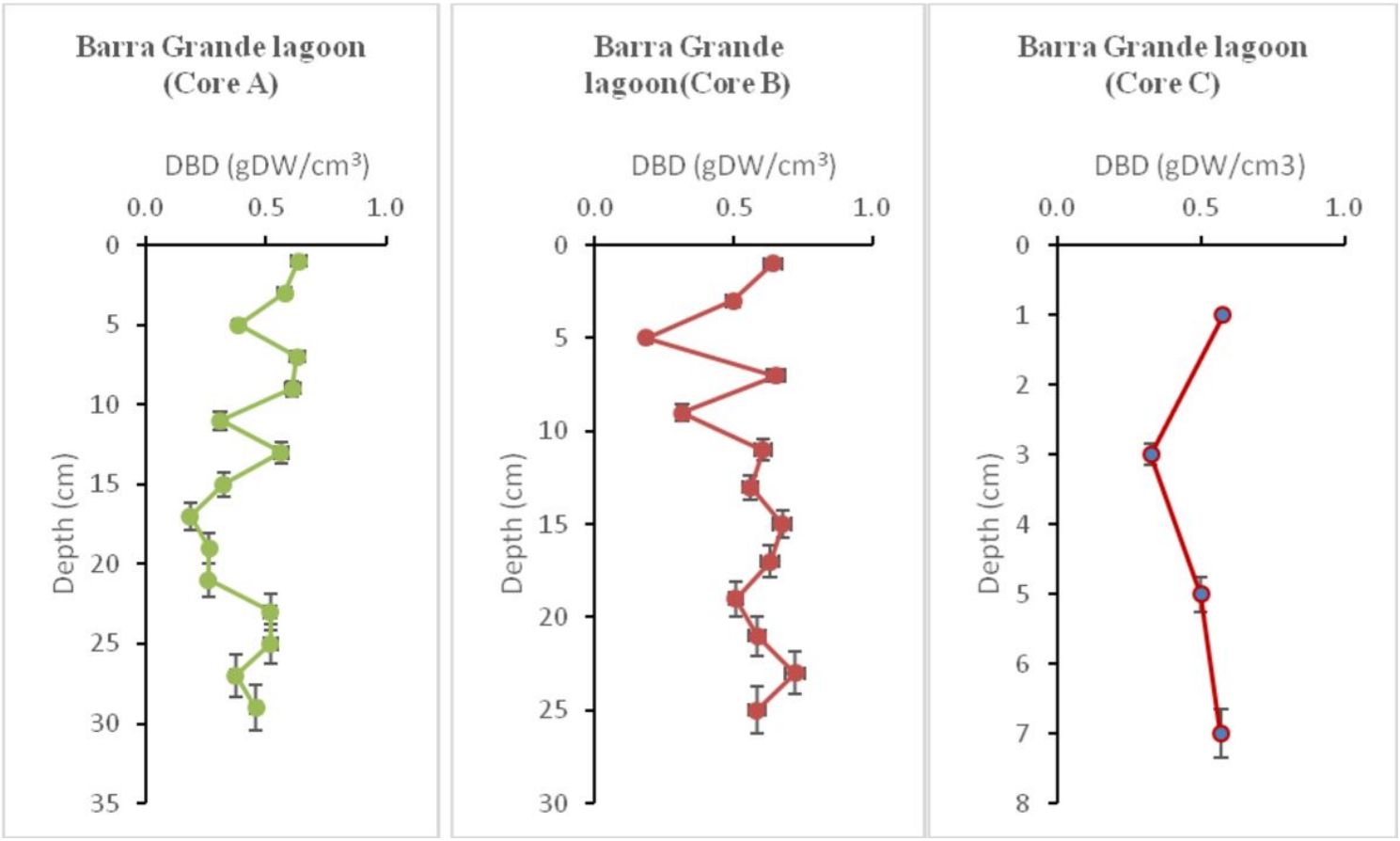

Figure 7

Figure f2 Profile of DBD with depth in sediment cores A, B and C of the Barra Grande lagoon seagrass beds (Ogbuka, 2015, unpublished M.Sc. thesis)