Determination of carbon sequestration rate in soil of a mangrove forest in Campeche, Mexico

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Abstract - It was determined carbon sequestration rate, total nitrogen content and several important physicochemical parameters (electrical conductivity, gravimetric moisture, salinity, pH and soil texture) in mangrove forest soil located within the natural protected area named "Términos Lagoon" in Carmen Island, Campeche-México. Six sampling zones were considered within a mangrove forest located in the Botanical Garden of the Autonomous University of Carmen City. Samplings were carried out considering three climatic periods ("Norths" season, dry season and rainy season) during 2009. The electrical conductivity was within the range of 1.38 to 26.2 dS m-1 and the highest values were found during the rainy season when the study sites were flooded most of the time. The seasonal influence on carbon storage was evident (from 1.2 to 22.2 kg C / m-2), with the highest rate of carbon sequestration in the dry season, in flooded soils with greater predominance of red mangrove, and is lower in those soils rarely flooded with a higher prevalence of buttonwood mangrove individuals. The organic matter content and organic carbon was greater at 30 cm depth for flooded areas, where long periods of flood tides and low rates of decomposition maintain anoxic conditions. Due to soils are sandy in the study areas and have high pH values with red mangrove associations, we can suggests that they have a high potential for carbon sequestration and it could be increased in future years.

Keywords - Carbon sequestration potential, carbon sinks, Mangrove forest, Términos Lagoon, Wwetlands, Campeche-México.

I. INTRODUCTION

IN last years, CO_2 atmospheric concentrations have increased in a sustained way. Climate change is caused directly or indirectly by human activity that alters the composition of the global atmosphere and which is observed over comparable time periods in addition to natural climate variability [1]. Atmospheric concentration of carbon dioxide has increased from a pre-industrial value of 280 parts per million (ppm) to current levels of 387 ppm. This is the highest level in 650,000 years and is expected to double pre-industrial levels during this century, which could raise global temperatures 2 to 5 Celsius degrees over the next hundred years. Despite efforts to stabilize greenhouse gas concentrations by some countries, global warming will continue as a result of climate system inertia [2]. The impacts of climate change are readily apparent around the planet.
Retreating glaciers and extreme precipitation events cause flooding in some areas while elsewhere water bodies are evaporating from the heat. Tropical diseases are spreading as hurricanes become stronger and more destructive. This has led to study the capacity of carbon sequestration in forests and other terrestrial and wetland ecosystems Most of the studies are related to forest ecosystems and crops, and there is no enough information on carbon sequestration potential of wetlands.

Wetlands play a key role as suppliers of environmental services, being the most important the carbon sequestration. The reservoirs of soil organic carbon can act as sources or sinks of atmospheric carbon dioxide, depending on land use practices, climate, texture and topography [3]-[6]. Wetlands cover about 5% of the trerrestrial surface, are important carbon sinks containing 40% of soil organic carbon at global level [7]. Estuarine wetlands have a capacity of carbon sequestration per unit area of approximately one order of magnitude greater than other systems of wetlands [8] and store carbon with a minimum emission of greenhouse gases due to inhibition of methanogenesis because of sulfate [9]. The importance of mangrove as a coastal barrier against hurricanes and the environmental services that it offers is widely known [10]. For all these reasons is important to carry out studies focused to protect this ecosystem.

Mangroves dominate about 75% of the coastline in the world between latitudes 25 º N and 25 º S, and are adapted to areas characterized by high temperatures, fluctuations in salinity and anaerobic substrates [11]. Carter and colaborators [12] reported that almost 80% of total organic balance in Union Bays, Florida was provided by exporting from the mangrove forest surrounding the bay. On the other hand, Xiaonan and his research equipment [13] evaluated the potential of carbon sequestration for swamps in China, finding that the mangrove forest showed the higher rate of carbon sequestration.

In order to reduce atmospheric CO_2 concentrations, some countries that signed the Kyoto Protocol have committed to establishing inventories of carbon storage which are currently integrating the inventory by region and ecosystem. Mexico has 113 Ramsar sites covering a total area of 8,161,357 ha, being the mangrove forest the most important ecosystem. There are disagreements in estimates of carbon storage due to differences in methodologies, besides that there is no certainty about the factors that influence changes over the time.

The Mexican Biodiversity Council [14] has attempted to unify criteria and methodologies, reporting for Mexico an area of mangrove cover of 655.667 ha. Campeche State has the highest percentage of mangrove cover in México (30% of total area) including protected areas and Ramsar sites such as "Términos Lagoon" and "Petenes" [14]. Carmen City has some areas of mangrove cover at the southeast of the island, having undisturbed mangrove forest within the facilities of the Botanical Garden of the Carmen Autonomous Universiy. Even, currently mangrove forest in Mexico is protected, the efforts and controls are not enough to mitigate the effects of the clandestine cut down and it is necessary to implement an effective forest management of this ecosystem.

The knowledge of carbon storage and the interaction between C storage and, edafologic and vegetative factors, could help to identify areas and types of land use or changes in land use that are of particular interest to the profit or loss carbon from the soil.

Although terrestrial forests are widely known as carbon reservoirs, few studies have been focused on mangrove forests. A proper forest management of mangrove ecosystem is an opportunity to increase carbon storage. The aim of this study is to quantify the carbon sequestration potential of mangrove soils in an undisturbed site located in Carmen Island, Campeche.

II. MATERIALS AND METHODS

A. Site Description

The study site is located in Carmen City, Campeche, Mexico within the facilities of the Botanical Garden of the Autonomous University of Carmen City at the border of the Terminos Lagoon, which has an approximate area of 29.5 ha and it is located at 18° 38 '09.01 "N and 91 ° 46' 51.38" W (Figure 1).

The site has a humid tropical climate with average annual rainfall of 1680 mm and a mean tide range of 0.5 m. The study site shows a pattern of weather well defined with three climatic seasons: the dry season (from mid February to May), rainy season (from June to October), and the "norths" season identified by cool fronts (from November to February each year).

The average temperature ranges from 18-36 ºC, maximum wind speeds occur during the "norths" season (50-80 km h^{-1}).

This area shows a great diversity in tropical vegetation including species of *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*, and *Conocarpus erectus* [15].

TABLE I
SPECIFIC LOCATION FOR EACH SAMPLING AREA

Samplig Area (SA)	Location		
	Sampling Point	Latitude N	Longitude W
SA1*	1	18° 38' 07.5"	91° 46' 46.4"
	2	18° 38' 07.6"	91° 46' 46.3"
	3	18° 38' 07.3"	91° 46' 46.6"
SA2*	1	18° 38' 07.2"	91° 46' 50.1"
	2	18° 38' 07.0"	91° 46' 50.2"
	3	18° 38' 07.4"	91° 46' 50.1"
SA3*	1	18° 38' 08.0"	91° 47' 01.0"
	2	18° 38' 07.8"	91° 47' 00.8"
	3	18° 38' 08.0"	91° 47' 01.2"
SA4*	1	18° 38' 09.3"	91° 47' 10.07"
	2	18° 38' 09.3"	91° 47' 09.6"
	3	18° 38' 09.0"	91° 47' 09.6"
SA5*	1	18° 38' 07.9"	91° 47' 08.2"
	2	18° 38' 07.9"	91° 47' 08.6"
	3	18° 38' 08.0"	91° 47' 08.6"
SA6*	1	18° 38' 07.7"	91° 47' 07.4"
	2	18° 38' 07.5"	91° 47' 07.2"
	3	18° 38' 7.4"	91° 47' 07.1"

Due to this forest is located in the surroundings of the natural protected area named "Terminos Lagoon", most of their individuals remains undisturbed.

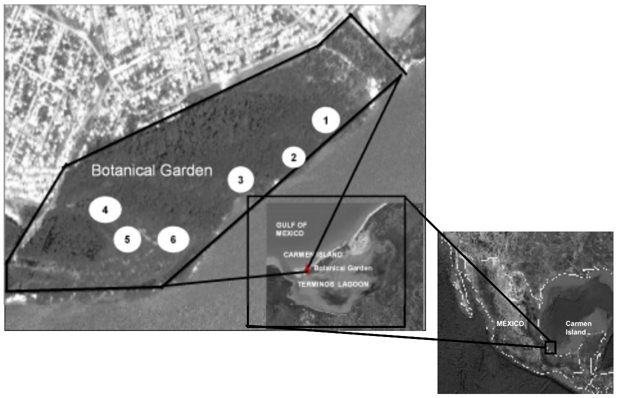

Fig. 1 Specific location of the six sampling areas and depht, for mangrove soil associated to the NPATL

B. Sampling Method and Forest Inventory

Six sampling areas of 4 m x 12 m were considered and transects were established based on visual inspections in a representative area of mangrove forest, locating three points from 1 m^2 for each sampling area. Sampling Area 1 (SA1) was located within the boundaries of the natural protected area named "Términos Lagoon" (NPATL), with frequent flooding and located on the coastline.

SA1 was characterized by the presence of red mangrove and white mangrove associations.

Sampling Area 2 (SA2) was located very close to the coast (20 m from the boundaries of NPATL) and showed the presence of uniform associations of red and white mangrove.

Sampling Area 3 (SA3) was covered with fresh water during the rainy season and showed the presence of red, buttonwood and white mangrove associations.

The Sampling Area 4 (SA4) never was flooded and showed individuals of all mangrove species being buttonwood mangrove the specie with higher prevalence.

The Sampling Area 5 (SA5) never was flooded and showed black and buttonwood mangrove associations, being black mangrove the dominant species.

The Sampling Area 6 (SA6) never was flooded and buttonwood mangrove associations and white mangrove.

Table 1 shows the specific location for each sampling areas, and Table 2 shows the forest inventory for each sampling area.

Duplicate soil samples were collected at 30 and 60 cm deep using a corer of 193.3 cm^3 volume. The corer was carefully introduced at 0.3 and 0.6 m deep.

Because of the soil samples showed a high moisture content, the corer was adapted with a one way check valve to create a vacuum inside the corer line and thus to obtain the sample by suction hold it inside the tube [19]- [20]. A total of 216 samples were collected with their replicas.

After extraction, each sample was labeled, sealed and sent to the laboratory for further analysis [21]- [22].

C. Carbon Sequestration Potential Determination

The carbon sequestration potential was determined in kg C m^{-2} according to the following equation:

$$\text{MgC ha}^{-1} = [\text{soil dry weight}]\ [\%\ \text{CO}] \qquad (1)$$

Where: Soil dry weight [t ha-1] = [sampled soil depth] [bulk density]

TABLE I I
GENERAL DESCRIPTION AND FOREST INVENTORY FOR EACH SAMPLING AREA

Samplig Area (SA)	Species distribution (number of individuals)				Average diameter at breast height
	RM[1]	WM[2]	BM[3]	Bwm[4]	
SA1*	7	34	-	-	6.95
SA2*	4	3	-	-	10.11
SA3*	7	3	-	6	9.10
SA4*	1	-	8	58	3.39
SA5*	-	4	6	10	5.26
SA6*	1	4	-	18	6.74

Average height of the tree (m)

Samplig Area	RM[1]	WM[2]	BM[3]	Bwm[4]
SA1*	11.9	12.4	-	-
SA2*	10.5	9.8	-	-
SA3*	10.3	9.4	-	9.5
SA4*	5.3	-	4.7	4.7
SA5*	-	4.9	6.2	5.4
SA6*	2.7	5.2	-	4.1

Maximum height of the tree (m)

Samplig Area	RM[1]	WM[2]	BM[3]	Bwm[4]
SA1*	11.9	13.1	-	-
SA2*	10.5	9.8	-	-
SA3*	10.5	9.6	-	10.8
SA4*	5.3	-	4.7	5.0
SA5*	-	6.1	5.3	6.6
SA6*	2.7	6.1	-	5.1

*Degree of evolution of the forest for all the sampling zones: from young individuals to mature individuals in reproductive age. Production of seeds each year. Average age: 15 years.

[1]Red mangrove., [2]White mangrove, [3]Black mangrove., [4]Buttonwod mangrove.

- Individuals not present in the study area.

D. Statistical Analysis

It was performed a descriptive statistics, a comparative and relational statistical analysis for storage of carbon per sampling area, sampling points, collection depth and season. Averaged values were obtained from different physical and chemical parameters. Hypotheses were established and evaluated by the method of one-way ANOVA to determine significant differences between sampling areas, sampling points and sampling depths for each climatic season. Tests were conducted for homogeneity of variance and normality tests (at $p < 0.05$) by the methods of Kruskal-Wallis and Kolmogorov-Smirnov respectively, using the software SPSS 18 [23]. It was carried out a multiple linear regression to relate the recorded carbon storage in each sampling area, sampling point, sampling depth and for each climatic season., with the physical-chemical variables (at $p<0.05$) to define the variables with a significant influence on the observed values of carbon storage.

III. RESULTS AND DISCUSSION

In Figures 2 to 10 are shown the found results for each sampling areas at different depths and climatic seasons. The bulk density ranged from 0.90 to 1.67 g cm^{-3} (Figure 2) and total nitrogen content ranged from 0.00 to 0.51% and was higher in SA1 and SA2.

Observed pH values were between 7.47 and 8.90. Higher values of pH were found in SA3, SA4, SA5 and SA6, which agreed with the dominant vegetation of mangrove buttonwood, which is a species characterized by its tolerance to salinity and high pH values (Figure 3).

It can be observed that the soils were wetter in the sample area 1 and 2 (SA1 and SA2) during the rainy season (Figure 4). Carmen Island has a sedimentary origin, for this reason, sandy soils are dominant in this study area. In Figure 5, it can be observed that all soil samples showed sandy texture. Sampling zones 1 and 2 showed a greater proportion of clay and silt.

All soil samples showed a sandy texture, and SA1 and SA2 showed a higher proportion of clay and silt.

The electrical conductivity was within the range of 1.38 to 26.2 dS m^{-1} (Figure 6), and the highest values were found in SA1 and SA2 during the rainy season when these sites were flooded most of the time.

In SA3, SA4, SA5 and SA6, the salinity was higher than in SA1 and SA2, which may explain the low nutrient content in these areas.

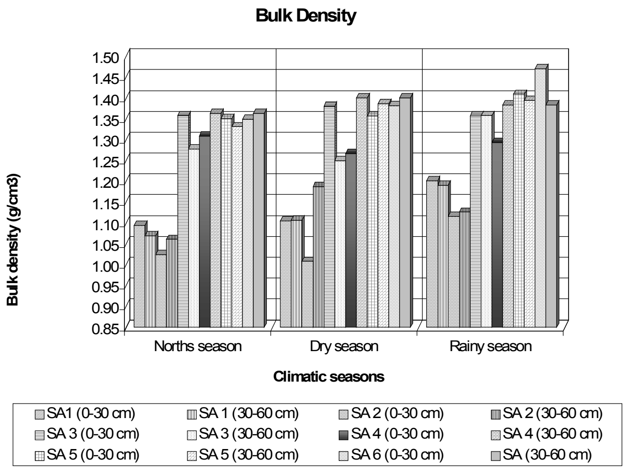

Fig. 2 Main values for bulk density for each climatic season, sampling area and depht, for mangrove soil associated to the NPATL

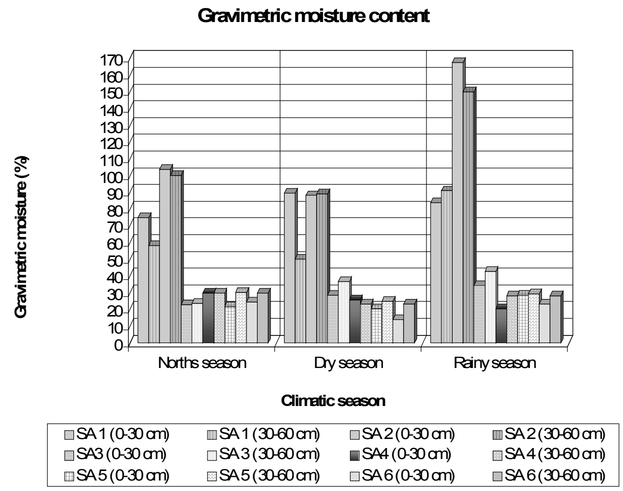

Fig. 4 Main values for gravimetric moisture for each climatic season, sampling area and depht, for mangrove soil associated to the NPATL

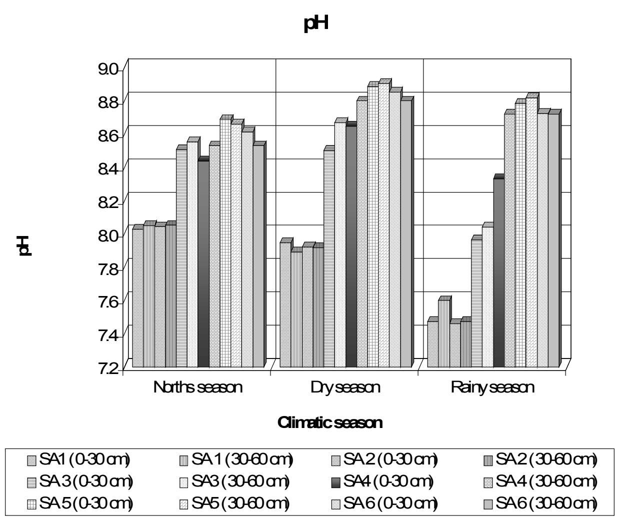

Fig. 3 Main values for pH for each climatic season, sampling area andepht, for mangrove soil associated to the NPATL

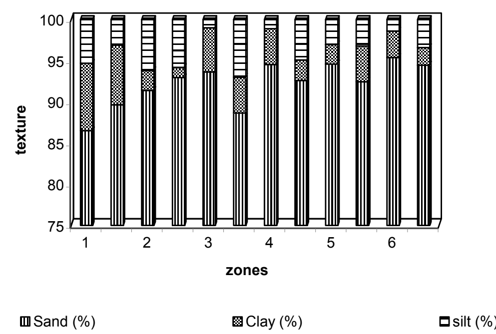

Fig. 5 Textural classes for the six sampling areas.

The salinity was lower in the rainy season which may explain the higher values in the total nitrogen content (Figure 7) during this season compared to other climatic periods.

The organic matter content was within the range of 0.54 to 29.58% and the highest values were found in the SA1 and SA2 during dry and rainy seasons (Figure 8).

It can be seen that the organic matter content was higher at 30 cm depth for SA1 and SA2 (Figure 8). Long periods of tidal flooding and low decomposition rates result in sustained anoxic conditions (below 10 cm depth) and high content of organic matter, which may explain the higher values in organic matter content at 30 cm depth. Therefore, the process of accumulation of organic matter increases in places with heavy rains or poor drainage, which is the case of SA1 and SA2.

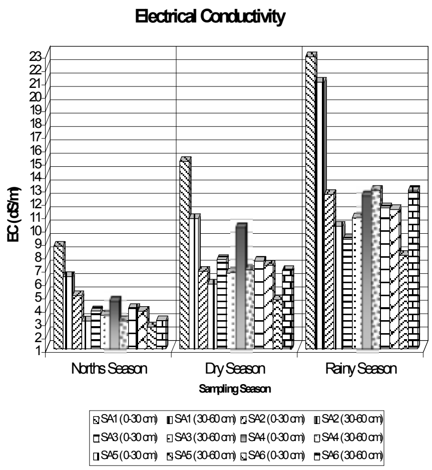

Fig. 6 Electric conductivity of soils sampled at six sampling zones for each climatic period.

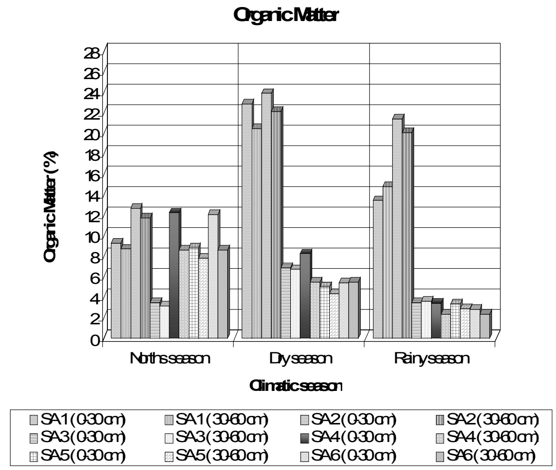

Fig. 8 Main values for organic matter for each climatic season, sampling area and depht, for mangrove soil associated to the NPATL

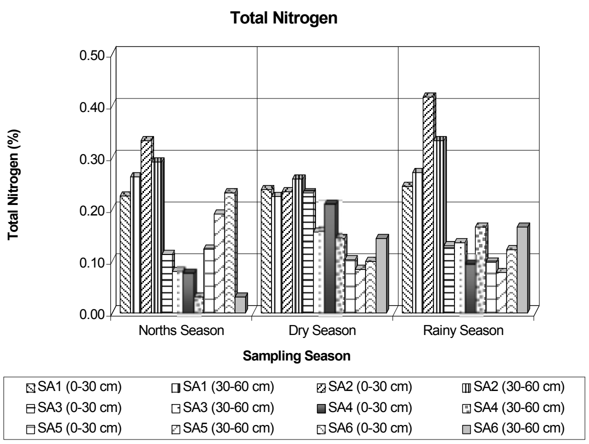

Fig. 7 Main values for total nitrogen for each climatic season, sampling area and depht, for mangrove soil associated to the NPATL

During the season of rains, the accumulation of organic matter increases, however, decomposition is low and this accumulation remained until the dry season showing their maximum values during this period.

This may explain the higher values of organic matter obtained the dry season and slightly lower values obtained for rainy season, considering that the sampling campaigns this season were carried out at the beginning this period.

Figures 9 and 10 show organic carbon content and carbon storage for the different climatic season and for each sampling area.

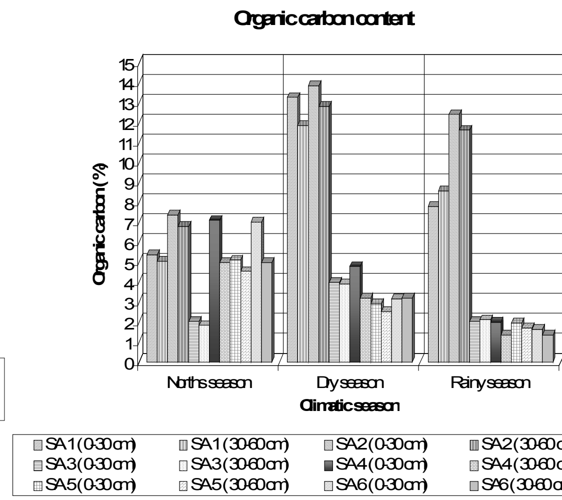

Fig. 9 Main values for organic carbon content for each climatic season, sampling area and depht, for mangrove soil associated to the NPATL

The pH strongly influences the net amount of dissolved organic matter and its decomposition process. onsequently, dissolved organic matter becomes more soluble at higher pH values [26]- [27].

The organic carbon content was within the range of 0.31 to 17.16% and the highest values were found in SA1 and SA2 during the dry and rainy seasons.

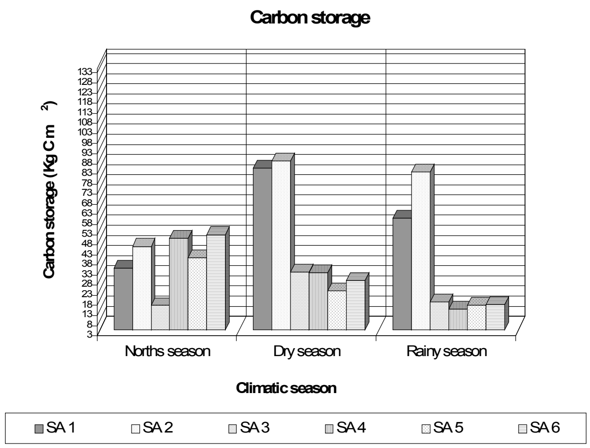

Fig. 10 Main values for carbon storage content for each climatic season, sampling area and depht, for mangrove soil associated to the NPATL

The organic carbon content decreased slightly as increased soil depth, the distribution pattern of organic carbon is a general phenomenon in tropical forests [28].

Anoxic conditions and prevalence of high pH values may be partially responsible for high concentrations of organic carbon. During the rainy season, water sources (contribution of tides, runoff and rainfall) were mixed resulting in organic carbon concentrations lower, while during the dry season, an increase in evapotranspiration, concentrated the salts and dissolved organic carbon which were transported vertically. The amount of C in soil differs greatly in different mangroves, which is a large extent influenced by forest age, the degree of tidal exchange and sedimentation of suspended matter. Dissolved organic carbon increases with forest evolution whatever the season.

The development of mangrove trees induces an increase in biomass and a corresponding increase in organic carbon.

From the statistical analysis, it was observed that except for total nitrogen content, all variables were statistically different ($p < 0.05$) for the three climatic periods. There were significant differences between the dry season and rainy season for gravimetric moisture, organic matter and organic carbon. SA1 and SA2 were statistically different for gravimetric moisture, organic matter and organic carbon ($p < 0.05$).

Organic matter showed a significant positive correlation with organic carbon content in the two sampling depths for the three climatic periods in the six sampling areas. There were not significant differences between sampling depths for the three climatic periods in the six sampling areas.

Carbon storage was greater in the dry and rain seasons for all sampling sites studied, being higher in SA1 and SA2.

The average total carbon storage in the study area was 39.61 kg C m^{-2}. As it can be observed in Table III, comparing our results for carbon storage with data from other sites [25]-[35], we can suggest that sandy soils as found in the study area with high pH and red mangrove associations have a high potential for carbon sequestration.

It should be noted that individuals involved in this study were young-age trees mature reproductive stage, so it might be expected that the carbon sequestration potential increases in future years.

TABLE III
COMPARISON OF THE FOUND RESULTS FOR CARBON STORAGE WITH OTHER STUDIES

Author	Site Characteristics	Carbon Storage (kg C m^{-2})
Bernal and Misch (2008)	Rainforest in Ohio, USA	3.03
Brevik and Homburg (2004)	Wetlands at the southeastern USA	0.033
Khan and colaborators (2007)	Mangroves in Okinawa, Japan	5.73
Moreno and colaborators (2002)	Mangrove swamps in Tabasco, México	47.2-82.2
Arreaga (2002)	Temperate forest in Guatemala	13.04
Howe and colaborators (2009)	Wetlands at the southeastern Australia	6.61
Webb (2002)	Coastal wetlands in Sidney, Australia	13.9
Zhong and Qiguo (2001)	Tropical vegetation in China	40
Lal (2001)	Oxysol in Brazil	12-24
Sawson and Rabenhorst (2000)	Agricultural soils in Brazil	2-10
Cerón and colaborators (2010)	Mangrove forest in Campeche, México (This study)	1.2-22.2

IV. CONCLUSION

In the study area during 2009, a long and severe period of drought prevailed, rains were scarce and they were presented so late compared to previous years. Despite these changes, the physical and chemical parameters determined in soil samples showed the expected behavior as has been reported in previous studies.

The sampling areas with sandy soils (SA3, SA4, SA5 and SA6) showed higher pH and lower rates of moisture and electrical conductivity compared with soils with higher silt and clay content (SA1 and SA2, were flooded most of the time).

The organic matter content and organic carbon decreased at greater depths of soil. The sampling areas with sandy soils where the buttonwood mangrove is the dominant species showed a reduced ability to capture carbon (1.2 kg C m^{-2}). The sampling areas, flooded most of the time, with associations of black mangrove-red mangrove-white mangrove, showed the highest rates of carbon sequestration (22.2 kg C m^{-2}).

The accumulation of organic matter and organic carbon content were higher during the dry season. It was expected, since in this climatic period the evapotranspiration process increases, which concentrates salts and dissolve organic carbon . Carbon storage was lower in the days of "rain" when the dilution effect was greater, resulting in lower concentrations of dissolved organic carbon, salinity and density.

The most important variables in this study were the climatic season and soil type (vegetative community present and hydrogeomorfology). Concentrations of carbon in tropical soils tend to decrease with depth. This rapid decrease in carbon content with depth indicates that a small fraction of carbon that is being introduced into the soil remains there. This pattern is typical of tropical forests where organic matter and nutrients do not accumulate because they are quickly used by biotic systems.

We can conclude that the accumulation of organic matter and carbon storage are determined by the rate of decay rather than the production rate of organic matter.

The combination of anaerobic conditions on site and productivity of the system makes the soils that remain flooded most of the time tend to be highly organic.

Soil type is a key factor in the categorization of the development potential of reservoirs of carbon in the soil. High rates of carbon sequestration in this study indicate that conservation efforts to protect wetlands have high benefits for the mitigation of global warming through the regulation of atmospheric carbon concentrations.

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