

# A contribution to understanding blue carbon sequestration and forest structure in mangroves of different ages in a small island (Mauritius)

DEVESEE RAMDHUN<sup>✉</sup>, CHANDANI APPADOO<sup>✉✉</sup>

Department of Biosciences and Ocean Studies, Faculty of Science, University of Mauritius. Réduit 80837, Republic of Mauritius.

Tel.: +230-59240270, ✉email: devesee.ramdhun@gmail.com; ✉✉chandani@uom.ac.mu

Manuscript received: 9 October 2020. Revision accepted: 21 December 2020.

**Abstract.** Ramdhun D, Appadoo C. 2020. A contribution to understanding blue carbon sequestration and forest structure in mangroves of different ages in a small island (Mauritius). *Ocean Life* 4: 74-81. Mangrove biomes, a blue carbon coastal ecosystem, are considered as the most carbon-rich forest in the tropics, but there is a knowledge gap on their ecosystem services especially in small islands. The purpose of this study was to evaluate the carbon stock in sediment and aboveground biomass of three different ages of *Rhizophora mucronata* forests along the coastline of Mauritius. Forest structure was assessed, and measurements of diameter at breast height were used to calculate biomass using allometric equation. Corer samples were collected in each site and sectioned into subsamples of 0-10 cm, 10-20 cm and 20-30 cm, to analyze soil bulk density and soil organic carbon. The highest SOC stock ( $470.08 \text{ t ha}^{-1}$ ) was recorded at Mahebourg and lowest ( $331.33 \text{ t ha}^{-1}$ ) in the young stand at Le Morne. The total organic carbon contents varied from  $931.50 \pm 17.06 \text{ t ha}^{-1}$  (at Mahebourg) to  $350.76 \pm 4.058 \text{ t ha}^{-1}$  (young forest at Le Morne). There was no significant difference in soil carbon density at different soil depths studied at Le Morne ( $n=81$ ,  $p=0.430$  (old forest),  $p=0.875$  (young forest)), however, a different scenario was observed at Mahebourg ( $n=81$ ,  $p=0.027$ ). This study is the first to report on the potential of carbon storage at these sites in Mauritius and add to the knowledge of the ecosystem services of this ecosystem.

**Keywords:** Above ground biomass, blue carbon, carbon stocks, coastal ecosystem, *Rhizophora mucronata*

## INTRODUCTION

Mangrove forests, seagrass meadows, and saltmarshes are blue carbon ecosystems, sequestering organic carbon in their sediments and biomass to mitigate climate change (Wu et al. 2018; Cuellar-Martinez et al. 2019). Although the terrestrial plants have greater area and function as carbon sinks, the coastal carbon sinks have larger carbon sequestration capacity (DeVecchia et al. 2014). The mangrove biomes growing profusely in the sea-land interface of the paleotropical and neotropical regions are considered as the richest blue carbon forest, blooming in anoxic and saline environment (Martin et al. 2019). These halophytic plants with valuable services such as buffering zones for heavy waves and winds, preventing coastal erosion and stabilizing sediments, nutrient filter and shelters for floras and faunas, are subjected to anthropogenic threats (Appadoo 2003).

The intertidal buttress once occupied 75% of the tropical coastal zone worldwide (Dahdouh-Guebas and Koedam 2008) but now the population has decreased steeply (Thorhaug et al. 2018). Being the wealthiest carbon forests, they have the capacity to sequester five times more carbon than other forests in both the above and below-ground biomass including in their soils (Cui et al. 2018) and thus contributing to global carbon budget (Yang et al. 2014). Carbon sequestration is when a mangrove ecosystem captures carbon from the atmosphere and stores them in their leaves, branches, roots, and soils (Wu et al. 2018). The anoxic soil prevents the organic carbon from

oxidizing to other forms thus providing long-term carbon storage (Luo and Gu 2016).

Nowadays, these evergreen forests do not even represent 1% of the tropical forests because of human disturbances (Penaranda et al. 2019) and they are still being exceedingly threatened (Wang et al. 2019), thus conservation is a necessity. It is a serious challenge in this century as carbon emission has exceeded its threshold and scientists and policymakers are initializing new blue carbon ideas to counter carbon emissions (Ahmed et al. 2017). Globally, deforestation is the main reason for the steep decline in mangrove population, together with unsustainable use of resources leading to species extinction and hurricanes and strong cyclones destroying above-ground biomass reducing the carbon-storing capacity (Ranjan 2019).

Studies on mangrove blue carbon storage and sequestration quantification in islands are important due to lack of concurrent data on mangrove population, carbon concentration, and quantity of carbon according to depth. These studies also raise awareness about the importance of carbon ecosystems. Blue carbon storage is studied on islands because of direct oceanic swell from sides and each part of the islands is affected by different amounts of wave energy because of coral reefs. The objective of this study is to assess the status of the organic carbon content in soil and above-ground biomass (AGB) in mangroves of different ages in three mangrove forests in Mauritius. It also aims at estimating the total carbon stocks and exploring variations in below-ground carbon.

## MATERIALS AND METHODS

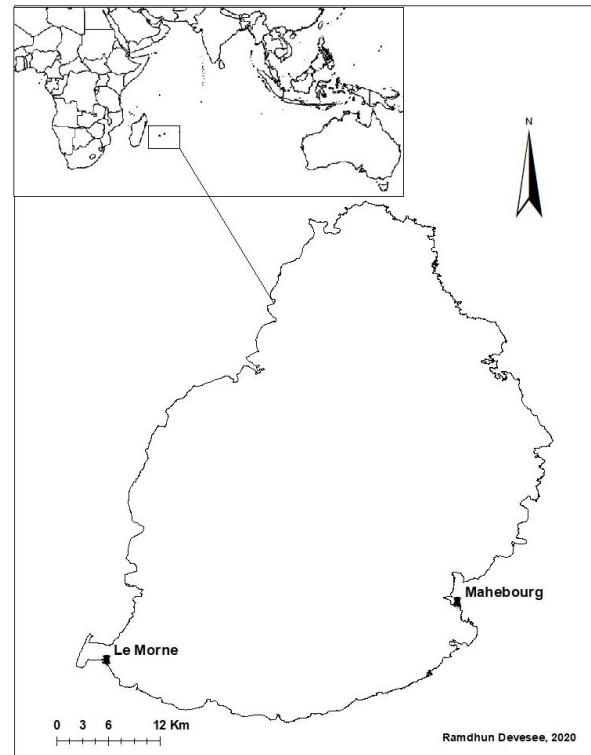
### Study site

The study was conducted from October 2019 to March 2020 and sampling was done during the months of October and November 2019 in old forests at Mahebourg (S 20°24'08.95", E 057°42'26.94") and at Le Morne (S 20°27'34.91", E 057°20'16.51") and in a young forest at Le Morne (S 20°27'45.87", E 057°20'26.03") in Mauritius (Figure 1). Le Morne, found in the south coastline, has a range of temperature between 17°C to 30°C and the rainfall ranges from 54 mm to 245 mm (Climate-Data.Org 2020a). The entire forest is about 2.4 hectares and consists of a large patch of old *Rhizophora mucronata* stands but mostly of young plants of *Rhizophora mucronata* and *Bruguiera gymnorrhiza*. The study sites at Le Morne consist only of *Rhizophora mucronata* but forest of different ages (Figure 2). The young plants at Bassin Leon, Le Morne were planted by Association pour la Developpement Durable (ADD) during 2008 and 2009. The study site in Mahebourg (Figure 3) is located in the southeast coastline of Mauritius, with temperature ranges from 17°C to 29.7°C and precipitation ranges from 61 mm to 255 mm (Climate-Data.Org 2020b) and the old forest is about 0.3 hectare and characterized by *Rhizophora mucronata* of different height categories. All studied regions are influenced by diurnal tides and the mean salinity in Mahebourg was  $26.11 \pm 0.74$  ppt and that for Le Morne in the old forest was  $34.30 \pm 0.37$  ppt and  $31.00 \pm 0.23$  ppt for the young forest.

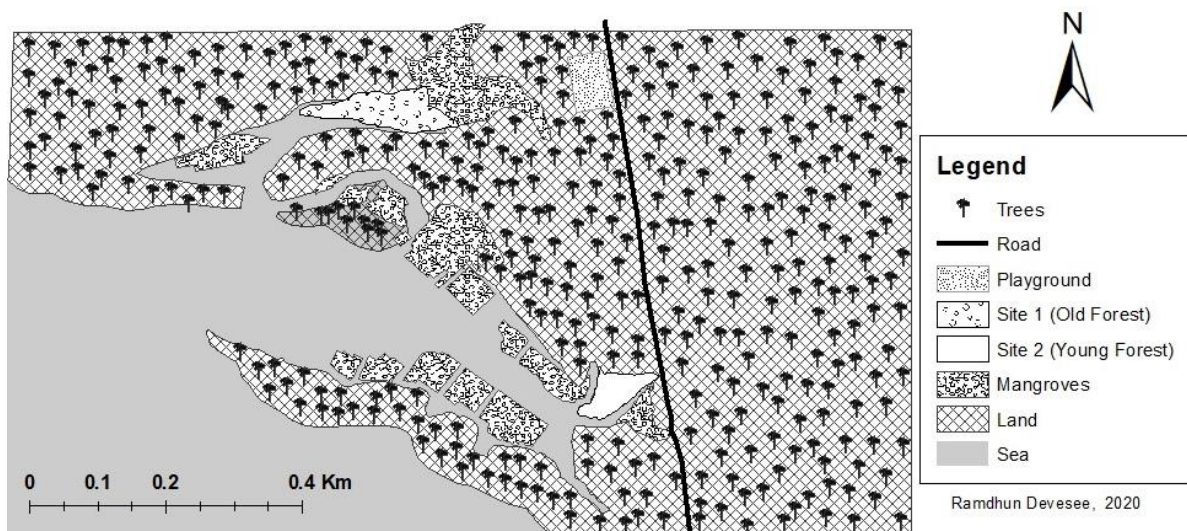
### Tree sampling and measurement procedures

The study was conducted in an area of 0.0225 ha at each site in different inundation zones which include the seaward, middle ward, and landward zone (Yang et al. 2014). A transect line of 25 m was laid parallel to the shore on each zone and three quadrats of 5 m x 5 m were set up in each transect leaving a space of 5 m between each quadrat.

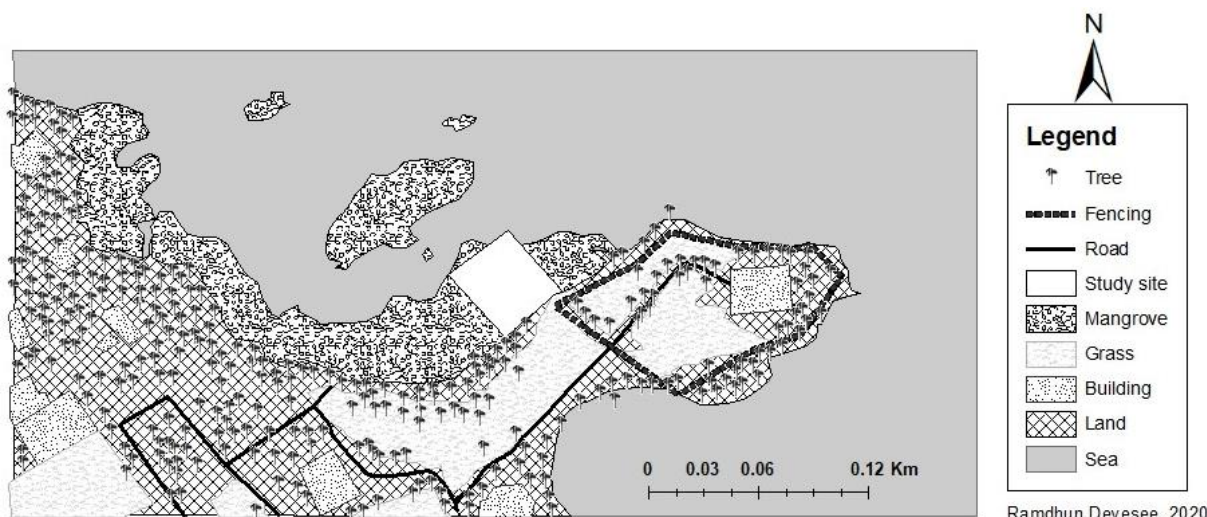
Heights of plants were measured with a graduated telescopic rod (Betts 2006). Diameter at breast height of the mangrove was measured with a measuring tape following the method of Penaranda et al. (2019). Mangrove plants were categorized into seedlings, saplings, and adult trees (Clarisse et al. 2016).



**Figure 1.** Map of Indian Ocean and map of Mauritius where the pin symbols represent the different studied regions



**Figure 2.** The study sites at Le Morne including an old forest (Site 1) and a young forest (Site 2) refer to as study area 1 and study area 2, in legend as well



**Figure 3.** Mahebourg (Old forest) study site

### Sediment samplings

For this study, 27 cores were collected at each site. The sediment samples were collected during low tide with a polyvinyl chloride hand corer having length and diameter of 30 cm and 10 cm respectively (Shaltout et al. 2019) and using the technique outlined by Howard et al. (2014a). Triplicates were undertaken in every quadrat. Each core was sectioned immediately with a knife according to 0-10, 10-20, and 20-30 cm depths, and stored in labeled zip-lock bags and kept at 4°C, preserving the organic matter, until further analysis (Shaltout et al. 2019).

### Sample analysis

The sediment samples were first air-dried on aluminum foil for two days and each sample was weighed on a petri dish using an electronic balance. It was then oven-dried at 60°C until a constant mass was obtained. The dried samples were crushed using a mortar and pestle to a constant size for homogenization and they were left in desiccator for further analysis (Cui et al. 2018). Organic carbon was analyzed using the Loss on Ignition method where 5g of each crushed sample was transferred into a ceramic crucible, weighed, and put in muffle furnace at 450°C for a time period of 4-8 hours (Heiri et al. 2001).

### Data analysis and statistical analyses

The data were entered in a spreadsheet and the following equations were used to compute different parameters.

Diameter at breast height (DBH) =  $C / \pi$  ( $C$  = Circumference and  $\pi = 3.14$ )

Allometric equation (Abib and Appadoo 2012)

$\text{Log AGB} = a \text{ Log DBH} + b$  ( $a = 2.383$  and  $b = -0.799$  are regression coefficients)

$\% \text{ LOI} = \{(\text{difference in mass after ignition (g)} / \text{dry mass before ignition(g)}) * 100$

Percentage of organic carbon =  $0.415 * \% \text{ LOI} + 2.89$

Before any statistical analysis, the normality test was carried out to know whether the data collected were normal

or not. The IBM SPSS STATISTICS Software was used for hypothesis testing where the Shapiro-Wilk Test showed that the data was not normal, thus non-parametric test should be used with 0.05 significance. The non-parametric, Kruskal-Wallis test was used to test the hypothesis between soil carbon density, soil organic carbon, and depths.

## RESULTS AND DISCUSSION

### Mangrove forest structure and above-ground biomass

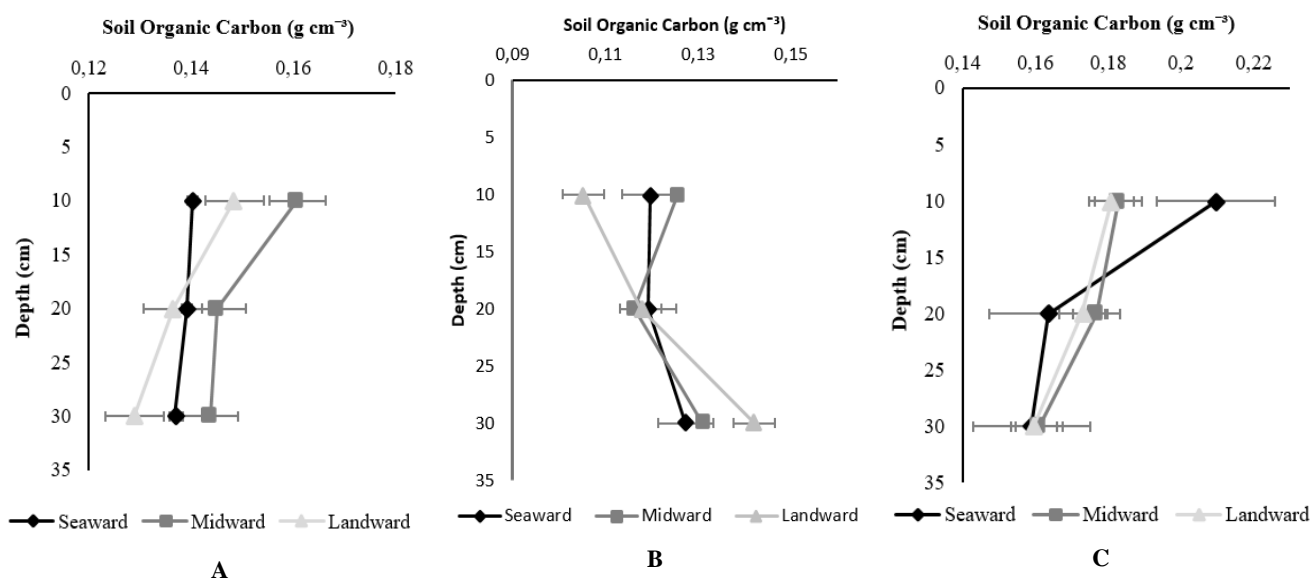
Forest structures are represented in Table 1. The tree density in the two old forests and young forests varied significantly: Mahebourg's forest had more trees than at Le Morne. Mahebourg had the tallest tree and shortest was found in the young forest at Le Morne. The old forest at Le Morne had the broadest DBH range meaning that its ecosystem contained the thickest trees among all the sites and the sapling dominating young forest had the shortest range. The relative density at le Morne was 99.38% in the old forest, 100% in the young forest, and 99.16% in Mahebourg. In the old forests, biomass ranged from 461.88 t ha<sup>-1</sup> from 591 plants at Mahebourg to 261.42 t ha<sup>-1</sup> from 479 plants at Le Morne whereas biomass of only 19.42 t ha<sup>-1</sup> from 360 plants was obtained in the young forest at Le Morne. At Le Morne, the maximum frequency was between the DBH range 2 < x < 4 cm (n=175) in the old forest, 0 < x < 2 cm (n= 180) in the young forest, and at Mahebourg, it was 6 < x < 8 cm (n= 260).

### Percentage of organic carbon in soil in different inundation zones

The mean organic carbon (OC) percentage in the seaward, middle and landward soil at Le Morne was  $9.27 \pm 0.03\%$ ,  $9.80 \pm 0.26\%$ , and  $9.86 \pm 0.47\%$  respectively in the old forest and  $9.90 \pm 0.16\%$ ,  $9.74 \pm 0.14\%$  and  $10.55 \pm 0.16\%$  respectively in the young forest and Mahebourg had a mean OC percentage of  $13.71 \pm 0.62\%$ ,  $13.21 \pm 0.25\%$  and  $13.20 \pm 0.34\%$  in the seaward, middle and landward respectively

**Table 1.** Structural features and above-ground biomass of the mangrove forests per 225 m<sup>2</sup> sample area

Site	Forest structure					Above-ground biomass (t ha <sup>-1</sup> )
	Height range (m)	Dbh range (cm)	Seedlings density (per hectares)	Saplings density (per hectares)	Adult density (per hectares)	
Le Morne (Old forest)	0.40 - 5.00	1.11- 15.60	4.67 x 10 <sup>4</sup>	1.16 x 10 <sup>4</sup>	9.73 x 10 <sup>3</sup>	261.42
Le Morne (Young forest)	0.20 - 3.50	0.95 – 5.09	1.03 x 10 <sup>4</sup>	1.51 x 10 <sup>4</sup>	9.33 x 10 <sup>2</sup>	19.42
Mahebourg (old forest)	0.30 - 6.90	2.23 – 9.55	9.0 x 10 <sup>4</sup>	6.9 x 10 <sup>3</sup>	1.94 x 10 <sup>4</sup>	461.88

**Figure 4.** Distribution of soil organic carbon [g cm<sup>-3</sup>] in the topsoil of 30 cm in the *Rhizophora mucronata* stands along the coastline of Mauritius in different inundation zones at Le Morne and Mahebourg where the horizontal bars indicate the standard error of the means [n = 81]. A. Le Morne (Old forest); B. Le Morne (Young forest); C. Mahebourg (Old forest)

### Soil organic carbon content

Figure 4 represents the soil organic carbon contents at Le Morne and Mahebourg. The greatest soil organic carbon (SOC) stock value was observed in the mangrove forest at Mahebourg with a mean total of  $1.567 \pm 0.005$  g cm<sup>-3</sup> in the 30 cm topsoil. At Le Morne, a mean total of  $1.271 \pm 0.003$  g cm<sup>-3</sup> and  $1.104 \pm 0.004$  g cm<sup>-3</sup> in the 30 cm topsoil in the old forest and young forest respectively was found. The difference between SOC and depths was significant at Mahebourg (Kruskal-Wallis Test, n= 81, p= 0.027) but not at Le Morne (Kruskal-Wallis Test, n= 81, p= 0.177 (old forest), p= 0.875 (young forest)).

### Soil carbon density

Soil carbon density (SCD) for 81 subsamples on each site for the upper 30 cm was determined at Le Morne and Mahebourg (Figure 5). SCD was not significantly different in each depth in the old forest (Kruskal-Wallis Test, n=81, p= 0.430) and in the young forest (Kruskal-Wallis Test, n= 81, p= 0.875) at Le Morne. The variations of SCD in the old forest represent a slight decrease from 0.0140 g cm<sup>-3</sup> at the depth 0-10 cm to 0.0137 g cm<sup>-3</sup> at the depth 20-30 cm in the seaward zone, a decrease from 0.0161 g cm<sup>-3</sup> at depth 0-10 cm to 0.0144 g cm<sup>-3</sup> at depth 20-30 cm in the middle zone and a decrease from 0.0149 g cm<sup>-3</sup> at the

depth 0-10 cm to 0.0129 g cm<sup>-3</sup> at the depth 20-30 cm in the landward zone. The variations in SCD in the young forest show that there was a decrease from 0.0120 g cm<sup>-3</sup> at the depth 0-10 cm to 0.0105 g cm<sup>-3</sup> at the depth 20-30 cm in the seaward zone, a slight decrease from 0.0119 g cm<sup>-3</sup> at the depth 0-10 cm to 0.0118 g cm<sup>-3</sup> at the depth 20-30 cm in the middle zone and an increase from 0.0127 g cm<sup>-3</sup> at the depth 0-10 cm to 0.0142 g cm<sup>-3</sup> at the depth 20-30 cm in the landward zone.

SCD was significantly different between 0-30 cm at Mahebourg (Kruskal-Wallis Test, n=81, p= 0.027). The variations at Mahebourg show that there was a decrease in all zones. In the seaward zone, SCD decrease from 0.0210 g cm<sup>-3</sup> at the depth 0-10 cm to 0.0159 g cm<sup>-3</sup> at the depth 20-30 cm. In the middle zone, SCD decrease from 0.018 g cm<sup>-3</sup> at the depth 0-10 cm to 0.0161 g cm<sup>-3</sup> at the depth 20-30 cm, and in the landward zone, SCD decrease from 0.0181 g cm<sup>-3</sup> at the depth 0-10 cm to 0.0160 g cm<sup>-3</sup> at the depth 20-30 cm.

### Total carbon storage

Organic carbon is sequestered in both biomass and soil in different quantities, with the soil pool as a greater contribution to total carbon storage. Table 2 represents the organic carbon in the above-ground biomass and soil which

are then computed to give the total organic carbon in the ecosystem. At Le Morne, in the old forest, AGB was highest in the middle zone (142.42 t ha<sup>-1</sup>) and lowest in the seaward zone (13.41 t ha<sup>-1</sup>), and in the young forest, AGB was highest in the seaward zone and lowest in landward accounting for 8.27 t ha<sup>-1</sup> and 4.19 t ha<sup>-1</sup> respectively. For the old forest at Le Morne, SOC was highest in the middle zone (135.00 t ha<sup>-1</sup>) and lowest in the landward zone (124.21 t ha<sup>-1</sup>) and for the young forest, SOC was highest in landward and lowest in seaward with recorded values of 120.12 t ha<sup>-1</sup> and 105.19 t ha<sup>-1</sup> respectively. At Mahebourg, AGB was highest in middle zone and lowest in landward having 199.84 t ha<sup>-1</sup> and 89.50 t ha<sup>-1</sup> respectively and SOC was highest in seaward and lowest in landward with recorded values of 159.71 t ha<sup>-1</sup> and 154.08 t ha<sup>-1</sup> respectively. The organic carbon between AGB and SOC was not significantly different at Le Morne (Kruskal-Wallis Test, n=81, p = 0.202 (old forest), p= 0.670 (young forest)) but it was significantly different at Mahebourg (Kruskal-Wallis Test, n=81, p = 0.027).

### Carbon storage in Mauritian mangrove forests of different ages compared to other mangrove forests

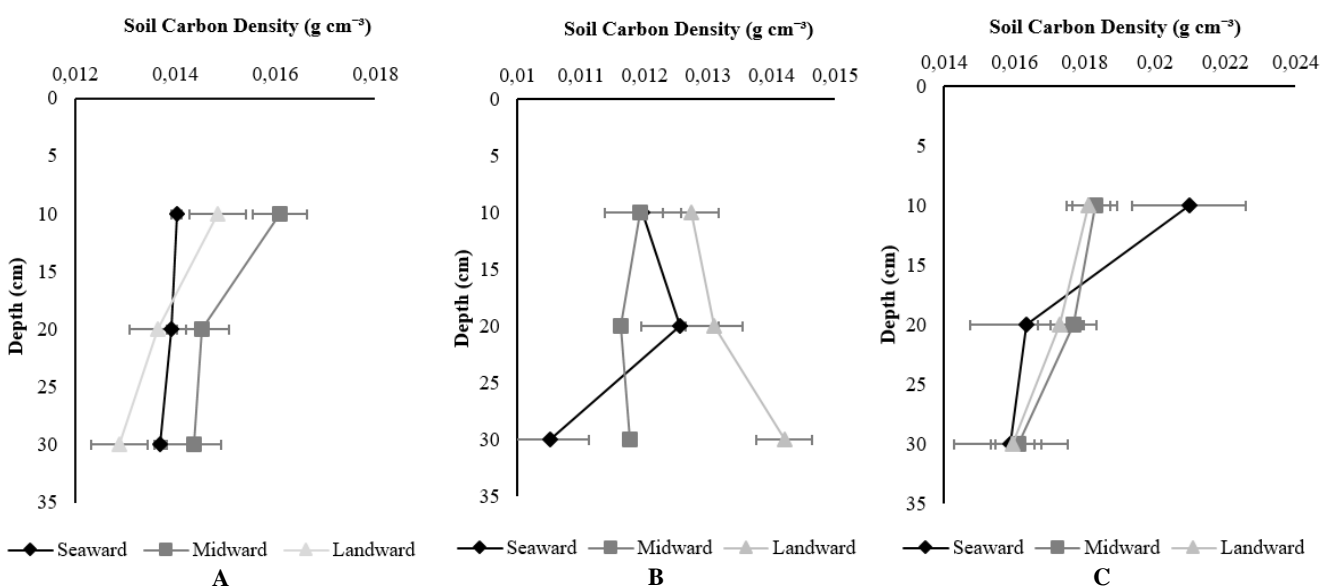
#### Total organic carbon in mangrove forests

Total carbon stock consisted of the carbon sequestered in soil and biomass. The mean carbon storage for this study (642.56 t ha<sup>-1</sup>) falls within the global range of 55-1376 t ha<sup>-1</sup> (Howard et al. 2014b). The mean carbon stock obtained during this study was higher compared to the mean value obtained from a mangrove stand in Kerala, India consisting of eight different species (153.64 t ha<sup>-1</sup>; Vinod et al. 2019) and in Farasan Islands in Saudi Arabia consisting of *Rhizophora mucronata* forest having 108 t ha<sup>-1</sup> of organic carbon (Eid et al. 2019). Comparing to other countries with different species, the mangrove *Avicennia marina* in Qatar had a total carbon stock of

45.70 t ha<sup>-1</sup> which was very low compared to Mauritian mangrove forest (Chatting et al. 2020) and a study in Berau and Segara Anakan Lagoon in Central Java, each site had a mean total organic carbon of 615 t ha<sup>-1</sup> and 298 t ha<sup>-1</sup> respectively (Kusumaningtyas et al. 2018). The OC varied spatiotemporally because of tree density, forest age, soil texture, primary productivity, geographical and morphological setting, species composition, and regional climate (Eid et al. 2019). Organic carbon in the old forests was higher because of more productivity and from autochthonous sources such as underground roots, dropped litter, and other locally produced mangrove materials.

#### Soil total organic carbon in mangrove forests

In this study, the soil carbon pool in the old forest at Le Morne accounted for 60% of the total blue carbon and 95 % for the young forest whereas the biome at Mahebourg accounted for 50% only. Other studies confirmed that mangrove soils have the capacity to sequester 50 to >90% of the total carbon storage of mangrove ecosystems (Johnson et al. 2019). The mean SOC stock for this study was 395.04 ± 66.3 t ha<sup>-1</sup> which was greater than the global mean value (361 t ha<sup>-1</sup>; Sanderman et al. 2018). The soil of the old forests holds larger stores of blue carbon than young forests, plausibly because the latter had small supplies of allochthonous material, small carbon accumulation time, low productivity, and increase in rate of sediment respiration. The high level of SOC was due to autochthonous matter as the old forest consisted of high biomass level which contributed to more productivity and the pedogenetic layers were enriched in autochthonous organic matter which increases with forest age, also leaves of seagrass, also a blue carbon ecosystem, were washed into the bushes by tidal flux, stuck between roots which then decomposed, adding to the SOC (Xue et al. 2009).



**Figure 5.** Distribution of soil carbon density [g cm<sup>-3</sup>] in relation to soil depth [cm] in the *Rhizophora mucronata* forest at Le Morne and Mahebourg along the coastline of south of Mauritius. Horizontal bars represent the standard error of the means [n=81]. A. Le Morne (Old forest); B. Le Morne (Young forest); C. Mahebourg (Old forest)

**Table 2.** Blue organic carbon ( $\pm$  SD) in the above-ground and belowground and the total carbon storage is the sum of all the carbon pools in each site

Studied sites	Aboveground ( $t\ ha^{-1}$ )	Belowground ( $t\ ha^{-1}$ )	Total carbon ( $t\ ha^{-1}$ )
	Using allometric equation	Soil (0-30 cm)	
Site 1 (Old forest at Le Morne)	258.94 $\pm$ 11.95	383.70 $\pm$ 0.14	642.64 $\pm$ 5.62
Site 2 (Young forest at Le Morne)	19.43 $\pm$ 2.66	331.33 $\pm$ 0.92	350.76 $\pm$ 4.06
Site 3 (Old forest at Mahebourg)	461.88 $\pm$ 53.44	470.08 $\pm$ 0.85	931.50 $\pm$ 17.06

#### Carbon sequestration in AGB in forests of different ages

The results showed that AGB first asymptotes with age of forest. Salum et al. (2020) did a study on Guaras Island in Brazil to get an estimate of 246.90  $t\ ha^{-1}$  of above-ground biomass in the forest consisting of *Avicennia germinus* and *Rhizophora* species by using the LiDAR method. A study by Kirui et al. (2006), showed a *Rhizophora mucronata* mangrove forest in Gazi Bay, Kenya had a biomass of 452.02  $t\ ha^{-1}$ , where the plants had a mean diameter of 11.62 cm. The difference in biomass was because of diameter, environmental conditions, geographical location, and different sampling methods, as for Kenyan study the harvested method was used whereas for this study, the non-destructive method was used. Biomass of mangroves in different parts of the world varies due to parameters such as climatic conditions, species and topography of surveyed region, geomorphology, history of the forest structure and its age, tide variations, and edaphic factors (Kamruzzaman et al. 2017). Another reason could be the distance of the forest from the equator as the production of mangroves depends on latitude and longitude (Saenger and Snedaker 1993). The biomass of the old forest was greater than the young forest as the former had taller trees with greater canopy acting as indicator of the status of the stand and also had larger DBH classes with greater circumference than the young forest resulting in greater biomass.

#### Carbon storage varies with different forest age, structure, and environmental factors.

Variability in carbon storage can be determined using several variables such as forest age, the structure, tree size, and density (Johnson et al. 2019). Taller trees have the capacity to store more carbon in their soil than the shrub mangroves and without structural variations, the estimation of carbon storage would be difficult. An old forest could have greater carbon storage due to years of accumulation of allochthonous and autochthonous carbon in their carbon pools (Johnson et al. 2019). Mangrove distribution is influenced by coastal geomorphological characteristics and their heights decrease as latitudes increased and as temperature and precipitation decreased, and due to high salinity also (Vinh et al. 2019). Wave action, rainfall, and ample freshwater input are important factors that help to determine the forest structure of the study sites as these factors have effects on erosion control, aridity, salinity, nutrient inputs, and soil quality (Lacerda 2002).

#### Structure and distribution of mangrove forests

Mauritian mangrove forest structures are different from other countries as Mauritius is a remote island and zonation patterns are influenced by the tidal influence (Ball 1980). Seedling density was highest in forests nearer to the sea due to the hydrochory process and most of them were observed in canopy gaps due to the requirements for growth such as light and space (Putz and Chan 1986). The old forests being closer to the oceans, seedlings were distributed all over the intertidal forest because of dispersion and establishment success of propagules with currents and tides. The eco-geomorphic conditions determine the mangrove's diversity pattern and terrestrial runoff maintains the eco-physiological condition of Mahebourg's forest as it was closer to the land, preventing salinity stress and supplying nutrients to support forest development (Chen and Twilley 1999). The young forest had lower seedling density because it was found far from the sea actions that could propagate. The seedling population was used as an indicator for the reproductive status of the studied sites.

#### Variability of soil organic carbon in different inundation zones

Mangrove wetlands have the potential to sequester blue carbon in their soil and most OC in this study was found in the soil. However, the quantity of SOC fluctuated widely due to environmental variables and their interactions (Chen et al. 2020). For example, in Mauritius at Le Morne, the old forest had highest SOC (135.00  $t\ ha^{-1}$ ) in the middle zone because of the accumulation of many years' leaf litters, belowground dead fine roots, and micro and macro algae colonizing the forest floor which was added to the total SOC. Lowest SOC was observed in the landward zone (124.21  $t\ ha^{-1}$ ) because many young plants resulted in a small supply of autochthonous matter and little inflow of freshwater. However, in the young forest, the landward zone had the highest SOC (120.12  $t\ ha^{-1}$ ) and the seaward zone had the lowest SOC (105.19  $t\ ha^{-1}$ ), as the landward zone had OC from allochthonous sources from terrestrial origin and fluvial inputs and less hydrological flushing which helped the accumulation of organic carbon-rich litter on the soil surface (Sasmito et al. 2020). Moreover, in Mahebourg, the highest SOC was observed in the seaward zone (159.70  $t\ ha^{-1}$ ) and lowest in the landward zone (154.08  $t\ ha^{-1}$ ), since the substratum consisted of a tidally submerged suboxic layer that supported anaerobic decomposition. The seaward zone had the highest OC because of autogenous changes on soil surface and larger inundation times. This facilitates prolonged anaerobic

conditions in the soil, resulting in retention of organic matter. The hydroperiod decreased soil bulk density which caused changes in porosity, permeability, and ventilation of the mangrove soil, giving rise to OC (Chen et al. 2020); but the landward zone had less adult density with little productivity and more man-made stressors.

#### *Variability of soil bulk density in different soil depths*

Soil bulk density (SBD) was used to describe the compaction and water permeability of soil. Soil carbon density was an important factor for blue carbon storage where higher SBD had little liquid phase space resulting in lower soil moisture content (Xiong et al. 2018). SBD had an effect on soil porosity, soil permeability, ventilation, and OC storage and a high SBD resulted in low OC accumulation (Chen et al. 2020). The variations of SCD were effects of physical and chemical factors such as pH, soil bulk density, soil types, and minerals (Eid and Shaltout 2015). Similar results were reported by Chen et al. (2020) in Zengying, China that SCD decreased with increasing depth, and this could be because of soil moisture and amount of fine roots decreasing with increasing depth. The SCD also changed due to interplay between variables such as decomposition, leaching, hydrologic regimes, biological cycling, soil erosion, and weathering of minerals (Eid et al. 2019). However, SCD was less on topsoil in the seaward and landward zone in the young forest because influence of tidal inundation on erosion of accumulated matter on the floor, less productivity and human stressors as the forest was near the main road.

It can be concluded that the structural attributes, including tree density, height and diameter at breast height, were considered in the present study as key factors to evaluate the variability of carbon storage of mangrove forests of different ages. The carbon content from above-ground biomass and soil was highest at Mahebourg with values of 461.88 t ha<sup>-1</sup> and 470.08 t ha<sup>-1</sup> respectively. Most of the results showed that the surface layers of the soil stored the highest amount of blue carbon. The forest with taller trees holds more blue carbon than the forest with shrub mangroves. The former benefited from autochthonous and allochthonous carbon and had high biomass level, which contributed to more productivity and eventually increased in litters, thus increasing the soil organic matter. This study is an important contribution to understand the mangrove ecosystem as stores of blue carbon and reducing atmospheric carbon in small islands. It is imperative to protect these ecosystems to ensure that their roles of sequestering blue carbon and other benefits they provide.

#### ACKNOWLEDGEMENTS

The authors are thankful to the Ministry of Blue Economy, Marine Resources, Fisheries, and Shipping for granting us the permission for collection of samples and we also acknowledge the logistical support of the University of Mauritius. Moreover, part of the work has been accepted

for presentation as poster at the University of Mauritius Research Week 2020.

#### REFERENCES

- Abib S, Appadoo C. 2012. A pilot study for the estimation of above-ground biomass and litter production in *Rhizophora mucronata* dominated mangrove ecosystems in the island of Mauritius. *J Coast Dev* 16 (1): 40-49.
- Ahmed N, Cheung WWL, Thompson S, Glaser M. 2017. Solutions to blue carbon emissions: Shrimp cultivation, mangrove deforestation and climate change in coastal Bangladesh. *Mar Policy* 82: 68-75. DOI: 10.1016/j.marpol.2017.05.007
- Appadoo C. 2003. Status of mangroves in Mauritius. *J Coast Dev* 7 (1): 1-3.
- Ball MC. 1980. Patterns of secondary succession in a mangrove forest of Southern Florida. *Oecologia* 44 (2): 226-235. DOI: 10.1007/BF00572684
- Betts T. 2006. An Assessment of Mangrove Cover and Forest Structure in Las Perlas, Panama. Thesis [Dissertation]. Heriot-Watt University, Edinburgh. [Scottish]
- Chatting M, LeVay L, Walton M, Skov MW, Kennedy H, Wilson S, Al-Maslmani I. 2020. Mangrove carbon stocks and biomass partitioning in an extreme environment. *Estuar Coast Shelf Sci* 244: 106940. DOI: 10.1016/j.ecss.2020.106940
- Chen J, Huang Y, Chen G, Ye Y. 2020. Effects of simulated sea-level rise on stocks and sources of soil organic carbon in *Kandelia Obovata* mangrove forests. *For Ecol Manag* 460: 117898. DOI: 10.1016/j.foreco.2020.117898
- Chen R, Twilley RR. 1999. Patterns of mangrove forest structure and soil nutrient dynamics along the shark river estuary, Florida. *Estuaries* 22: 955-970.
- Clarisse JO, Appadoo C, Boojhawon R. 2016. Spatial distribution of *Rhizophora mucronata* and *Bruguiera gymnorhiza* mangroves using kriging technique: A contribution to understanding forest structure in south-east coast of Mauritius (Indian Ocean). *Univ Mauritius Res J* 22: 458-483.
- Climate-Data.Org, 2020b. Mahebourg Climate. Mauritius. <https://en.climate-data.org/africa/mauritius/grand-port/mahebourg-25187/#:~:text=Mahebourg%20climate%20summary&text=The%20average%20annual%20temperature%20in,mm%20%7C%2071.4%20inch%20per%20year.> [Accessed 15<sup>th</sup> December 2020].
- Climate-Data.Org, 2020a. Le Morne Climate. Mauritius. <https://en.climate-data.org/africa/mauritius/black-river/le-morne-773895/#:~:text=Le%20Morne%20climate%20summary&text=The%20K%3B%20Geiger%20climate%20classification,is%2016%29%20mm%20%7C%2064.1%20inch.> [Accessed 15<sup>th</sup> December 2020].
- Cuellar-Martinez T, Ruiz-Fernández AC, Sanchez-Cabeza JA, Libia-Hascibe PLH, Sandoval-gil J. 2019. Relevance of carbon burial and storage in two contrasting blue carbon ecosystems of a north-east pacific coastal lagoon. *Sci Total Environ* 675: 581-593. DOI: 10.1016/j.scitotenv.2019.03.388
- Cui X, Liang J, Lu w, Chen H, Liu F, Lin G, Xu F, Luo Y, Lin G. 2018. Stronger ecosystem carbon sequestration potential of mangrove wetlands with respect to terrestrial forests in subtropical China. *Agric For Meteorol* 249: 71-80. DOI: 10.1016/j.agrformet.2017.11.019
- Dahdouh-Guebas F, Koedam N. 2008. Long-term retrospective on mangrove development using transdisciplinary approaches: A review. *Aquat Bot* 89: 80-92. DOI: 10.1016/j.aquabot.2008.03.012
- Delvecchia AG, Bruno JF, Benninger L, Alperin M, Banerjee O, Morales IDD. 2014. Organic carbon inventories in natural and restored Ecuadorian mangrove forests. *PeerJ* 2: e388. DOI: 10.7717/peerj.388
- Eid EM, Khedher KM, Ayed H, Arshad M, Moatamed A, Mouldi A. 2019. Evaluation of carbon stock in the sediment of two mangrove species, *Avicennia marina* and *Rhizophora mucronata*, growing in the Farasan islands, Saudi Arabia. *Oceano* 227: 1-14. DOI: 10.1016/j.oceano.2019.12.001
- Eid EM, Shaltout KH. 2015. Distribution of soil organic carbon in the mangrove *Avicennia marina* (Forssk) Vierh. Along the Egyptian Red Sea Coast. *Reg Stud Mar Sci* 3: 76-82. DOI: 10.1016/j.rsma.2015.05.006

- Heiri O, Lotter A, Lemcke G. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J Paleolimnol* 25 (1): 101-110. DOI: 10.1023/A:1008119611481
- Howard J, Hoyt S, Isensee K, Pidgeon E, Telszewski M. 2014a. Coastal blue carbon methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses meadows. In: Fourqurean J, Johnson B, Kauffman JB, Kennedy H, Lovelock C, Saintilan N, Alongi DM, Cifuentes M, Copertino M, Crooks S, Duarte C, Fortes M, Howard J, Hutahaean A, Kairo J, Marba N, Murdiyarto D, Pidgeon E, Ralph P, Serrano O (eds). *Field Sampling of Vegetative Carbon Pools in Coastal Ecosystems*. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.
- Howard J, Hoyt S, Isensee K, Pidgeon E, Telszewski M. 2014b. Coastal blue carbon methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses meadows. In: Howard J, Hoyt S, Isensee K, Telszewski M, Pidgeon E, Telszewski M, Crooks S, Emmer I, Herr D, Hoyt S, Laffoley D, Quesada M, Valdes JL, Wagey T (eds). *Why Measure Carbon Stocks*. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.
- Johnson JL, Raw J, Adams JB. 2019. First report on carbon storage in a warm-temperate mangrove forest in South Africa. *Estuar Coast Shelf Sci* 235: 106566. DOI: 10.1016/j.ecss.2019.106566.
- Kamruzzaman M, Ahmed S, Osawa A. 2017. Biomass and net primary productivity of mangrove communities along the Oligohaline zone of Sundarbans, Bangladesh. *For Ecosyst* 4: 16. DOI: 10.1186/s40663-017-0104-0.
- Kirui B, Kairo JG, Karachi M. 2006. Allometric equations for estimating above ground biomass of *Rhizophora mucronata* Lamk. (Rhizophoraceae) mangroves at Gazi Bay, Kenya. *Western Indian Ocean J Mar Sci* 5 (1): 27-34. DOI: 10.4314/wiojms.v5i1.28496.
- Kusumaningtyas MA, Hutahaean AA, Fischer HW, Pérez-Mayo M, Pittauer D, Jennerjahn TC. 2018. Variability in the organic carbon stocks, sources, and accumulation rates of Indonesian mangrove ecosystems. *Estuar Coast Shelf Sci* 218: 310-323. DOI: 10.1016/j.ecss.2018.12.007
- Lacerda LD. 2002. Mangrove ecosystem: Function and management. In: Lacerda LD, Conde JE, Kjerfve B, Alvarez-Leon R, Alarcon C, Polania J (eds). *American Mangroves*. Springer, Verlag Berlin Heidelberg, New York.
- Luo L, Gu JD. 2016. Alteration of extracellular enzyme activity and microbial abundance by biochar addition: Implication for carbon sequestration in subtropical mangrove sediment. *J Environ Manage* 182: 29-36. DOI: 10.1016/j.jenvman.2016.07.040
- Martin C, Almahasheer H, Duarte CM. 2019. Mangrove forests as traps for marine litter. *Environ Pollut* 247: 499-508. DOI: 10.1016/j.envpol.2019.01.067.
- Penaranda MLP, Kintz JRC, Pena EJ. 2019. Carbon stocks in mangrove forests of the Colombian pacific. *Estuar Coast Shelf Sci* 227: 106299. DOI: 10.1016/j.ecss.2019.106299.
- Putz FE, Chan HT. 1986. Tree growth, dynamics, and productivity in a mature mangrove forest in Malaysia. *For Ecol Manag* 17: 211-230. DOI: 10.1016/0378-1127(86)90113-1.
- Ranjan R. 2019. Optimal mangrove restoration through community engagement on coastal lands facing climatic risks: The case of Sundarbans region in India. *Land Use Policy* 81: 736-749. DOI: 10.1016/j.landusepol.2018.11.047.
- Saenger P, Snedaker SC. 1993. Pantropical trends in mangrove above-ground biomass and annual litterfall. *Oecologia* 96 (3): 293-299. DOI: 10.1007/BF00317496.
- Salum RB, Souza-Filho PWM, Simard M, Silva CA, Fernandes MEB, Cougo MF, Rogers K. 2020. Improving mangrove above-ground biomass estimates using LiDAR. *Estuar Coast Shelf Sci* 236: 106585. DOI: 10.1016/j.ecss.2020.106585.
- Sanderman J, Heng T, Fiske G, Solvik K, Adame MF, Benson L, Bukoski JJ, Carnel P, Cifuentes-Jara M, Daniel-Donato D, Duncan C, Eid EM, Ermgassen PZ, Lewis CJ, Macreadie PI, Glass L, Gress S, Jardine SL, Jones TG, Nsombo EN, Rahman M, Sanders CJ, Spalding M, Landis E. 2018. A global map of mangrove forest soil carbon at 30m spatial resolution. *Environ Res Lett* 13: 055002. DOI: 10.1088/1748-9326/aabe1c
- Sasmitho SD, Kuzzyakov Y, Lubis AA, Murdiyarto D, Hutley LB, Bachri S, Friess DA, Martius C, Borchard N. 2020. Organic carbon burial and sources in soils of coastal mudflat and mangrove ecosystems. *Catena* 187: 104414. DOI: 10.1016/j.catena.2019.104414.
- Shaltout KH, Ahmed MT, Alrumman SA, Ahmed DA, Eid EM. 2019. Evaluation of the carbon sequestration capacity of arid mangroves along nutrient availability and salinity gradients along the red sea coastline of Saudi Arabia. *Oceanologia* 227: 1-14. DOI: 10.1016/j.oceano.2019.08.002
- Thorhaug AL, Poulos HM, Portillo JL, Barr J, Lara-Dominguez AL, Ku TC, Berlyn GP. 2018. Gulf of Mexico estuarine blue carbon stock, extent and flux: Mangroves, marshes, and seagrasses: A North American hotspot. *Sci Total Environ* 653: 1253-1261. DOI: 10.1016/j.scitotenv.2018.10.011.
- Vinh TV, Marchand C, Linh TVK, Vinh DD, Allenbach M. 2019. Allometric models to estimate above-ground biomass and carbon stocks in *Rhizophora apiculata* tropical managed mangrove forests (Southern Viet Nam). *For Ecol Manag* 434: 131-141. DOI: 10.1016/j.foreco.2018.12.017.
- Vinod K, Asokan PK, Zacharia PU, Ansar CP, Vijayan G, Anasukoya A, Koya VAK, Nikhiljith M. 2019. Assessment of biomass and carbon stocks in mangroves of Thalassery estuarine wetland of Kerala, South West Coast of India. *J Coast Res* 86: 209-217. DOI: 10.2112/SI86-031.1
- Wang L, Jia M, Yin D, Tian J. 2019. A review of remote sensing for mangrove forests: 1956-2018. *Remote Sens Environ* 231: 111223. DOI: 10.1016/j.rse.2019.111223
- Weather atlas, 2019. Monthly weather forecast and climate Le Morne, Mauritius. Mauritius. <https://www.weather-atlas.com/en/mauritius/le-morne-climate#rainfall>.
- Wu J, Chen B, Mao J, Feng Z. 2018. Spatiotemporal evolution of carbon sequestration vulnerability and its relationship with urbanization in China's coastal zone. *Sci Total Environ* 645: 692-701. DOI: 10.1016/j.scitotenv.2018.07.086
- Xiong Y, Liao B, Proffitt E, Guan W, Sun Y, Wang F, Liu X. 2018. Soil carbon storage in mangroves is primarily controlled by soil properties: A study at Dongzhai Bay, China. *Sci Total Environ* 619-620: 1226-1235. DOI: 10.1016/j.scitotenv.2017.11.187
- Xue B, Yan C, Lu H, Bai Y. 2009. Mangrove-derived organic carbon in sediment from Zhangjiang estuary (China) mangrove wetland. *J Coast Res* 25: 949-956. DOI: 10.2112/08-1047.1
- Yang J, Gao J, Liu B, Zhang W. 2014. Sediment deposits and organic carbon sequestration along mangrove coasts of the Leizhou Peninsula, Southern China. *Estuar Coast Shelf Sci* 136: 3-10. DOI: 10.1016/j.ecss.2013.11.020.