Title: Blue carbon storage in a tropical coastal estuary: insights for conservation priorities

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Highlights

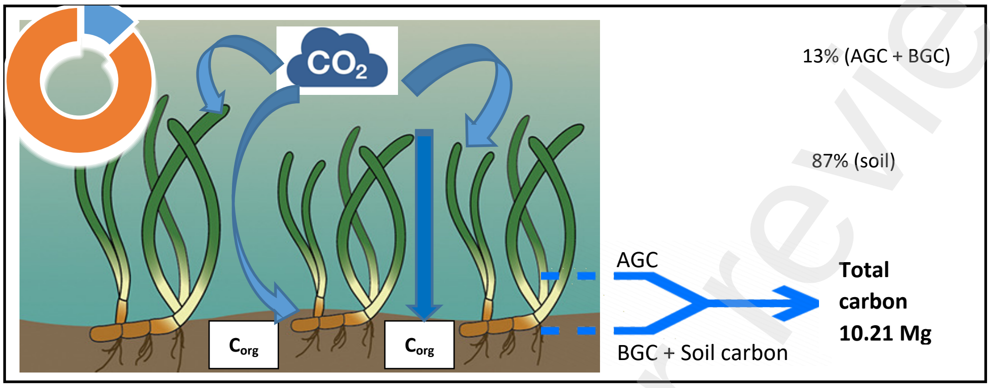
- Sea grasses, one of prominent blue carbon ecosystems, store carbon and contributes to mitigate impacts of climate change while providing many co-benefits.
- Large knowledge gaps remain on carbon estimates, in tropical seagrass meadows in the South Asian region.
- The present study reveals that sediments below the seagrass beds contain highest carbon accumulation than the aboveground parts.
- Proper management actions for sea grass habitats are urgently needed to secure better carbon related benefits.

Abstract

Seagrass ecosystems have been determined as necessary sinks in the global carbon cycle and contribute towards climate change mitigations. In the recent past, there has been an increase of studies focused on blue carbon opportunities provided by seagrasses but large knowledge gaps and uncertainties remain, particularly in tropical seagrass meadows in the South Asian regions. Therefore, the current study aims to quantify the organic carbon stocks in the seagrass meadows on the tropical estuary in southern coast of Sri Lanka and highlights the need of conserving seagrasses specially in the context of effective management of lagoons to achieve Sustainable Development Goals. Landsat 9 (OLI/ TIRS) images were used to develop seagrass distribution maps for 2022 and the data were verified with ground truthing. Vegetation and soil samples were taken from eight sampling locations representing the Rekawa Lagoon. Aboveground biomass (AGB) and belowground biomass (BGB) were determined by multiplying the biomass with the carbon conversion factor whereas the loss-on-ignition (LOI) technique was applied to calculate the soil organic carbon. Results revealed that the soil core carbon content of the study site were ranged between 2.56± 0.29 to 3.04 ± 0.44 Mg C/ha. The calculated total carbon content of the 0.0324 km^2 study area in Rekawa Lagoon was 10.21 Mg C, giving 87.06% contribution from sediment organic carbon pool. This study provides insights for the conservation of these critical ecosystems and highlights the need of policy and action agendas for better management.

Key words: Climate change, Blue carbon, Seagrass meadows, Biomass

Graphical abstract



Introduction

Seagrass beds are important living components of the shallow coastal areas in many parts of the world (Short et al., 2016). Sea grasses can be considered as marine counterparts of terrestrial grasses as they are flowering plants where most species have long green, grass-like leaves. They inhabit clear, shallow lagoons, estuaries and coastal areas. These grasses propagate both sexually and vegetatively. These plant communities often exist as dense meadows which are inundated and yet some are prominent making them to be observable from the space. Seagrasses are one of the most productive ecosystems in the world which extend many ecosystem services (Duarte,2000; Duarte et al., 2005; Nordlund et al., 2016). They offer provisioning services by providing shelter and food to a wide array of fauna, from invertebrates to large organisms such as turtles and mammals (Unsworth et al., 2018; Fourqurean et al., 2012; Infantes et al., 2020). The regulatory services offered by these habitats include improving water quality and operation of bio-geochemical cycles. On the other hand, seagrasses are capable of capturing and storing atmospheric carbon or "sequestering" carbon, potentially one of the most important contributions towards mitigating climate change effects (Kennedy et al., 2010; Fourqurean et al., 2012). Although they occupy a very insignificant area, about 0.2% of global ocean beds, the seagrasses habitats contribute to around 10 % of annual carbon storage in the ocean (Fourqurean et al., 2012). Therefore, seagrass meadows are increasingly receiving attention as a potential habitat to reduce global warming as they are beneficial in counterbalancing anthropogenic CO_2 emissions (Miyajima et al., 2015; Ortega et al., 2020).

In the recent past, there has been an increase of studies focused on blue carbon opportunities provided by seagrasses (Gullstrom et al., 2018; Juma et al., 2020; Omollo et al., 2022). Blue carbon implies the storing of carbon in aquatic plants, soils and sediments (Victoria et al., 2018; Macreadie et al., 2021). Accumulation of organic carbon as blue carbon in the coastal beds and ocean flow is one of the few instances where carbon atoms bury in soil and become “inactive” in the carbon cycle, at least for a short time and removing atmospheric carbon temporarily (Houghton, 2007). Despite the services they provide, seagrasses are undergoing changes and deteriorations due to high rates of habitat loss resulting mainly from anthropogenic threats including pollution, sedimentation, and climate change (Liu et al., 2016; Oreska et al., 2017).

In this study, we investigate carbon storage in seagrasses in a shallow coastal lagoon in Sri Lanka, a tropical island in the Indian Ocean with a variety of costal habitats (Silva et al., 2013; Wickramasinghe, 2010). Rekawa lagoon constitutes a major saline water body in the southern coast of the island. Although many literatures exist on carbon sequestration in coastal habitats in the country, little attention is paid to seagrasses. This study contributes to filling this knowledge gap. We report here the aboveground and belowground carbon stocks as well as those that are buried in sediments. Using Geographic Information System (GIS) and Remote Sensing (RS), we present the distribution of seagrass meadows in the lagoon. We also highlight the need of conserving seagrasses specially in the context of effective management of lagoons to achieve 13 (climate action) and 14 (life below water) of Sustainable Development Goals. The results we present here will help to understanding of how costal lagoons could contribute to a broader context of management of coastal areas.

2. Methodology

2.1. Study area

The study was conducted at Rekawa Lagoon located in the Hambantota district on the southern coast of Sri Lanka. This lagoon is connected to the Indian Ocean with a 3 km narrow inland waterway (Gunaratne et al., 2013). Kirama-oya that enters the lagoon at the sea ward end of the inlet canal is the main freshwater supply and there are two small freshwater streams that bring water into the lagoon. The Rekawa Lagoon area lies on the intermediate zone between the dry and wet climatic zones, with an average rainfall of about 2,000 mm per year (Atapattu and Nissanka, 2005). The average temperatures range between 26.6 and 27.2 degrees Celsius with nearly 7 hours of unobstructed sunlight (Samaranayake, 1983). The adjacent coastal area is composed of diverse habitats with lagoon, mangroves and seagrass. They are home to numerous local and migratory birds, fish and shellfish reptiles, mammals and invertebrates (Ganewatte et al., 1995).

2.2. Seagrass distribution map preparation

The maps were developed using GIS and RS. Thermal Infrared Sensor (TIRS) acquired from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/), in 2022 was used as the base data for the study. The Images are of GEOTIFF format obtained through the Worldwide Reference System (WRS) Path 141 and Row 056 and projected to UTM Specific Parameters of Hemisphere "N", Zone "44". Radio metrically corrected thirty-meter resolution Landsat 9 (OLI/ TIRS) images were used for this study. The Landsat images were classified using an Iso cluster unsupervised classification techniques, which was performed in ArcGIS 10.6.1. using the ISODATA clustering method and maximum likelihood classification tools. Unsupervised classification allows identification of pixels automatically according to its pixel values, post identification and categorization in to several classes (Rozenstein and Karnieli, 2011). All the satellite images were classified into seven classes: water bodies, bare lands, paddy fields, marsh lands, settlement areas, mangrove and other terrestrial plants and seagrass. The Google earth pro software, topographic maps from the Survey Department of Sri Lanka, local knowledge and ground truthed data that were collected with the GPS during the field visits were utilized for the accuracy assessment of the prepared maps. Finally, we calculated the area of the seagrass within the lagoon using the classified images.

2.3. Field data collection

A pilot study was carried out to understand the locations where the seagrasses were found. Within the Rekawa lagoon, eight sampling locations (Table 1) were selected along the coastline and the main inlet (Kirama Oya) based on the extent of the vegetation cover. At each selected site, vegetation sampling was carried out using three transect (50 m) laid perpendicular to the shoreline with 5 m intervals between each transect using a three replicate 50 x 50 cm^2 quadrate (Burdick and Kendrick, 2001; McKenzie et al., 2001). Nine quadrats were laid along the each transects at intervals of 15 m to determine the distribution and abundance of seagrass species. Percentage of seagrasses was visually estimated within each quadrats across the transect using skin diving. Collected specimens were identified based on the key developed by Abeywickrama and Arulgnam, (1991) and Kuo and den Hartog, (2001).

2.4. Sampling of the aboveground and belowground vegetation

The sampling approach adopted the protocol recommended by the Coastal Blue Carbon manual and the Intergovernmental Panel for Climate Change (Hiraishi et al., 2014). Living aboveground and belowground component of biomass were collected by inserting a core tube (15 cm diameter) into the sediment through the aboveground plant material (with care not to cut the leaves) and into the upper root dominated soils (Lwin et al., 2019). Three cores (core diameter 15cm; core height 30 cm) were taken from each of the 50 x 50 cm^2 quadrate, whereas nine core samples were taken from each transect. The cores were washed through a 500 mm sieve (Howard et al., 2014) and the cleaned material was sorted into leaves, stems, rhizomes, and roots. Sorting was done followed by scraping using a razor blade to remove the epiphytes (Githaiga et al., 2017; Juma et al., 2020).

2.5. Sampling of the soil cores

Undisturbed soil cores (n=62) were extracted from both vegetated and non-vegetated surfaces by gently hammering PVC cores (15 cm in diameter, 30 cm long) into the soil column. Soil cores were sealed using lids before retrieval to avoid the loss of loosely bound soil within the cores (Bedulli et al., 2020). Plant material, infauna, and larger shells were removed from the soil samples and transported to the laboratory and refrigerated below 5 °C until the processing (Howard et al., 2014; Smeaton et al.,2016). In each sampling location, soil temperature, pH, and salinity were measured as abiotic parameters.

Table 1: Site locations and aboveground and belowground sampling information

Site ID	Site Name	GPS coordinates	Observes seagrass species	Retrieved soil core number
1	Rekawa	6° 3.360'N, 80° 51.271'E	Si	10
2	Hettiyapokuna	6° 3.155'N, 80° 50.832'E	Si	10
3	Boraluwa	6° 3.236'N, 80° 50.285'E	Si, Hd	13
4	Beliwala	6° 2.952'N, 80° 49.846'E	Si	4
5	Godigamuwa	6° 3.164'N, 80° 49.435'E	Si	4
6	Kapuhenwala	6° 2.836'N, 80° 49.223'E	Si	7
7	Kirama Oya inlet	6° 2.616'N, 80° 49.211'E	Si	7
8	Suduwella	6° 2.798'N, 80° 50.573'E	Si, Hd	7

(Si- *Syringodium isoetifolium* ; Hd- *Halophila decipiens*)

2.6. Laboratory analysis

Aboveground (shoots and leaves) and belowground (roots and rhizomes) parts of seagrass were separated carefully and were dried in an oven (specification) at 60 C^0 for 72 h until a constant mass was obtained (Radabaugh et al., 2018; Rahmawati et al., 2019; Bulmer et al., 2020). Aboveground biomass (AGB) and belowground biomass (BGB) were determined by multiplying the biomass with the carbon conversion factor of 0.34 and extrapolation done per hectare (Hiraishi et al., 2014). Biomass measurements were determined using an analytical balance to a precision of 0.0001 g. Total biomass carbon was calculated by summing the AGB and BGB. Each soil aliquot was dried at 60 °C for 48 h until a constant weight was obtained. Dry bulk density (DBD) was computed by using dry weight and the original volume of soil (Howard et al., 2014; Githaiga et al., 2017; Juma et al., 2020). Similar cores were collected in un-vegetated seagrass areas to serve as controls.

DBD (g/cm^3) =Dry weight of sample (g) / Original volume of Sediment (cm^3)

where

Volume of dry soil sample = [π × (radius of corer) ^{2}] × (height of the sample)

Dried soil samples were homogenized using a motar and pestle, sieved through a 2 mm sieve, and combusted at 450 °C for 5 h in a muffle furnace for determination of organic carbon content using the loss on ignition (LOI) technique (Craft et al., 1991; Waycott et al., 2004; Howard et al., 2014; Githaiga et al., 2017; Rahmawati et al., 2019; Juma et al., 2020). Percentage LOI (percentage organic matter (OM)) and percentage organic carbon were calculated as follows:

% LOI = (weight before ashing - weight after ashing) / weight before ashing × 100%

Depending on the organic matter in each of the sample, the sediment C_{org} (OC) values were calculated using the following relations

$\%LOI<0.2\%$ $C_{org} = -0.21 + 0.4 (\%LOI)$

$\%LOI>0.2\%$ $C_{org} = -0.33+ 0.43 (\%LOI)$

In order to determine the soil carbon density (g/cm3), dry bulk density was multiplied by % Corg / 100 (Githaiga et al., 2017; Juma et al., 2020). The amount of carbon in each core section was then calculated by multiplying the soil carbon density (in grams per cubic centimeter) by the soil core thickness (Howard et al., 2014; Githaiga et al., 2017). To determine the total amount of carbon within the study area, the average carbon stocks from each pool (Aboveground, belowground and soil) was summed up and the sum multiplied by the seagrass area of the lagoon which taken from the GIS maps (Githaiga et al., 2017; Juma et al., 2020).

2.7. Measurement of Physiochemical Parameters

Different physiochemical parameters of water were measured in situ, within the plots. Temperature was monitored using portable YSI portable meter. The pH, depth and salinity of the sampling locations were taken from portable pH meter (Model ELE -711), Digital Sonar and handheld Refractometer respectively. Secchi depth transparency was measured using a black and white Secchi disk with a diameter of 25 cm respectively. All the tests were performed according to the standard methods for Water and Waste Water Analysis given by American Public Health Association (APHA, 2012).

2.8. Statistical analysis

One-way ANOVA (Tukey honestly significant difference test, P = 0.05) was used to test for the differences in carbon stocks among the sampling locations and post hoc Tukey test in Pearson correlation was used to identify which treatment comparisons showed significant differences. Regression analysis was conducted between the organic matter content (%) and bulk density as predictors of the organic carbon (OC) (%) obtained from soil samples. All the tests were conducted with the SPSS© software package version 25.

3. Results

3.1. Spatial distribution of the seagrass within the lagoon

Among the 15 identified seagrass species in Sri Lanka (De Silva and Ranathunga 1987; Abeywickrema and Arulgnanam 1991; Jayasuriya 1991; Dayaratne et al. 1997; Amarasinghe et al. 2003) only two species were identified in the Rekawa Lagoon during present study. *Syringodium isoetifolium* was recorded as the dominant species whereas *Halophila decipiens* (Figure 1) was recorded very little. But three seagrass species (*Syringodium isoetifolium, Halophila decipiens and Halophila ovalis*) were recorded during 2018 and *Halophila ovalis* was the dominant species (Jayathilaka et al., 2018).

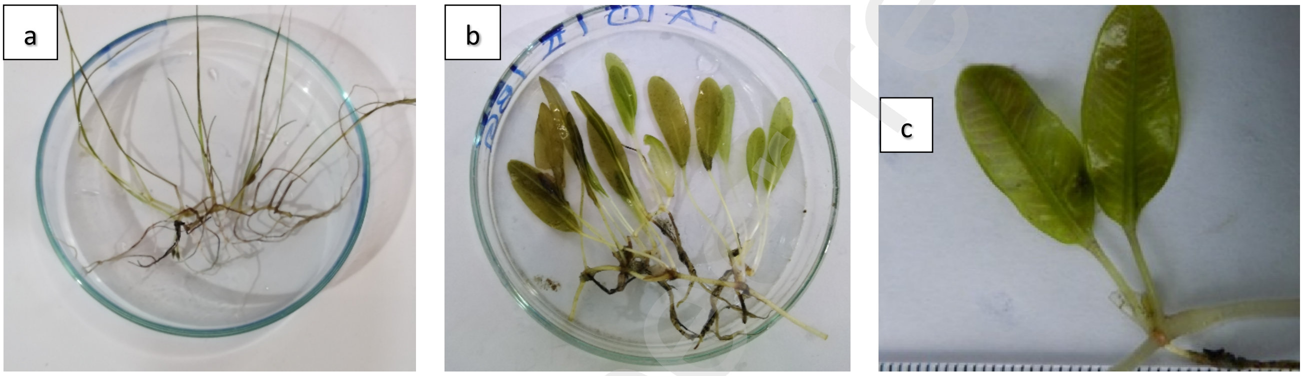


Figure 1: Identified seagrass species within the Rekawa Lagoon, a: *Syringodium isoetifolium* ; b: *Halophila decipiens* ; c: *Halophila ovalis*

Seagrass distribution map of the Rekawa Lagoon is illustrated in Figure 2 and indicates that the area of the seagrass distribution was 0.0324 km^2. Results revealed that the highest percentage canopy cover obtained in site 2 whereas no seagrass species observed in site 8. Percentage canopy cover for the sampling sites were given in below table 2.

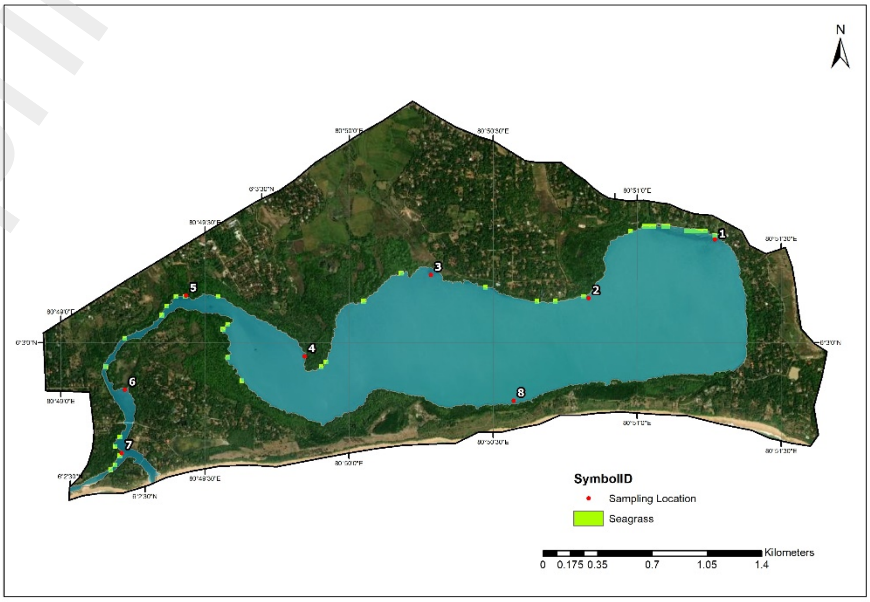


Figure 2: Seagrass distribution map of the Rekawa Lagoon 2022

3.2. Variation of aboveground, belowground and total biomass carbon of seagrass between sampling locations

Statistical analyses revealed that there was a significant difference of aboveground biomass carbon between sampling locations as determined by one-way ANOVA (F (7,42) = 3.118, p = 0.010). Average aboveground biomass carbon ranged between 0±0 Mg C/ha to 0.87± 0.74 Mg C/ha and the highest average value was recorded in location 2. Aboveground biomass carbon was not recorded for location 8 (Table 2). A Turkey post hoc test revealed that the aboveground biomass carbon was statistically lowest in location 1 with location 2 (p = 0.016) and location 2 with location 8 (p = 0.011). There was no statistically significant difference of aboveground biomass carbon between other sampling locations.

The mean values of belowground biomass were not significantly different (p >0.05) between the sites at the 95% confidence level. It ranged between 0±0 Mg C/ha to 0.11 ± 0.13 Mg C/ha and the highest value was recorded for site 6 (Table 2).

Total biomass carbon was obtained by summing the aboveground and belowground carbon values for each sites. There was a statistically significant difference of total biomass carbon between sampling locations as determined by one-way ANOVA (F (7,42) = 3.169, p = 0.009). Average total biomass carbon ranged between 0±0 Mg C/ha to 0.92 ± 0.73 Mg C/ha and the highest average value was recorded in location 2 (Table 2). A Turkey post hoc test revealed that the total biomass carbon was statistically lowest in location 1 with location 2 (p = 0.02) and location 2 with location 8 (p = 0.006). There was no statistically significant difference of total biomass carbon between other sampling locations. Results indicated that the aboveground parts of the seagrass showed high carbon content than the roots.

Table 2: Variation in Aboveground and Belowground Biomass and Total biomass carbon between sampling locations

Sampling Location	% Canopy cover	AGB (Mg C/ha)	BGB (Mg C/ha)	TB (AGB + BGB)(Mg C/ha)
1	92	0.20 ± 0.060 ab	0.06 ± 0.13 a	0.26±0.15ab
2	100	0.87 ± 0.74 b	0.05 ± 0.02a	0.92±0.73b
3	79	0.37 ± 0.20 ab	0.03 ±0.01a	0.40±0.20ab
4	75	0.38 ± 0.03ab	0.02 ±12.81a	0.41±0.02ab
5	68	0.43± 0.32 ab	0.05±0.03a	0.48±0.31ab
6	69	0.32 ± 0.33 ab	0.11±0.13a	0.44.74±0.30ab
7	84	0.33± 0.12ab	0.09±0.12a	0.43.11±0.18ab
8	0	0±0a	0±0a	0.00±0a

AGB-Aboveground Biomass Carbon, BGB- Belowground Biomass Carbon, TB-Total Biomass Carbon

Variation of soil carbon between sampling locations

The average soil dry bulk density (DBD) was between 0.0620 ± 0.007 (g cm^{-3}) in location 1 and 0.0741 ± 0.015 (g cm^{-3}) in location 8. As for organic matter (OM) content, the lowest average value occurred in location 1 (96.80% ± 0.26) and the highest occurred in location 4 (98.06% ± 1.66). A strong and positive relationship was observed between % OM and % OC in the samples collected at the study sites ($r^2 = 1.00$; $p < 0.05$). According to the linear model, 100 % of OC variability can be explained by the OM content (%). Soil core carbon content of the eight locations were ranged between 2.56± 0.29 to 3.04 ± 0.44 Mg C/ha. Results of the soil core carbon content was illustrated in figure 3 and that the variation of soil core carbon stock, depending on the sampling locations was determined to be insignificant (p>0.05). Soil carbon content did not significantly differ between vegetated and non-vegetated areas (p>0.05) and illustrated by figure 3.

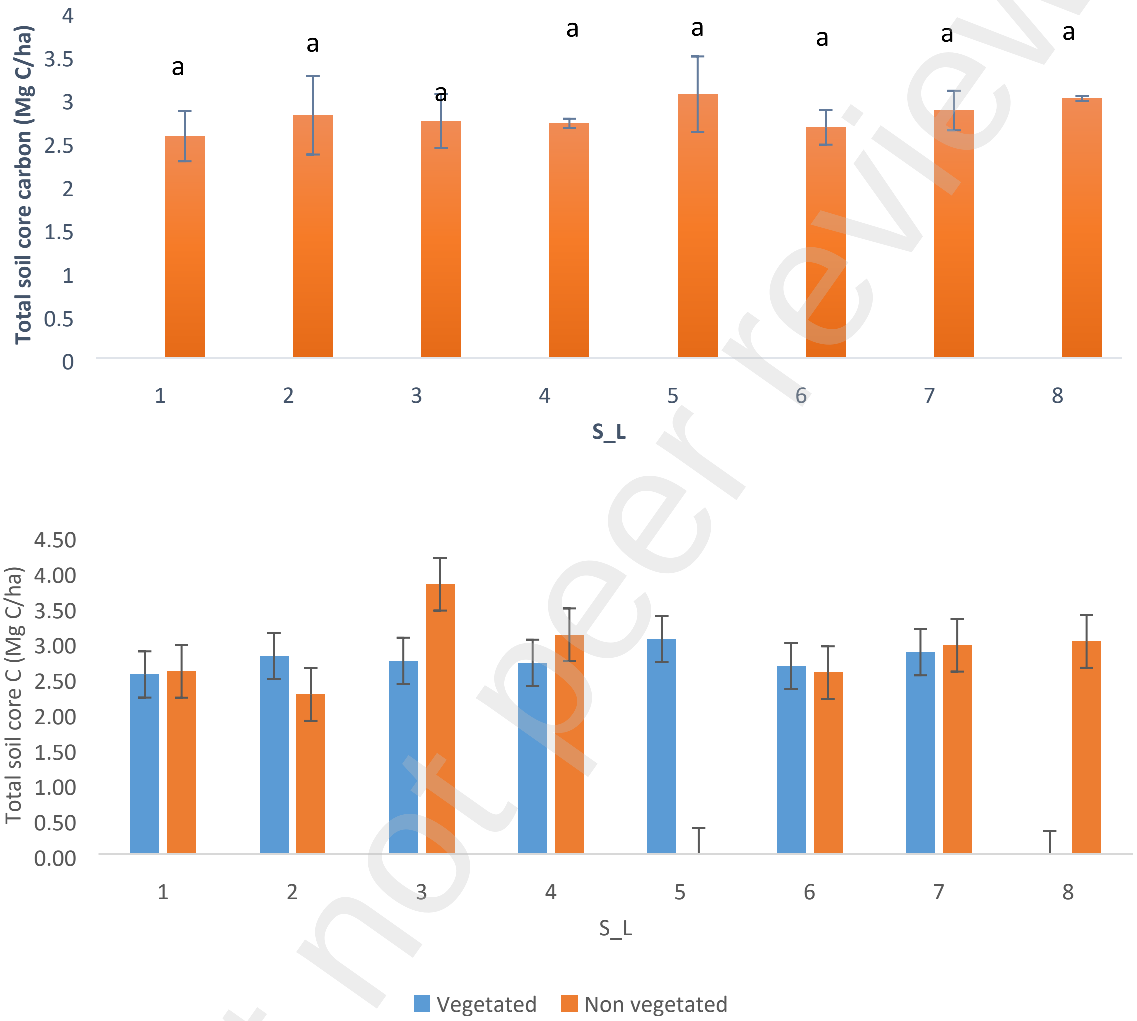


Figure 3: Variation of sediment organic carbon between sampling sites

3.3. Variation of seagrass Total carbon between sampling locations

The total C stock considering aboveground parts, belowground roots, and soil were ranged between 2.82 ± 0.38 Mg C/ha (location 1) and 3.72 ± 0.90 Mg C/ha (location 2) within the study site. Mean total carbon content of the study area was 3.21 ± 0.29 Mg C/ha. Aboveground carbon was significantly different among sites considering un-vegetated (location 8) and vegetated sites. Results indicated that the aboveground carbon level is higher than the root carbon level in the seagrass within the Rekawa lagoon. Further, seagrass soil carbon content was highest with comparing other carbon pools (aboveground and belowground biomass carbon) within the study site. Variation of carbon pool data were illustrated in figure 4.

Total Carbon stock for the study site were calculated by multiplying the mean total carbon by the seagrass area of the lagoon. The calculated total carbon value from 0.0324 km^2 seagrass bed in Rekawa lagoon was 10.21 Mg C.

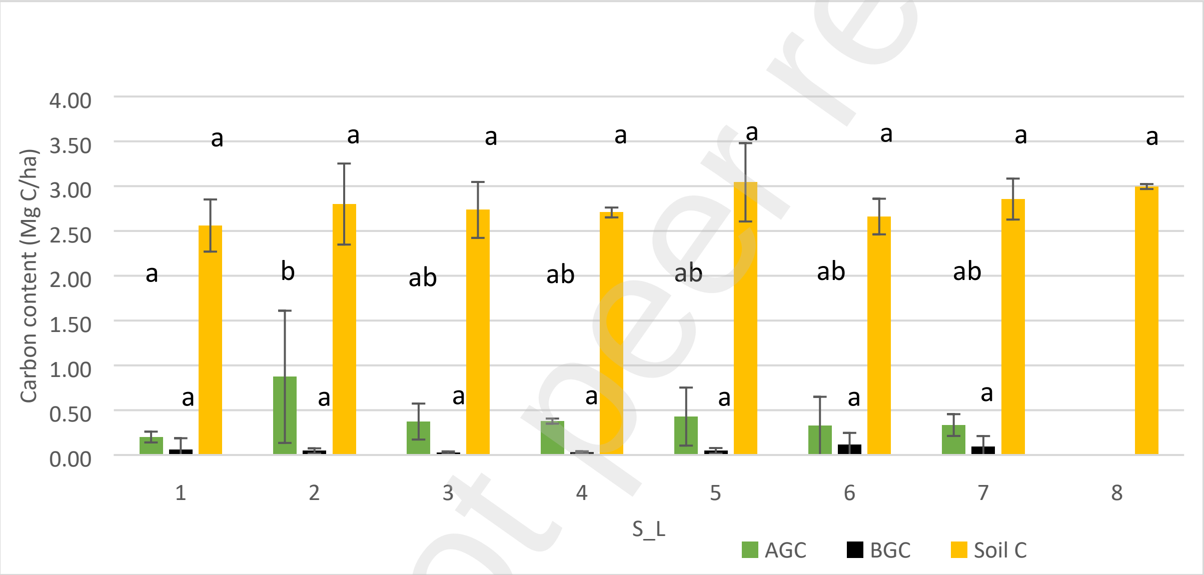


Figure 4: Carbon stocks in aboveground, roots and soil in seagrass beds Rekawa lagoon

3.4. Water quality parameters related to carbon stocks

Environmental parameters of the sampling sites were given in table 3. No correlations were obtained for aboveground biomass with water quality and soil parameters. A significant negative correlation was observed with depth and percentage composition of seagrass within the study site ($r = -0.709$; $p < 0.01$).

Table 3: Environmental parameters in different study sites

Sampling site	Salinity/ppt	Depth/cm	pH	Soil percentage composition/%		
				Sand	Silt	Clay

1	4	30.3	6.87	38	41	21
2	4	48.0	7.07	47	49	4
3	4	33.0	7.10	44	47	9
4	8	53.0	6.38	61	34	5
5	5	49.0	6.50	65	30	5
6	9	51.0	6.40	55	40	5
7	10	35.0	6.40	90	8	2
8	5	70.0	6.60	24	70	6

4. Discussion

The present study highlights the contribution of seagrass beds to trap greenhouse gases and increase carbon stocks thereby providing important ecosystem services to reduce the impacts of climate change. Our study reveals important information on the link between seagrasses and carbon storage. The contribution of sediments beneath the seagrass beds to store carbon is higher than that of the plant itself. These sediments which bury carbon for many decades thus act as underwater "inert power houses" for carbon storage. Our study reports the presence of *Syringodium isoetifolium* in the entire lagoon as the dominant species and yet occur as discontinuous -patchy distribution.

4.1. Spatial distribution of the seagrass within the lagoon

In Sri Lanka, many lagoons are reported to contain seagrasses, yet their potential to store carbon has been evaluated very little. Seagrasses are found in the island, primarily in shallow, sheltered marine and estuarine waters on sandy, salty, or clay substrate in the Gulf of Mannar, the lagoons around the Jaffna Peninsula and Puttalam, the Negombo estuary, Weligama, Mulathivu, Trincomalee, Chilaw Lagoon, Batticaloa Lagoon, Koggala Lagoon, Valaichchenai Lagoon and Rekawa lagoon (Ranatunga and Pethiyagoda, 2015; Udagedara et al., 2017; Jayathilaka et al., 2018; Ranahewa et al., 2018; Liu et al., 2020; Udagedara and Dahanayaka, 2020). Studies report that, in most areas seagrass was observed either homogenously or heterogeneously in mixed populations (Ranatunga and Pethiyagoda, 2015). In our study in the Rekawa Lagoon seagrass was observed as homogenous population with *Syringodium isoetifolium* during the entire study period. *Halophila decipiens* was observed in few places. Patchy distribution of seagrass was observed during the present study and same distribution pattern was observed in Valaichchenai Lagoon, Sri Lanka (Udagedara and Dahanayaka, 2018). Fonseca and Bell (1998) and others also showed a patchy distribution of seagrass from a few meters to several kilometers wide within the coastal area (Bowden et al., 2001; Jelbart et al., 2007; Borg et al., 2009).

According to Jayathilaka et al. (2018), fishermen's experience, and personal observations, *Halophila ovalis* spread most parts of the lagoon during 2018 - 2019 period as a dominant species. Present study revealed that there was no *Halophila ovalis* in the lagoon and *Syringodium isoetifolium* becomes the dominant species except two or three patches of *Halophila decipiens.* This is similar to the condition of Puttalam lagoon, Sri Lanka as some species have been totally vanished from the South Eastern region of the lagoon (Ranahewa et al., 2018). This could be either due to the seasonal changes in physicochemical environment in the lagoon that affect the occurrence of seagrass species (Duarte et al., 2004; Asha et al., 2020). Several structural characteristics of seagrasses, including level and arrangement of fiber, and water content, make it particularly amenable to mechanical and subsequent microbial degradation (Lanyon and Sanson 2006). Less fiber-containing seagrasses such as *Halophila ovalis* can be expected to break down at a faster rate (De Silva and Amarasinghe, 2007) than comparatively a high fiber containing seagrass such as *Syringodium isoetifolium*, and that could be cause to extinct *H.ovalis* from the environment soon. Larger seagrass species are also able to survive longer because of the slow turnover of roots and rhizomes compared to small species like *Halophila ovalis* (Kaewsrikhaw et al., 2016).

4.2. National and global level carbon sequestration potential in seagrass

Seagrass ecosystems are the most significant natural carbon sinks worldwide. Therefore, many studies conducted about seagrass carbon in different geographic regions. Only a few studies were conducted in Sri Lanka regarding carbon sequestration in seagrass beds (Faazil et al., 2019). Sediment organic carbon levels in regional scale were given in table 5.

Table 4: Sediment organic carbon content in relation to sea grass habitats in different countries in the region

Region	Sediment organic carbon (Mg C/ha)	References
Global range	115.5 – 829.2	Fourqurean et al., 2012
Southeast Asia	14.51–37.65	Alongi et al., 2016; Thorhaug et al., 2020; Stankovic et al., 2021
Kenya	160.7 – 233.8	Githaiga et al., 2017
Mediterranean bioregion	372 ± 74.52	Fourqurean et al., 2012
Indo-pacific bioregion	23.6 ± 8.32	Fourqurean et al., 2012
North Atlantic seagrass meadows	48.7 ± 14.5	Fourqurean et al., 2012
Europe	500 ± 50.00 g C m^2 to 4324.50 ± 1188.00 g C m^2	Dahl et al., 2016
Sub-tropical Australia	173.98 ± 27.07	Cacho et al., 2021
Thailand	37.5 to 120.5	Miyajima et al., 2015

Malaysia	46 to 70	Rozaimi et al., 2017
Indonesia	34.3 to 293.3	Alongi et al., 2016
Singapore	129.4 to 149.6	Phang et al., 2015
Arabian Gulf	1.9 to 109	Campbell et al., 2014
Mozambique	21.3 to 73.8	Gullström et al., 2017

4.3. Variation of aboveground, belowground and total biomass carbon of seagrass between sampling locations

Aboveground and belowground seagrass biomass are important factors in determining the carbon storage and sequestration potential and approximately 40% of sediment/soil organic carbon comes from seagrass plant and its associated epiphytes (Greiner et al., 2013). Aboveground biomass carbon of the study site ranged between 0±0 Mg C/ha to 0.87± 0.74 Mg C/ ha which is lower than the global value (2.51 ± 0.49 Mg C/ ha), as reported by Fourqurean et al., 2012. This may due to seasonal changes of seagrass within the lagoon. Furthermore, the top of the seagrass, such as the leaves, is a short-term carbon store because it is widely consumed by herbivores and is susceptible to exposure to aerobic conditions and chemicals (Fourqurean et al., 2012). On the other hand, there was a significant difference in aboveground biomass carbon among the sampling locations in the study site; this possibly indicates a relatively non homogenous environment in the lagoon.

Belowground biomass organic carbon of seagrasses in the lagoon did not show significant differences among sampling sites. Variation among habitats is often attributed to differences in environmental conditions that influence the seagrass growth, such as light, temperature and nutrient supply (Mateo et al., 2006; Lavery et al., 2013). The lack of significant variation observed in this study could be an indicator that the biophysical setting in the area is homogenous and that the species in the lagoon do not exhibit large differences in accumulation of belowground biomass. On the other hand, this could indicate the general absence of herbivory of belowground biomass (Omollo et al., 2022).

Belowground organic carbon was significantly lower than aboveground carbon and it is deviated with observations from previous studies across the globe (Röhr et al., 2018; Alonso Aller et al., 2019; Palacios et al., 2021). In contrast, the intertidal and subtidal below ground biomass estimates for the Clayoquot Sound meadows were ~10 times lower than values for Z. *marina* found in other regions (Orth et al., 1986; Rohr et al., 2016). The low belowground biomass values are likely a response to sub-optimal light conditions, and possible nitrogen limitation in the growing season (Postlethwaite et al., 2018) and this could be the reason for low belowground biomass in the Rekawa Lagoon.

Total biomass carbon of the present study ranged between 0±0 Mg C/ha to 0.92 ± 0.73 Mg C/ha and this value is lower than the values recorded from Hikkaduwa coastal medow, Sri Lanka (3006.67 Mg C/ha) and previous finding of the Rekawa lagoon (1.35 Mg C/ha) (Faazil et al., 2019). In both cases *Thalassia hemprichii* (Hikkaduwa) and *Halophila ovalis* (Rekawa Lagoon) have broad leaf blades than the noodle seagrass *Syringodium isoetifolium* (present study). Several studies suggested that bigger size seagrass species have better ability to store carbon than the smaller species (Stankovic et al., 2017). Smaller species support high grazing pressure and need to be able to transfer their production to the food webs (Kaewsrikhaw et al., 2016). Also, the bigger species are considered more constant species, with longer life span, low mortality rates and long lived shoots (Vermaat et al. 1995). Furthermore, dominant seagrass species changed from time to time in Rekawa lagoon and this may be some reason for the reduction of the total biomass carbon during this study period.

4.4. Variation of soil carbon between sampling locations and Total carbon stocks

The present study shows considerable organic carbon in the underlying soil substratum of the seagrass species. The study finally establishes the capability of seagrass species to store carbon in their biomass and underlying soil. Sediment C_{org} for the Rekawa lagoon ranged between 2.56± 0.29 to 3.04 ± 0.44 Mg C/ha and this is lower than the global range of 115.5–829.2 Mg C/ha (Fourqurean et al., 2012). However, the global estimates were derived from a limited data set biased by the extremely high C_{org} content of soils from Mediterranean P. *oceanic*a meadows (Fourqurean et al., 2012a). Furthermore, available information from a global database revealed that the carbon storage capacity within one-meter depth of sediment of seagrasses varied largely among globally. The Mediterranean bioregion had the highest C stock at 372 ± 74.52 Mg C/ ha, while the lowest was in the Indo-pacific bioregion at 23.6 ± 8.32 Mg C/ ha (Fourqurean et al., 2012). Similar variability has also been observed on regional, meadow, landscape scales and across species around the world (Lavery et al., 2013).

Several regional assessments indicated the lower sediment organic carbon values than the global level. Sediment organic carbon level in Zanzibar was 33.9 ± 7.7 Mg C/ ha (Belshe et al., 2018) whereas it was 28.99 ± 13.70 tonnes C/ ha and 40.14 ± 3.45 tonnes C/ ha in Mozambique and Tanzania (York et al., 2018, Palacios et al., 2021) respectively. Further sediment organic carbon in Baltic Sea and Black sea, were 23.1 Mg C/ ha and 29 Mg C/ ha (Röhr et al., 2018). The organic carbon stocks in the top 50 cm of the seagrass sediment ranged from a minimum of 14.94 Mg C/ ha to a maximum of 105.72 Mg C/ ha in intertidal seagrass meadows in Scotland (Potouroglou et al., 2021). Also meadows formed by large species (i.e., Amphibolis spp. and Posidonia spp.) showed higher stocks (24–29 Mg C/ ha) than those formed by smaller species (e.g., *Halodule, Halophila, Ruppia, Zostera, Cymodocea*, and *Syringodium*; 12–21 Mg C/ ha (Mazarrasa et al., 2021).

Seagrass structural complexity, turbidity, water depth, and wave height were the key factors influencing the carbon content in seagrass sediments (Samper-Villarreal et al., 2016).

Both the species of seagrass and the abiotic habitat characteristics are also important in driving variability of sedimentary C_{org} stocks (Lavery et al., 2013). While the habitats we studied were characterized by one or two dominant seagrasses, we cannot conclude that these same species were dominant at the study sites over the duration of carbon accumulation to a depth of 25 cm. Further, a global study of seagrass sediments found that, on average, 50% of the sedimentary C_{org} matter in seagrass meadows was derived from allocthonous sources (Kennedy et al., 2010). This highlights the significance of the sediment carbon pool in seagrass ecosystems, as the organic carbon in sediment is more stable and can be stored for millennia, in contrast to that stored in living biomass (Fourqurean et al., 2012; Howard et al., 2014). Sediment organic carbon content did not significantly differ between vegetated and non-vegetated areas within the lagoon and this was similar to another Sri Lankan finding (Faazil et al., 2019).

The calculated total carbon content of the 0.0324 km^2 study area in Rekawa Lagoon was 10.21 Mg C, giving 87.06% contribution from sediment organic carbon pool. Similar carbon allocations have been obtained in previous research conducted within the seagrass beds indicated that the sediment carbon pool was larger than the biomass carbon (Githaiga et al., 2017; Juma et al., 2020; Omollo et al., 2022).

4.5. Conservation and recommendations

Seagrass is proven to be able to absorb and store carbon dioxide in its biomass. This shows that seagrass has an important role in climate change mitigation and suggests the need to preserve the seagrass ecosystem in a sustainable manner. However, should the seagrass beds be damaged, this would eliminate their ecological function and releases the carbon stored back into the atmosphere (Russel et al., 2013; Lovelock et al., 2017). Several studies stated that seagrass is a vegetation that can be used to reduce the CO_2 leakage because it can fix carbon for years (Greiner et al., 2013). These carbon accumulation rates will be useful for planners and policy makers in assessing the potential of restored seagrass ecosystems to sequester blue carbon (Gacia et al., 2002). Given their ecological significance, policies must be implemented (both at regional and global level) to both preserve and restore the seagrass systems which have been destroyed and damaged in many parts of the globe by dredging, draining, roads construction and are now threatened by sea level rise. Multiple strategies are essential to secure a future of seagrass habitats, including developing effective mechanism for long-term monitoring of seagrass meadows in Sri Lanka (Udagedara and Dahanayaka, 2020).

Sea grass beds have been degraded the during past few decades due to high loading of sediments and dipping holes for fishing activities, expansion of salt pans, unsustainable fishing practices, expansion of settlement and other infrastructures, establishment of prawn farms and excessive use of agrochemicals (IUCN, 2008). Significant threats to the Rekawa lagoon ecosystem include the use of harmful fishing gears such as monofilament gill nets, sedimentation and agricultural runoff from the inlet canals, higher fresh water influx from the Kirama oya stream, and reduce mixing of sea water and lagoon water. Furthermore, it was recently observed that heavy load of polluted water was discharged into Rekawa lagoon from the shrimp farm which may cause to increase nitrogen and phosphorous load of the lagoon as well as sediments. All these may also be harmful for the functioning of seagrass system in the near future. Knowledge of the carbon stocks associated with seagrasses in the lagoon is critical for better management strategy for the whole lagoon system and to establish a healthier seagrass community.

Conclusion

The seagrasses of Rekawa lagoon are dominated by only one species and are found as patchy meadows. Although there have been three species in the previous years, from 2021 year only *Syringodium isoetifolium* dominates. Comparatively, the sediments below the seagrasses contained the highest carbon store. But we cannot conclude that the same species has contributed mostly to the sediment carbon store. There was no variability of soil carbon storage among the sites studied. Contribution of seagrasses in Rekawa lagoon to store carbon is lower than global average. There is also an urgent need to better understand the environmental and human factors that could affect the occurrence and sustainability of seagrasses in the lagoon.

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Wathsala Suwandhahannadi : Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft

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Declaration of competing interests

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper

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