DOI: http://doi.org/10.4038/jepsl.v11i1.7884

Journal of Environmental Professionals Sri Lanka: 2022 – Vol. 11 – No. 1

Assessment of the Blue Carbon Stocks Including Mangroves, Seagrasses and Salt Marshes in Puttalam, North West Sri Lanka

G. Sathiyamohan[1], D.M.S.H.K. Ranasinghe[1,#], and W.M.P.S.B. Wahala[2]

[1]Department of Forestry and Environmental Science, University of Sri Jayewardenepura, Nugegoda, SRI LANKA

[2]Department of Tourism Management, Sabaragamuwa University of Sri Lanka, Belihuloya, SRI LANKA

[#]Corresponding Author:
Tele: (94) 71 4478756; E-mail: hemanthiranasinghe@gmail.com

ABSTRACT

Blue carbon is the carbon stored in coastal and marine ecosystems. Coastal ecosystems such as mangroves, tidal marshes, and seagrass meadows sequester and store 4-5 times more carbon per unit area than terrestrial forests and are now being recognized for their role in mitigating climate change. However, most of these coastal ecosystems are not under protection; hence their potential as carbon sinks could be threatened. Therefore, it is vital to conserve these ecosystems, but the inadequacy of data on the ecosystem services provided by them, including carbon sequestration and storage poses a great debacle. This study aimed to assess the carbon storage capacities of mangroves, seagrasses and salt marshes in Sri Lanka.

The study was conducted in mangrove, seagrass and salt marsh habitats in connection with the Puttalam Lagoon in Anawasala and Soththupitiya in Puttalam District, North Western Sri Lanka. Both natural mangroves and 15 years old planted mangroves were included in the study. Belt transects were taken from the shore towards the land. Nested circular plots having a 7m radius were established, large trees were sampled for diameter at breast height (DBH) and height. Small trees (<3 cm DBH) were sampled in 2m radius. Litter, pneumatophores and seedlings were sampled in 30 cm x 30cm area plots. Soil samples were taken at depths; 0-30cm, 30-60cm, 60-100 cm for the measurement of bulk density and carbon content. The biomass of the mangrove plants was measured using species-specific allometric equations.

In the seagrass beds and salt marshes, belt transects were set up parallel to the beach (along the coastline), and 1 x 1m plots were sampled along this. The carbon content of the aboveground components was analyzed using Walkey Black Method, while the soil carbon was measured by Loss on Ignition (LOI) method using a muffle furnace. The data were analyzed using MINITAB statistical software.

Rhizophora mucronata and Avicennia marina were abundant in the natural mangroves while the former was the only one in the planted mangrove site. Enhalus acoroides was observed in the sea grass beds. The species observed in salt marshes were Suedo varae and Salicornia Brachiata.

In all three ecosystems the organic carbon content was higher in the Soil compared with the tree components. Natural mangroves showed the highest soil organic carbon (382.72 t/ha), while the planted mangroves showed only 148.26 tC/ha. The soil organic carbon of sea grass beds was 236.76 tC/ha, and salt marshes was 199.30 tC/ha. With regards to the organic carbon in the vegetative matter, natural mangroves showed the highest (206.48 tC/ha) followed by planted mangroves (175.8 tC/ha).

The contribution from the sea grass beds and salt marshes were negligent. When the total organic carbon from the ecosystem is considered, natural mangroves showed the highest (589.20 tC/ha), followed by planted mangroves (324.06 tC/ha), seagrass beds (236.76 tC/ha) and then salt marshes (199.3 tC/ha).

Key words: *Blue carbon, mangroves, seagrasses, salt marshes, carbon sequestration*

Introduction

Carbon captured and managed by the world's ocean and seascape ecosystems, including seagrass meadows, mangroves, salt marshes and algae are called Blue Carbon. They are reported to store/sequester organic carbon often 4-5 times higher than the terrestrial ecosystems due to the anaerobic condition of the Soil in which carbon is lodged for much longer (*Bouillon et al., 2008;Nellemann et al., 2009; McLeod et al., 2011*).

Studies on the blue carbon environments show that mangroves can store carbon around 280 MgC/ha, tidal marshes around 250 Mg C/ha, and seagrass meadows around 140 Mg C/ha. That is equivalent to capturing 1,030 mega grams of CO_2 per hectare (Mg CO_2 /ha) in mangroves, 920 Mg CO_2 /ha in tidal marshes, and 520 Mg CO_2 /ha in seagrass meadows (Howard et al., 2014). Perera and Amarasinghe in 2018 reported total organic carbon in the mangrove ecosystems in Batticaloa Lagoon in Sri Lanka to be 506 tC/ha. The contribution of aboveground components was 131 tC/ha while that of the belowground vegetative components (roots) was 27 tC/ha. The Soil contributed 348 tC/ha, which was the highest.

The organic carbon sequestration in sea grass beds was between 41 and 66 gCm^2yr^1 (*Kennedy et al.,2010*). The carbon storage of sea grass beds was reported to be around 140 tC/ha (Serrano et al, 2021). With regards to salt marshes, the carbon storage was around 162 tC/ha (Kelleway et al, 2015). However, studies conducted on carbon storge/sequestration of sea grass beds and salt marshes in Sri Lanka are extremely rare, thus the commencement of this study. The main objective of the research was to quantify the biomass and organic carbon content lodged in the blue carbon ecosystems associated with Puttalam Lagoon, including mangroves, seagrasses, and salt marshes.

Materials and Methods

Study site

The study was conducted in and around the Puttalam Lagoon in Anawasala and Soththupitiya in the Puttalam District, North Western Sri Lanka. Figure 1 shows the study sites for mangroves, sea grasses and salt marshes.

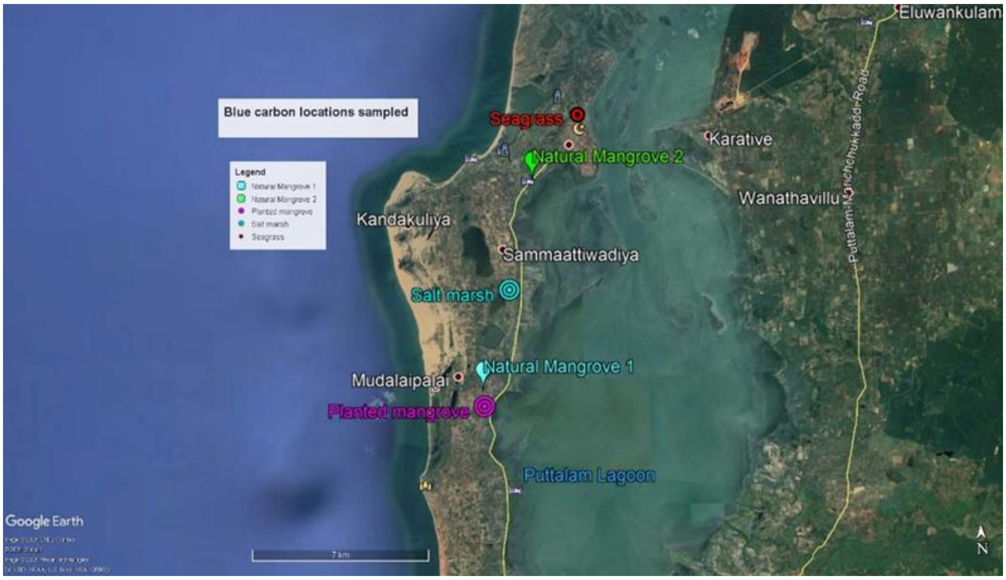

Figure 1: Locations of the sampling sites

The description of the sampling sites are given in table 1.

Table 1: The description of the sampling sites.

Ecosystem type	**Location Name**	**GPS location of sites**	**Area (m²)**
Planted Mangroves	Soththupitiya	N8.139202° E79.725790°	1078
Natural Mangroves	Sothtupitiya (site 1)	N8.145254° E79.725440°	1230.8
	Anawasala	N8.217986° E79.745906°	
Seagrass beds	Anawasala	N8.240290° E79.763490°	16
Salt marshes	Anawasala	N8.179553° E79.736307°	37

Sampling methods

Mangroves

Fifteen years old planted mangroves with *Rhizophora mucronata* and natural mangroves were sampled. Planted mangroves were located in Soththupitiya, while natural mangroves were present in both Sothupitiya and Anawasala. In the sampling, belt transects were taken from the shore towards the land. Nested circular plots having 7m radius were established, large trees were sampled for diameter and height. Small trees (<3 cm DBH) were sampled in 2m radius. Litter, pneumatophores and seedlings were sampled in 30 cm x 30 cm area plots. Soil samples were taken using a soil auger at depths; 0-30cm, 30-60cm, 60-100 cm for the measurement of bulk density and carbon content. Litter samples including all organic surface material, excluding woody particles were collected from three 30×30 cm plots in each large plot. Pneumatophores were counted in the 30×30 cm micro plots established for the litter layer sampling. Few pneumatophores were sampled destructively to get the fresh weight. Samples of both litter and pneumatophores were taken to the laboratory for analysis of organic carbon.

Seagrass beds

Belt transects were set up parallel to the beach (along the coastline), and 1m x 1m plots were sampled along this. A total of 15 plots were sampled. Each plot assessed the species composition and the number of plants in each species. Few plants were uprooted and taken to the laboratory for organic carbon analysis. The soil samples were taken with a soil auger to represent the following depths; 0-30 cm and 30-60 cm, 60-100 cm. They were taken to the laboratory for analysis of organic carbon.

Salt Marshes

Belt transects were set up parallel to the beach (along the coastline), and 1 x 1m plots were sampled along this. A total of 37 plots were sampled. Each plot assessed the species composition and the number of plants in each species. Few plants were uprooted and taken to the laboratory for analysis of organic carbon. The soil samples were taken with a soil auger to represent the following depths; 0-30 cm and 30-60 cm, 60-100 cm. They were taken to the laboratory for analysis of organic carbon.

Assessment of the biomass and carbon content

Assessment of biomass in Mangroves

The aboveground and belowground biomass of the mangroves were assessed using species specific Allometric Equations shown below;

- For *Rhizophora spp*

Aboveground Biomass (AGB) $=0.1709\ (D)^{2.516}$ (Source: Putz and Chan 1986),

Belowground Biomass (BGB) $=0.199\ p^{0.899}\ (D)^{2.22}$.

Wood Density p = 1.05 (Source: World Agroforestry Centre, 2011).

- For *Avicennia marina*

Aboveground Biomass (AGB) =0.1848 $(DBH)^{2.3524}$ (Source: Dharmawan and Siregar, 2008)

Belowground Biomass (BGB) = 0.199 $p^{0.899}$ $(DBH)^{2.22}$

Wood Density p = 0.66 (Source: World Agroforestry Centre, 2011).

(DBH: Diameter at breast height of trees, p: Wood density values)

Assessment of the carbon content

The ratio between the green weight and the dry weight was assessed by oven drying the above ground and belowground samples brought from the field to a constant weight of 105^0 C. Carbon content was taken as 50% of the dry weight following the reference Sampson, 1992.

The litter samples and pneumatophore samples were also oven dried at 105 ^{0}C to constant weight and dry weight taken. The carbon content of them was assessed using the following equations;

Carbon in the litter component (kg C/m^2) = (Average biomass of the litter x carbon conversion factor (0.45)/area of the plot ((m^2)

Carbon in the pneumatophore component (kg C/m^2) = [(Estimated biomass of the pneumatophores x carbon conversion factor (0.39)] / area of the plot (m^2).

Assessment of the carbon content in Soil

The soil samples brought to the laboratory were oven dried to a constant weight at 105 ^{0} C. Bulk density was determined by dividing the oven-dry soil sample mass by the volume of the sample. The bulk density equation is as follows:

Soil Bulk Density (g cm^{-3}) = Oven dry sample mass (g)/ sample volume cm^3 *(Kauffman et al. (2011)*

Soil carbon content was assessed using the LOI (Loss on Ignition) method. The organic carbon content was calculated as follows;

%C (combustion) = 0.03 + 0.36 * %weight loss by LOI, (Konare *et.al, 2010).*

Total soil carbon pools were determined by summing the mass of each sampled soil depth. The total soil carbon pool was determined by partitioning the soil horizon into depth intervals and taking measurements of bulk density and carbon concentration of the partitioned layers; 00 - 30 cm, 30–60 cm, 60– 100 cm as shown in the following equation.

Soil Carbon (Mgha-1) = Bulk density x Soil Depth interval x %C (%C is the carbon concentration expressed as a whole number)

The total carbon in the mangrove ecosystem was estimated by adding all the component pools as shown in the following equation;

Total carbon Stock (Mg) = C treeAG+ CtreeBG + C seedling+ C litter + C pneumatophore+ Csoil

Assessment of the biomass and carbon content in Seagrasses

The samples of the uprooted plants were identified at the species level; they were washed thoroughly, air dried for one day, and oven dried to a constant weight at 50 °C and dry weight was recorded. Dry weight values were converted to carbon equivalents assuming the carbon content of the seagrass biomass is 35 % of dry weight (Fourqurean *et al*., 2012a). The average mass of one plant was calculated and extrapolated to 1ha.

Soil carbon content was assessed using the LOI (Loss on Ignition) method. The organic carbon content was calculated as follows;

%C (combustion) = 0.03 + 0.36 x %weight loss by LOI, (Konare *et al*., 2010).

Total soil carbon pools were determined by summing the mass of each sampled soil depth. The total soil carbon pool was determined by partitioning the soil horizon into depth intervals of and taking measurements of bulk density and carbon concentration of the partitioned layers; 00 - 30 cm, 30–60 cm, 60– 100 cm as shown in the following equation.

Soil Carbon ($Mgha^{-1}$) = Bulk density x Soil Depth interval x %C

(%C is the carbon concentration expressed as a whole number)

The total carbon in the seagrass ecosystem was estimated by adding all the component pools as shown in the following equation;

Total carbon Stock (Mg) = Cseagrass vegetation + Csoil

Assessment of the biomass and carbon content in salt marshes

The samples of the uprooted plants were identified at species level, They were washed thoroughly, air dried for one day and oven dried to a constant weight at 50 °C and dry weight recorded. Dry weight values were converted to carbon equivalents assuming a carbon content of the seagrass biomass of 35 % of dry weight (Fourqurean *et al*. 2012a). The average mass of one plant was calculated and extrapolated to 1ha.

Soil carbon content was assessed using the LOI (Loss on Ignition) method. The organic carbon content was calculated as follows;

%C (combustion) = 0.03 + 0.36 x %weight loss by LOI, (Konare *et al*., 2010).

Total soil carbon pools were determined by summing the mass of each sampled soil depth. The total soil carbon pool was determined by partitioning the soil horizon into depth intervals of and taking measurements of bulk density and carbon concentration of the partitioned layers; 00 - 30 cm, 30–60 cm, as shown in the following equation.

Soil Carbon ($Mgha^{-1}$) = Bulk density x Soil Depth interval x %C

(%C is the carbon concentration expressed as a whole number)

The total carbon in the mangrove ecosystem was estimated by adding all the component pools as shown in the following equation;

Total carbon Stock (Mg) = Csalt marsh vegetation + Csoil

Converting to carbon dioxide equivalents

The total carbon density or total carbon stock of all the ecosystems studied was converted to CO_2 equivalents by multiplying carbon density of the stock by 3.67 using the following equation;

1 tC = 3.67 t CO_2 (US EPA, 2019)

Analysis of data

The data thus obtained on the biomass and carbon contents were analysed using descriptive statistics using MS Excel and Analysis of variance of MINITAB statistical package.

Results and Discussion

Biomass and Organic Carbon Content of Mangroves

The biomass and organic carbon content of both natural and planted mangroves are shown in Table 2. Since there was no statistical significance ($p>0.05$), the values obtained from the sampling sites were pooled and shown as a mean value.

The total organic carbon in the Soil of the mangroves up to 1m depth was recorded 148.26 tC/ha for the planted mangroves, while it was 382.72 tC/ha for the natural mangroves. The organic matter content is reduced with the depth of the soil layers.

Table 2: Biomass and Total Organic Carbon (TOC) content (above and below ground) recorded for natural and planted mangroves in the study sites

Sampling area	Biomass (Mg ha^{-1})			Total organic carbon (TOC) content (Mg C ha^{-1})		
	Above ground	**Below ground**	**Total**	**Above ground**	**Below ground**	**Total**
Planted mangroves	233 ±2.18	153.35 ±1.44	386.35 ±3.62	116 ± 1.20	59.80 ± 0.56	175.8 ± 1.76
Natural mangroves	301.4 ± 49.97	144.73 ± 21.35	446.13 ± 71.32	150 ± 24.6	56.425 ± 8.32	206.48 ± 32.92

Note: the total aboveground includes trees, pneumatophores, litter and seedlings

Figure 2 shows the partitioning of organic carbon between aboveground and below ground plant components and the Soil in both natural and planted mangrove ecosystems.

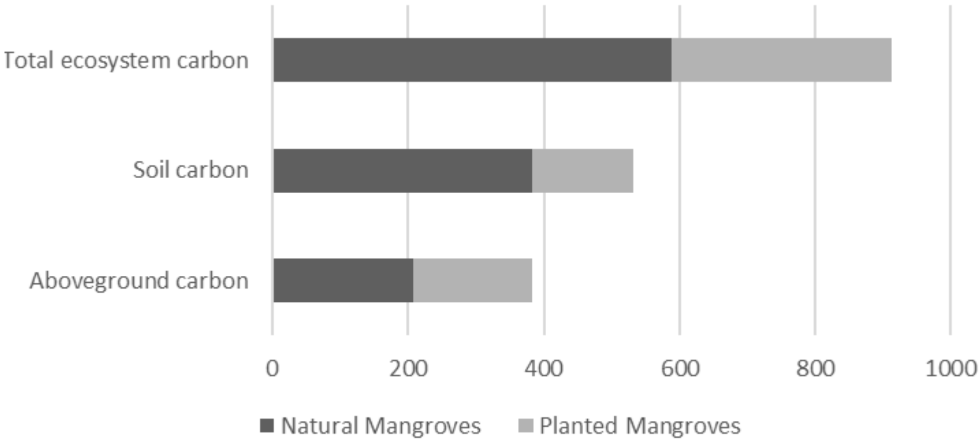

Figure 2: The partitioning of the organic carbon between the tree components (aboveground and belowground) and the Soil in mangrove ecosystem. Values are given in t C per ha.

These results agree with those Perera and Amarasinghe in 2018 on ecosystem carbon pools associated with mangroves in Batticaloa Lagoon where they had reported the total aboveground organic carbon to be 158.57 Mg//ha while the soil organic carbon was reported to be 347.8 Mg/ha.

The total ecosystem carbon was 506.4 Mg/ha. The same authors reported soil organic carbon to be 376.2 Mg/ha in mangroves in Kala Oya. Research conducted outside the country also provides findings which are comparable with the ones reported above. According to the findings of Kauffman et al in 2011 on the mangroves in the Western Pacific Ocean, the mean soil carbon pools up to 1 m depth was 414 Mg/ha.

Sea grass beds

The most prominent species in the sea grass beds sampled was *Enhalus Acoroides*. The biomass and the total organic matter content in aboveground matter and Soil in sea grass beds are shown in Table 3.

Table 3: The biomass and the total organic matter content in the aboveground matter and Soil in sea grass beds

Aboveground Biomass (t/ha)	Aboveground Carbon Content (tC/ha)	Soil carbon content (tC/ha)	Total Ecosystem carbon content (tC/ha)
2.00 ± 0.131	0.70 ± 0.046	236.06	238.76

Findings which are in agreement with the present study was reported by Fourgurean et al, 2012b who reported biomass of the seagrasses in Florida Bay in USA to be 1.44 Mg/ha. Mediterranean meadows reported the highest carbon stock in seagrass ecosystems which was 7.29 Mg/ha in the plant component which was dominated by *Posidonia oceanica.* The carbon storage in the Soil was 372.4 Mg/ha. He further reported that average soil carbon stock of the seagrass meadows account for 165.6 Mg/ha in the top 1m layer. According to Lavery et al. 2016 seagrass meadows dominated by *Z. muelleri* recorded carbon storage of 232 Mg/ha in the entire ecosystem.

Salt Marshes

The most prominent species in the sea grass beds sampled were *Suedo varae*, and *Salicornia Brachiata.* The biomass and the total organic matter content in aboveground matter and Soil in the salt marshes are shown in Table 4

Table 4: The biomass and the total organic matter content in aboveground matter and Soil in the salt marshes

Aboveground Biomass (t/ha)	Aboveground Carbon Content (tC/ha)	Soil carbon content (tC/ha)	Total Ecosystem carbon content (tC/ha)
2.141 ± 0.122	0.752 ± 0.045	196.41 ±28.5	199.30

The results of the present study was in agreement with those of Fourqurean et al., 2012a where the value of *Amphibolis antarctica* is 4.66 Mg/ha. For those dominated by *T. testudinum* was 1.44 Mg/ha . Kelleway et al., (2016) reported that in 9 different habitats of salt marshes in New South Wales (NSW) the organic carbon had been 164.45 Mg C/ha. Brown et al., in 2016 reported the organic carbon content of the Coffs Creek harbor salt marsh in Australia dominated *by Sporobolus virginicus* to be 333 Mg C/ha. Drake and Halifax (2015) reported the organic carbon content to be 162 Mg/ha in the salt marshes in North East USA. Chaeho byun et al., (2019) reported findings of a similar nature from South Korea having the figure of 260 Mg/ha.

The Total Organic Carbon Contents in all the blue carbon ecosystems studied; mangroves, sea grass beds, salt marshes, and their capacity in reducing the CO_2 are shown in Table 5.

Table 5: The summary of the Total Organic Carbon content and partitioned organic matter content (Mg/ha) of the four ecosystems studied

Ecosystem type	**Soil organic carbon**	**Vegetative carbon**	**Total Org carbon**	**CO_2/ha**
Planted Mangroves	148.26 ±31.6	172.21 ± 1.76	320.47 ± 33.36	1176.12 ± 122.43
Natural Mangroves	382.72 ±55.4	213.485 ± 33.55	596.20 ±88.95	2188.07 ± 326.45
Seagrasses	236.06 ± 25.77	0.70 ± 0.046	236.76 ±25.816	868.90 ± 94.74
Salt marshes	196.41 ±28.5	0.752 ± 0.045	197.16 ± 28.54	723.58 ± 104.76

Note: the total carbon content was multiplied by 3.67 to get the total removal of atmospheric carbon dioxide ((Source: USEPA, 2019)

Conclusions and Recommendations

The study revealed the enormous potential in blue carbon ecosystems in acting as carbon sinks. Of the ecosystems studied, natural mangroves contributed the highest in organic carbon storage (596.20 tC/ha) followed by 15 years old planted mangroves 320.47 tC/ha. Sea grass beds contributed 236.76 tC/ha and the Salt marshes 197.16 tC/ha.

Since most of these ecosystems are located outside protected areas, it is required to strengthen their protection in order to utilize the ecosystem services they provide including carbon storage/sequestration, and act as carbon sinks to reduce the GHG emissions.

References

Bouillon, S., Borges, A.V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J. and Rivera-Monroy, V.H., 2008. Mangrove production and carbon sinks: a revision of global budget estimates. Global biogeochemical cycles, 22(2).

Brown, D.R., Conrad, S., Akkerman, K., Fairfax, S., Fredericks, J., Hanrio, E., Sanders, L.M., Scott, E., Skillington, A., Tucker, J. and van Santen, M.L., 2016. Seagrass, mangrove and saltmarsh sedimentary carbon stocks in an urban estuary; Coffs Harbour, Australia. Regional Studies in Marine Science, 8, pp.1-6.

Byun, C., Lee, SH. & Kang, H. Estimation of carbon storage in coastal wetlands and comparison of different management schemes in South Korea. j ecology environ 43, 8 (2019). https://doi.org/10.1186/s41610-019-0106-7

Drake, K., Halifax, H., Adamowicz, S.C. and Craft, C., 2015. Carbon sequestration in tidal salt marshes of the Northeast United States. Environmental Management, 56(4), pp.998-1008.

Fourqurean, J.W., Kendrick, G.A., Collins, L.S., Chambers, R.M. and Vanderklift, M.A., 2012 b. Carbon, nitrogen and phosphorus storage in subtropical seagrass meadows: examples from Florida Bay and Shark Bay. Marine and Freshwater Research, 63(11), pp.967-983.

Howard, J., Hoyt, S., Isensee, K., Telszewski, M. and Pidgeon, E., 2014. Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses.

Kauffman, J.B., Heider, C., Cole, T.G., Dwire, K.A. and Donato, D.C., 2011. Ecosystem carbon stocks of Micronesian mangrove forests. Wetlands, 31(2), pp.343-352.

Kauffman, J.B. and Donato, D.C. (2012) Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests, Working Paper 86, Center for International Forestry Research (CIFOR)

Kelleway, J.J., Saintilan, N., Macreadie, P.I. and Ralph, P.J., 2016. Sedimentary factors are key predictors of carbon storage in SE Australian saltmarshes. Ecosystems, 19(5), pp.865-880.

Kennedy, H., Beggins, J., Duarte, C.M., Fourqurean, J.W., Holmer, M., Marbà, N. and Middelburg, J.J., 2010. Seagrass sediments as a global carbon sink: Isotopic constraints. Global Biogeochemical Cycles, 24(4).

Konare, H., Yost, R.S., Doumbia, M., McCarty, G.W., Jarju, A. and Kablan, R., 2010. Loss on ignition: measuring soil organic carbon in soils of the Sahel, West Africa. African Journal of Agricultural Research, 5(22), pp.3088-3095.

Lavery, P.S., Mateo, M.Á., Serrano, O. and Rozaimi, M., 2013. Variability in the carbon storage of seagrass habitats and its implications for global estimates of blue carbon ecosystem service. PloS one, 8(9), p.e73748.

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H. and Silliman, B.R., 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment, 9(10), pp.552-560.

Nellemann, C. and Corcoran, E. eds., 2009. Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment. UNEP/Earthprint.

Perera, K.A.R.S. and Amarasinghe, M.D., 2018. Ecosystem carbon stock of mangroves at the Batticaloa Lagoon, Sri Lanka.

Perera, K. A. R. S., Sumanadasa W. A. and Amarasinghe M. D. (2012). Carbon retention capacity of two mangrove species, Bruguiera gymnorrhiza (L.) Lamk. and Lumnitzera racemosa Willd. in Negombo estuary, Sri Lanka. Journal of the Faculty of Graduate Studies, 2012, University of Kelaniya, Sri Lanka, 1: 56-70 pp.

Perera, K.A.R.S. and Amarasinghe, M.D., 2019. Carbon sequestration capacity of mangrove soils in micro tidal estuaries and lagoons: A case study from Sri Lanka. Geoderma, 347, pp.80-89.

Sampson R.N. (1992). Forestry opportunities in the United States to mitigate the effects of global warming. Water,Air and Soil Pollution 64: 157–180.

Dharmawan, I.W.S. and Siregar, C.A., 2008. Karbon tanah dan pendugaan karbon tegakan Avicennia marina (Forsk.) Vierh. di Ciasem, Purwakarta. Jurnal Penelitian Hutan dan Konservasi Alam, 5(4), pp.317-328.

Putz, F.E. and Chan, H.T., 1986. Tree growth, dynamics, and productivity in a mature mangrove forest in Malaysia. Forest ecology and management, 17(2-3), pp.211-230.