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Abstract

Rates of carbon sequestration were determined in seven different mangroves ecosystems within seven coastal communities of the municipality of Laguna de Perlas, South Atlantic Coast of Nicaragua. Mangrove ecosystems are of great importance in these areas, since the inhabitants are direct stakeholders of goods and services provided by mangrove ecosystems (fishing, coastal protection from natural disasters or other natural phenomenon and provision of timbers for domestic use). Despite these major benefits, mangrove forests are highly threatened due to the continuous human intervention in these ecosystem (deforestation, forest fire, solid waste disposal), which unfortunately often result in an over-exploitation of the resources that leads to destabilizing effects and to the detriment of the environmental health of mangrove ecosystems.

This thesis is the first to present data on the rate of carbon sequestration along mangrove soil's profile in the municipality of Laguna de Perlas. It was imperative to address the gap on carbon sequestration in mangrove soils in this area, in order to have documented data that demonstrate the rate of carbon sequestration and identify strategies to forestall environmental concern and contributes to the protection of mangrove ecosystems.

To meet the objective of this thesis, soil sampling, ecosystem inventory and interviews with five community leaders aware of historical and current conditions of the mangrove's ecosystems in their community was applied during the months of June to August 2018; soil samples were taken from seven sites with three respective sampling points/replicates from 0-20 cm, 20-40 cm and 40-60 cm soil depth at each sampling point. Soil's pH, bulk density, organic matter, organic carbon concentration and its respective recalcitrance with depth and mangrove species, as well as soil organic carbon stock were determined.

Four species of mangrove were found in the mangrove ecosystem in Laguna de Perlas: *Rhizophora mangle*, *Aviscennia germinans*, *Laguncularia racemos*o and *Peliciera rhizophorae*. Species diversity varied in all sites, though are considered very low -according to Shannon's and Simpson's diversity index. Mangrove soils contain considerable amounts of organic matter (4.45–68.89%) and carbon concentrations (2.22- 34.45%), as well as the overall soil organic carbon stocks (3.44 – 20.84 kg/m^2), with the highest amount sequestered at sites that presented the lowest species diversity. Thus, the latter is not the controlling factor on carbon sequestration in this study.

Structural composition of mangroves trees range from 13-31 cm DBH and 7-16 m height. Soil organic carbon stocks on the basis of mangrove's structure were 3.44 kg/m^2, 18.35 – 19.49 Kg/m^2, 20.83 kg/m^2, for senescence, mature and young mangroves respectively. Soils dominated by *Rhizophora mangle* contained the highest and most recalcitrant carbon. It is suggested that the rate of carbon sequestration by mangroves in Laguna de Perlas is controlled by the type of species and site specific physicochemical conditions.

A parallel trend between carbon accretions, its recalcitrance, nitrogen concentration, bulk density and pH values was observed. Values for these parameters varied throughout the soil layer depending on site specific physicochemical conditions in each ecosystem. For instance, Carbon sequestration and recalcitrance in the upper most examined soil layer (0-20 cm) was mainly controlled by soil texture, moisture content, anthropogenic disturbances and translocation of oxygen by mangrove species, whereas soil texture, fine roots and Grapsid crabs (*Grapsidae*) are considered influencing factors controlling the vertical distribution of organic carbon in the deepest examined soil layer.

Key words:

Carbon sequestration, carbon recalcitrance, mangrove species, soil

Zusammenfassung

In der Gemeinde Laguna de Perlas (nicaraguanische Südatlantikküste) wurden die Kohlenstoffbindungsraten in sieben verschiedenen Mangrovenökosystemen bestimmt. Mangroven sind in der Region von großer Bedeutung für die BewohnerInnen da diese direkt von den Waren und Dienstleistungen, die von Mangrovenwäldern bereitgestellt werden profitieren (Fischerei, Küstenschutz vor Naturkatastrophen oder anderen Naturereignissen, Bereitstellung von Holz für den Hausgebrauch).

Trotz dieser Vorteile sind Mangrovenwälder aufgrund der intensiven Eingriffe des Menschen stark bedroht (Entwaldung, Waldbrand, Entsorgung fester Abfälle). Dies führt häufig zu einer Übernutzung der Ressourcen und zu einer Destabilisierung des Ökosystems. Die vorliegende Arbeit liefert erstmals Daten zur Kohlenstoffbindungsrate des Mangrovenbodens in der Gemeinde Laguna de Perlas. Durch den Beleg der Kohlenstoffbindungsraten des Ökosystems können in weiterer Folge Strategien entwickelt werden, wie das Umweltbewusstsein gestärkt und der Schutz der Mangroven vorangetrieben werden Kann.

Für die Arbeit wurden in den Monaten Juni bis August 2018 Bodenproben genommen, Ökosystemparameter erhoben und Interviews mit führenden Vertretern der Bevölkerung durchgeführt. Die interviewten Personen wurden hinsichtlich der historischen und aktuellen Situation der Mangroven in ihrer Gemeinde befragt. Bodenproben wurden an sieben Stellen mit jeweils drei Wiederholungen untersucht. Dabei wurden je drei Proben aus einer Bodentiefe von 0-20 cm, 20-40 cm und 40-60 cm entnommen. Bei den untersuchten Bodenproben wurden der pH-Wert, die Schüttdichte und die organische Substanz ermittelt. Zudem wurden die organische Kohlenstoffkonzentration und ihre Stabilität in Abhängig von Bodentiefe und Art der Mangrove, sowie der organische Kohlenstoffbestand des Bodens bestimmt. In den Mangrovenwäldern der Laguna de Perlas wurden folgende vier Mangrovenarten gefunden: *Rhizophora mangle, Aviscennia germinans, Laguncularia racemoso und Peliciera rhizophorae*. Die Verteilung und Zusammensetzung der einzelnen Arten war an allen Standorten unterschiedlich und nach Shannon und Simpson wird diese (Species Diversity) als sehr gering eingestuft.

Die vorliegenden Mangrovenböden enthalten hohe Mengen an organischem Material (4,45–68,89 %) und Kohlenstoff (2,22–34,45%). Die gesamten organischen Kohlenstoffvorräte des Bodens machen 3.44 – 20.84 kg/m^2 aus. Die höchste Menge an gebundenem Kohlenstoff haben jene Standorte mit der geringsten Artenvielfalt. Somit ist die Artenvielfalt kein bestimmender Faktor für die Kohlenstoffbindung.

Die strukturelle Zusammensetzung der Mangrovenbäume reicht von 13 bis 31 cm BHD und 7 bis 16 m Höhe. Die organischen Kohlenstoffvorräte des Bodens auf Basis der Mangrovenstruktur betrugen 3.44 kg/m^2 bei alternden, 18.35 – 19.49 Kg/m^2, bei reifen bzw. 20.83 kg/m^2, für junge Mangroven. Böden, die von *Rhizophora mangle* dominiert wurden, enthielten den höchsten und stabilsten Kohlenstoff. Es wird vermutet, dass das Kohlenstoffbindungsvermögen von Mangroven in der Laguna de Perlas von der Pflanzenart und ortsspezifischen physikalisch-chemischen Bedingungen abhängt. Es wurde ein paralleler Trend zwischen Kohlenstoffansammlungen, seiner Rekonzentration, Stickstoffkonzentration, Schüttdichte und pH-Werten beobachtet. Die Werte für diese Parameter variierten in der gesamten Bodenschicht in Abhängigkeit von den ortsspezifischen physikalisch-chemischen Bedingungen in jedem Ökosystem. So wurde die Kohlenstoffbindung und -wiederaufnahme in der obersten untersuchten Bodenschicht (0-20 cm) hauptsächlich durch die Bodentextur, den Feuchtigkeitsgehalt, die anthropogenen Störungen und das Einbringen von Sauerstoff durch die Mangrovenarten beeinflusst. In den tiefsten untersuchten Bodenschichten stellen Bodentextur, feine Wurzeln und Krabben (Grapsidae) die wesentlichen Einflussfaktoren für die vertikale Verteilung von organischem Kohlenstoff dar.

Schlagwörter:

Kohlenstoffbindung, Kohlenstoffstabilität, Mangrovenarten, Boden

1. Introduction:

Between 1750 and 2011, cumulative anthropogenic CO_2 emissions to the atmosphere increased from pre-industrial era to 2040 ± 310 $GtCO_2$. This increase is mainly attributed to the combustion of fossil fuels and land use change (mainly deforestation). About 40% of these emissions have remained in the atmosphere (880 ± 35 GtCO2) and the rest was removed and stored on land (in plants and soils) and in the ocean (Thomas, 2013). Nowadays anthropogenic activities continues accelerating the increasing emission of atmospheric CO_2 which is recorded by NOAA (2019) to have reached a peak of 414.7 ppm in the month of May. Due to this increase and its potential impacts, there is a need to understand carbon sequestration within global ecosystems and its mitigating effort on climate change.

Mitigation is considered to reduce climate change impacts (IPCC, 2014), by halting or reversing it through management strategies (FAO, 2017) aimed at reducing the severity of global anthropogenic emissions (Thomas, 2013). Globally there is a strong interest in stabilizing the abundance of CO_2 and other greenhouse gases as a response to mitigate the risk of global warming (Lal, 2008). Efforts have been set forward, for instance, since the past 50 years, research on mangrove ecological functions, as the rate of carbon sequestration, has increased exponentially (Lee et al., 2014). The main research focus in this area was to understand how factors such as vegetation and climate, control organic carbon accumulation in soils and sediments and whether this process could mitigate CO_2 impacts on climate change (Jobbagy & Jackson, 2000). Mangroves ecosystems have thus proven to be widely recognized for their major role in contributing to the effects of climate change mitigation and adaptation (Taillardat et al., 2018) which is considered as a low-cost choice to reduce the content of atmospheric CO_2 (Houghton et al., 2001).

Mangroves are woody forests distributed along the coast in tropical and subtropical zones (Donato et al., 2011). They are considered the world’s most productive wetlands with a rapid rate of sequestration (Daniel M Alongi, 2012) and a large storage of carbon in their soils which has high carbon sink potential and thus contributes to a secure reduction and storage of CO_2 that would otherwise remain in the atmosphere (FAO, 2017; Metz et al., 2007). They are therefore considered as disproportionately important component in the global carbon cycle (Bhattacharyya et al., 2015) and in the regulation of both local and global climate (Pendleton et al., 2012).

Soil is globally the most important stores of carbon (Lal, 2008; Lehmann & Kleber, 2015) and wetland soils may contain as much as 200 times more carbon than the associated vegetation (Milne & Brown 1997; Garnett et al. 2001; (Lal, 2008). Different mangroves soil in tropical wetlands are peat-forming layers, through the accumulation of organic matter (Middleton & Mckee, 2016) originated from decaying tissues from the aboveground biomass (Chmura et al.,2003). This layer reach up to 10 m thickness (Mckee et al.,2007), which facilitates the accumulation of high concentration of carbon down the soil profile. Due to their soil's unique characteristics, saline, frequent flooding and anoxic conditions, carbon stored in mangrove soils can resist decomposition and therefore accounts for a considerable long term carbon sink (Middleton & Mckee, 2016; Tamooh et al., 2008) which unlike in terrestrial ecosystems, is a process that could continue over millennia (Mitra & Zaman, 2014).

Additionally to the aforementioned, mangroves among other coastal ecosystems are considered as 'important blue carbon resource' (Xiong et al., 2018) which is internationally recognized as an essential tool to contribute to climate change mitigation (Taillardat et al., 2018). They contain on average 1,023 Mg carbon per hectare, accounting for 98 % of the total carbon stored in their ecosystem. Mangroves are therefore considered as the most carbon-rich forests in the tropics (Donato et al., 2011). Annually they accumulate 26.1 Tg of organic carbon (Andreetta et al., 2014). Main contributors are tree growth, which influences vertical accretion and horizontal expansion rates in mangrove forests and leaf litter which continually deposits to the mangrove forest floor, and is incorporated into sediments through the consumption by Sesarmid crabs and other invertebrates (Alongi, 2014).

An estimate of global area covered by mangrove forest along the coasts of the world is roughly 137,760 km^2 (Giri et al., 2011).This area represent a small fraction of the tropical forest (Twilley et al., 1992). However, soil carbon content in mangrove forests is considered four to eight times higher than in any other terrestrial ecosystems (Huan et al., 2018) and are usually characterized by sediment accretion (Eagle et al., 2004), that could be distributed to significant depth soil profile (Chmura et al., 2003). Root formation and deposition, plays a crucial role in the vertical distribution of organic matter in mangrove soil (Middleton & Mckee, 2016) as it shapes the depth profile of labile fraction of organic carbon (Schrumpf et al., 2013).

On the other hand, it’s to be noted that the content of essential nutrients such as nitrogen, –which is efficiently accumulated by wetlands (Adame et al., 2015), phosphorus and sulphur are associated with soil organic carbon (Kirkby et al., 2011). This is because sequestering soil carbon depends upon the availability of stabilizing these elements which are essential components of the stable organic carbon pool (Himes, 1998 ; Lal, 2008). Thus, integrated management of these nutrients in soil is crucial for both the rate of biomass growth (Komiyama et al., 2008) and the enhancement of soil organic carbon sequestration (Himes, 1998). It’s noteworthy that the latter depends on both the type and diversity of mangrove species (Pandey et al., 2012; Hemati, 2015). Indeed, a mixed mangrove forest containing mature species store much more carbon than an immature monospecific forest (Alongi, 2011;Adame et al., 2013; Kauffman et al., 2014). This is because the interconnectivity and ecosystem health is greater in mixed forests, thus the overall ecosystem functionality suite a complete service (Kasawani et al., 2007).

Additionally to the above stated, the presence of a large pool of dead roots can serve as a nutrient conserving mechanism, and even large dead roots may serve this purpose. For instance, large trees with complex root systems, such a *Rhizophora* species, facilitate the deposition of particles to as much larger extent than trees that are smaller and of much simpler architecture (Alongi,2012).

Moreover, it is important to note that mangroves ecosystems provide multiple goods and services. They play important ecological and socioeconomic role (Bhattacharyya et al., 2015) by providing food and clean water (by filtering chemical and organic pollutants from the water) and thus contributing to the maintenance of the water quality, soil composition regulation, habitat for a variety of coastal and marine species and risk reduction (Murdiyarso et al., 2009). One of the important service provided by mangroves what will be further developed in this thesis is its key role as carbon sink through the sequestration of atmospheric CO_2. However, often the role of carbon storage in mangroves has been overlooked and either underestimated or overestimated (Daniel M Alongi, 2012).

Despite the major importance of mangrove ecosystems, globally they are under threat from increasing anthropogenic exploitation, reaching a loss of an alarming 1-3 % per year (Pendleton L., 2012). It is estimated that half of the world's mangrove have been loss in the past 50 years (Benson et al., 2017). Yearly 0.003 Pg CO_2 of sequestration potential are lost (Pidgeon, 2009). This loss of potential carbon sink (Vinod et al., 2018), has a negative impact on the ecosystem ability to store carbon, and thus, would effectively increase its emission back to the atmosphere (Pendleton L., 2012), which may result in higher concentration than occurred in terrestrial ecosystems (Vinod et al., 2018).

This thesis entitled "Carbon sequestration in soil of mangrove forest in Laguna de Perlas, Nicaragua", was carried out on the south Caribbean coast of Nicaragua, specifically in the municipality of Laguna de Perlas. There are four different species of mangroves in the Laguna de Perla's wetland: *Rhizophora Mangle* (red mangrove), *Aviscennia germinans* (black mangrove), *Laguncularia racemos*o (white mangrove) and *Peliciera rhizophorae*. These ecosystems are considered key part of the life cycle of many marine-coastal species in the study site, such as Snook (*Centropomus spp.),* tarpon (*Tarpon atlanticus*), mangrove snapper (*Lutjanus griseus*)*,* shrimp (*Penaeus and Trachypenaeus spp*) and blue crab (*Callinectes spp*) (González, 1997).

Inhabitants in Laguna de Perlas are direct stakeholders of environmental goods and services provided by mangrove ecosystems, which are among others; wood extraction for domestic use (timber for construction, firewood's and fishing gear), coastal barriers from natural phenomena/disasters and the provision of habitats for varieties of aquatic species, which increase the availability of aquatic resources for fishing to support the livelihood of coastal communities. Unfortunately, and regardless of their major services, mangroves ecosystems in the study area have been highly influenced by anthropogenic activities and have not been given the attention they deserve.

At a regional level, different projects have been carried out on creating awareness on the sustainable use of coastal ecosystems, as adaptation and mitigation efforts to the effects of climate change. IBEA-BICU in Consortium with HORIZONT 3000, (2012-2014) reforested 2.5 ha. of mangroves in “Puerto el Bluff” and the municipality of Corn Island. Similarly, a recent marine ecosystem project by IBEA-BICU (2019), has reforested 6.1 hectares of mangroves in 11 communities and 4 cays within the municipality of Laguna de Perlas, (of which the study sites are included; Haulover, Raitipura, Awas, San Vicente, La Fe, Pearl Lagoon, Kahkahbila), as part of its objectives to contribute to the recovery of mangrove forest in this municipality.

Additionally, there is an ongoing developing management plan, aimed at conservation and sustainable management of marine ecosystem and their respective biodiversity – including mangrove forest – in 18 different cays in the municipality of Laguna de Perlas (BICU & URACCAN, 2019). Similarly, there’s an ongoing reduction emission program aimed at reducing the concentration of atmospheric CO_2 on the northern and southern Caribbean Coast of Nicaragua by reducing the rate of forest deforestation, land degradation and expansion of agricultural frontier, in order to improve food security, biodiversity and adaptation to climate change (MARENA, 2018).

Still, to the best of my knowledge there’s no study at regional nor national level on carbon sequestration and its respective budget in mangrove soil/sediment in the municipality of Laguna de Perlas. Thus, this thesis is the first to document the rate of carbon sequestration in Laguna de Perlas. Data obtained will be useful for decision-makers, on the implementation of future projects for the management and protection of mangrove forest (increase the sink and reduce the source). Similarly, it will contribute to mitigating effects of climate change.

It was the aim of this study to determine the amount of carbon stored in mangrove soil and its recalcitrance in relation to soil horizons and mangroves species. The specific objectives were to:

1. Characterize selected mangrove ecosystems in terms of diversity and health.
2. Determine the content of organic–matter and concentration of organic carbon stored in mangrove soil.
3. Determine the recalcitrance of organic carbon stored in relation to soil horizons and mangrove species.

Within the framework of this study, the following questions were addressed:

1. How much carbon is being stored in soil facilitated by mangrove growth in "Laguna de Perlas?"
2. Are the amount and recalcitrance of carbon in soil controlled by ecosystem characteristics and mangroves species?

It is hypothesized that carbon sequestration in mangrove soil increase with increasing species diversity. To meet the objective of this thesis, surveys, observations *in situ* and laboratory experiments (pH measurements, Loss on ignition and Hot water soluble carbon) were used to characterize mangrove ecosystems in seven different communities within the municipality of Laguna de Perlas, and to determine soil carbon stock, it's accretion and recalcitrance in relation to soil horizons and mangrove species.

2. Methodology

2.1. Study site

This thesis was carried out in the mangrove ecosystems in the municipality of "Laguna de Perlas", located between the coordinates 12 ° 20' of North Latitude and 83 ° 40 'West Longitude, 49 km north of the municipality of Bluefields, and 475 km from the city of Managua Nicaragua, Central America. It's limits to the north with the river mouth of "Rio grande" and "el Tortuguero", to the south with Kukra Hill , to the east with the Atlantic ocean and to the west with "el Tortuguero and Kukra Hill, it has an approximate territorial extension of 3,876 km² (City hall, 2012).

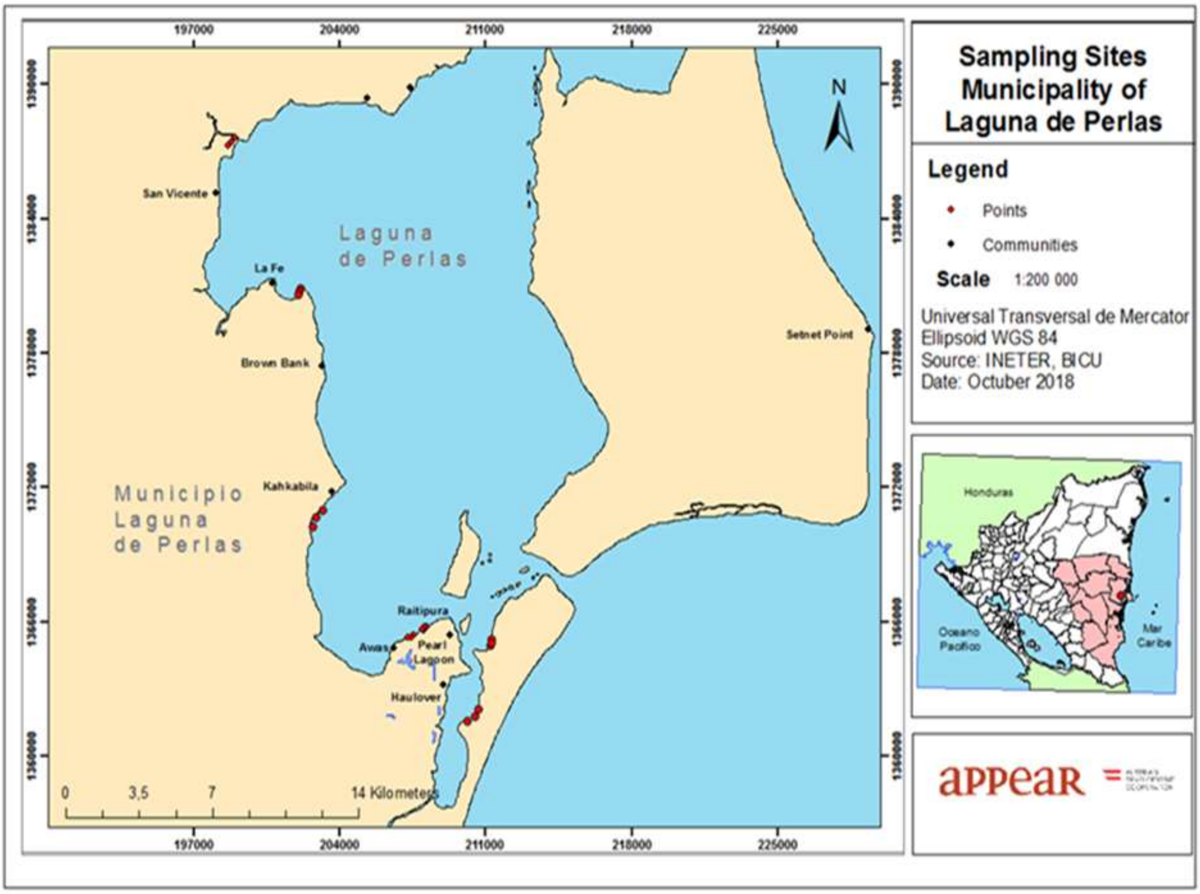

Figure 1: Geographical location of the seven sampling sites (red dots) in the municipality of Laguna de Perlas, South Atlantic Caribbean Coast of Nicaragua

2.1.1. Climate

The climate corresponds to the classification of Tropical Rainforest, prevailing in the lower parts of the Atlantic Coast, especially southeast of the coast. Due to its location on the costal line of the most humid municipalities of Nicaragua, annual precipitation is on average 5000 mm. The average annual temperature is 27 ^{o}C and the maximum temperature does not exceed 38 ^{o}C, and the temperature of the coldest months is higher than 18 ^{o}C (INETER).

2.1.2. Relief and soil

The landscape is characterize by a flat dominant to strongly wavy landscape with slopes ranging from zero to 15%. The slope of the terrain throughout the unit is irregular and dissected, and the areas are sectioned by an abundant system of natural drains, which offers good surface runoff (municipal record, 2008). The soils of the municipality of Laguna de Perlas have been developed from fine alluvial sediments, with abundant siliceous gravels and occasionally small pebbles basic igneous rock gravel worn by water. Both gravels and the sediment clays consist of very acid minerals, rich in silica and aluminum (City hall, 2008).

2.1.3. Land Use

According to the Municipal development plan 2010-2020 (City hall, 2012), land use is in an agro-ecological manner. The main crops are Musaceaes, roots and tubers, all planted on a small scale for consumption. However, the strong immigration of farmers to the municipality has caused an accelerated deterioration to the good management of natural resources and the uncontrolled advance of the agricultural frontier. This situation has been changing land use, by displacing forest through grassland and thus contributing to ecosystem degrading.

2.2. Sample sites

Sampled sites encompassed seven different mangrove ecosystem with varying characteristics, each corresponding to seven communities within the municipality of Laguna de Perlas. The trajectory to the communities is through the pearl lagoon, main body of water of the municipality. It connects naturally with the Caribbean Sea at its southeast end, through the point known as La Barra, located in front of the municipality, and has in its narrowest part (internal) 450 m and in the widest (external) 850 m. In this part, there are numerous islets, produced by the dredging of the lagoon in 1978 and covered vegetation, which serve as a refuge for various aquatic species.

Table 1: Description of sample sites, Laguna de Perlas, Nicaragua

Sample sites	**Description**
Haulover	The first sample site is located between the coordinates X: 21º 03’ 52’’, Y: 13 º 61’03.7’’. The mangrove ecosystem has an approximate area of 25 ha. (2.40 km away from the municipality of Laguna de Perlas). The site is dominated by a dense population of *Rhizophora mangle* (Red mangrove), situated at the edge of the ridge; followed by *Laguncularia racemosa* (white mangrove) and *Avicenia germinans* (black mangrove). The ecosystem is in association with *Raphia taedigera*, a species found on flat landscape and developed from organic material and lake sediments, histosoles and entisoles soils, and silty loam to loam black silty clay; with high contents of organic matter (MARENA 2004).
San Vicente	The second sample site (X: 19º 78’ 80.34’’; Y: 13 º 85’ 372’’) is situated 15 km away from the municipal headquarter of Laguna de Perlas. The mangrove ecosystem has an approximate area of 10 ha. Samples were taken around the river “Billan creek”, one of the principal river within the hydrography of the Pearl lagoon, situated between the sub-basins of Patch River and Wawashang, (Vanegas et al., 2015). At the entrance of the river, one can appreciate an extensive area of *Rhizophora mangle* in association with *Raphia taedigera*. At the end of the ridge, approximately 10 m away from the shore, the mangroves coexist at a smaller scale with

	Calophyllum brasiliense (Santa Maria) a commercial species with high economic value in the region.
Pearl Lagoon	The third sample area is located in Pearl Lagoon, a creole community; situated to the southern part at the entrance of the “pearl” lagoon within the municipality of Laguna de Perlas (X: 20 º89’24.14’’ Y:13 º 65’360.18’’). The mangrove ecosystem has an approximate area of 17 ha. in which three different species of mangroves coexist; *Rhizophora mangle* located at the edge of the ridge, followed by *Laguncularia racemosa* and *Pellicierra rizhophorae.* Generally, the ecosystem is associated with *Tracheophyta*.
La Fe	La Fe, a community, predominated by the Garifuna ethnicity , is located 13 km north of the municipality of Laguna de Perlas (X: 20º 21’18.30’’, Y: 13º 80’ 96.9’’). The mangrove ecosystem in this area is approximately 10 ha; dominated mainly by *Rhizophora mangle* (red mangrove) in association with *Raphia taedigera* and *Calophyllum brasiliense*.
Kahkabila	Kahkabila is a Miskitu community located 6.70 km south of the municipality of Laguna de Perlas (X: 20º 36’ 75’’, Y: 13 º 64’81.1’’); the mangrove ecosystem in this area is approximate 20 ha.; where a dense population of *Rhizophora mangle* (red mangrove) and at a smaller scale *Laguncularia racemosa* (white mangrove) dominates this site.
Awas	Awas is a Miskitu community located 1.82 km (X: 20º73’02.08’’ Y: 13 º 65’324.37’’) from the municipality of Laguna de Perlas. The mangrove ecosystem in this site is approximately 5 ha, dominated mainly by *Laguncularia racemosa* (white mangrove) in association with *Rhizophora mangle* (red mangrove).
Raitipura	Raitipura is another Miskitu community situated 1.62 km west of the municipality of Laguna de Perlas (X: 20º 86’69’’ Y: 13º 66’296’’). The mangrove ecosystem in Raitipura have an approximate area of 5 ha; dominated by *Laguncularia racemosa* (white mangrove) and *Rhizophora mangle* (red mangrove) in association with *pterophyta*

2.3. Methods and techniques for data collection

2.3.1. Literature review

Secondary information was reviewed to be acquainted with the study area in a general way, before data collection *in situ*. The seven communities have similar social and economic structure, considered fundamentally fishing communities combined with small scale agriculture which is usually implemented through agro-silvicultural systems, and the use of organic and chemical fertilizers (the portion of the latter varies with sites).

2.3.2. Data collection

Data collected *in situ* from August 06 to 20, 2018. Surveys were made to five leaders from each community who are aware of the affectations and changes that influenced the geography of their community over the past years.

a. Soil sampling

In order to determine bulk density, soil organic matter, carbon concentration and stock, as well as its accretion and recalcitrance, a total of 63 samples were collected from all seven sites, each corresponding to 0.25 ha. At every location, line transect method of 250 m x 10 m was establish across the whole area and divided into three sampling points/replicates (to assure representativeness of the samples) with a distance of 125 m respectively. Soil samples were then taken with a poste hole digger (9 cm width and 25 cm long), from 0-20 cm, 20-40 cm and 40-60 cm soil depth at each sampling point, and were weighed and placed in closed plastic bags with their respective label. Subsequently, samples were stored in a cooler, capable to maintain a stable temperature and avoid danger of contamination.

b. Species diversity:

The structural attributes of mangrove were assessed by a stratified inventory which was implemented in each sampled sites (0.25 ha); linear transect of 250 m x 10m was establish and subdivided into 3 plots of 20m x 40m across the whole area with a distance of 33 m between each plots. Height was determined in meter with a clinometer in order to calculate the average height of species per sampling point. Diameter at breast height (DBH) measured in cm, using a diametric measuring tape, was determined from all mangrove species within the plot with DBH ≥10 cm. DBH was measured from 1.30 m above ground level for all species except *Rhizophora mangle* (red mangrove), which measurements were taken from 30 cm above the last aerial root.

Species diversity was determined for all sampled sites by Shannon and Simpson's index. Shannon index indicates the representativeness and abundance of mangrove species:

$$\text{Shannon Index (H)} = - \sum_{i=1}^{s} p_i \ln p_i$$

Where, **p** is the proportion (n/N) of individuals of one particular species found (n) divided by the total number of individuals found (N), **ln** is the natural log, Σ is the sum of the calculations, and **s** is the number of species (Aguirre).The indicators for the result interpretation is detail in the following table:

Values	**Significance**
<1.5	Low
1.6 – 3.5	Medium
>3.5	High

High value of H would be representativeness of a diverse and equally distributed community and lower values represent less diverse community. If species are evenly distributed the H value would be high. Thus, the H value allows knowing the number of species and the abundance of species distributed among all species in the communities. Typical values are generally between 1.5 and 3.5 in most ecological studies, and the index is rarely greater than four. The Shannon index increases as both the richness and the evenness of the community increases (Kerkhoff, 2010). On the other hand, Simpson's index measures the probability that two individuals from a site belongs to the same species. The formula for calculating the value of the index (D) is:

$$D = 1 - \frac{\Sigma n(n-1)}{N(N-1)}$$

Where n is the number of individuals displaying one trait and N is the total number of all individuals. The value of D usually falls between zero and one. Zero represents complete uniformity and one represents complete diversity.

c. Ecosystem health

The health of mangrove ecosystem was determined following the methodology used for the evaluation of mangrove health in the Cuban Archipelago, (Menendez et al., 2006; Costa-Acosta et al.,2014) where the following aspects were taken into consideration: quantitative health index, natural regeneration of the forest and presence of attack by insects or other organism on the leaves.

d. Quantitative health index

The Quantitative Health Index was determined from the quotient obtained between the numbers of pressure identified in each sampled site on the total pressure on the study area. The result of the quotient was subtracted from 1 and multiplied by 100 to express it in whole numbers. From the obtained index, each level of mangrove health was identified following a scale ranging from: Very High (from 100 to 71), High (from 70 to 67), Medium (from 66 to 62), Low (from 61 to 42) or Very Low (41 or less) (Costa-Acosta et al., 2014).

e. Natural regeneration

The natural regeneration of mangrove forest and the presence of herbivory on their leaves was evaluated according to the following scale: scarce or null, not abundant, moderately abundant, abundant and very abundant.

2.3.3. Physicochemical parameters

a. Bulk density

Field moist samples obtained from all sites and their respective points were air dried for 3 days (the temperature in the region was 32 ^oC), then weighed to determine bulk density by the following formula: BD (g/cm^3) = dry weight (g) / soil volume (cm^3). Soil organic carbon was further calculated as a direct function of the concentration of organic carbon and bulk density: SOC= OC * BD * DH*0.1 in order to determine below ground carbon stock. Where SOC is the soil organic carbon stock (kg/m^2), OC (%) the concentration of organic carbon for each depth interval, BD is the bulk density (g/cm^3), DH is the soil thickness interval (cm) and 0.1 is the conversion factor to yield SOC in kg/m^2.

b. pH measurement

The values for pH (H_2O) were obtained from all samples by using a portable electrode with 5 g of air-dried soil. Prior to measurements, samples were sieved through a 2 mm mesh and mixed with 50 ml of dionized water. Mixtures were dispersed by using a shaker for 2 hours, and then settled for 30 min before measuring.

c. Loss-On-Ignition

The amount of organic matter and the concentration of organic carbon was determine from all samples by Loss on Ignition (LOI), a convenient assessment method used from the nineteen century to nowadays (Howard, 1965; Howard & Howard, 1990;De Vos et al., 2005; Pribyl, 2010; Chaikaew & Chavanich, 2017). LOI is a simple and rapid gravimetric technique in which the soil is heated to a temperature high enough to ignite organic carbon and release it as CO_2 (Wang et al., 1996). Samples preparation for LOI included the following steps:

- Air dried samples were sieve through a 2 mm sieved and then grinded in ceramic pestele bowl.
- An aliquot (15 g) of each samples was oven dried overnight at 105 ^oC to remove all contained moisture.

- Metal crucibles were heated in a muffle furnace at 550 ^{o}C for 1 hour, after extraction, cooled down in an exsiccator for 1 hour and subsequently weighed on a precision scale of 10^{-4} g.
- Samples were added to crucibles and weighed (weighed crucibles + samples)
- Finally, crucibles containing samples were ignited for 4 h at 550 ^{o}C in a muffle furnace. After extraction, the remaining samples were cooled for an hour in an exsiccator, followed by their post weight taken on a precision scale.

Values for organic matter (OM) were calculated from the following formula: %OM = Pre.W - Post.IW / Pre.IW*100 where Pre.W is the pre ignition weight and Post. IW the post ignition weight. The result was converted by a factor of 2 as an accurate conversion from the OM: SOC ratio, determined and recommended by various authors (Howard, 1965; Howard & Howard, 1990;De Vos et al., 2005; Pribyl, 2010; Chaikaew & Chavanich, 2017) to estimate the concentration of organic carbon in wetlands, based on the assumption that organic matter contains 50% carbon. Additionally, carbon accretion was obtained by the relationship between the concentration of organic carbon (per sampling point) stored at 3 different soil depths (0-20 cm, 20-40 cm, and 40-60 cm), to the respective species diversity per sampled sites.

d. Carbon recalcitrance

Carbon recalcitrance was obtained by extracting labile content of soil carbon by Hot-water-soluble carbon (HWSC) on a Shimadzu Total Organic Carbon analyzer. HWSC is a simple and reliable method (Weigel et al., 2011) to determine carbon recalcitrance , as it is a sensitive indicator of ecosystem changes, containing binding agents influencing soil aggregate stability (Atanassova et al., 2014).

Prior to the chemical analysis, two grams of air-dried soil (sieved with a 250-micron sieve) per sample were added to 100 ml of deionized water and placed on a shaker for 30 min and subsequently in a hot water bath at 70^{o} C for 18 hours. After extraction, the supernatant solutions were passed through a 20-µm sieve and then filtered through 0.45 µm syringe filters. A 9 ml portion of the solution was placed into separate capped test tubes and injected in the detection chamber for carbon analysis, where samples were burned at 680 ^{o}C and converted to carbon dioxide. This process was done through acidifying the samples with a small amount of hydrochloric acid to obtain a pH between 2 or 3. Carbonates were converted to carbon dioxide (CO_2) to eliminate the inorganic carbon contained in samples, leaving behind the Non Purgeable Organic Carbon (NPOC), which represents the recalcitrance fraction of carbon in the samples.

e. Nitrogen content of extracted HWSC samples

Nitrogen content was obtained from all samples, through the HWSC method on a Shimadzu TOC/TN analyzer, following the above mentioned procedures used for carbon recalcitrance. After the samples were burned in the combustion furnace, they generated nitrogen monoxide which is further cooled and dehumidified and enter a chemiluminescence analyzer where the total nitrogen was detected.

2.3.4. Data analysis

The one-way ANOVA method was used to determine descriptive statistics from all physicochemical parameters; evaluate the hypothesis of this thesis as well as determine statistical significance between sampled sites, their respective points and depth. Homogeneity of variance was conducted by Tukey's and Levene's test. A post-hoc test was subsequently used to determine and compare differences, in cases when ANOVA yielded significant difference (< 0.05). All statistical analyses were performed using IBM SPSS (version 25). ArcGis software was used to construct maps that depicts the geographical location of the study area and respective sampled sites. Excel, and R programming were used to create tables and figures to facilitate a visual understanding of the data.

3. Results

3.1. Species diversity per sample sites

Table 2: Species diversity at seven different sample sites in the municipality of Laguna de Perlas, Nicaragua. ("D" represents the values obtained by Simpson's index and "H", the results from Shannon's index).

Mangrove species	Site 1 Haul.	Site 2 S. V	Site 3 P.L	Site 4 La Fe	Site 5 Kah	Site 6 Awas	Site 7 R.pura	Sum	%
R. mangle	47	15	31	15	23	22	30	183	70
A.germinans	1	0	0	0	0	0	1	2	1
L. racemosa	7	0	13	0	11	16	22	69	27
P.rizhophorae	0	0	5	0	0	0	0	5	2
TOTAL								**259**	**100**
Σ Individual	**55**	**15**	**49**	**15**	**34**	**38**	**53**	**259**	
H	0.47	0	0.87	0	0.63	0.68	0.76		
D	0.26	0	0.53	0	0.45	0.50	0.52		

As shown in table 2, the vertical composition of the ecosystem (species diversity) varies with species and sampling site. The ecosystem in the municipality of Laguna de Perlas is characterize by four different species of mangroves: *Rhizophora mangle* (red mangrove) the predominant species; followed by *Laguncularia racemosa* (white mangrove) which occupies the second category in abundance; *Pellicierra rizhophorae* third in abundance and on a smaller scale very scares in abundance *Avicenia germinans* (black mangrove). A total of 255 individuals were evaluated, distributed in 7 sampling sites, of which the most dominant species with a total of 70 % correspond to *Rhizophora mangle*, followed *Laguncularia racemosa* with a 27 %, and a lesser contribution of *Pellicierra rizhophorae* with 2 % and *Avicenia germinans* with 1 %.

Results obtained from both Shannon and Simpson's indexes indicate that in Pearl Lagoon (site 3), the number of individuals per species is greater than in all other sampled sites, thus corresponding to a higher species diversity (see annex table 11 and 12 for the calculations). Unlike Pearl Lagoon, the lowest in diversity corresponds to the community of San Vicente and La Fe where only one species of mangrove with a low number of individuals was found, which is equivalent to a species diversity of zero in both sites. However, according to the effective number of species interpretation from both diversity indexes (Shannon's and Simpson's) all sampled sites present a low species diversity and distribution, which could influence the ecosystem services in the study area, since an increase in mangrove tree diversity, may result in an increasing ecosystem services provided by mangrove forests (Twilley et al., 1996; Mackenzie et al., 2016).

3.2. Diametric and height characterization of mangroves

Figure 2: Measuring DBH-mangrove ecosystem in Raitipura, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

Average DBH and height were measured in order to relate with the species diversity and disturbances in all sampled sites (figure 2). Values ranged from 13 to 31 cm and 6.57 m – 16m, respectively (table 3) *A. germinans* is the species on average with greatest DBH (31cm) and height (16 m), followed by *L. racemosa* which has an average DBH of 22 .4 cm and height of 22 m. Unlike these species *Rhizophora mangle and Pellicierra rizhophorae* had on average the lowest DBH and height. The species with both highest DBH and height were observed in the community of Haulover and Raitipura.

Table 3: Diameter at breast height (DBH) and height for mangrove species found in seven different mangrove ecosystem within the municipality of Laguna de Perlas, Nicaragua

Sample sites	Mangrove Species	DBH (cm)	Height (m)
Haulover	*R. mangle*	20.4	11.3
	A.germinans	31	16
	L. racemosa	22.33	22.4
San Vicente	*R. mangle*	13.8	8.07
Pear Lagoon	*R. mangle*	12.24	9.2
	L. racemosa	18.5	9.95
	P.rizhophorae	13	8
La Fe	*R. mangle*	12.8	7.17
Kahkabila	*R. mangle*	17.24	6.57
	L. racemosa	26	8
Awas	*R. mangle*	14.25	8.85
	L. racemosa	12.55	7.9
Raitipura	*R. mangle*	16.5	8.3
	A.germinans	17	10
	L. racemosa	17.17	12.13

3.3. Ecosystem health

According to interviews and observations *in situ*, three different anthropogenic activities or pressures were identified in the mangrove ecosystems in the sampled sites:

i. Clearance of trees

Figure 3: clearage of mangrove tree, Laguna de Perlas Nicaragua (source:Crista Stubb, August 2018)

In all sampled sites, there is a continuous human intervention in the mangrove ecosystem for the extraction of timber (image 3), which is used in the construction of fishing gear, infrastructure as well as for fire woods. The clearance of mangroves is greater in the communities of Haulover and Kahkabila where rural families are settled near the ecosystem and rely on the usage of the timber to meet some of their needs at the expense of the mangrove forest.

ii. Forest fire


Figure 4: Forest fire in mangrove ecosystem, Haulover, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

Forest fire in mangrove's ecosystem is a common practice implemented by community members in Haulover (figure 3) for the hunting of wild life and plantation of rice (*Oryza sativa*) during the dry weather seasons (February – April), as it presents optimal conditions for the crop productivity. The fire is usually provoked among *Raphia taedigera* and advance towards the mangroves (since there is an association between species), which influence the dynamic of the ecosystem, thereby causing significant losses in the biodiversity of this area.

iii. Garbage disposal


Figure 5: Accumulation of Solid waste at the entrance of mangrove ecosystem- Awas, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

The direct disposal of solid waste is another inadequate practice implemented in all sampled sites, with greater accumulation in the community of Awas due to its location in the populated area, at the edge of the road that connects the community with the municipality of Laguna de Perlas. Thus, there is a frequent accumulation of domestic waste both at the entrance and inside the ecosystem. Additionally, it's important to note that the affectation by transit and domestic liquid effluent can directly or indirectly influence the ecosystem health as well.

3.3.1. Natural regeneration

Figure 6: Seedlings of mangrove species in Haulover, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

The natural regeneration of the mangrove's ecosystems (figure 5) serves as a physical indicator of its health and stability. A good regeneration in the ecosystem favors the maintenance of the mangrove in time (Costa-Acosta et al. 2014). In the communities under study the regeneration varies with location and species. In Pearl Lagoon, Awas, Haulover and Raitipura the level of natural regeneration is abundant (*Rhizophora mangle, Laguncularia racemosa* and *Pellicierra rizhophorae)*, medium abundant in La Fe (*Rhizophora mangle)*, not abundant in Kahkabila (*Rhizophora mangle, Laguncularia racemosa)* and scarce in San Vicente (*Rhizophora mangle)*.

3.3.2. Reproductive phenology

Reproductive phenology such as flowering and fructification, was observed in all sampled sites except La Fe and San Vicente. In Haulover and Pearl Lagoon, the presence of flowers and seeds or propagules was present on species of *Rhizophora mangle* and *Laguncularia racemosa*; in Raitipura and Awas the majority of the *Laguncularia racemosa* presented flowers and fruits (figure 8). Whereas in Kahkabila approximately 80 % of all species (*Rhizophora mangle)* had flowers and fruits (figure 7).

Figure 8: *R.magle* with Propagules, Kahkabila, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

Figure 7: *L.racemosa* with fruits, Awas, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

Figure 9: *R. mangle* with Propagules, Kahkabila, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

In incontrast, both flowers and propagules (figure 9) on mangrove trees in Kahkabila are vulnerable to dispersal by abiotic factors such as wind, currents, tidal forces, (Marchand et al., 2004; Mckee, 1995) as well as by rainfall events (Twilley, 1985).These are factors that could negatively affects the recruitment of seedlings to the forest, and influence its community structure.

3.3.3. Damages to leaves

Herbivory on the leaves (figure 10) was observed on all mangroves species, but more abundantly in *Rhizophora mangle*; medium abundant in *Laguncularia racemosa*; null in *Avicennia germinans* and *Pellicierra rizhophorae*. Similarly, abundant damages to leaves was detected on seedlings in regeneration. On the other hand, chlorosis and necrosis (figure 11) were also observed on mangrove leaves, followed by their death (leaf drop). The damages were severe on *Rhizophora mangle* compared to the other species, where the damage was scarcest.

Figure 11: Herbivory on *R. mangle* leaves, Haulover, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

Figure 10: Chlorosis on *R. Mangle* leaves, Kahkabila, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

Figure 12: Damages on *R.mangle* stem at Pearl Lagoon and Kahkabila, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

Similarly, rots and gall disease were observed on the stems of *Rhizophora mangle* (figure 12). This disease is caused by the fungus Cylindrocarpon didymium which is developed by an indoleacetic acid produced by the fungus and occurs on branches, trunks and prop roots of trees and is very common on *Rhizophora mangle* (Barnard & Freeman, 1982).

Considering the aforementioned environmental and esthetic problems facing mangrove's ecosystems in the municipality of Laguna de Perlas contribute to a continuous alteration of the natural structure and function of the ecosystems to the detriment of its health and stability. According to the ecosystem health index, the mangrove ecosystems in Haulover, Kahkabila and Pearl Lagoon has a low health, and the pressures influencing them are close to its resilience threshold. On the other hand, the ecosystem health in San Vicente, La Fe and Awas and Raitipura is higher, because the intensity of the pressures on the ecosystem does not exceed the resilient threshold and the ecosystem still maintain its environmental services.

3.4. Organic matter content

Total organic matter stored in mangrove's soil varies among the seven different sampled sites. Values range from 4.45- 68.89% (table 4), with the highest amount exhibited in La Fe and lowest in Kahkabila which is on average 64% different (*p* = 0.000). Intermediates values are reported in Haulover with 51.62 % (*p* = 0.42), which is only 13.83 % different from that found in La Fe. Differences in edaphic properties which are crucial for the maintenance of soil organic matter (Cerón-Bretón et al., 2014), was observed in all sampled sites. The apparent soil type differs from black organic soil (Haulover, Pearl Lagoon, San Vicente, La Fe, Awas) to a sandy type (Kahkabila and Raitipura). Similarly, the apparent soil moisture varies from one site to another, Haulover, San Vicente, Pearl Lagoon, La Fe and Kahkabila are characterize as the most saturated soils, with the latter being the most flooded. Unlike these ecosystems, the mangroves in Awas and Raitipura are less flooded.

Table 4: Organic matter content (%) from seven mangrove ecosystem in Laguna de Perlas, Nicaragua (mean and standard deviation of three replicates in relation to soil depth are shown)

Sample sites	**Organic matter content (%)**			**Total mean (%)**
Soil depth	**0-20 cm**	**20-40 cm**	**40-60 cm**	
Haulover	61.51 (±4.39)	44.80 (±30.61)	48.53 (±35.52)	51.62
San Vicente	26.09 (±19.56)	37.98 (±6.06)	44.09 (±24.80)	36.06
Pearl Lagoon	15.22 (±7.67)	21.37 (±12.33)	37.96 (±24.92)	24.85
La Fe	67.63 (±4.87)	74.32 (±8.14)	64.73 (±5.14)	68.89
Kahkabila	5.02 (±2.86)	3.48 (±0.47)	4.85 (±2.28)	4.45
Awas	7.44 (±2.79)	8.92 (±4.88)	17.46 (±7.36)	11.27
Raitipura	42.60 (±13.28)	30.05 (±24.92)	40.89 (±30.02)	37.84

Figure 13: Senescence *R. mangle*-Kahkabila, Laguna de Perlas,Nicaragua (source: Crista Stubb, August 2018)

High amount of sedimentation (including garbage) was observed along the mangrove fringe in Kahkabila. However, and despite the productive characteristics of mangrove trees (as mentioned earlier), still Kahkabila is the area with the lowest concentration of organic matter. As shown in figure 13, the mangroves at this site are stress and the different influencing factors could be impeding the rate of organic matter accumulation within the ecosystem.

3.5. Organic carbon concentration

The concentration of organic carbon obtained by LOI, varies in sampled sites, their respective replicates (annex table 13) and soil depth. The spatial variability follows the order, La Fe (34.45%), Haulover (25.81%), Raitipura (18.92%), San Vicente (18.03%), Pearl Lagoon (12.43%), Awas (8.33%) and Kahkabila (2.22 %). Carbon concentration at La Fe is significantly different from all sites (p =0.001), except Haulover (p =0.26), where the second to highest values are reported and edaphic properties are similar to that of La Fe.

Figure 14: Grapsid crabs at La Fe, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

This is obvious for example in both Haulover and La Fe, with a black organic (muddy) very humid soil (the latter is most flooded) with the presence of high numbers of Grapsid crabs, which usually inhabit typically carbon rich sediments (Alongi et al., 2005). Unlike these sites, soil in Kahkabila is characterized by a more sandy type with less presence of Grapsid crabs.

Figure 15, depicts the vertical distribution of carbon concentration along soil profiles. Values tendentially increased with increasing soil depth at Awas, Pearl Lagoon and San Vicente and slightly decreased with depth in Raitipura, Kahkabila, La Fe and Haulover. The highest values were observed at La Fe in the second horizon (20-40 cm) which contained an average 37.16% organic carbon and the lowest at Kahkabila with only 1.74% OC in the second horizon (20-40 cm), which is highly significant from that in La Fe ($p < 0.0001$). At the deepest examined soil horizon (40-60 cm), a significant amount of fine roots was encountered in samples, which serves as an indicator of the enrichment of organic carbon in subsoil as roots are important source of carbon (Tue et al., 2012).

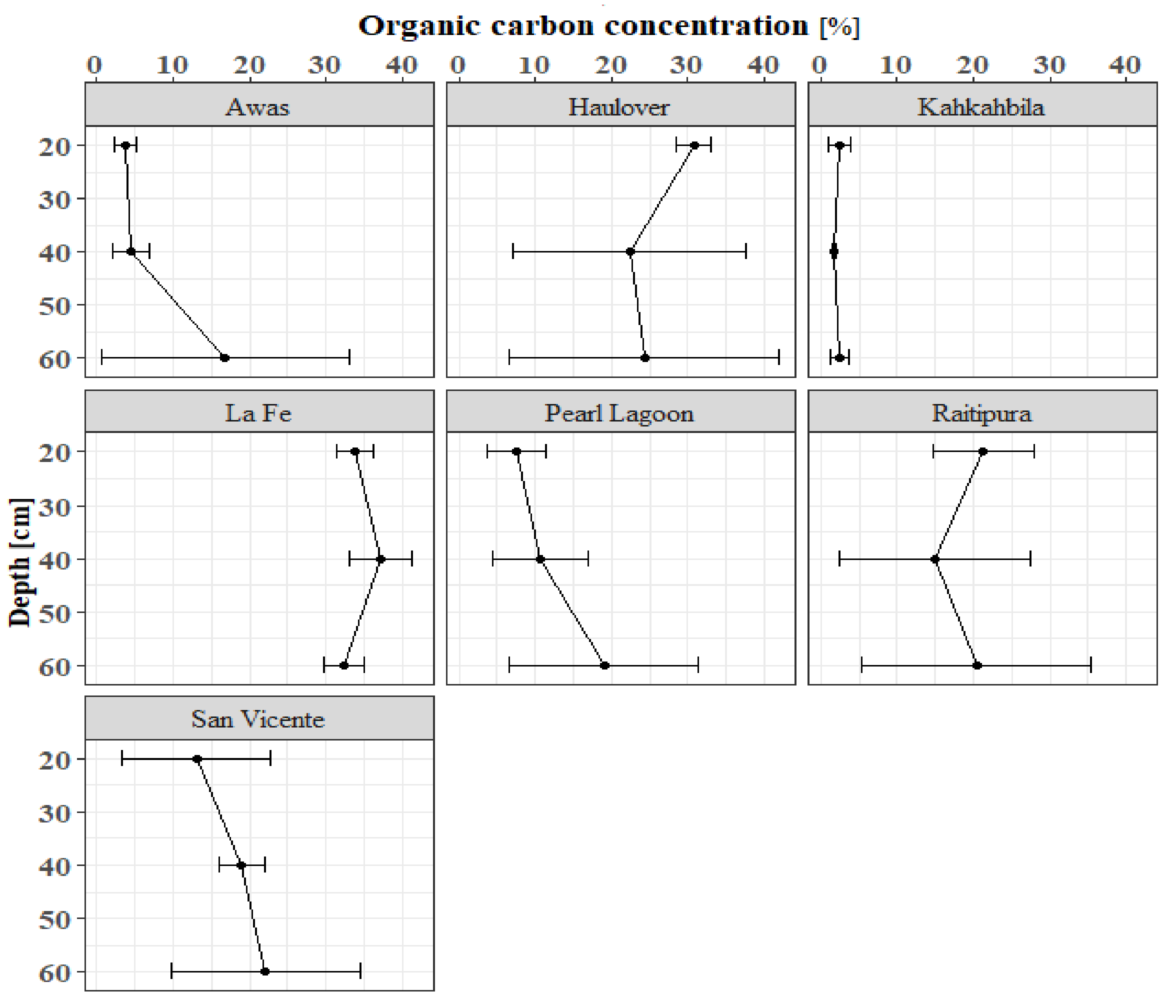

Figure 15: vertical distribution of organic carbon concentration obtained by loss on ignition for seven sampled sites and their 3 respective replicates in the mangroves ecosystem in Laguna de Perlas, Nicaragua. (Mean and standard deviation are shown throughout the soil profile from 0-20 cm, 20-40 cm and 40-60 cm).

3.6. Nitrogen concentration of extracted HWSC samples

Nitrogen concentration differs among sites, the highest concentration was observed in the community of La Fe (3.1 mg/L) and the lowest in Awas (0.84 mg/L). Per sampling point, both the highest and lowest concentration was observed in sampling point 1 in the first mangrove fringe, and in all the sampled sites except Kahkabila and Haulover where there's a similar trend in the rate of total nitrogen towards depth (Appendix table 13). Figure 15, depicts a highly significant linear relationship between carbon concentration and total nitrogen (R=0.91, $p < 0.0001$). The conspicuous parallel trend between carbon and nitrogen sequestration, indicates that increasing concentration of nitrogen is coupled with organic carbon. For instance, in Raitipura, at sampling point 1, there is an increasing concentration of carbon with increasing nitrogen compared to the other two sampling points (Annex table 13).

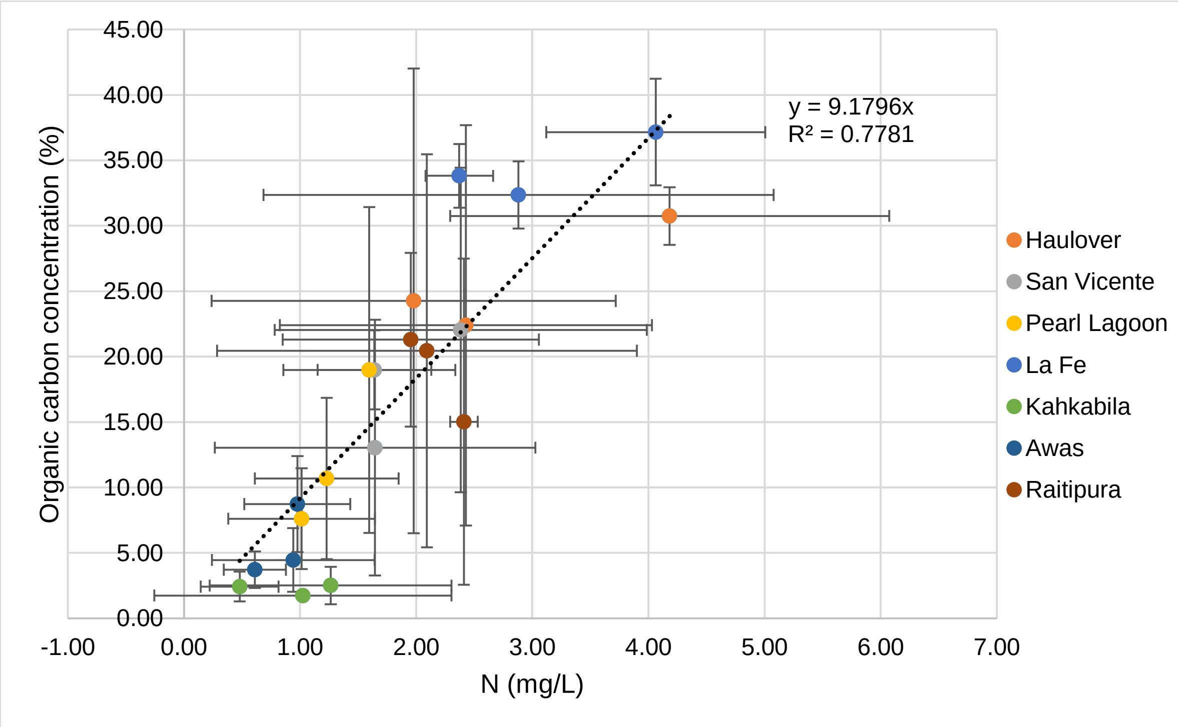

Figure 16: Correlation between nitrogen (of extractable HWSC) and carbon concentration (obtained by LOI) for seven sampled sites within the municipality of Laguna de Perlas, Nicaragua. Mean and standard deviation of the vertical distribution throughout soil depth (0-20 cm, 20-40 cm, 40-60 cm) and their respective replicates are shown.

3.7. Bulk density

Values for bulk density varied between sampling sites. Soil compactness was greater in the community of Kahkabila at the second examined soil horizon (20-40 cm) with a mean bulk density of 0.42 g/cm^3 (± 0.01) due to the apparent higher mineral content. Unlike Kahkabila, the lowest values for bulk density was exhibited in the community of La Fe, at the upper soil horizon (0-20 cm) which is on average only 0.14 g/cm^3 (± 0.01) owing to the highest amount of organic carbon than all other sampled sites. A perfect negative relationship between carbon concentration and bulk density is reported in all sampled sites (figure 17). With an increasing concentration of organic carbon its respective bulk density decrease in a non linear way. thereby resulting in an inversely relationship between both paramenters.

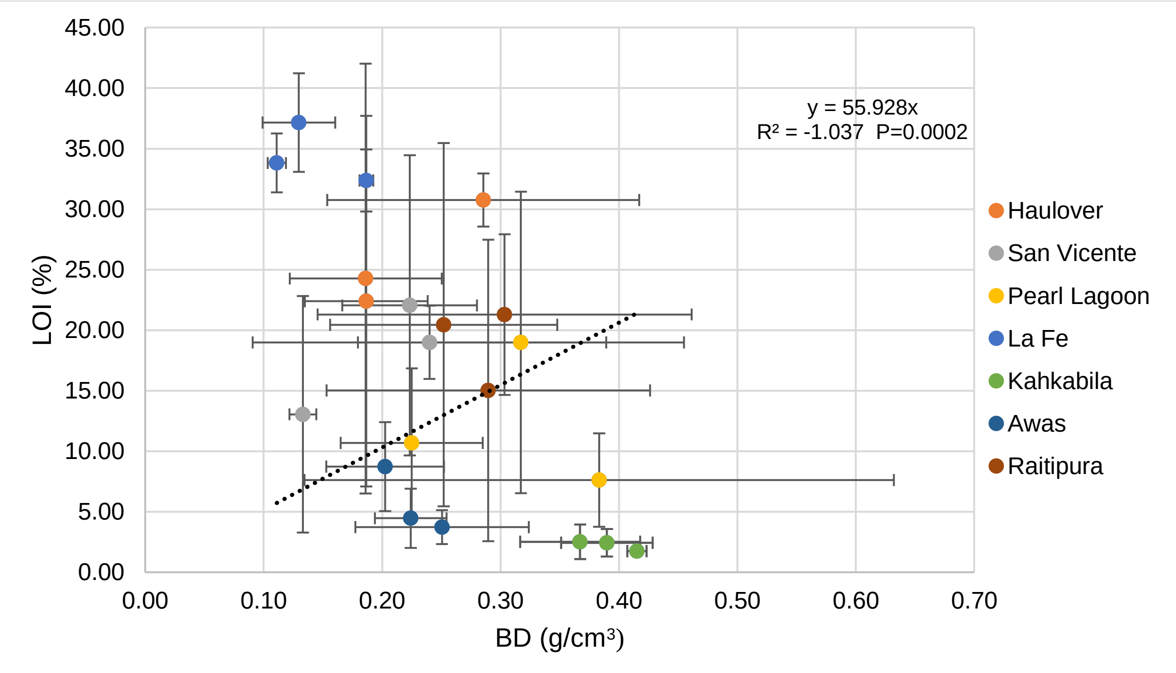

Figure 17: Correlation between bulk density (BD) and carbon concentration (obtained by Loss on Ignition "LOI") for seven sampled sites within the municipality of Laguna de Perlas, Nicaragua. Mean and standard deviation of the vertical distribution throughout soil depth (0- 20 cm, 20-40, 40-60 cm) and their respective replicates are shown.

3.8. Belowground Carbon Stock

According to ANOVA, values for SOC displayed significant spatial differences ($p = 0.05$). Highest values are reported in La Fe (20.84 kg/m^2) site with young mangrove forest and the lowest in Kahkabila (3.44 kg/m^2) mature mangrove sampling site. Intermediate values are reported in Raitipura (19.49 kg/m^2) and Haulover (18.35 kg/m^2), sites with mangroves that are both the tallest and greatest in DBH. These values are averages of carbon mass from all sampled sites and their respective replicates. Additionally, the belowground carbon stock for all sampled sites in relation to their respective species diversity is shown in table 5. Results reveals that La Fe, even though with a diversity index of zero (according to both indexes) has the greatest potential to sequester and store atmospheric CO_2 compared to all other sites. In the first sampling point at La Fe, the number of individuals encountered was higher (5 individuals; SOC = 20.23 kg/m^2) than in point 2 (3 individuals SOC = 22.88 kg/m^2) where the highest amount of SOC was stored. Similarly, in Kahkabila, the number of individuals were greater (16 individuals; SOC = 2.60 kg/m^2) at sampling point 3. This result indicate that Species diversity is not the main factor controlling the fate of sequestration in mangrove soil.

Table 5: Soil organic carbon stocks for seven sampled sites in Laguna de Perlas, Nicaragua (Values are averages from three replicates and their respective soil depth)

Sample sites	**SOC (**kg/m^2)	**Shannon Index (D)**	**Simpson Index (H)**
Haulover	18.35	0.26	0.47
San Vicente	17.97	0	0
Pearl Lagoon	15.48	0.53	0.87
La Fe	20.84	0	0
Kahkabila	3.44	0.45	0.63
Awas	9.14	0.5	0.68
Raitipura	19.49	0.52	0.76

3.9. Carbon recalcitrance

As shown in figure 17, carbon recalcitrance slightly varied between sampling sites. The most labile fraction of organic carbon was observed at the upper most examined soil layer (0-20 cm) for all sampled sites except Haulover (*p* = 0.09) and Kahkabila (*p* = 0.05) where the organic carbon is more stable at the first horizon and decreased towards depth. On the other hand, semi-labile fractions of organic carbon is present in the second soil horizon (20-40 cm) and the most recalcitrant carbon was found in the deepest examined soil layer (40-60 cm), as indicated by the greater dilution in HWSC.

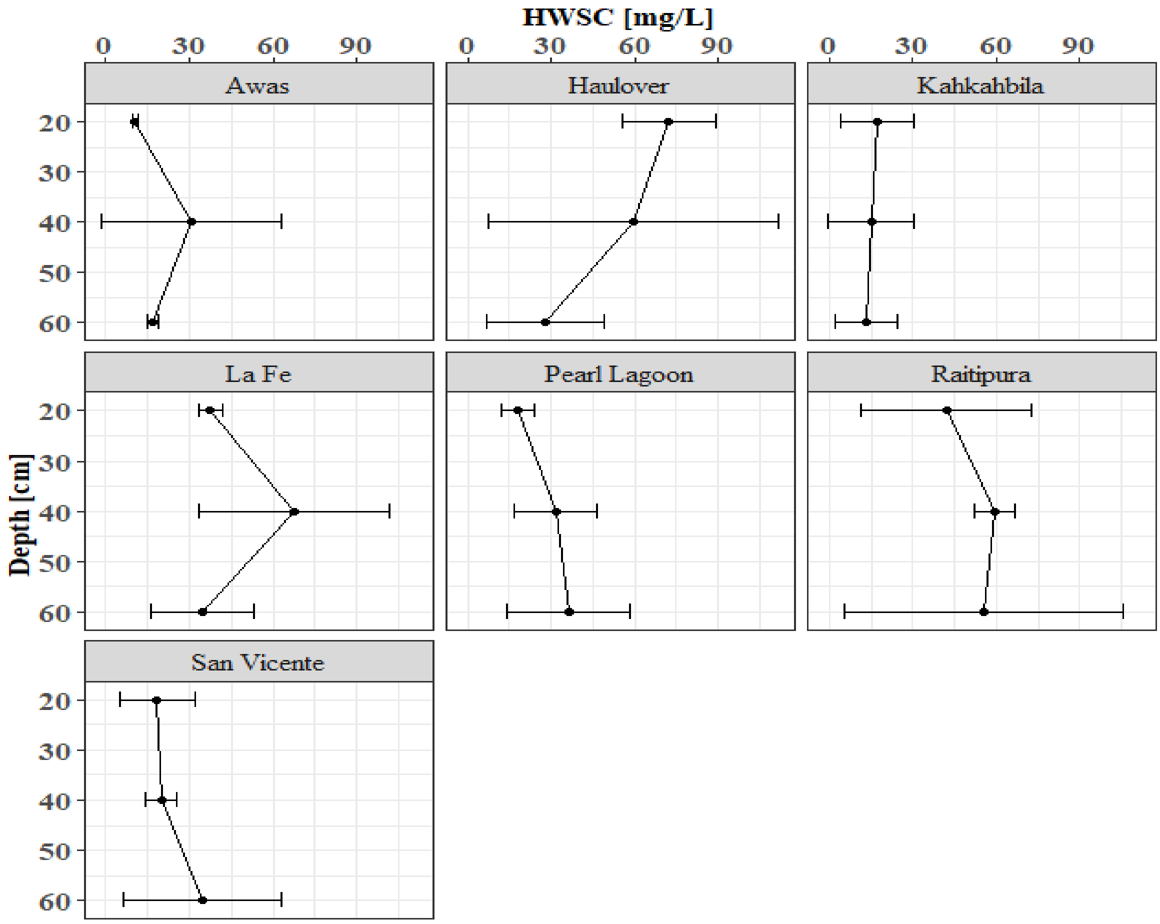

Figure 18: Vertical distribution (0-20 cm, 20-40 cm, 40-60 cm soil depth) of Hot Water Soluble Carbon from seven sample sites in Laguna de Perlas, Nicaragua (mean and standard deviation of three replicates are shown).

3.9.1. Carbon sequestration-recalcitrance in relation to species

Figure 19: *Rhizophora mangle*, La Fe, Laguna de Perlas, Nicaragua (source: Crista Stubb, August 2018)

Rhizophora mangle (figure 19) is the dominant species in all sampled sites and their respective points, except in the third sampling point at Kahkabila and Awas which is dominated by *Laguncularia racemos*; and Raitipura point 2 and 3, by *Laguncularia racemos* and *Pelliciera Rizhophorae* respectively. Disintegrating Raitipura into sample points, table 6 depicts the highest belowground carbon storage in the first point; however, carbon in the latter is less recalcitrant (p = 0.06) than the other points in the same site. Unlike *Rhizophora mangle,* sample points dominated by *Laguncularia racemosa* and *Pelliciera rizhophorae* are found on sandy type soil with less moisture content and higher bulk density, and thus contribute to a less residence time of organic carbon in the soil.

Table 6: Belowground carbon stock for seven mangrove ecosystem in Laguna de Perlas, Nicaragua (values shown are means and standard deviation of three replicates), on the bases of dominant mangrove species found in each site

Sample Sites	**SOC (kg/m²)**	**HWSC (mg/L)**	**Dominant Species**
Sample point 1.			
Haulover	20.15 (±6.06)	22.79 (± 31.66)	*R. Mangle*
San Vicente	10.86 (±7.23)	25.30 (± 6.11)	*R. Mangle*
Pearl Lagoon	20.85(±7.99)	42.52 (± 17.92)	*R. Mangle*
La Fe	20.27 (±13.53)	43.89 (± 11.07)	*R. Mangle*
Kahkabila	4.63 (±3.76)	7.21 (± 0.61)	*R. Mangle*
Awas	5.11 (±3.43)	32.66 (± 30.35)	*R. Mangle*
Raitipura	31.68 (±8.77)	30.84 (± 21.98)	*R. Mangle*
Sample point 2.			
Haulover	22.99 (±12.26)	79.32 (± 24.35)	*R. Mangle*
San Vicente	11.26 (±5.39)	18.01 (± 2.29)	*R. Mangle*
Pearl Lagoon	10.59 (±8.86)	18.39 (± 4.82)	*R. Mangle*
La Fe	22.88 (±15.96)	59.54 (± 41.17)	*R. Mangle*
Kahkabila	3.08 (±0.91)	17.10 (± 14.02)	*R. Mangle*
Awas	16.74 (±26.49)	10.67 (± 3.74)	*R. Mangle*
Raitipura	14.87 (±13.72)	68.77 (± 39.51)	*L. Racemosa*
Sample point 3.			
Haulover	12.86 (±12.73)	37.65 (± 27.98)	*R. Mangle*
San Vicente	31.64(±28.89)	29.37 (± 33.47)	*R. Mangle*
Pearl Lagoon	15.00 (±20.91)	25.05 (± 13.90)	*R. Mangle*
La Fe	19.36 (±13.98)	36.40 (± 16.87)	*R. Mangle*
Kahkabila	2.60 (±1.48)	21.43 (± 14.46)	*L. Racemosa*
Awas	5.57 (±4.06)	14.47 (± 3.20)	*L. Racemosa*
Raitipura	11.91 (±10.56)	57.46 (± 23.85)	*P.Rizhophorae*

On the other hand, it's noteworthy that nitrogen concentration was significantly correlated to carbon recalcitrance ($R = 0.77$, $p < 0.000$). As shown in figure 20, the concentration of nitrogen tended to be highest in sites where the concentration of carbon was also the highest, since recalcitrant or stable fraction of soil organic carbon contributes mainly to soil's nutrient holding capacity (FAO, 2017).

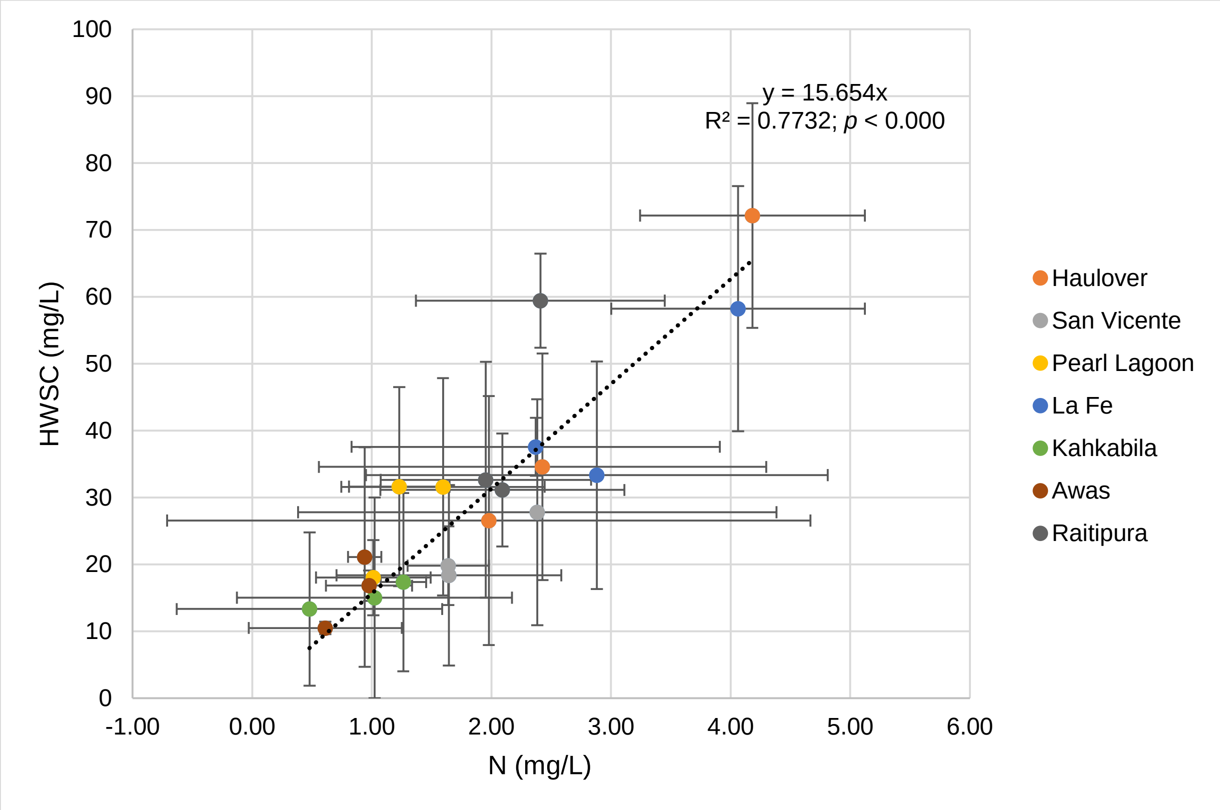

Figure 20: Relationship between nitrogen concentration and carbon recalcitrance (obtained by Hot water Soluble Carbon) for seven sampling sites within the municipality of Laguna de Perlas, Nicaragua. Mean and standard deviation of three replicates in relation to soil depth (0- 20 cm, 20-40, 40-60 cm) are shown.

3.10. Mangrove Soil pH

The pH values of mangrove soils reported herein were acidic to almost mild acidic, with values ranging from 3.4 ± 0.06 (Kahkabila) to 6.2 ± 0.58 (Raitipura), as a function of soil depth. As depicts in figure 19, pH values slightly differed ($p > 0.05$) throughout the soil profile with an increasing tendency towards depth at Haulover, Pearl Lagoon, La Fe, Awas, and Raitipura and decrease with depth at San Vicente and Kahkabila.

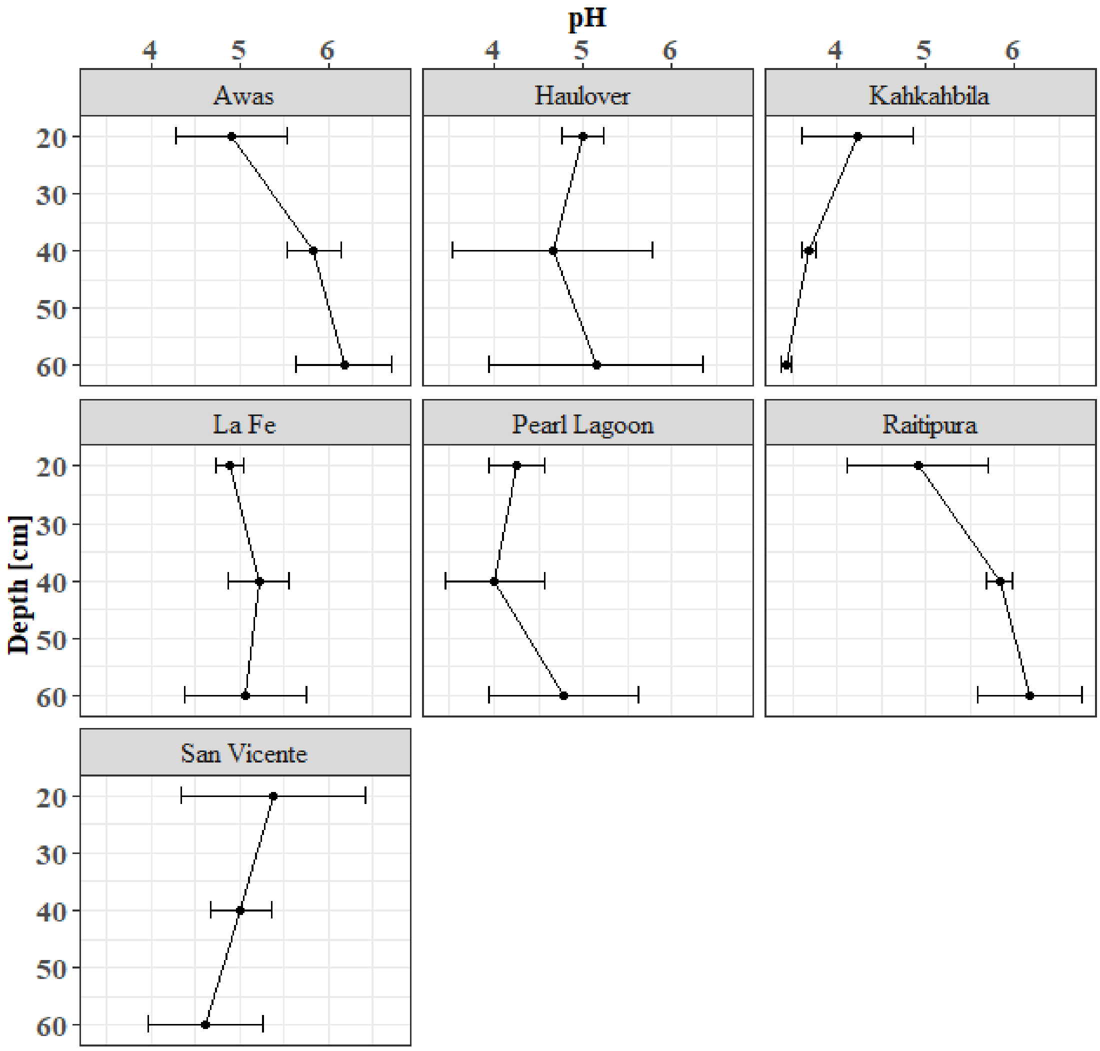

Figure 21: Depth distribution of mangrove soil's pH for seven different mangrove ecosystems within the municipality of Laguna de Pelas South Caribbean Coast of Nicaragua. Mean and standard deviation of the vertical distribution throughout soil depth (0- 20 cm, 20-40, 40-60 cm) and their respective replicates are shown.

4. Discussion

4.1. Species diversity and health of mangrove ecosystem

Mangrove forests in Laguna de Perlas are mainly dominated by *Rhizophora mangle*, a species which was recorded as frequently distributed at a regional level along the Caribbean and pacific Coast of Nicaragua (González, 1997). This species is considered the most tolerant type of mangrove to high concentrations of salinity and flooded substrate (Chan-keb et al., 2018), it also represents an important source of food, shelter and habitat for at least 32 species of fish and invertebrates (González, 1997). Similarly, root systems of *Rhizophora mangle* are an important area of nurseries for these species and the organic matter that they generate from the base of the food chain of the coastal lagoons.

On the other hand, the Neotropical species *Pellicierra rizhophorae* is one of the scarcest mangroves in Laguna de Perlas due to different influencing factors on the mangrove ecosystem and its respective habitat. This species is distributed in small patches along the Caribbean coast of Nicaragua (Castillo-cardenas et al., 2015) and is listed on the IUCN red list as a threatened species due to hurricanes that occurred in Nicaragua in the late 1920s (Roth, 1992). The spontaneous seasonal variability (rainy and dry season) on the Caribbean coast of Nicaragua could also hinders populations of *Pellicierra rizhophorae* to recover naturally over time. Indeed, parameters such as rainfall events and temperature directly influence the concentration of salt in soils dominated by *Pellicierra rizhophorae* and given the fact that this species is intolerant to high concentration of salts (Castillo-cardenas et al., 2015), abrupt climatic variability could directly influence its spatial distribution.

A further example of the negative influence of hurricane on mangrove forest, is the low species diversity in La Fe and San Vicente (sites with diversity index of zero). Compared to the other sampled sites, coastal communities located northern part of Laguna de Perlas –where La Fe and San Vicente are situated– were severely destroyed by Hurricane Joan which occurred on the south Caribbean coast of Nicaragua in 1988 (City hall, 2012). As a response to this devastating event, it is speculated that mangrove forests in both La Fe and San

Vicente were not resilient enough to maintain in time and that only a small number of individuals had recovered over time. Similarly, the low species diversity could probably due to the topographical and hydrological characteristics of the area that hinders the growth of mangrove species, which according to Schaeffer-novelli et al. (1990) are characteristics that influence mangrove's diversity and structure. The overall low species diversity in all sampled sites is suggested to be mainly attributed to site specific conditions.

The structure and functions of mangrove forest are greatly threaten by anthropogenic and natural disturbances that hinders species growth and optimal development. For example, the low number of individuals of *Avicennia germinas* (especially the larger ones) are suggested to be mainly related to the harvesting of mangrove wood. This is mainly because *Avicennia germinas* is the species with the greatest DBH and height. Therefore in terms of volume, this species yields the most wood to local stakeholders of mangrove forest.

Relating the above mentioned to the distribution of *R. mangle*, it is suggested that the latter is utilize less by communities' members since it is the species with the smallest DBH and height. Therefore the production of wood is less compared to the others species. The DBH and height of mangrove forests play an essential role in shaping mangrove ecosystems since they serves as an indicator of the level of stress under which the forests are subjected to. For instance, due to the location at the first fringe in the mangrove forest, *R. mangle* is considered the most vulnerable species to natural disturbances which greatly modifies the physiological characteristics of mangroves (Chan-keb et al., 2018)**.** This could be seen for example with the height of mangrove trees; natural factors such as increase in salinity, and/or decrease in nutrients, (Gomez & Menendez, 2006) as well as soil fertility (Hossain & Nuruddin, 2016) are considered influencing factors that decrease both the height and distribution of mangrove species (Twilley & Chen 1998).

Moreover, Identified human induced pressures on mangrove forest in Laguna de Perlas such as clearance of mangrove trees –mentioned above–, forest fires and garbage disposal are considered influencing factors on the ecosystem health of mangrove forest. Both the clearage of mangrove trees and forest fires not only damage the biodiversity of the area but also reduce the capacity of the soil to further regenerate mangrove species (Ishtiaque, Myint, & Wang, 2016; Piątek & Yorou, 2019). It is important to note that clearage of mangrove forest also influence neighboring habitats. Granek & Ruttenberg (2008), reported modifications in algal communities (a drastic increase of algal growth) as a response to mangrove clearage. Moreover, a far-reaching consequence of the clearage of mangrove forest can lead to serious erosion of coastal areas (Kathiresan & Bingham, 2001), which could result in repercussions to coastal habitats, as well as to human wellbeing by leaving coastal communities and their respective infrastructures more vulnerable to storms and storm surges.

On the other hand, it is suggested that the accumulation of solid waste could affect different species of fisheries inhabiting mangrove ecosystem (e.g. shell species and other food sources) as well as surrounding habitats like the important fragile coral reefs. This could negatively impact the social structure of livelihood of local stakeholders whose historical culture has been closely linked with mangrove ecosystem and are therefore dependent on fisheries resources for their subsistence.

Even though the mangrove ecosystems in the study area still maintain their environmental services, it is to be noted that even the relatively low human impact can affect mangrove environment (Kathiresan & Bingham, 2001). Still, 'mangroves often exhibit considerable resilience to disturbance, undergoing perpetual change in ecosystem development commensurate with the evolution of the environmental settings they inhabit, and are, thus, mosaics of successional stages arrested or interrupted over time and space by natural ecological responses in relation to disturbances both large and small' (Alongi, 2012). However, the degree of recovery depends on the type of species and the site specific condition supporting its development as well as the surrounding environment for the exchange of matter and energy (Lugo, 1980).

Furthermore, the abundant regeneration of mangrove species in Pearl Lagoon, Awas, Haulover and Raitipura and the medium abundance in La Fe, indicates that the ecosystem in these sites present optimum characteristics to recover naturally after being disturb and a high tendency to reproductive output. On the other hand, the lower number of seedlings in Kahkabila and San Vicente, suggest that there is less recruitment of species to the mangrove forest, which negatively influence the ecological succession of mangroves in these two sites. However, the presence of abundant seeds and flowers on some of the mangrove trees (*Rhizophora mangle* and *Laguncularia racemosa*) in Kahkabila, suggest that there is still potential for future regeneration in this site. Nonetheless, it is to be noted that the vulnerability of both flowers and propagules to dispersal by wind and tidal dynamic, impede the process of germination and subsequent establishment of seedlings in the mangrove forest at Kahkabila, since a successful germination of propagules is crucial for the establishment and survival of seedlings.

The aforementioned susceptibility of flowers and propagules are suggested to be one of the reason explaining the low rate of mangrove regeneration in Kahkabila. Another possible reason could be the effect of different physico-chemical factors on seedlings after establishment. According to Kathiresan & Bingham (2001), factors such as waterlogging and soil properties inhibit growth and survival of seedlings. This is evident for instance with the characteristics of the mangrove substrate at Kahkabila which was the most flooded due to the direct contact with the lagoon and had a sandy texture soil. According to Duarte et al. (1998) sandy soils hinders the growth of seedling due to the constrained by insufficient nutrient.

On the other hand, the abundant herbivory on young leaves of saplings observed on *R. mangle* species, suggest that seedlings are vulnerable to predation. This is in agreement with findings by Burrows (2003) who reported greatest damages by insect herbivory to young leaves than older ones, as they are more vulnerable during their early age (Kathiresan & Bingham, 2001). Burrows (2003) further suggested that it is mainly due to the high nutritious values contain in their leaves, since the physical and chemical composition of mangroves leaves changes considerably as they age. These are important attributes that are likely to affect the resistance of leaves to herbivory, their growth, productivity and subsequent death of mangrove's trees (Kathiresan, 2003; Trisnawati et al. 2019).

Additionally to the above mentioned, it is suggested that leaves herbivory is a natural threat to mangrove development but mostly to *R. mangle*, as a result of different environmental stresses that alter the chemical composition of leaves and make them more susceptible to herbivores (Cornelissen & Stiling, 2005). Leaves of *Rhizophora mangle* are also susceptible to chlorosis and necrosis. This is in agreement with Gilbert et al. (2002), who reported greater damages to leaves of *R. mangle* and suggested that foliar disease on mangroves in the tropics is associated to insect damages, and that *R. mangle* is the most susceptible species, due to the level of resistance of its leaves. Furthermore, the authors discussed that leaves necrosis on *R. mangle* is due to the fungi Pestalotiopsis 'and some-times with species of Colletotrichum', which is the most common fungi that causes lesions to leaves of *R. mangle* (Garcia-Lopez et al., 1989).

Moreover, the presence of tumor caused by the fungi Cylindrocarpon didymium which was observed on stem of *R. mangle* in Pearl Lagoon and Kahkabila, is another indicator of stress to *R. mangle*. Even though little have been reported about the life cycle of Cylindrocarpon didymium, some authors argues that it can occur through natural or mechanical wounds (Tattar et al., 2016). This disease threaten the development of infected tree by weakening the stem and slowdown both the growth in diameter and height. Adding to this, the anthropogenic pressures on the mangrove forest and environmental variability can increase the trees susceptible to the disease (Teas & McEwan, 1982). The latter could affect the ecosystem structure in long term or in some cases even causes the death of the tree (Wier et al., 2000). It is important to note that health problems for mangrove trees are in many parts of the world overlooked until they aggravate and become complicated to substantially reduce (Alappatt, 2002). At present, mangrove forests in Laguna de Perlas are highly threatened, hence, detailed study on the pathology of the forest is required to further document damages to the aboveground biomass and their association with the overall ecosystem health.

4.2. Organic matter content and carbon concentration

The content of organic matter in mangrove soils in Laguna de Perlas varied in each mangrove ecosystem. Ultimate sources contributing to the accumulation of organic matter could be autochthonously through litter fall, old branches, seeds upon decomposition and also by tides from adjacent environment (Kristensen, Bouillon, Dittmar, & Marchand, 2008). The striking difference of organic matter between the sampled sites, is mainly their specific physiological, hydrological and edaphic characteristics. For instance, the low content of organic matter in mangrove soil at Kahkabila was obvious with the prevailing sandy soil. Similarly, different internal and external pressures on the mangrove forest (mentioned earlier) at this site, hinders the accumulation of organic matter in the soil. One of these factors could probably be the amplitude and forces of tides influencing the trees (figure 13), which apparently are old and not capable enough to withstand such intensity. Moreover, the forces of the tides can wash away the litter fall, flowers and propagules, thereby limiting the accumulation of organic matter, as well as negatively affecting biodiversity, since the accumulation of litter fall not only plays a key role in mangrove ecosystem but also in the surrounding by nurturing the food chain (López-Medellín & Ezcurra, 2012).

On the other hand, a higher accumulation of organic matter in mangrove soil could be seen with greater concentration of organic carbon at La Fe. The muddy saturated coverage at this site and the abundant presence of Grapsid crabs serve as an indicator of the high concentration of organic carbon storage in the soil. Indeed, Grapsid crabs plays an essential role in the transport and storage of organic carbon along soil profile (Alongi et al., 2005). It is noteworthy that physicochemical parameters not measured in this study could also have great impact on the rate of carbon concentration. As reported by various authors, parameters such as, temperature, (Melillo et al., 2002), tidal variability (Yuan et al., 2014), activity of microorganism (Holguin et al., 2001), enzymes (Acosta-Martínez et al., 2007), salinity and the overall soil redox processes (Gleason et al.,2003) are considered important physicochemical parameters influencing soil's condition and its subsequent effect on nutrient availability. Further studies are required to improve knowledge on the controlling factors of carbon in mangrove soil, since mangrove may respond in different ways to influencing factors.

All sampled site showed different rate of carbon concentration throughout the soil's profile for which carbon either increase or decrease (figure 14). The increasing trend of carbon concentration with depth is suggested to be attributed to the clearage of mangrove trees which does not only severely influence the aboveground biomass but also significantly decrease the content of belowground carbon (Eong, 1993; Granek & Ruttenberg, 2008; Kristensen et al., 2008). This result support the explanation of Huang et al. (2004) that the highest content of carbon at deeper soil layer is due to both anthropogenic and natural disturbances influencing the rate of carbon at the top 0-20 cm. Similarly, activity of Grapsid crabs (*Grapsidae*) may also explain the higher rate of carbon storage with depth. As mentioned earlier, Grapsid crabs (*Grapsidae*) are ecosystem engineers as they continuously deposits organic matter down the soil profile (Andreetta et al., 2014) and thus increase the content of organic matter by increasing the area of detritus retention (Sakho et al., 2015).

On the other hand, the decreasing trend with depth is related to the site specific conditions influencing the accumulation of organic carbon at the soil surface layer and the reactivity of microbial activity in the transport of organic carbon down the soil profile, as it has been reported that bioturbation by burrowing sesarmids induced the oxidation of organic matter in sub layers and thus a decrease in the content of organic carbon in sub layers (Kristensen & Alongi, 2006; Ferreira et al., 2007; Araújo et al., 2012; Andreetta et al., 2014). This observed pattern mainly occur through the increase of aerobic conditions and subsequent mineralization (Wilson et al., 2012), since aerobic bacteria are well known to break down carbon source more rapidly than anaerobic bacteria at deeper soil layers (Keiling et al., 2017), where there's less reactive detritus accumulation (Andreetta et al., 2014).

The aforementioned is consistent with the finding by many authors who reported higher concentrations of carbon at the upper most examined soil layer, than at deeper soil horizons (Khan et al., 2007;Hiederer, 2009; Banerjee et al., 2012; Schrumpf et al., 2013; Chaikaew & Chavanich, 2017;Hien et al., 2018). However, it is important to note that the activities of Grapsid crabs (*grapsidae*) are not the only driven force for bioturbation in mangrove's soils. This is noticeable for instance in the mangroves in Raitipura where there are least crabs present in the ecosystem, and the rate of carbon was higher at the first soil horizon. This could be explained with the diffusion of oxygen to the soil which occurred through its translocation from the above to below ground and subsequently oxidizes the living root of mangrove species as well as the soil, thus resulting in a reduction or degradation of organic matter and its respective organic carbon thereof (Mckee, 1993; Gleason et al., 2003; Marchand et al., 2004).

Additionally to the above mentioned, the *Avicennia* species, which due to their specific physiological characteristics with pneumatophores root system, introduces oxygen into the soil sub layer, which leads to sub-oxic prevailing conditions (Marchand et al., 2004). This could be a possible reason explaining the decreasing rate of organic carbon towards deeper soil depth at sampling point 1 in Haulover and Raitipura, since these are the only sites where Avicennia species were found (appendix table 3). Conversely, it is suggested that the saturation of water within the top soil layer preserve the content of organic matter and respective carbon, thereby resulting in a higher concentration than in deeper layers, as according to Cerón-Bretón et al. (2014) this type of pattern is a common phenomenon observed in mangrove forest.

With increasing carbon concentration in mangrove soils its bulk density decreased nonlinearly. The relationship between carbon concentration and bulk density obtained in this study, is in agreement with the findings by Bhomia et al. (2006) who also reported similar results in mangrove soils on the Caribbean coast of Honduras. Kauffman et al. (2014), also reported a negative relationship between carbon concentration and bulk density, with the latter being associated with the deepest examined soil layers. Indeed, soils with higher content of minerals are more compact (Bhomia et al., 2016) than those with greater concentration of organic matter/carbon, since the latter is more resistance to soil compaction (Koenková & Urík, 2012). This suggest that bulk density is mainly regulated by the texture of the sampled soil, it's respective porosity and the specific gravity of both organic and inorganic particles (Mitra, 2012).

On the other hand, belowground carbon concentration is strongly correlated with nitrogen (figure 16). Even though nitrogen is one of the limiting factors for mangrove growth (Reef et al., 2010), during the last years its anthropogenic mobilization and transport have increase to coastal ecosystems (Seitzinger et al., 2010), where it is sequestered by mangroves at a higher rate compared to other terrestrial ecosystems (Bauza et al., 2002). It can also be incorporated to mangroves ecosystem through the decomposition of organic matter (Keuskamp, 2014). The linear relationship between belowground carbon and nitrogen concentration suggest that soil organic matter is most likely the major source of nitrogen, since nitrogen concentration was high in sites where the concentration of carbon was also high. According to Keuskamp (2014), an increase in nitrogen sink in mangrove soil hinders CO_2 release from soil organic carbon decomposition. Thus nitrogen sequestration by mangroves, strongly influences belowground carbon (Keuskamp et al., 2013), an essential process leading to global climate change inhibition.

4.3. Soil organic carbon in relation to species diversity

Despite the fact that La Fe accounts for the site with both the lowest species diversity and richness, it has the greatest potential to sequester and store atmospheric CO_2 compared to all other sites. However, even though Kahkabila presented a higher species diversity than La Fe, the latter was still the site with the highest belowground carbon stock. Similar results were reported by Mackenzie et al. (2016), who reported a negative relationship between species diversity and soil organic carbon content. The authors suggested that in a less diverse ecosystem, there's lesser interspecific root competition occurring as compared to a diverse ecosystem where a reduced input of carbon to the soil is due to interspecific root interaction. Additionally, the mangrove forest in La Fe is a mosaic of trees with smaller DBH and height (younger forest) than the other sampled sites, especially in Kahkabila where these are much higher (mature forest). This is in accordance to the result of a study conducted on the pacific coast of Nicaragua, where higher amounts of below ground carbon were reported among young mangrove trees than older ones (Kronebrant, 2017), since below ground carbon decreases as stand age increases (Alongi, 2012).

A recent study conducted in Vietnam confirms the aforementioned (Hien et al., 2018), with results revealing a positive linear relationship between carbon content and young mangrove forest, when compared to a mature 18 years mangrove forest. This could be further explained with the findings by Song & Woodcock (2003) that old-growth stand is carbon neutral, neither storing nor loosing carbon to the atmosphere. However, it is uncertain if the mature mangrove in this study are close to, or are already carbon neutral. Succession herein plays an important role, it could be possible that carbon has been accumulating in the soils of mature forest over a long period of time, but are greatly influenced from modifications occurring in its physical environment driven by the biological community (Odum, 1969). This could be further explained for example with the mangroves forest in Kahkabila, the concomitant environmental and anthropogenic stressors (clearage of trees, disease, tidal activity), are highly influencing the mangroves to the extent of compromising their ability to capture and retain below ground carbon. This coincide with the findings by Barr et al. (2009) on the physiological studies of *Rhizophora mangle* in Florida Everglades, where the response to environmental stressors significantly impacted the rate of sequestration and subsequent ecosystem carbon balance.

Values for belowground carbon stock in Laguna de Perlas (3.44 - 20.84 kg/m^2) suggest that mangrove soils play an essential role in storing carbon. However, if manage sustainably, mangrove forest can sequester and store considerable amount of belowground carbon while supporting the livelihood of local stakeholders.

4.4. Carbon recalcitrance in relation to mangrove species

The observed pattern of carbon recalcitrance throughout soil profile increase or decrease with depth. The recalcitrant carbon at the uppermost examined soil layer (0-20 cm) at Haulover and Kahkabila is suggested to be attributed to high accumulation of organic carbon at the surface that persisted for a long period of time, and despite natural and anthropogenic disturbances, the content of carbon still prevailed. Similarly, recalcitrant carbon in deeper layers (40-60 cm) could be a result of plant material deposited in the past (Andreetta et al., 2014), which remained stable owing to a slow decomposition rate under anaerobic conditions, due to the limitation of microbial activity under low oxygen concentration (Davidson & Janssens, 2006), resulting in greater stability towards deeper soil layers (Sharma et al., 2015).On the other hand, the labile fraction of carbon at the surface layer (0-20 cm) in all sampled sites except Haulover and Kahkabila, is mainly attributed to the consumption of fresh organic matter by indigenous microorganism that quickly decompose the material, as it is sensitive and prone to oxidation thus resulting in a shorter residence time in the soil.

Vegetation type plays an essential role in carbon storage in mangrove soils. When compared all sites, *Rhizophora mangle*, is the species that contributes to the highest amount of carbon and it's recalcitrance in mangrove soils. This indicates that the residence time of carbon is higher in *Rhizophora mangle* soil as compared to the species of *Laguncularia racemosa*, *Avicenia germinans and Pellicierra rizhophorae*. The complex aerial root system and the prevailing anoxic and flooded mud layer in the *Rhizophora mangle* dominated sites, has a positive effect on the preservation of organic matter. This is mainly because the latter is slowly decompose (Cerón-Bretón et al., 2014) due to the high amount of tannins in the *R. mangle* litter, which inhibits SOC decomposition (Keuskamp, 2014). Unlike *R. mangle*, species like for example *Avicenia germinans,* with pneumatophores root system has an oxidizing effect that induces the oxidation of organic carbon, thereby leading to a less residence time of carbon in the soil (Keuskamp, 2014).

Moreover, it is suggested that labile organic carbon influence soil pH. In almost all sampled sites, pH was more acidic where the fraction of organic carbon was less stable in the soil. This could be a result of the production of organic acids through actively metabolize mangrove roots, (Banerjee et al., 2012) release of hydrogen ions from organic anions upon decomposition of organic matter and/or oxidation of sulphur which could strongly acidify the sediment (Marchand et al., 2004).On the other hand, recalcitrant carbon for instance in surface layers (0-20 cm) at Kahkabila which was tidally flooded, presented mild acidic conditions. The latter is probably due to tidal supplies of basic cations (Marchand et al., 2004) which slightly increase the soil pH and thereby induce the adsorption of organic matter/carbon to soil mineral surface, which protects it from microbial decomposition (Kleber et al., 2007).The overall acidic to mild acidic pH values for mangrove soils in Laguna de Perlas fell within the range of previous studies that reported acidic conditions in mangrove soil's (Hemati et al., 2015; Salmo III et al., 2014), since mangrove's sediments are considered worldwide as acidic or alkaline (Hossain & Nuruddin, 2016).

5. Conclusion

This study presents for the first time carbon sequestration in mangroves soils in the municipality of Laguna de Perlas, South Caribbean Coast of Nicaragua. It can be concluded that the size of carbon stocks in this municipality is significant. However, despite the major anthropogenic and natural influences in the ecosystem, mangroves still act as significant carbon sink throughout soil's profile, since they store high concentrations of organic carbon and maintain it in their soil for a long period of time.

Varying rates of organic carbon accretion, its recalcitrance, and soil's pH were determined and evaluated as a function of soil depth, which are primarily driven by mangrove species in relation to site specific physicochemical conditions and inadequate anthropogenic activities influencing the input and/or loss of carbon along soil's profile. Indeed, these factors are fundamental controllers of the sensitivity of carbon decomposition and/or mineralization as well as the overall functions provided by mangroves ecosystems to both the environment and human beings. The hypothesis of this thesis, that carbon sequestration increase with increasing species diversity was rejected. A higher amount of organic carbon sequestered in in sites where species diversity was the lowest (La Fe, Haulover and San Vicente). However, due to its site specific conditions –mainly edaphic characteristics- it has proven to have the greatest ability for storing atmospheric CO_2.

This suggest that future research on the physicochemical factors undergoing in mangrove ecosystem, as well as humans induced effects that alter the natural functioning of mangrove, are needed to fully document the succession in mangrove forest over time. This would therefore lead to a better understanding of its complex dynamic ecosystem and the response to both internal and external disturbances.

Additionally to the aforementioned, results of this study indicate that there is a high potential to increase carbon sequestration in the future, by implementing sustainable projects to curb carbon emission through mangrove restoration and protection as it is known that the structure and characteristics of these species are crucially important leading to certain level of tolerance to the effects of climate change (Bautista-Olivas et al., 2018), as well as to contribute to a healthy mangrove ecosystems with high biodiversity, suitable to enhance habitat connectivity and exerts ecosystem functions. Indeed, programs such as REDD+ and/or other financial incentives for climate change mitigation could play an important role in the conservation of mangrove ecosystems and their respective carbon stocks in both above and belowground.

Moreover, it's important to note that if anthropogenic CO_2 emissions continues to drastically increase, the effects of climate change will aggravate, thus, altering the natural function of mangrove ecosystems and leading to reemission of the stored soil organic carbon back to the atmosphere as a cause of the destruction of both above and below ground mangrove biomass, which would then contribute to repercussions of global warming.

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8. Appendix

8.1. Survey

Description of the mangrove ecosystem:

1. What are the main benefits of the mangroves ecosystem in Laguna de Perlas?

Environmental:

Social:

Economic:

Others:

2. What are the potential threats to the mangrove ecosystem?

Forest fire_____ effluent disposal______ domestic garbage disposal______

Deforestation_________ Others:

3. What are the changes observed in mangrove ecosystems over the past years?

4. What are the major impacts of climate change in the community?

5. What improvement strategy has been implemented to adapt and/or mitigate climate change?

6. What’s the importance of carbon sequestration in mangroves ecosystem? How does this contribute to the mitigation of climate change?

7. Observed wind dynamic and its influence on the mangrove ecosystem:

8.2. Ecosystem Inventory

Table 7: Mangrove Species encountered in seven sampled sites in Laguna de Perlas, Nicaragua

Mangrove species					
	R. mangle	*A.germinans*	*L. racemosa*	*P.rizhophorae*	Total
Sample Point 1					
Haulover	21	1	5		27
S. Vicente	6				6
P. Lagoon	10		4		14
Lafe	5				5
Kahkabila	9				9
Awas	9		5		14
Raitipura	20	1	3		24
Sample Point 2					
Haulover	17		1		18
S. Vicente	5				5
P. Lagoon	9			1	10
Lafe	3				3
Kahkabila	8		1		9
Awas	13		7		20
Raitipura	4		9		13
Sample Point 3					
Haulover	9		1		10
S. Vicente	4				4
P. Lagoon	12		9	2	23
Lafe	3				3
Kahkabila	6		10		16
Awas			4		4
Raitipura	6			10	16

8.2.1. Evaluation of phytophagous attack to leave

Date: _______________ Community: ____________________

Location: X ______________________ Y____________________

SA__________________ S. point ________________

Table 8: Damages to mangrove leaves in seven sampled sites in Laguna de Perlas, Nicaragua

Damages to leaves								
				Indicators				
Species	Trees	Shrubs	Seedlings	Scarce or none	Not abundant	Medium abundant	Abundant	Very Abundant

8.2.2. Anthropogenic disturbances

Table 9: Identified pressures on mangrove ecosystem in seven different sampled sites in Laguna de Perlas, Nicaragua

Sampling sites	**Deforestation**	**Forest fire**	**Garbage disposal**	**Damages to mangrove leaves**	**Desease on mangrove stem**	**Health index**
Haulover	x	x	x			40
San Vicente	x		x			60
P. Lagoon	x		x		x	40
La Fe	x		x			60
Kahkabila			x	x	x	40
Awas	x		x			60
Raitipura	x		x			60

8.2.3. Ecosystem Health

Table 10: Mangrove Ecosystem health description

Health	Category	Definition
Very high	100-75	When there are no pressures or these are very low, so the ecosystem is in optimal health development. All ecosystem services are maintained.
High	74-67	When the pressures have a low incidence on the high health of the ecosystem. Ecosystem services are maintained.
Medium	66-51	When pressures have begun to start on the health of the ecosystem, but the threshold of resilience is still high and health is still accepted. Ecosystem services for human well-being begin to have limitations.
Low	50-36	When the pressures that affect the health parameters of the mangrove are very close to the resilience threshold of the ecosystem. Ecosystem services for human well-being are very limited.
Very low	≥35	When the pressures that affect the mangrove health parameters exceed the resilience threshold of the ecosystem. Deterioration of all ecosystem services provided by mangroves for human welfare.

8.3. Species diversity indexes

Table 11:Shannon's Index Calculation

Sites	Species	Number of individuals	Pi (n/N)	lnPi	Pi * ln Pi	H
Haulover	*R. mangle*	47	0.85	-0.16	-0.13	
	A.germinans	1	0.02	-4.01	-0.07	**0.47 0**
	L. racemosa	7	0.13	-2.06	-0.26	
S. Vicente	*R. mangle*	15	1	0	0	**0**
P. Lagoon	*R. mangle*	31	0.63	-0.46	-0.29	
	L. racemosa	13	0.27	-1.33	-0.35	**0.87**
	P.rizhophorae	5	0.10	-2.28	-0.23	
La Fe	*R. mangle*	15	1.36	0.31	0	**0**
Kahkahbila	*R. mangle*	23	0.68	-0.39	-0.26	**0.63**
	L. racemosa	11	0.32	-1.13	-0.37	
Awas	*R. mangle*	22	0.58	-0.55	-0.32	**0.68**
	L. racemosa	16	0.42	-0.86	-0.36	
Raitipura	*R. mangle*	30	0.57	-0.57	-0.32	
	A.germinans	1	0.02	-3.97	-0.07	**0.76**
	L. racemosa	22	0.42	-0.88	-0.36	

Table 12: Simpson's index calculation

Sites	Species	N	n-1	$n(n\text{-}1)$	D
Haulover	*R. mangle*	47	46	2162	
	A.germinans	1	0	0	**0.26**
	L. racemosa	7	6	42	
S. Vicente	*R. mangle*	15	14	210	**0**
P. Lagoon	*R. mangle*	31	30	930	**0.53**
	L. racemosa	13	12	156	
La Fe	*R. mangle*	11	10	110	**0**
Kahkahbila	*R. mangle*	23	22	506	**0.45**
	L. racemosa	11	10	110	
Awas	*R. mangle*	22	21	462	
	L. racemosa	16	15	240	**0.50**
Raitipura	*R. mangle*	30	29	870	
	A.germinans	1	0	0	**0.52**
	L. racemosa	22	21	462	

8.4. Physicochemical parameters

Table 13: pH values per sampling sites and their respective sampling points and soil depth (mean and standard deviation are shown)

pH values					
Sites	**S. Point**	**Soil Depths (cm)**			**Total**
		0-20	**20-40**	**40-60**	
Haulover	1	4.79	5.24	6.06	5.36 (±0.64)
	2	4.95	5.37	5.6	5.31 (±0.33)
	3	5.27	3.37	3.78	4.14 (±1.00)
Total		**4.87 (±0.11)**	**4.31 (±1.32)**	**4.92 (±1.61)**	**4.94 (±0.86)**
San Vicente	1	4.49	5.22	5.19	4.97 (±0.41)
	2	5.14	5.21	4.74	5.03 (±0.25)
	3	6.52	4.61	3.9	5.01 (±1.36)
Total		**5.38 (±1.04)**	**5.01 (±0.35)**	**4.61 (±0.65)**	**5.00 (±0.72)**
Pearl Lagoon	1	3.9	3.38	3.39	3.56 (±0.30)
	2	4.36	4.45	4.81	4.54 (±0.24)
	3	4.5	4.2	5.6	4.77 (±0.74)
Total		**4.25 (±0.31)**	**4.01 (±0.56)**	**4.78 (±0.84)**	**4.29 (±0.80)**
La Fe	1	4.96	5.3	4.46	4.91 (±0.42)
	2	4.98	5.5	5.8	5.43 (±0.41)
	3	4.7	4.82	4.92	4.81 (±0.11)
Total		**4.88 (±0.16)**	**5.21 (±0.35)**	**5.06 (±0.68)**	**5.05 (±0.39)**
Kahkahbila	1	3.85	3.7	3.4	3.65 (±0.23)
	2	4.95	3.75	3.5	4.07 (±0.78)
	3	3.9	3.6	3.4	3.63 (±0.25)
Total		**4.23 (±0.62)**	**3.68 (±0.08)**	**3.43 (±0.06)**	**3.78 (±0.47)**
Awas	1	4	4.86	5.29	4.72 (±0.66)
	2	4.01	4.27	4.97	4.42 (±0.50)
	3	5.1	4.45	4.23	4.59 (±0.45)
Total		**4.37 (±0.63)**	**4.53 (±0.30)**	**4.83 (±0.54)**	**4.58 (±0.49)**
Raitipura	1	4.48	5.67	5.76	5.30 (±0.71)
	2	5.83	5.86	5.92	5.87 (±0.05)
	3	4.41	5.97	6.84	5.74 (±1.23)
Total		**4.91 (±0.80)**	**5.83 (±0.15)**	**6.17 (±0.58)**	**5.64 (±0.76)**

Table 14: Determination of Organic matter (OM %)=Pre.W-Post.IW/Pre.IW*100 and carbon concentration (%OM/2) by Loss on ignition for sampling point 1 at all

sampled sites. W represent the weight of the sample, Pre-I is the pre ignition weight and Post-I the post ignition weight

LOI (%)							
Sampling Point 1							
Soil depth (cm)	S. Sites	CW (g)	Pre-I. (g)	Pre-I. +CW (g)	Post- I (g)	OM (%)	LOI (%)
0-20	Haulover	30.1714	14.4482	44.6196	6.2779	56.55	28.27
	S. Vicente	30.4621	13.4664	43.9285	8.9204	33.76	16.88
	P. Lagoon	30.6782	12.8377	43.5159	10.2593	20.08	10.04
	La Fe	31.2129	11.1293	42.3422	4.1285	62.90	31.45
	Kahkahbila	32.5429	14.7229	47.2658	14.1317	4.02	2.01
	Awas	30.3511	14.7473	45.0984	13.6533	7.42	3.71
	Raitipura	31.5282	13.358	44.8862	7.1275	46.64	23.32
20-40	Haulover	30.8524	13.6787	44.5311	5.0356	63.19	31.59
	S. Vicente	31.5299	13.9212	45.4511	8.9211	35.92	17.96
	P. Lagoon	31.2129	11.1293	42.3422	7.2909	34.49	17.24
	La Fe	30.5739	13.8145	44.3884	4.7631	65.52	32.76
	Kahkahbila	31.5269	14.7171	46.244	14.1276	4.01	2.00
	Awas	30.5767	14.6565	45.2332	12.6562	13.65	6.82
	Raitipura	30.3467	8.0504	38.3971	3.5592	55.79	27.89
40-60	Haulover	29.6086	13.4411	43.0497	5.0876	62.15	31.07
	S. Vicente	31.9324	13.0572	44.9896	8.0676	38.21	19.11
	P. Lagoon	30.8772	14.08	44.9572	9.1332	35.13	17.57
	La Fe	31.4198	11.5534	42.9732	4.4923	61.12	30.56
	Kahkahbila	30.6689	14.6114	45.2803	13.5239	7.44	3.72
	Awas	30.6671	14.65	45.3171	13.3353	8.97	4.49
	Raitipura	31.3472	9.415	40.7622	4.3059	54.27	27.13

Table 15: determination of Organic matter (OM %)=Pre.W-Post.IW/Pre.IW*100 and carbon concentration (%OM/2) by Loss on ignition for sampling point 2 at all sampled sites. W represent the weight of the sample ignition weight, Pre-I is the pre ignition weight and Post-I the post

LOI (%)							
Sampling Point 2							
Soil depth (cm)	S. Sites	CW (g)	Pre-I. (g)	Pre-I. +CW (g)	Post- I (g)	OM (%)	LOI (%)
0-20	Haulover	31.2125	11.7811	42.9936	4.3472	63.10	31.55
	S. Vicente	31.4193	13.2429	44.6622	7.8584	40.66	20.33
	P. Lagoon	29.2255	14.4329	43.6584	11.6615	19.20	9.60
	La Fe	31.4892	12.281	43.7702	3.3615	72.63	36.31
	Kahkahbila	29.2554	14.8001	44.0555	13.5807	8.24	4.12
	Awas	29.6086	14.976	44.5846	14.2792	4.65	2.33
	Raitipura	31.3271	14.988	46.3151	6.9880	53.38	26.69
20-40	Haulover	30.4601	12.971	43.4311	4.9613	61.75	30.88
	S.Vicente	30.4626	14.1541	44.6167	9.4520	33.22	16.61
	P. Lagoon	30.9162	14.5786	45.4948	11.7195	19.61	9.81
	La Fe	31.4213	6.085	37.5063	1.1208	81.58	40.79
	Kahkahbila	29.6756	14.8857	44.5613	14.4240	3.10	1.55
	Awas	31.8522	14.7946	46.6468	14.2170	3.90	1.95
	Raitipura	31.8522	14.2748	46.127	13.4131	6.04	3.02
40-60	Haulover	31.3471	10.2107	41.5578	2.5286	75.24	37.62
	S. Vicente	30.4524	12	42.4524	9.2688	22.76	11.38
	P. Lagoon	29.6966	14.3843	44.0809	12.2884	14.57	7.29
	La Fe	32.5457	10.6844	43.2301	3.1402	70.61	35.30
	Kahkahbila	31.8516	14.7565	46.6081	14.1725	3.96	1.98
	Awas	30.4625	12.3799	42.8424	3.6488	70.53	35.26
	Raitipura	29.6068	13.0213	42.6281	4.9608	61.90	30.95

Table 16: Determination of Organic matter (OM %)=Pre.W-Post.IW/Pre.IW*100 and carbon concentration (%OM/2) by Loss on ignition for sampling point 3 at all sampled sites. W represent the weight of the sample, Pre-I is the pre ignition weight and Post-I the post ignition weight

LOI (%)							
Sampling Point 3							
Soil depth (cm)	S. Sites	CW (g)	Pre-I. (g)	Pre-I. +CW (g)	Post- I (g)	OM (%)	OC (%)
0-20	Haulover	31.4896	10.5812	42.0708	3.7152	64.89	32.44
	S. Vicente	30.8754	14.5475	45.4229	13.9858	3.86	1.93
	P. Lagoon	30.3472	14.9652	45.3124	14.0093	6.39	3.19
	La Fe	29.6751	13.3301	43.0052	4.3506	67.36	33.68
	Kahkahbila	31.5298	14.7964	46.3262	14.3834	2.79	1.40
	Awas	29.6745	14.5146	44.1891	13.0284	10.24	5.12
	Raitipura	31.9327	14.4623	46.395	10.4466	27.77	13.88
20-40	Haulover	31.2129	14.1951	45.408	12.8512	9.47	4.73
	S. Vicente	29.6969	16.3691	46.066	9.0346	44.81	22.40
	P. Lagoon	31.4198	14.4071	45.8269	12.9639	10.02	5.01
	La Fe	31.6056	13.0704	44.6760	3.1558	75.86	37.93
	Kahkahbila	31.9328	14.9273	46.8601	14.4291	3.34	1.67
	Awas	31.4219	14.3645	45.7864	13.0424	9.20	4.60
	Raitipura	30.6804	12.9705	43.6509	9.2971	28.32	14.16
40-60	Haulover	31.3417	14.5759	45.9176	13.3780	8.22	4.11
	S. Vicente	31.8525	8.8896	40.7421	2.5507	71.31	35.65
	P. Lagoon	29.2571	11.9557	41.2128	4.2832	64.17	32.09
	La Fe	30.5749	11.435	42.0099	4.2931	62.46	31.23
	Kahkahbila	31.2121	14.709	45.9211	14.2470	3.14	1.57
	Awas	29.2559	14.5347	43.7906	11.4317	21.35	10.67
	Raitipura	30.6664	13.6343	44.3007	12.7475	6.50	3.25

Table 17: Content of organic matter stored in mangrove soils (values are means and standard deviation of three replicates are shown) in each sampled site

Organic Matter OM (%)					
Sites	**S.Point**	**Soil Depths (cm)**			**Total**
		0-20	**20-40**	**40-60**	
Haulover	1	56.55	63.19	62.15	60.63 (±3.57)
	2	63.10	61.75	75.24	66.70 (±7.43)
	3	64.89	9.47	8.22	27.52 (±32.36)
Total		**61.51 (±4.39)**	**44.80 (±30.61)**	**48.53 (±35.52)**	**51.62 (±24.74)**
San Vicente	1	33.76	35.92	38.21	35.96 (±2.23)
	2	40.66	33.22	22.76	32.21 (±8.99)
	3	3.86	44.81	71.31	39.99 (±33.98)
Total		**26.09 (±19.56)**	**37.98 (±6.06)**	**44.09 (±24.80)**	**36.06 (±17.93)**
Pearl Lagoon	1	20.08	34.49	35.13	29.90 (±8.51)
	2	19.20	19.61	14.57	17.79 (±2.80)
	3	6.39	10.02	64.17	26.86 (±32.37)
Total		**15.22 (±7.67)**	**21.37 (±12.33)**	**37.96 (±24.92)**	**24.85 (±17.20)**
La Fe	1	62.90	65.52	61.11	63.18 (±2.21)
	2	72.62	81.58	70.61	74.94 (±5.84)
	3	67.36	75.86	62.46	68.56 (±6.78)
Total		**67.63 (±4.87)**	**74.32 (±8.14)**	**64.73 (±5.14)**	**68.89 (±6.87)**
Kahkahbila	1	4.02	4.01	7.44	5.15 (±1.98)
	2	8.24	3.10	3.96	5.10 (±2.75)
	3	2.79	3.34	3.14	3.09 (±0.28)
Total		**5.02 (±2.86)**	**3.48 (±0.47)**	**4.85 (±2.28)**	**4.45 (±1.98)**
Awas	1	7.42	13.65	8.97	10.01 (±3.24)
	2	4.65	3.90	22.06	10.21 (±10.27)
	3	10.24	9.20	21.35	13.60 (±6.73)
Total		**7.44 (±2.79)**	**8.92 (±4.88)**	**17.46 (±7.36)**	**11.27 (±6.59)**
Raitipura	1	46.64	55.79	54.27	52.23 (±4.90)
	2	53.38	6.04	61.90	40.44 (±30.10)
	3	27.77	28.32	6.50	20.86 (±12.44)
		42.60 (±13.28)	**30.05 (±24.92)**	**40.89 (±30.02)**	**37.84 (±21.43)**

Table 18: Organic carbon concentration stored in mangrove soils (values are means and standard deviation of three replicates are shown) in each sampled site

Organic carbon concentration (%)					
Sites	**S. Point**	**Soil Depths (cm)**			**Total**
		0-20	**20-40**	**40-60**	
Haulover	1	28.27	31.59	31.07	30.31 (±1.79)
	2	31.55	30.88	37.62	33.35 (±3.71)
	3	32.44	4.73	4.11	13.76 (±16.18)
Total		**30.76 (±2.20)**	**22.40 (±15.30)**	**24.27 (±17.76)**	**25.81 (±12.37)**
San Vicente	1	16.88	17.96	19.11	17.98 (±1.11)
	2	20.33	16.61	11.38	16.11 (±4.50)
	3	1.93	22.40	35.65	20.00 (±16.99)
Total		**13.05 (±9.78)**	**18.99 (±3.03)**	**22.05 (±12.40)**	**18.03 (±8.96)**
Pearl Lagoon	1	10.04	17.24	17.57	14.95 (4.25±)
	2	9.60	9.81	7.29	8.90 (±1.40)
	3	3.19	5.01	32.09	13.43 (±16.18)
Total		**7.61 (±3.83)**	**10.69 (±6.17)**	**18.98 (±12.46)**	**12.43 (±8.60)**
La Fe	1	31.45	32.76	30.56	31.59 (±1.11)
	2	36.31	40.79	35.30	37.47 (±2.92)
	3	33.68	37.93	31.23	34.28 (±3.39)
Total		**33.82 (±2.43)**	**37.16 (±4.07)**	**32.36 (±2.57)**	**34.45 (±3.44)**
Kahkahbila	1	2.01	2.00	3.72	2.58 (±0.99)
	2	4.12	1.55	1.98	2.55 (±1.38)
	3	1.40	1.67	1.57	1.54 (±0.14)
Total		**2.58 (±0.99)**	**2.55 (±1.38)**	**1.54 (±0.14)**	**2.22 (±0.99)**
Awas	1	3.71	6.82	4.49	5.01 (±1.62)
	2	2.33	1.95	11.03	5.10 (±5.14)
	3	5.12	4.60	10.67	6.80 (±3.37)
Total		**3.72 (±1.40)**	**4.46 (±2.44)**	**8.73 (±3.68)**	**5.64 (±3.29)**
Raitipura	1	23.32	27.89	27.13	26.12 (±2.45)
	2	26.69	3.02	30.95	20.22 (±15.05)
	3	13.88	14.16	3.25	10.43 (±6.22)
Total		**21.30 (±6.64)**	**15.02 (±12.46)**	**20.45 (±15.01)**	**18.92 (±10.07)**

.

Table 19: Hot water soluble carbon in mangrove soils (values are means and standard deviation of three replicates are shown) in each sampled site

HWSC (mg/L)					
Sites	**S. Point**	**Soil Depths (cm)**			**Total**
		0-20	**20-40**	**40-60**	
Haulover	1	56.58	27.18	11.8	22.79 (±31.66)
	2	89.94	96.56	51.46	79.32 (±24.35)
	3	69.93	22.61	20.41	37.65 (±27.98)
Total		**72.15 (±16.79)**	**59.59 (±52.29)**	**27.89 (20.86±)**	**52.41 (±32.17)**
San Vicente	1	30.67	26.59	18.65	25.30 (±6.11)
	2	20.51	16.01	17.51	18.01 (±2.29)
	3	3.96	16.86	67.3	29.37 (±33.47)
Total		**18.38 (±13.48)**	**19.82 (±5.88)**	**34.49 (±28.42)**	**24.23 (±17.77)**
Pearl Lagoon	1	22.3	48.78	56.48	42.52 (±17.93)
	2	20.16	22.07	12.93	18.39 (±4.82)
	3	11.66	24.07	39.41	25.05 (±13.90)
Total		**18.04 (±5.63)**	**31.64 (±14.88)**	**36.27 (±21.94)**	**28.65 (±16.49)**
La Fe	1	32.58	44.38	54.7	43.89 (±11.07)
	2	40.38	106.8	31.45	59.54 (±41.17)
	3	39.79	51.32	18.1	36.40 (±16.87)
Total		**37.58 (±4.34)**	**67.50 (±34.11)**	**34.35 (±18.64)**	**46.61 (±25.10)**
Kahkahbila	1	7.9	6.94	6.78	7.21 (±0.61)
	2	11.57	33.04	6.69	17.10 (±14.02)
	3	32.62	5.11	26.57	21.43 (±14.46)
Total		**17.36 (±13.34)**	**15.03 (±15.62)**	**13.35 (±11.45)**	**15.25 (±11.89)**
Awas	1	11.27	67.4	19.32	32.66 (±30.35)
	2	9.48	7.66	14.86	10.67 (±3.74)
	3	10.77	16.32	16.32	14.47 (±3.20)
Total		**10.51 (±0.92)**	**30.46 (±32.28)**	**16.83 (±2.27)**	**19.27 (±18.44)**
Raitipura	1	13.7	55.62	23.21	30.84 (±21.98)
	2	37.89	55.12	113.3	68.77 (±39.51)
	3	74.59	67.56	30.22	57.46 (±23.85)
Total		**42.06 (±30.66)**	**59.43 (±7.04)**	**55.58 (±50.11)**	**52.36 (±30.62)**

Table 20: Nitrogen concentration (of extractable Hot water soluble carbon) in mangrove soils (values are means and standard deviation of three replicates are shown) in each sampled site

N (mg/L)					
Sites	**S. Point**	**Soil Depths (cm)**			**Total**
		0-20	**20-40**	**40-60**	
Haulover	1	2	2.83	3.87	2.90 (±0.94)
	2	5.34	3.79	1.61	3.58 (±1.87)
	3	5.21	0.66	0.45	2.11 (±2.69)
Total		**4.18 (±1.89)**	**2.43 (±1.60)**	**1.97 (±1.74)**	**2.86 (±1.82)**
San Vicente	1	3.03	2.13	1.15	2.10 (±0.94)
	2	1.65	1.15	1.81	1.54 (±0.34)
	3	0.26	1.64	4.19	2.03 (±2.00)
Total		**1.65 (±1.38)**	**1.64 (±0.49)**	**2.38 (±1.60)**	**1.89 (±1.15)**
Pearl Lagoon	1	1.18	1.95	2.07	1.73 (±0.48)
	2	1.54	0.90	0.74	1.06 (±0.42)
	3	0.31	0.84	1.97	1.04 (±0.85)
Total		**1.01 (±0.63)**	**1.23(±0.62)**	**1.60 (±0.74)**	**1.28 (±0.55)**
La Fe	1	2.39	3.24	5.38	3.67 (±1.54)
	2	2.07	3.86	1.99	2.64 (±1.06)
	3	2.65	5.09	1.27	3.00 (±1.93)
Total		**2.37 (±0.29)**	**4.06(±0.94)**	**2.88 (±0.20)**	**3.10 (±1.42)**
Kahkahbila	1	0.57	0.23	0.24	0.35 (±0.19)
	2	0.76	2.50	0.33	1.20 (±1.15)
	3	2.46	0.34	0.86	1.22 (±1.11)
Total		**1.26 (±1.04)**	**1.02 (±1.28)**	**0.48 (±0.34)**	**0.92 (±0.91)**
Awas	1	0.44	1.70	0.86	1.00 (±0.64)
	2	0.47	0.32	0.59	0.46 (±0.14)
	3	0.92	0.80	1.48	1.07 (±0.36)
Total		**0.61 (±0.27)**	**0.94 (±0.70)**	**0.98 (±0.46)**	**0.84 (±0.47)**
Raitipura	1	0.73	2.44	1.21	1.46 (±0.88)
	2	2.25	2.51	4.17	2.98 (±1.04)
	3	2.88	2.28	0.89	2.02 (±1.02)
Total		**1.95 (±1.10)**	**2.41 (±0.12)**	**2.09 (±1.81)**	**2.15 (±1.08)**

Table 21: Bulk density BD (g/Cm^3)=DM/S.Vol (3.14*3cm*3cm*25cm) per sample sites and respective replicates and depths. DM represent dry mass and S.Vol soil volume. Mean (standard deviation)

Bulk density (BD g/cm^3)							
Sites	S.point	Soil depth (cm)					
		0-20		20-40		40-60	
		Mass (g)	BD (g/cm3)	Mass (g)	BD (g/cm3)	Mass (g)	BD (g/cm3)
Haulover	1	190	0.27	102.5	0.15	102	0.14
	2	115	0.16	120	0.17	108.73	0.15
	3	300	0.42	173	0.24	186	0.26
Total			**0.29 (±0.13)**		**0.19 (±0.05)**		**0.19 (±0.06)**
San Vicente	1	98.36	0.14	89.19	0.13	116	0.16
	2	98.42	0.14	124.11	0.18	170	0.24
	3	87.4	0.12	291	0.41	190	0.27
Total			**0.13 (±0.01)**		**0.24 (±0.15)**		**0.22 (±0.06)**
Pearl Lagoon	1	475	0.67	201.7	0.29	196.8	0.28
	2	159	0.23	121.1	0.17	335	0.47
	3	180	0.25	151	0.21	143.5	0.20
Total			**0.38 (±0.25)**		**0.23 (±0.06)**		**0.32 (±0.14)**
La Fe	1	75	0.14	110	0.16	130	0.18
	2	75.6	0.14	92.18	0.13	132	0.19
	3	84.83	0.12	69.75	0.14	132	0.19
Total			**0.13 (±0.01)**		**0.14 (±0.02)**		**0.19 (±0.01)**
Kahkahbila	1	290	0.41	300	0.42	280	0.40
	2	220	0.31	290	0.41	246	0.35
	3	268.18	0.38	290	0.41	300	0.42
Total			**0.37 (±0.05)**		**0.42 (±0.01)**		**0.39 (±0.04)**
Awas	1	182	0.26	226	0.32	123	0.17
	2	137.2	0.19	180	0.25	158	0.22
	3	139	0.20	180	0.25	110.3	0.16
Total			**0.25 (±0.07)**		**0.22 (±0.03)**		**0.20 (±0.05)**
Raitipura	1	340	0.48	206.94	0.49	173.2	0.25
	2	180	0.25	107	0.15	111	0.16
	3	124	0.18	300	0.42	246.5	0.35
Total			**0.30 (±0.16)**		**0.29 (±0.14)**		**0.25 (±0.10)**

Table 22: Soil organic carbon stock for sampling point 1 at all sampled sites and their respective depth (H) was determination by the following formulas: SOC (Kg C /m^2) = LOI (%) *BD (g/cm^3)*H (cm)*0.1(conversion factor)

Soil organic carbon				
Sampling Point 1				
Sites	H (cm)	LOI (%)	BD (g/cm^3)	SOC (kg C /m^2)
Haulover	0-20	28.27	0.27	15.21
San Vicente	0-20	16.88	0.14	4.70
Pearl Lagoon	0-20	10.04	0.67	13.53
La Fe	0-20	31.45	0.11	6.68
Kahkahbila	0-20	2.01	0.41	1.65
Awas	0-20	3.71	0.26	1.91
Raitipura	0-20	23.32	0.48	22.45
Haulover	20-40	31.59	0.15	18.33
San Vicente	20-40	17.96	0.13	9.07
Pearl Lagoon	20-40	17.24	0.29	19.69
La Fe	20-40	32.76	0.16	20.40
Kahkahbila	20-40	2.00	0.42	3.42
Awas	20-40	6.82	0.32	8.73
Raitipura	20-40	27.89	0.29	32.68
Haulover	40-60	31.07	0.14	26.92
San Vicente	40-60	19.11	0.16	18.82
Pearl Lagoon	40-60	17.57	0.28	29.36
La Fe	40-60	30.56	0.18	33.74
Kahkahbila	40-60	3.72	0.40	8.85
Awas	40-60	4.49	0.17	4.68
Raitipura	40-60	27.13	0.25	39.91

Table 23: Soil organic carbon stock for sampling point 2 at all sampled sites and their respective depth (H) was determination by the following formulas: SOC (Kg C /m^2) = LOI (%) *BD (g/cm^3)*H (cm)*0.1(conversion factor)

Soil organic carbon stock				
Sampling Point 2				
Sites	H (cm)	LOI (%)	BD (g/cm^3)	SOC (kg/m^2)
Haulover	0-20	31.55	0.16	10.27
San Vicente	0-20	20.33	0.14	5.66
Pearl Lagoon	0-20	9.60	0.23	4.32
La Fe	0-20	36.31	0.11	7.77
Kahkahbila	0-20	4.12	0.31	2.57
Awas	0-20	2.33	0.19	0.90
Raitipura	0-20	26.69	0.25	13.60
Haulover	20-40	30.88	0.17	20.98
San Vicente	20-40	16.61	0.18	11.67
Pearl Lagoon	20-40	9.81	0.17	6.72
La Fe	20-40	40.79	0.13	21.29
Kahkahbila	20-40	1.55	0.41	2.55
Awas	20-40	1.95	0.25	1.99
Raitipura	20-40	3.02	0.15	1.86
Haulover	40-60	37.62	0.15	34.74
San Vicente	40-60	11.38	0.24	16.43
Pearl Lagoon	40-60	7.29	0.47	20.73
La Fe	40-60	35.30	0.19	39.58
Kahkahbila	40-60	1.98	0.35	4.13
Awas	40-60	35.26	0.22	47.32
Raitipura	40-60	30.95	0.16	29.18

Table 24: Soil organic carbon stock for sampling point 3 at all sampled sites and their respective depth (H) was determination by the following formulas: SOC (Kg C /m^2) = LOI (%) *BD (g/cm^3)*H (cm)*0.1(conversion factor)

Soil organic carbon stock				
Sampling Point 3				
Sites	H (cm)	LOI (%)	BD (g/cm^3)	SOC (kg/m^2)
Haulover	0-20	32.44	0.42	27.55
San Vicente	0-20	1.93	0.12	0.48
Pearl Lagoon	0-20	3.19	0.25	1.63
La Fe	0-20	33.68	0.12	8.09
Kahkahbila	0-20	1.40	0.38	1.06
Awas	0-20	5.12	0.20	2.01
Raitipura	0-20	13.88	0.18	4.87
Haulover	20-40	4.73	0.24	4.64
San Vicente	20-40	22.40	0.41	36.91
Pearl Lagoon	20-40	5.01	0.21	4.28
La Fe	20-40	37.93	0.10	14.98
Kahkahbila	20-40	1.67	0.41	2.74
Awas	20-40	4.60	0.25	4.69
Raitipura	20-40	14.16	0.42	24.05
Haulover	40-60	4.11	0.26	6.49
San Vicente	40-60	35.65	0.27	57.53
Pearl Lagoon	40-60	32.09	0.20	39.10
La Fe	40-60	31.23	0.19	35.01
Kahkahbila	40-60	1.57	0.42	4.00
Awas	40-60	10.67	0.16	10.00
Raitipura	40-60	3.25	0.35	6.81