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Blue Carbon Stocks; Distribution, Threats, and Conservation in Sri Lanka; Insight Towards Climate Change Mitigation

[#1]Gunathilaka DUV, [#1]Wijesundara WMIC, [1]Abeysinghe NK, [1]Ranawaka DPD, [2]De Silva PMCS, [3]Madarasinghe SK, [1]Wijerathna GGNK, [1]Jayatissa LP, [4]Andrieu J & [*1]Kodikara KAS

[1]Department of Botany, Faculty of Science, University of Ruhuna, Matara, Sri Lanka

[2]Department of Zoology, Faculty of Science, University of Ruhuna, Matara, Sri Lanka

[3]Department of Physics, Faculty of Science, University of Ruhuna, Matara, Sri Lanka

[4]GEOspatial Monitoring and Information Technology (GeoSMIT) Department, French Institute of Pondicherry (IFP), Pondicherry, 605001, India

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[*]Corresponding Author
Email:sunandaruh@gmail.com
[#]First Co-authors

ABSTRACT

As a tropical island nation, Sri Lanka has a 1740 km coastal strip, dominated by mangroves, salt marshes and seagrass meadows i.e., blue carbon ecosystems, that play a vital role in ecosystem functioning and services. These ecosystems have a high capacity for storing carbon within their ecosystem pools by capturing atmospheric carbon dioxide (CO_2) through photosynthesis and gained huge attention as the most carbon rich soil containing ecosystems in the world. The current study focuses on the gaps pertaining to blue carbon ecosystems including, total carbon stocks, challenges, and conservation prospects in Sri Lanka. Accordingly, a complete scientific survey to determine carbon stocks in all blue carbon ecosystems has not been carried out and only a limited number of studies have quantified the carbon sequestration in different mangrove areas in Sri Lanka. Studies on salt marshes and seagrass meadows were only directed towards distribution, species diversity or occurrence and also limited to fewer sites in the country. Thus, precise estimation of the total carbon stocks of the blue carbon ecosystems would be difficult without conducting proper scientific studies in salt marshes, seagrass meadows and mangrove areas. Moreover, the current study suggests seeking knowledge through estimating ecosystem values towards sustainable coastal management that could pave the pathway to conserve blue carbon ecosystems as a part of climate change mitigation.

1. Introduction

The rapid increment of the emission of carbon and other greenhouse gasses play a dominant role in global warming and subsequent associated environmental crises. Human activities have unequivocally caused crucial environmental issues since pre-industrial period and have been driving it to an alarming rate in recent years [4]. The scientific community has revealed that a new high record was reported for the global average atmospheric carbon dioxide which was 409.8 ± 0.1 ppm (parts per million) in 2019 reaching the highest level in the past 800,000 years. In the 1960s, the annual rate of global atmospheric carbon dioxide growth was approximately 0.6 ± 0.1 ppm whereas in 2018 the increment was reported as 2.5 ± 0.1 [32]. Anthropogenic emission of carbon dioxide through burning fossil energy, industrial production, forest fires, deterioration and deforestation of natural vegetation and ecosystems of natural carbon sinks majorly contribute to the rapid increment of atmospheric carbon dioxide [39].

In the future, the increased rate of atmospheric carbon dioxide concentrations will mainly depend on human activities and the interactions of the natural carbon sinks [59]. Ocean ecosystems have been recorded as the largest natural carbon sink on earth which absorbs and fix one third of the anthropogenic carbon dioxide emissions in the atmosphere, whereas terrestrial ecosystems sequester atmospheric carbon dioxide in soil and plant biomass through photosynthesis [18, 55]. Cyclically, carbon is released back to the atmosphere as carbon dioxide or methane through anaerobic respiration and decomposition of dead biomass [4]. However, recent studies have highlighted that both efficiencies of carbon dioxide sequestration and longevity (centuries to millennia) of the sequestered carbon sinks of coastal wetland ecosystems are higher than tropical, boreal and temperate forest ecosystems resulting in extensive carbon stocks [4, 43]. Tropical forests, temperate forests, boreal forests and tropical savannas are considered as important terrestrial ecosystems and each ecosystem stores less than 400 Mg C ha^{-1}[26].

2. Blue carbon ecosystems

Coastal wetland ecosystems, are dominated by mangroves, tidal marshes and seagrass meadows [7]. The carbon sequestered and stored within the aboveground living biomass (branches, stems and leaves), belowground living biomass (roots) and nonliving biomass (deadwood and litter) and soil or underlying sediments of the mangroves, tidal salt marshes and seagrass meadows is called as blue carbon [19]. The soil or the sediments in blue carbon ecosystems are saturated with continuous waterlogging, anaerobic condition and high rates of vertical accretion giving rise to increased carbon pools over time [9]. Unlike terrestrial soil, however, soils in blue carbon ecosystems have a high potential in soil carbon accumulation due to low oxygen availability. These conditions allow reducing aerobic microbial carbon oxidation releasing carbon dioxide back into the atmosphere [57]. Given that, the blue carbon is sequestered in living biomass for a short term (decennia) while longer terms (millennia) in the soil [34]. Furthermore, in a global context, blue carbon ecosystems coverage accounts for 51 million hectares, of which mangroves solely account for 31%, (15.6 million hectares). Interestingly, even though, only 0.2% of the oceanic ecosystem consists of blue carbon ecosystems, approximately, 50% of the total marine sediment carbon deposits consist of coastal wetland sediment carbon deposits [37].

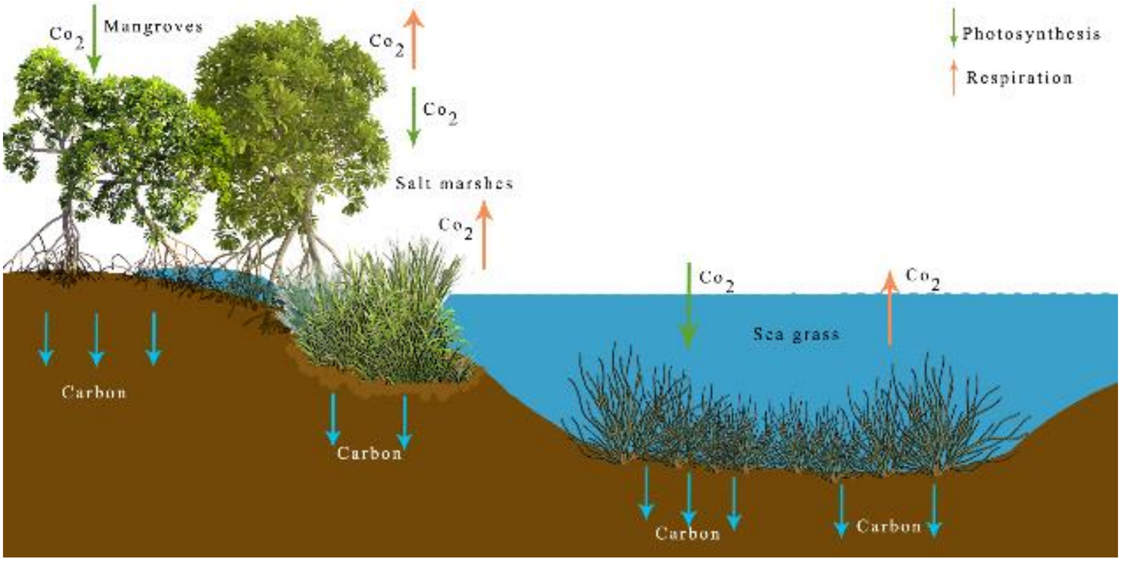

Figure 1: A typical illustration of the fate of carbon dioxide in blue carbon ecosystems (Source: Concept adapted from Arulnayagam and Park, 2019 and illustrated by D.P.D. Ranawaka)

Mangroves, the tidal forests, are unique plant communities that grow in extreme environmental conditions such as high and fluctuating salinity, extreme tides, frequent inundation with associated hypoxia, low air humidity and high temperatures. Predominantly living at the interfaces in the land and sea in tropical and subtropical coasts, mangrove ecosystems are rich in blue carbon [31, 61]. Recent studies revealed that approximately 24 Tg C yr^{-1} has been captured by mangroves globally as well as accumulated approximately 6.5 Pg C (petagrams of carbon) [7, 47]. Total ecosystem carbon stock of mangroves was reported to ranging from 154 to 1484 Mg C ha^{-1} with a mean global carbon stock of 885 Mg C ha^{-1} from an estimated global mangrove coverage of 13.8 – 15.5 million hectares [10,15, 27]. 20% of the mangrove blue carbon is stored in the living biomass of the trees (roots and shoots) whereas, 2% is in downed wood and a prominent proportion of 78% in soil due to a tendency of relatively rapid accumulation [1, 2].

Tidal marshes are biodiversity-rich, unique ecosystems located at the interface between marine and terrestrial ecosystems connecting freshwater and saline ecosystems. Tidal marshes occur in all regions except extreme regions like Antarctica, particularly in temperate areas in high to middle latitudes, and are commonly restricted to sheltered locations [42]. According to the spatial data obtained from UNEP-WCMC (United Nations Environment Programme-World Conservation Monitoring Centre) in 2005, global tidal marsh covers range from 2.2 – 40 M ha with a central estimate of 5.1 M ha. These communities consist of upper, vegetated mudflats lying in the mean high intertidal areas and layers of deep mud and peat. In addition, the salt marsh vegetation, the carbon sequestering biomass comprises of halophytic low shrubs and grasses influenced by zonation patterns and tidal immersions. Further, the rapid colonization of sediments enhances the vertical expansion and horizontal spreading of the salt marshes over time contributing as an important carbon sink [54]. Comparatively, tidal marshes store moderate to high carbon stock than other blue carbon systems yet participate in low carbon dioxide emissions due to their relatively small global area coverage. The literature states that tidal marshes store 237-949 Mg CO_2 ha^{-1} (approximately 593 Mg CO_2 ha^{-1}) of near surface carbon stocks (cumulatively, biomass and top meter sediment) and emit 0.02 – 0.24 Pg CO_2 yr^{-1} (0.06 Pg CO_2 yr^{-1}) of carbon dioxide to the atmosphere [48].

Seagrass meadows are a unique group of underwater angiosperms occurring in shallow oceanic and estuarine waters across 191 countries and six bioregions spanning temperate and tropical seas [58]. The spatial distribution estimates of seagrass meadows differ throughout literature due to their static nature and lack of mapping data [40]. However, according to UNEP-WCMC spatial data in 2005 globally, seagrass meadows range from 17.7 to 60 M ha with a central estimate of 30 M ha. Seagrass meadows depend on the penetrating sunlight for photosynthesis thus, distributed 10 – 15 m depth in turbid shallow coastal waters or sometimes up to 50 m depth in less turbid waters. Blue carbon is trapped in the living biomass (leaves, fruits, flowers and seeds) and sediments [46]. Seagrass meadows estimate to store 131 – 522 Mg CO_2 ha^{-1} (326 Mg CO_2 ha^{-1}) and emit 0.05 – 0.33 Pg CO_2 yr^{-1} (0.15 Pg CO_2 yr^{-1}) [48].

The anaerobic nature of the soil blue carbon ecosystems causes prolonged decomposition rates of litter and dead biomass trapping and preserving soil organic carbon pools for centuries. Surprisingly, even the lower primary production outweighs the slow decomposition rates [56]. Thus, these substantial amounts of stored carbon sinks weigh the danger of being released proving the enhanced climate mitigation strategies of blue carbon ecosystems [11]. Additionally, towards the impacts of global warming such as sea level rises and increased storms, these ecosystems act as a natural buffer of waves against storm surges, tsunamis and floods [41]. Moreover, quantification of carbon stocks in blue carbon ecosystems should be taken into high priority concerns to get a wide understanding of climate change mitigation.

Therefore, this paper attempts to seek three major research questions; a) What is the state in the literature of coastal blue carbon ecosystems in Sri Lanka b) amounts of below ground and above ground blue carbon stocks in Sri Lanka c) challenges for effective conservation and prospects of blue carbon ecosystems in Sri Lanka and stating some of the knowledge gaps that could support to understand blue carbon dynamics in Sri Lanka which could pave the path to policymaking and climate change mitigation.

3. Blue carbon in Sri Lanka

Sri Lanka is a tropical, island country, located in South Asia, surrounded by the Indian ocean (5.55^0 - 9.51^0 N and 079.41^0 - 081.54^0 E.), with a total land extent of 65,610 km^2 and a coastal strip of 1,740 km [10]. According to the Coast Conservation Act No. 57 of 1981 in Sri Lanka, the demarcation of a coastal zone describes as “the area lying within a limit of 300 m landward of the mean high-water level and a limit of 2 km seaward of the mean low water level. In the case of rivers, streams, lagoons or any other body of water connected to the sea either permanently or periodically, the landward boundary extends to a limit of 2 km measured perpendicular to the straight baseline drawn between the natural entrance points. Thereof and includes the waters of such rivers, streams and lagoons or any other body of water so connected to the sea”. Sri Lankan coastline consists of blue carbon ecosystems predominating by mangrove ecosystems. The total mangrove coverage of the island accounts for approximately 8000 ha [29]. However, Premakantha et al. (2021) have reported the mangrove extent in Sri Lanka to be 19,758 ha. Micro-tidal conditions along with coastal topography restrict mangrove areas into narrow strips along the coast, except in the estuaries of larger rivers [65]. Tidal marshes distribute across 23,819 ha on the southern, western, northern and eastern coasts of Sri Lanka [46]. Seagrass meadows extensively existed on the northern, northwestern, northeastern coasts of Sri Lanka while they occur to a lesser extent on the southern, southwestern and southeastern coasts, covering approximately 37,137 ha [62]. Even though Sri Lanka is rich in mangrove species diversity with 21 true mangrove species [21], only a limited number of studies have quantified the carbon profiles in these ecosystems (Figure 2) [10, 22, 50, 51, 52], Similarly, for tidal salt marshes and seagrass meadows, studies were only directed towards distribution, species diversity or occurrence and restricted to a limited number of sites in the country [46, 62].

A study carried out by Perera & Amarasinghe (2019) has quantified the soil carbon content in seven mangrove sites; Negombo, Kala Oya (river) estuary, Malwathu Oya estuary, Chilaw lagoon, Rekawa lagoon, Batticaloa lagoon and Uppar lagoons that cover dry, intermediate and wet zones in Sri Lanka [51].

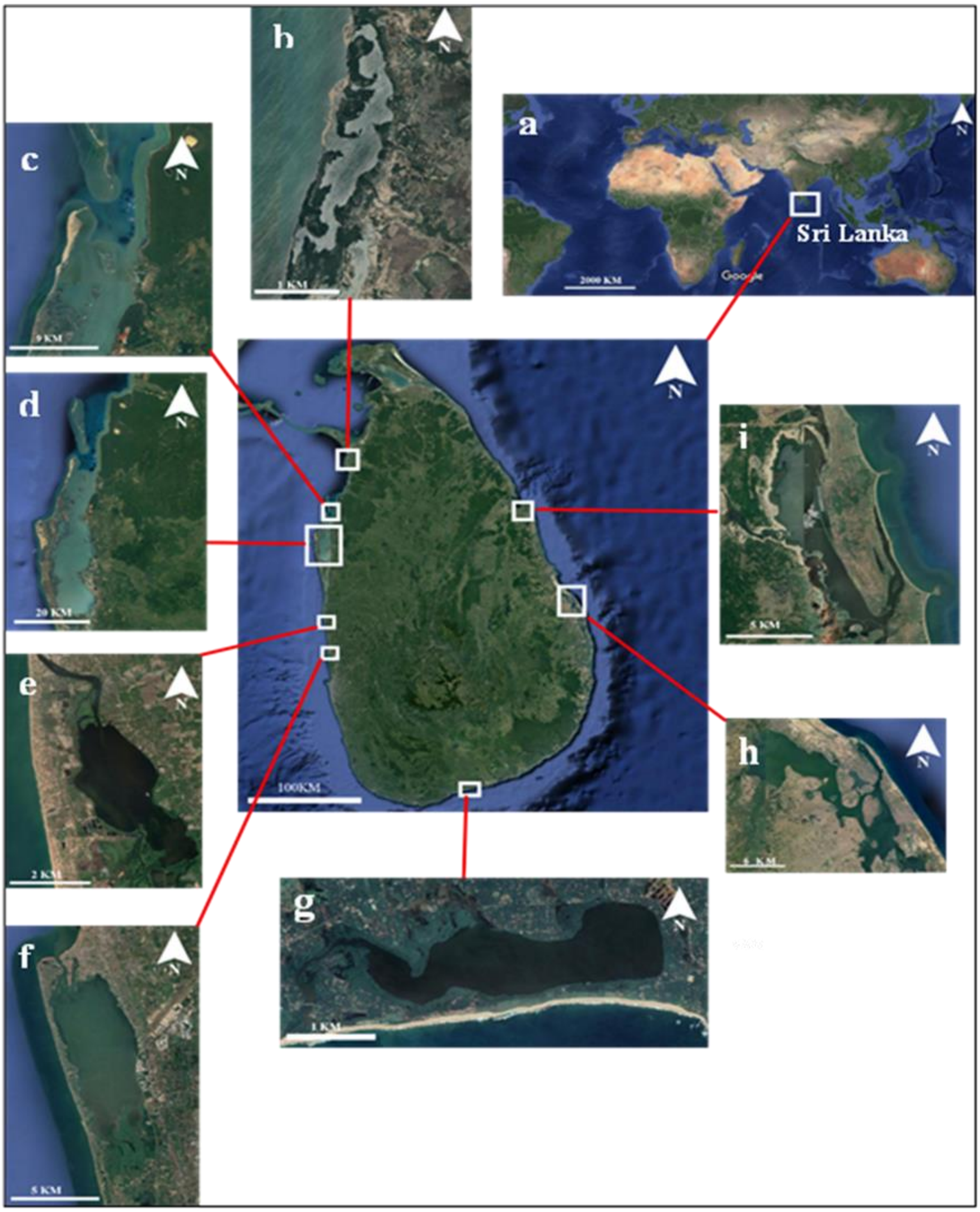

Figure 2: Locations where the mangrove carbon assessment studies have been conducted in Sri Lanka a) Location of Sri Lanka b) Malwathu Oya estuary c) Kala Oya estuary d) Puttalam – Kalpitiya lagoon e) Pambala – Chilaw lagoon f) Negombo Lagoon g) Rekawa lagoon h) Batticaloa lagoon i) Uppar lagoon (Source: Perera & Amarasinghe, 2018, Perera et al., 2018, Jonsson & Hedman, 2019, Perera & Amarasinghe, 2019, Cooray et al., 2021)

Soil samples were taken from three different depths; 0-15 cm, 15-30 cm and 30-45 cm of mangrove sites. Total soil organic carbon content was measured by chromic-acid wet oxidation method followed by colourimetry. According to Perera & Amarasinghe (2019), 0-15 cm layer has obtained a higher amount of carbon in mangrove soils of wet and intermediate climatic zones [51]. The largest carbon sink (580.84 ± 32.91 Mg ha^{-1}) was reported in the Rekawa lagoon (intermediate zone) and the lowest carbon sink (316.29 ± 33.8 Mg ha^{-1}) was reported in Batticaloa lagoon (dry zone) in Sri Lanka (Figure 3).

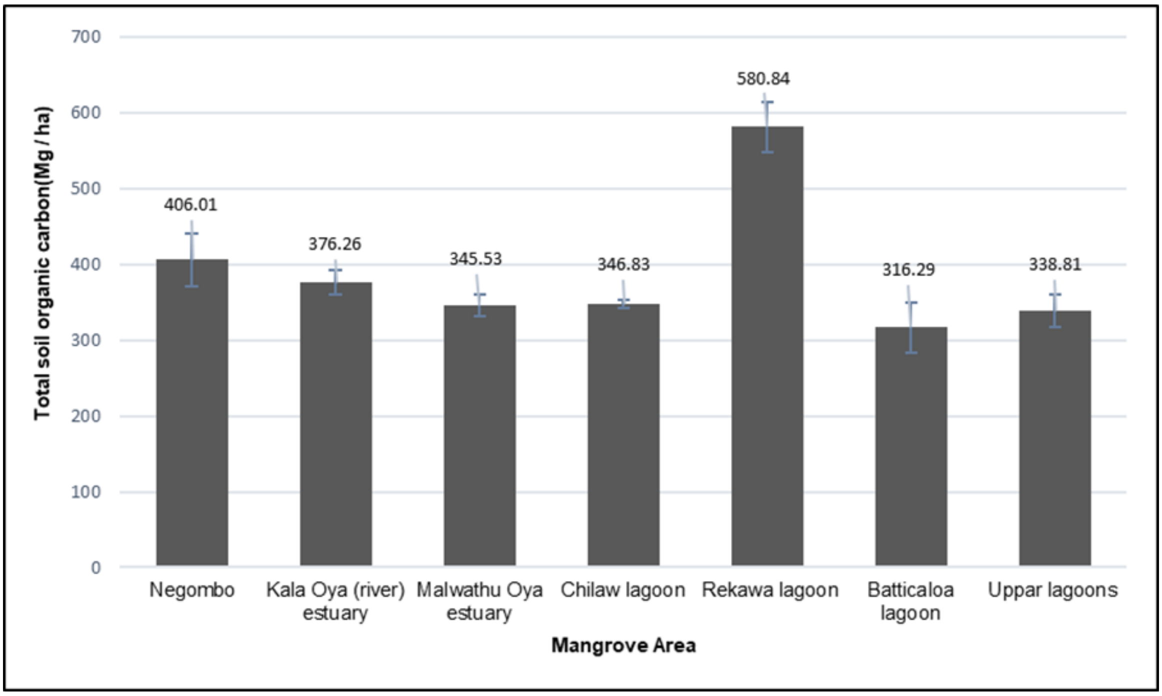

Figure 3: Total soil organic carbon in selected mangrove areas in Sri Lanka (Source; Perera & Amarasinghe, 2019)

One of the key results describes that there is a significant correlation ($p < 0.05$) between total soil organic carbon stocks in mangroves with annual rainfall. This study revealed that the total organic carbon content of Sri Lankan mangrove soils are two times higher than the total organic soil carbon content of tropical savanna forest in Yap and Palan island in the Pacific Ocean (146–198 Mg ha^{-1}) [14] and mangrove soils at Hooker Bay, San Andres Island (90–160 Mg ha^{-1}) [17]. Interestingly, according to the results of Perera & Amarasinghe (2019), the total organic carbon content of Sri Lankan mangrove soils (118–424 Mg ha^{-1}) is in a higher range among the other global mangrove soil carbon pools [5, 51].

A study has been conducted by Cooray et al, (2021) to assess the above ground and below ground carbon stocks, selecting five mangrove sites; Rekawa lagoon, Pambala-Chilaw lagoon, Puttalam-Kalpitiya lagoon, Batticaloa lagoon, Negombo lagoon, situated in three climatic zones (dry, intermediate and wet zone) in Sri Lanka [10]. The important fact in that study was, soil samples were taken from up to the maximum depth that soil corer penetrated. Soil samples were taken from eight different depths; 0-15cm, 15-30 cm, 30-45 cm, 45-60 cm, 60-90 cm, 90-120 cm, 120-150 cm, 150 cm < (to the maximum depth or bedrock). Root samples were taken from four different depths; 0-15 cm, 15-30 cm and 30-45 cm, 45-60 cm. Total soil organic carbon content was measured by the loss on ignition (LOI) method using a muffle furnace and the total root carbon content was measured by multiplying the oven dried weight of roots with the conversion factor of 0.39 given by [26]. Whereas above ground biomass was measured by common allometric equation (a) given by [30] and above ground, carbon was measured using equation (b).

$$\text{Above ground biomass (AGB)} = 0.251.d.D^{2.46} \quad \text{(a)}$$

$$\text{Above ground carbon} = \text{AGB} \times 0.48 \quad \text{(b)}$$

Where, AGB = Above ground biomass (kg), d = wood density (g cm^{-3}), D = diameter at breast height (cm). According to the results of Cooray et al, (2021), the highest total organic carbon stock was reported in the Rekawa lagoon (1455.39 ± 45.16 Mg C ha^{-1}) and the lowest total organic carbon stock was reported in the Batticaloa lagoon (734.75 ± 57.68 Mg C ha^{-1}) (Figure 4) [10]. Above ground carbon and below ground root carbon were ranging from 75.5 to 189.1 Mg C ha^{-1}, 7.9 to 14.3 Mg C ha^{-1} respectively. This study has revealed that soil carbon contributes 83% - 90% of the total organic carbon stock in selected sites in Sri Lanka.

Soil sampling depth is one of the most important factors that should be considered when assessing the carbon stocks in blue carbon ecosystems. Previous studies have shown [13, 51] that the higher amount of soil carbon contained in the upper 0-30 cm of the soil and it is the common and standard method of taking samples from the upper 100 cm. According to Cooray et al. (2021), the sample depth influenced the precise estimation of the carbon stock of a particular mangrove ecosystem [10]. If the samples have not been taken from up to the maximum depth, it will have a high tendency to give underestimation values for the carbon stock of a particular mangrove ecosystem [6, 10]. Therefore, Cooray et al. (2021) suggested that soil sampling depth should be taken into account when estimating total soil organic carbon content in a particular mangrove ecosystem [10].

Jonsson & Hedman (2019) have conducted research to investigate the total organic carbon stocks in three sites; Kokkaddicholai, Manmunai bridge island and Kannankudah in Batticaloa lagoon (obtaining 14.2 km^2 mangrove area), in Sri Lanka [22]. Samples were taken from three different depths; 0-30 cm, 30-60 cm and 60-80 cm of mangrove soil. The Walkley-Black procedure [63] was used to measure the soil organic carbon content and general allometric equations were used to measure the above ground carbon stock in mangroves [8, 19, 26].

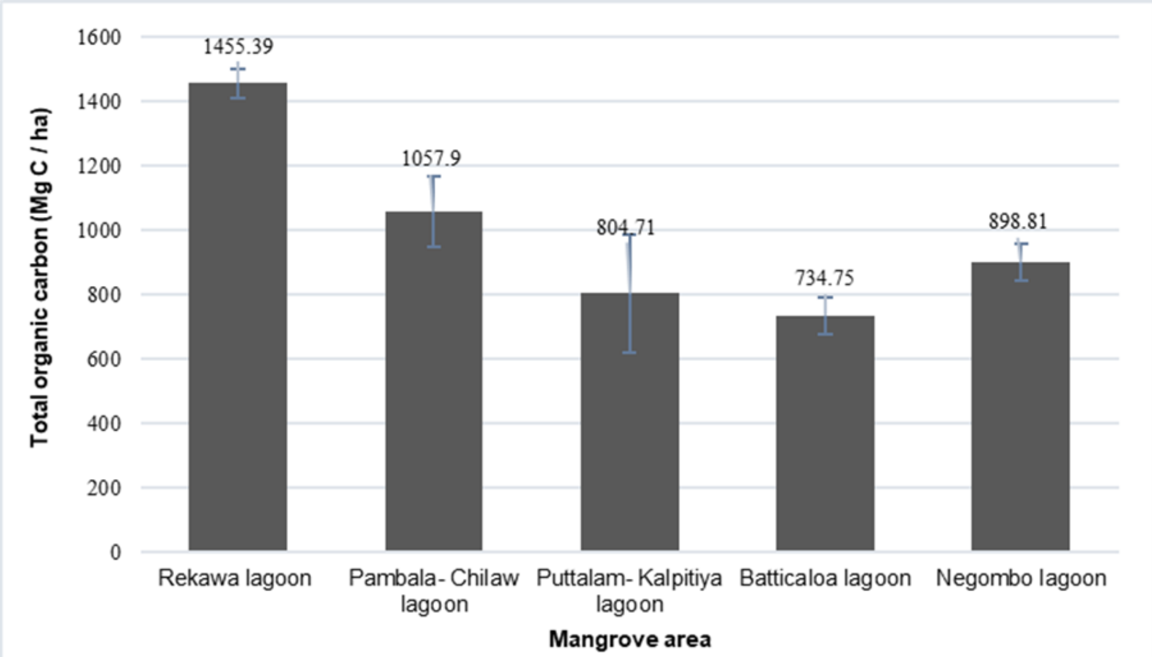

Figure 4: Total organic carbon in selected mangrove areas in Sri Lanka (Source; Cooray et al., 2021)

The total organic carbon stocks have resulted in Kokkaddicholai, Manmunaibridge island and Kannankudah sites: 100.9 kg C m^{-2}, 786.4 kg C m^{-2}, 593.1 kg C m^{-2} respectively. The study which was conducted by Jonsson & Hedman (2019), has provided a basic estimation of carbon stocks in the Batticaloa lagoon [22].

Another study was carried out by Perera & Amarasinghe (2018) to investigate the total organic carbon content in the Batticaloa lagoon in Sri Lanka [50]. Samples were taken from three different depths; 0-15 cm, 15-30 cm and 30-45 cm of mangrove soil. Chromic-acid wet oxidation method was used to measure the soil organic carbon content and species specific allometric equations and common allometric equations were used to measure the above ground and below ground biomass. The above study revealed that the obtained total organic carbon was 506.40 ±36.04 Mg C ha^{-1} while the total soil organic carbon, total aboveground carbon and total root carbon amounts were 347.83 ±33.80 Mg C ha^{-1}, 131.60 ±1.62 Mg C ha^{-1}, 26.96 ±0.26 Mg C ha^{-1} respectively. According to Perera & Amarasinghe (2018), mangrove soil is responsible for sequestrating a comparatively large fraction (68%) of organic carbon [50].

Perera et al. (2018) have conducted research to quantify the carbon stocks in the Negombo lagoon area in Sri Lanka [52]. Samples were taken from three different depths; 0-15 cm, 15-30 cm and 30-45 cm of mangrove soil. Total soil organic carbon content was measured by the rapid-dichromate oxidation method and species specific allometric equations as well as common allometric equations were used to measure the above ground and below ground biomass. According to the results, the total organic carbon, soil organic carbon, above ground carbon and below ground root carbon amounts were 499.54 ± 6.35 Mg

C ha^{-1}, 418.98 ± 5.19 Mg C ha^{-1}, 65.31 ± 0.97 Mg C ha^{-1}, 15.25 ± 0.19 Mg C ha^{-1} respectively. Further, this study suggested that factors such as hydrological and oceanographic alterations and anthropogenic processes affect the carbon sequestration of the above site.

A high carbon amount is stored in the upper 30 cm of the soil and could be easily disturbed due to anthropogenic activities. As a result, the oxidation process of soil organic matter will occur with rapid carbon dioxide emission [3, 36, 60]. The average soil organic carbon amount of the upper layer (100 cm) of mangrove soil is 404.37 Mg C ha^{-1}. Therefore, 1484.04 Mg CO_2e (CO_2e = soil carbon dioxide equivalent) could be emitted from the deforestation of each hectare of the mangrove ecosystem, which is higher than the value; 1060 Mg CO_2e ha^{-1} reported for the estuarine mangrove sediments globally (McKinley et al., 2011). According to Giri et al. (2015), 242 ha of mangroves area have lost between 2000 to 2012 [15]. It resulted in a 29,933.09 Mg CO_2e emission per year and interestingly, Cooray et al. (2021) have estimated that if all mangrove areas located in Sri Lanka (approximately 8000 ha) are disturbed, ~ 12.72 × 106 Mg CO_2e will be emitted to the atmosphere [10]. Therefore, the conservation of mangroves and the other blue carbon ecosystem should have taken much attention.

4. Threats and challenges for effective conservation of blue carbon ecosystems

As we discussed earlier, blue carbon ecosystems have been threatened mainly due to the various anthropogenic activities [35]. In Sri Lanka, 20.17 ha of mangrove area has been degrading per year [15] caused by development programmes, converting mangrove ecosystems into agricultural lands, building artificial infrastructures (e.g., house constructions, hotels, industrial buildings) and especially shrimp farming [12, 16, 25, 29].In addition to that, the lack of a proper monitoring system to detect the mangrove forest degradation, limited knowledge of people about the ecosystem services and values of mangroves, have driven to the degradation of mangrove forests in Sri Lanka [12, 16]. However, the present Sri Lankan government is in the process of taking necessary action to conserve all remaining mangrove forests and planned to restore 10,000 ha of coastal wetlands under the United Nations Decade of Ecosystem Restoration programme in Sri Lanka [10].

Seagrass meadows are one of the highly threatened ecosystems in Sri Lanka [62] due to unsustainable and destructive fishing activities, eutrophication (Negombo lagoon has lost 20% of seagrass meadows caused by microalgal proliferation on seagrass meadows) and digging of polychaetes causing siltation [24, 49, 62]. According to Ranahewa et al. (2018), anthropogenic activities such as nutrient and sediment loading, expansion area extension of salt pans, shrimp farming, the extension of buildup areas and expansion of man-made infrastructure have increased the rate of the sea bed degradation [53]. The conservation of seagrass meadows in Sri Lanka has not yet been recognized as an important matter [44]. However, there are research studies that have been conducted to investigate the diversity, abundance and distribution of seagrass species in Sri Lanka [20, 33]. Moreover, Udagedara & Dahanayaka, (2020) have prepared a checklist, focusing on diversity, distribution and conservation of seagrass species in Sri Lanka [62]. In addition, national seagrass meadows monitoring system and conservation policy plan should be established towards sustainable coastal zone management through conserving seagrass meadows as a valuable blue carbon ecosystem in Sri Lanka.

Less attention has also been given to the tidal marshes in Sri Lanka, though they are called tidal marshes in the temperate areas which are macro-tidal, Sri Lankan vegetation classification named them as salt marshes and they are markedly different to tidal marshes with respect to species composition, structure and functioning, compared to the mangroves and seagrass meadows. The coastal communities have not identified the importance of salt marshes since their importance is not as direct as mangroves [45]. Salt marshes are the nursery grounds for many culturable fish species, especially due to the presence of algal species (green algae and cyanobacteria). Shrimp farming is the major threat to salt marshes, especially in the Puttalam lagoon area in Sri Lanka. In addition, people use salt marsh areas to build houses that reduce the extent of salt marshes in Sri Lanka [45]. Therefore, policy enforcement to conserve salt marsh areas is critical in Sri Lanka. Moreover, research should be carried out to assess the carbon stocks and their distribution as well as to evaluate the socio-economic importance of salt marshes.

5. Policies and legislations to conserve blue carbon ecosystems in Sri Lanka

Sri Lankan government has endorsed policies and legislations in the country's constitution for the protection of coastal wetlands including mangroves as a blue carbon ecosystem [10, 23]. Sri Lanka is in the vanguard of mangrove conservation along with the other countries in the world [10, 28]. In 2020, "The National Policy on Conservation and Sustainable Utilization of Mangrove Ecosystem in Sri Lanka" has been established. However, we believe that implementation and monitoring of appropriate action plans (realistic) is the key to conserve mangrove ecosystems and their blue carbon stocks and Sri Lanka still has to materialize it. In addition, The Fauna and Flora Protection Ordinance furnishes the protection of animals (both invertebrates and vertebrates) and plants (including mangroves). Furthermore, the Fisheries and Aquatic Resources Act provides legal protection for the aquatic resources to avoid the extinction of some aquatic species that reside in lagoons and estuaries and intern it will also protect the mangrove forests located in those ecosystems.

Sri Lanka has signed several international conventions to protect the blue carbon ecosystems and is obliged to follow and obey their statutes i.e., Convention of Biological Diversity (CBD) and United Nations Framework Convention of Climate Change (UNFCCC). Sri Lanka is also a signatory to the Paris Agreement (21st session of UNFCCC Conference, 2015 in France) and submitted Nationally Determined Contributions (NDC) in 2016 (Ministry of Mahaweli Development and Environment, 2016) emphasizing the protection, conservation and restoration of mangroves and seagrass meadows as well as the other ecosystems towards climate change mitigation. Interestingly, Sri Lanka has prepared a National Biodiversity Strategic Action Plan (NBSAP) for the period 2016 – 2022 following the Convention of Biodiversity (Article 6 of CBD) which highlights the importance of mangrove restoration and the capacity improvement of ecosystem services.

6. Knowledge gaps in blue carbon dynamics in Sri Lanka

Scientists have been continuously studying strategies to reduce the increment of atmospheric CO_2 levels as it gives rise to critical global environmental problems such as global warming, glaciers melting and sea level rising [32]. Therefore, blue carbon ecosystems have been identified as the best natural systems that are capable of capturing and storing CO_2 within their biomass and soil environment [26]. For that, the total blue carbon content of a particular country should be quantified to get a clear understanding of the current carbon pool [10]. Therefore, blue carbon stocks in mangroves, tidal marshes and seagrass meadows in Sri Lanka should be quantified precisely. According to the best of our knowledge, blue carbon stock assessment studies of tidal salt marshes and seagrass meadows are scanty in Sri Lanka. It would be hard to estimate the total blue carbon content, without assessing the carbon stocks in tidal marshes and seagrass meadows extensively in Sri Lanka. Few research studies have been conducted to estimate carbon stocks in mangrove sites, covering the largest existing mangrove areas in the major climatic zones in Sri Lanka, to provide an understanding sufficient to have an insight into the overall potential of Sri Lankan mangrove ecosystems in sequestering atmospheric carbon and the magnitude of mangrove blue carbon pool [10, 22, 50, 51, 52]. Most of the studies have been conducted by taking soil samples 0 - 80 cm depth range of a carbon stock at a particular mangrove site since mangrove areas in Sri Lanka, which are micro-tidal, often have very shallow anaerobic soil layers and the many studies reveal that the soil organic carbon content that had fixed by the mangrove vegetation currently occupying the site, decreases with depth. Organic carbon in deep soils may indicate geological changes that have occurred in locations and changed the vegetation types and processes that assist the burial of organic carbon produced by the plants. Therefore, the deep soil carbon content may not necessarily represent the carbon sequestration capacity of the current vegetation [22, 50, 51, 52]. If the facilities are available, it is also recommended to take soil samples from the maximum depth that soil corer penetrates in a mangrove ecosystem as possible [10]. One study has focused on assessing soil organic carbon in seven mangrove sites in Sri Lanka [51]. Carbon emission data are an important factor to study the blue carbon dynamics in any country. Blue carbon sequestration processes (mangrove primary productivity) are even more important in having an insight into the potential of these blue carbon ecosystems in capturing and storing atmospheric carbon. Amarasinghe and Balasubramaniam (1992) have investigated the NPP (Net Primary Productivity) of above ground mangrove forest stands on the northwestern coast of Sri Lanka, using the litterfall data and above ground biomass increment. Interestingly, the NPP of fringing mangrove stands is lower than the estuarine mangrove stands [66]. The Gross primary productivity of mangrove stands at

Kadolkele in Meegamuwa (Negombo) estuary, Sri Lanka has been affected by the key factors such as; stem density, plant height, species richness, and leaf area index [67]. In addition to that, a significant relationship ($p < 0.05$) has been shown between the structure of vegetation which is represented by complexity index, NPP, and organic carbon accumulation rate in mangroves [68].

The factors that affect the carbon sequestration and storage of blue carbon ecosystems should be investigated to get an understanding of the capability of sequestrating and storing carbon in high capacity within their ecosystem pools. Perera & Amarasinghe (2019) have described that there is a significant correlation ($p < 0.05$) between total soil organic carbon stocks in mangroves with annual rainfall and Cooray et al. (2021) revealed that the mangrove soil carbon stock was higher where the vegetation biomass and stand densities are high [10, 51]. According to the Wijerathna et al., (2021), Soil porosity, soil moisture content, conductivity and salinity positively correlated with the soil organic carbon content while soil bulk density and nitrate content negatively correlated with soil organic carbon content (Spearman rank correlations; $P<0.001$) [69]. Besides, not all the factors will affect the mangroves, salt marshes and seagrass meadows similarly and that knowledge is essential for sustainable coastal zone management. In addition, evaluation of direct and indirect values of blue carbon ecosystems in Sri Lanka is critical and it would be supported by policy enforcement, conservation of coastal zone and proper soil carbon management. Except for a few studies based on mangroves of Batticaloa lagoon and Mannar area, salt marshes and seagrass meadows have not yet been characterized for their primary productivity and their potential for sequestering atmospheric carbon. With the current thrust on aquaculture development in the coastal areas, these blue carbon ecosystems become most vulnerable.

7. Limitations

Sri Lankan blue carbon research lack data on the carbon sequestration capacity of salt marshes and seagrass meadows, both in plant biomass (above and below ground) and in soil. Research is needed to fill this gap along with generating data on their current extents and distribution. This domain is not a priority of national research and therefore the state sponsorship is marginal.

8. Conclusion

Blue carbon ecosystems are recognized for their important role in climate change mitigation always combating the global climate crisis sequestering and storing significant amounts of atmospheric carbon dioxide in their biomass and soil despite their limited area coverage relative to other ecosystems. Few studies have been focused on quantifying carbon stocks in mangroves and the data of carbon stock assessments in tidal salt marshes and seagrass meadows are scanty in Sri Lanka. Quantifying carbon stocks in the remaining blue carbon ecosystems in Sri Lanka is critical. Similar to the mangrove ecosystems, it is highly recommended to impose policy enforcement to conserve remaining tidal salt marshes and seagrass meadows for climate change mitigation through proper coastal zone management in Sri Lanka.

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