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FORESTED WETLANDS

Ecosystem Carbon Stock and Stable Isotopic Signatures of Soil Organic Carbon Sources Across the Mangrove Ecosystems of Kerala, Southern India

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Abstract

Mangrove ecosystems have high carbon storage and sequestration rates and become substantial sources of greenhouse gases when disturbed by land-use change. Thus, they are extremely valuable for inclusion in climate change mitigation and adaptation strategies. However in Kerala, a west coast state of India, has lost 95% of its mangroves in the last three decades, posing a serious threat to global climate. The regional carbon stock data of mangroves that are at risk of depletion are rarely reported, despite the fact that they are crucial for mitigating and managing climate change impacts. In response, the study estimated the ecosystem carbon stocks and soil organic carbon sources of three different estuarine mangrove habitats of Kerala. The mean total ecosystem carbon stock of Kerala mangroves was estimated to be 218.98 ± 169.86 Mg C ha^{-1} which is equivalent to 803.66 ± 621.47 Mg CO_2 ha^{-1}, contributing a substantial amount of carbon to the global ecosystem carbon. Further 88% of the estimated ecosystem carbon stock was represented by vegetation biomass and 22% by the soil carbon stock. The stable isotopic signatures revealed that the accumulated autochthonous mangrove source attributed to the organic carbon in the soils of site 1 (Munroe island) and site 3 (Vypin) while the suspended organic matter in tidal water contributed to the soil organic carbon of site 2 (Ayiramthengu) mangroves. Mangrove structure, salinity, soil pH and bulk density were found to be the correlating factors for the carbon stock variations across the study sites. Hence, the understanding of the amount of carbon stocks in the mangroves of Kerala coupled with other ecosystem services they offer highlights their importance in the creation of conservation, restoration and climate change mitigation plans in the country.

Keywords Mangroves · Carbon stock · Vegetation · Stable isotope · Kerala

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Introduction

Mangrove ecosystems occupy only 0.17% of Earth's continental area (~137,600km^2) (Bunting et al. 2018), but they are among the most carbon-rich forests on the planet (Bouillon et al. 2008a; Donato et al. 2011; Atwood et al. 2017). Mangroves, unlike terrestrial forests, are capable of storing vast quantities of carbon in their soils over centuries as these unique ecosystems have higher carbon burial rates and a thousand times slower soil C turnover rates than terrestrial forests due to the complex root structures, high sedimentation rates, and anoxic soils (Mcleod et al. 2011; Alongi 2012). This long-term capacity to store significant quantities of soil carbon (5–10.4 Pg globally) (Duarte et al. 2013; Jardine and Siikamaki 2014) for centuries makes them essential carbon sinks. Furthermore, reducing or preventing greenhouse gas (GHG) emissions caused by the depletion of these soil carbon reserves is considered as a low-cost alternative for mitigating climate change (Siikamaki et al. 2012; Murdiyarso et al. 2015; Howard et al. 2017).

Studies revealed that 8–20% of global anthropogenic carbon dioxide emission was contributed by land-use change and deforestation, next to the combustion of fossil fuels (van der Werf et al. 2009; Arifanti et al. 2019). In this context, Reduced Emissions from Deforestation and Degradation (REDD+) has been highlighted in the recent international climate agreements as a crucial and reasonably cost-effective alternative for climate change mitigation and adaptation (Adame et al. 2021). The major objective of this program is to conserve terrestrial carbon stocks by providing financial incentives for the protection and conservation of forest ecosystems. However, REDD + and other CCMA programs need a regular evaluation of carbon stocks and emissions (IPCC, 2007), highlighting the relevance of robust carbon storage valuation for various forest types, especially those having high C density coupled with extensive land-use change (Keith et al. 2009).

Mangrove forests, found along the coasts of most major oceans in 124 tropical and subtropical countries (Bunting et al. 2018) are facing a multitude of anthropogenic threats such as coastal development, aquaculture expansion, and pollution which in turn resulting in large scale global destruction (Alongi 2002; Polidoro et al. 2010; Giri et al. 2011; Murdiyarso et al. 2015; Kauffman et al. 2018). Rapid sea-level rise in the twenty-first century has also been identified as a major threat to mangroves (Gilman et al. 2008), which have adapted to past sea-level rise by migrating landward or upward (Alongi 2008; Lovelock et al. 2015). Over the last 60 years, more than one-third of the world's mangroves have been disappeared (Alongi 2002; Hamilton and Casey 2016). Although many countries have adopted several conservation initiatives, mangroves continue to be lost at a global pace of about 0.2% each year (Hamilton and Casey 2016). This loss of mangroves around the world creates uncertainty about the fate of the huge amounts of carbon deposited in their soils since the degradation and loss of coastal vegetation may lead to the disruption of soil carbon down to 1 m depths, causing it to remineralize to CO_2 (Pendleton et al. 2012). Further, the remineralization of mangrove soil carbon may considerably contribute to the part of anthropogenic GHG emissions labeled as 'land-use change' which is currently not documenting in the carbon estimations across the globe (IPCC Climate change 2007).

The International Panel on Climate Change (IPCC) release the guidelines for quantifying and reporting stocks and emissions includes those arising from mangroves and other blue carbon habitats (IPCC 2014). Enhancing the data collection of carbon stock at regional level and conservation initiatives of these carbon stocks is also encouraged by the Paris Agreement for increasing natural C sinks to prevent climate change. This reflects the growing awareness of the importance of mangrove ecosystem conservation and restoration in GHG emissions reduction strategies. However, data are scarce on the full extent of ecosystem carbon stocks that are vulnerable to depletion. Even though mangroves are recognized for their high carbon assimilation and flux rates (Kristensen et al. 2008; Komiyama et al. 2008; Bouillon et al. 2008a), information on the total ecosystem carbon stock, the amount that will be released with land-use change, is surprisingly scarce. While only a few components of carbon stock have been reported, the most notable of which is vegetation biomass (Twilley et al. 1992; Komiyama et al. 2008), but evidence of deep organic-rich soils (Eong 1993; Matsui 1998; Fujimoto et al. 1999) indicates that these inventories ignore the vast majority of total ecosystem carbon.

Kerala, located on the west coast of India, has 44 rivers as well as a vast network of estuaries and backwaters with tidal action, once had 700 km^2 of mangroves along its coast (Ramachandran et al. 1986) but now declined to 9 km^2 (FSI 2019) indicating that 95% of the mangrove vegetation has declined over the last three decades (Sreelekshmi et al. 2021). Altogether 18 species of true mangrove species were reported from Kerala of which *Avicennia officinalis* and *Rhizophora mucronata* are the most common species whereas *Ceriops tagal*, *Avicennia alba* and *Sonneratia alba* are rare (Sreelekshmi et al. 2018). In addition, the Kerala mangroves have the potential to contribute a substantial amount of carbon to the global ecosystem carbon reserve (Rani et al. 2021). Further, to be a part of a land-based GHG emission reduction activity, information on C storage and its dynamics is necessary. Considering these facts, our objectives are to estimate the carbon stocks in various compartments of mangrove ecosystems of Kerala and to characterize the historical source of organic carbon in these ecosystems. We hypothesized that Kerala mangroves have a high carbon storage potential in biomass and soil compared to other mangrove systems, and this potential would vary significantly among study sites based on the environmental (soil) characteristics and forest structure.

Materials and Methods

Study Area

Kerala's physiographic setting is unique since it is a tiny strip wedged between the Lakshadweep Sea and the Western Ghats, comprising a sequence of lagoons and estuaries. It extends between the latitudes 8°18′ and 12°48′ N and longitudes 71°53′ and 77°24′E, with a total area of 38,864 km^2, of which the coastal wetlands make up a quarter i.e., 937.3 km^2 (Nair and Sankar 2002). The coastline stretches for around 590 km, with the northern end at Manjeswaram

(Kasargod district) and the southern end at Pozhiyar (Thiruvananthapuram district). Asymmetrical landscape, typified by undulating subdued hills and steep slopes, characterizes the shoreline, with altitude ranging from below mean sea level (MSL) to 2694 m above MSL (Jagtap et al. 2004).

Field samplings were conducted on a seasonal basis in three different estuarine mangrove forests in Kerala (Fig. 1) during 2019–2020. The study sites were, Site 1, Munroe island (8° 59' 27'' N 76° 36' 47 '' E), a degrading mangrove forest owing to excessive tourism activities fringing the Ashtamudi estuary which is a Ramsar site in Kerala. The mangrove species seen in this site are *Excoecaria agallocha*, *Avicennia officinalis* and *Rhizophora mucronata*. Site 2, Ayiramthengu (9° 6' 58'' N 76° 28' 49'' E), a lush mangrove ecosystem that borders the Kayamkulam estuary, a part of Vembanad lake which is also a Ramsar site in Kerala. *Avicennia officinalis*, *Avicennia marina*, *Avicennia alba*, *Bruguiera cylindrica*, *Excoecaria agallocha* and *Lumnitzera*

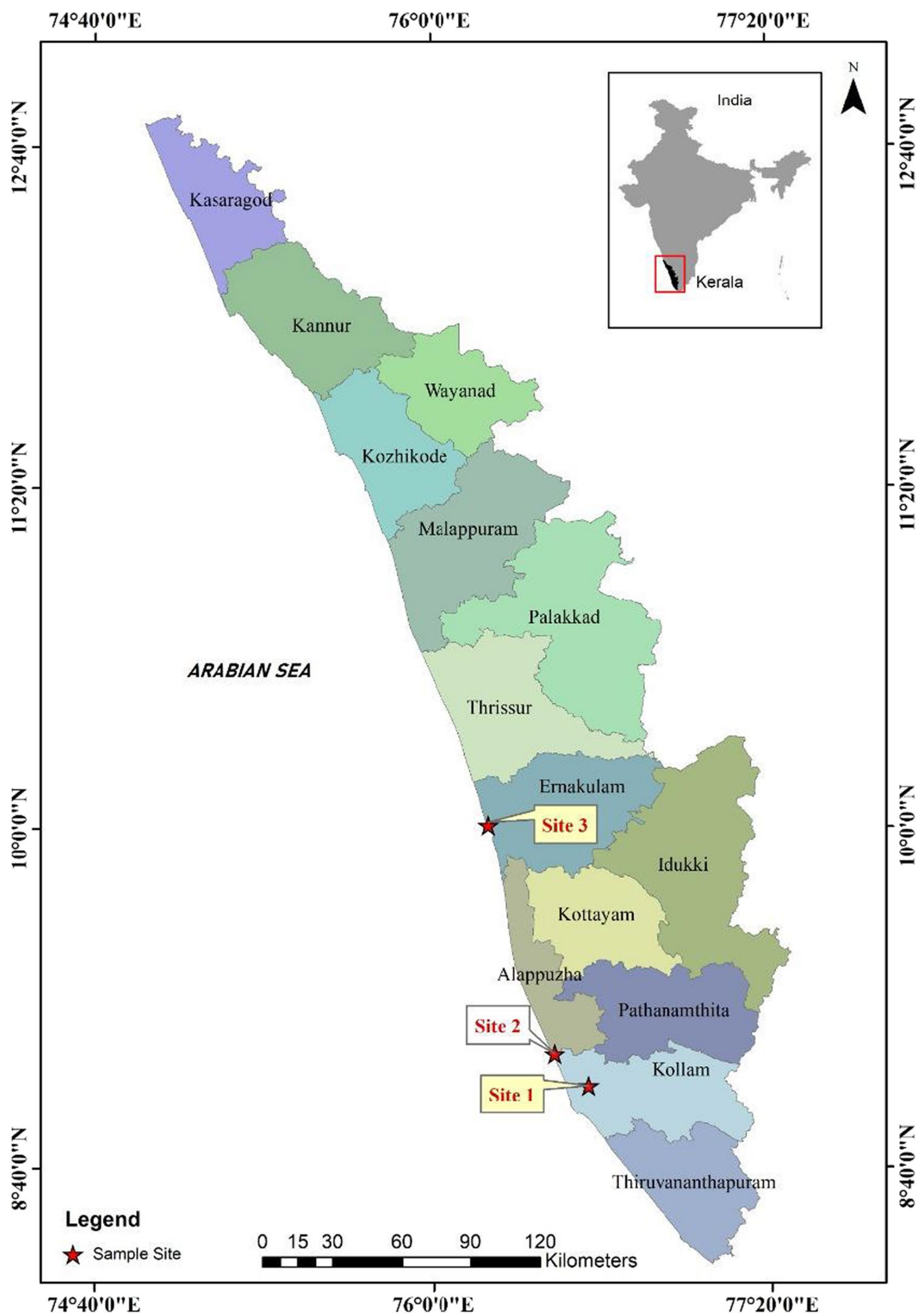

Fig. 1 Map showing the study sites along Kerala coast

racemosa are some of the primary species found here. Site 3, Vypin/Valappu (10° 0' 45'' N 76° 13' 22'' E), an island in Cochin estuary, is also a part of Vembanad lake. *Bruguiera gymnorhiza*, *Bruguiera cylindrica*, *Avicennia officinalis* and *Excoecaria agallocha* made up this mangrove forest.

Environmental Parameters

Soil samples (upto 1 m depth) were collected with a corer (4.6 cm diameter and 120 cm length) in each site and divided into four sections with depth intervals of 0–15, 15–30, 30–50, 50–100. The pH, Eh, and temperature of each section were measured *insitu* using a portable pH meter (Systronics make), Eh meter (Systronics make) and thermometer (AOAC 2000). The salinity and pH of the porewater were also measured *in-situ* using a hand held refractometer (make:Atago S/Mill-E) and pH meter (Systronics make). The textural analysis (Folk 1980) and bulk density measurement were carried out according to standard procedure. A known volume of the soil sample was dried to constant weight at 105^0 C in a hot air oven for determining the bulk density. Bulk density (g cm^{-3}) = Dry soil weight (g) / Soil volume (cm^3). The total nitrogen content of the soil was analyzed using the Kjeldahl digestion method and nitrogen distillation equipment (Anderson and Ingram 1993).

Structural Analysis

Fixed-area plot measurement was used to characterize structural attributes of the mangrove vegetation, as described by Cintrón & Schaffer-Novelli (1984). Four transects perpendicular to the waterline were put at 50 m intervals in each site and five quadrats (10 × 10 m) were laid at 50 m intervals in each transect, taking into account mangrove diversity and accessibility. Using a measuring tape, the dbh (diameter at breast height) of each species in the quadrats were determined. As suggested by Cintrón and Schaffer-Novelli (1984) trunk density, basal area and species dominance (% basal area) were estimated.

Biomass Stock Estimation

Living Biomass

The aboveground and belowground vegetation biomasses were calculated using the species-specific allometric equations established by Komiyama et al. (2005). Both formulae are based on Diameter at Breast height (DBH) and wood density of mangrove species. For belowground biomass calculations, species-specific wood density (g cm^{-3}) was derived from the wood density database (Zanne et al. 2009). The mangrove biomass was transformed into carbon stock by multiplying it by a factor of 0.47 for aboveground biomass and 0.39 for belowground biomass (Kauffman and Donato 2012).

Dead Biomass Stock

Depending on the state of decay, dead trees were classified into one of three classes (I, II and III) (Kauffman and Donato 2012). Class I dead trees are those that have recently died but still have the bulk of their primary and secondary branches, whereas Class III dead trees have only the main trunk and have lost all of their branches. The dead trees with primary branches attached to the main trunk were allocated to the Class II category. The biomass of dead trees was computed depending on their decay class. Status I dead trees were estimated to be 97.5% of a live tree's biomass, status II dead trees were expected to be 80% of a live tree's biomass, and status III trees were projected to be 50% of a live tree's biomass (Kauffman and Donato 2012). Biomass of downed wood was converted to carbon mass using biomass to carbon conversion ratios.

Soil Carbon Stock

A PVC corer (4.6 cm diameter and 120 cm length) was used to collect samples from a depth of 100 cm for soil carbon analysis from five quadrats in each transect and the samples were dried and pulverized. Total Carbon (TC), Total Organic Carbon (TOC) were determined from these samples using the TOC analyzer HT 1300 solid module (Analytik Jena make).

Soil Carbon stock (MgC ha^{-1}) = C con (%) x Bulk density (g cm^{-3}) x depth (cm).

Source Characterisation of Organic Carbon and Nitrogen

The stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes were determined in each core sample from the three study sites. Air-dried subsamples were acidified with dilute HCl (5%) and then oven-dried at 40 °C to remove the carbonates. The samples were encapsulated in tin capsules and analyzed with an elemental analyzer coupled with an isotope ratio mass spectrometer (EA-IRMS) (Kauffman and Donato 2012) and the stable isotopic composition was reported in δ notation [per mil (‰) units].

Total Ecosystem Carbon Stock and Economic Valuation

The total ecosystem carbon stock was estimated by adding the carbon stock in above-ground biomass, belowground biomass, dead biomass, and soil together. The carbon dioxide (CO_2) equivalents, or CO_2e was calculated by multiplying the total ecosystem carbon stock with a factor of 3.6 (IPCC, 2007). The social cost of carbon was calculated by multiplying the CO_2e with 86 as a ton of CO_2 costs US $ 86 (Ricke et al. 2018).

Statistical Analyses

The Kolmogorov–Smirnov (K-S) test was used to determine the normality of the variables and Levene's test for homogeneity of variance. The variations in the vegetation biomass and carbon stocks between study sites were assessed using two way-ANOVA and if the variation appeared significant ($p < 0.05$), the Tukey post hoc test was done to evaluate the variation. To analyze the relationships of major environmental characteristics with C stocks, Pearson's correlation coefficients were calculated in all the study sites. All the statistical analyses were done using SPSS v16 software.

Results and Discussion

Community Structure and Vegetation Biomass

The study stations comprised a total of 8 true mangrove species (Table 1). The density data revealed that site 1 was dominated by *Excoecaria agallocha* (2100 ± 843 ha^{-1}), site 2 by *Avicennia marina* ($22{,}000 \pm 3202$ ha^{-1}) while *Bruguiera gymnorhiza* (4000 ± 3219 ha^{-1}) dominated site 3. Among the three sites, the tree density was highest in site 2 (4475 ± 8597 ha^{-1}) followed by site 3 (1950 ± 1843 ha^{-1}) and site 1 (1233 ± 901 ha^{-1}). The highest basal area was represented by *Rhizophora mucronata* (39 ± 53.6 m^2 ha^{-1}) in site 1, *Bruguiera cylindrica* (56.7 ± 38.7m^2 ha^{-1}) in site 2 and *Avicennia officinalis* (12.3 ± 17.7 m^2 ha^{-1}) in site 3 (Table 1). The mean density in the study sites ranged from 200 to 22,000 ha^{-1}and the mean basal area was 0.6–49.3m^2 ha^{-1} (Table A1) which fell within the range reported from tropics (Trettin et al. 2016, Sreelekshmi et al. 2018; Satyanarayana et al. 2002; Das et al. 2014 and Hinrichs et al. 2009). The mean aboveground,belowground and total biomass of mangroves of Kerala were 130.43 ± 163.88 Mg ha^{-1}, 423.55 ± 496.96 Mg ha^{-1}and 553.98 ± 660.75 Mg ha^{-1}respectively. Further *Rhizophora mucronata* (595.56 Mg ha^{-1}) had the maximum total biomass in site 1 and *Avicennia marina* (1913.31 Mg ha^{-1}) in site 2 and *Avicennia officinalis* (120.27 Mg ha^{-1}) in site 3. Relatively higher mean DBH for *Avicennia marina* (24.8 ± 4.44 cm) and *Bruguiera cylindrica* (23.66 ± 13.90 cm) were measured at site 2, resulting in higher above-ground and below-ground biomasses ($p < 0.05$) than the other two sites (Table 1). Earlier, Suresh et al. (2017) recorded 132.83 ± 97.5 Mg ha^{-1}biomass from central Kerala, while Vinod et al. (2018) reported 236.56 t ha^{-1} biomass from Kadalundi mangroves (North Kerala).

Environmental Parameters

The study stations exhibited relatively low temperatures, neutral pH, highly reducing and mixo-mesohaline soil conditions (Table 2), which matched the findings of Rani et al. (2021); Sreelekshmi et al. (2020a). The soil temperature varied with the seasons ranging from 28^0 to 31^0 C with a mean of 29.47 ± 1.04^0 C. This pattern of temperature variation was due to the seasonal influences of freshwater owing to rainfall, wind force, high intensity of solar radiation and lower atmospheric air temperature (Sahu et al. 2012). The peak salinity was recorded during the pre-monsoon season in all the study sites owing to the low rainfall while lower salinity during monsoon season. The high and low salinity values recorded varied from 4 PSU (Mon, site 3) to 35 PSU (pre mon, Site 2). The high pH value (7.8) was recorded in site 3 during pre monsoon season, and the low value (6) was recorded in site 2 during post monsoon season. These alterations in pH could be attributed to freshwater influx, fluctuations in salinity and temperature (Rajasegar et al. 2002). The granulometric composition revealed silty sand in all the sites. The bulk density varied from 0.35 to 0.85 gcm^{-3} and organic carbon content from 11.50 to 52.54 mgg^{-1} (Table A2). While the organic carbon and total nitrogen content in all the sites appeared low owing to the sandy nature of the soil. Further site 2 exhibited relatively lower organic carbon (15.78 ± 3.63 mgg^{-1}) attributed to the continuous tidal flushing and increased salinity. The organic carbon concentrations in the study sites were comparable with the values reported from other mangrove ecosystems like Sundarbans (Rahman et al. 2014; Sreelekshmi et al. 2020b) and Pichavaram (Kathiresan et al. 2021). As indicated in Table 2, all parameters except soil temperature and total nitrogen exhibited significant variations between stations ($p < 0.05$), whereas all parameters except soil texture and bulk density showed significant differences across seasons ($p < 0.05$). In comparison to the other two sites, site 2 had higher salinity (Table 2), however in sites 1 and 3 the decrease in salinity resulted in an increase in organic carbon input through mangrove litter (Zhu 2001; Bandyopadhyay et al. 2003; Rahman et al. 2014).

Vegetation Carbon Stock

The mean total vegetation carbon stock in the mangrove ecosystems of Kerala was 194.03 ± 177.51 Mg C ha^{-1}. The belowground vegetation C pools (142.61 ± 127.67 Mg C ha^{-1}) were significantly higher ($p < 0.05$) than the aboveground C pools (51.42 ± 49.87 Mg C ha^{-1}) in all the sites. The findings matched the vegetation carbon stock reported from Vietnam (Tue et al. 2014), Indonesia (Donato et al. 2011) and Bhittarkanika, India (Banerjee et al. 2020). In comparison to the other two sites, site 2 showed significantly

Table 1 Community structure and vegetation biomass of different sampling stations

Station	Species	Tree density (no/ha)	Basal area (m^2/ha)	DBH (cm)	Above ground biomass/ABG (Mg/ha)	Belowground biomass/BGB (Mg/ha)	Total biomass/TB (Mg/ha)	ABG C (MgC/ha)	BGB C (MgC/ha)	TB C (MgC/ha)	CO_2 equi (Mg)
Site 1	*Avicennia officinalis*	300 ± 292	11.9 ± 11.6	9.40 ± 8.72	37.49	146.15	183.64	17.39	56.99	74.39	273.02
	Rhizophora mucro-nata	1300 ± 1783	39 ± 53.6	14.00 ± 19.18	134.16	461.39	595.56	62.25	179.95	242.20	888.86
	Excoecaria agallocha	2100 ± 843	21.9 ± 12.8	16.00 ± 4.84	98.92	351.22	450.14	45.90	136.97	182.87	671.15
Site 2	*Avicennia officinalis*	700 ± 353	34.80 ± 7.6	20.80 ± 2.25	264.50	852.21	1116.72	122.73	332.36	455.09	1670.19
	Avicennia marina	22000 ± 3202	50.2 ± 17.4	24.80 ± 4.44	473.29	1440.02	1913.31	219.60	561.61	781.21	2867.05
	Avicennia alba	500 ± 696	7.2 ± 10.0	6.00 ± 8.24	10.92	48.04	58.96	5.07	18.73	23.80	87.35
	Bruguiera cylindrica	1550 ± 903	56.7 ± 38.7	23.66 ± 13.90	436.88	1339.48	1776.35	202.71	522.40	725.11	2661.14
	Excoecaria agallocha	1450 ± 867	39.9 ± 26.7	19.75 ± 11.68	167.09	563.67	730.76	77.53	219.83	297.36	1091.31
	Lumnitzera racemosa	650 ± 626	3.5 ± 4.8	4.75 ± 5.07	8.45	38.06	46.52	3.92	14.85	18.77	68.88
Site 3	*Avicennia officinalis*	200 ± 293	12.3 ± 17.7	7.80 ± 10.83	23.69	96.58	120.27	10.99	37.67	48.66	178.58
	Bruguiera gym-norhiza	4000 ± 3219	3.6 ± 3.0	5.85 ± 3.77	14.83	63.25	78.08	6.88	24.67	31.55	115.79
	Bruguiera cylindrica	3000 ± 4195	1.4 ± 2.0	2.67 ± 3.65	2.03	10.53	12.56	0.94	4.11	5.05	18.53
	Excoecaria agallocha	600 ± 289	7.6 ± 6.2	8.92 ± 4.50	23.37	95.52	118.89	10.84	37.25	48.09	176.51

Table 2 Environmental parameters prevailed in the sites during the study period

Parameters	Site 1			Site 2			Site 3		
	Pre mon	Mon	Post mon	Pre mon	Mon	Post mon	Pre mon	Mon	Post mon
Temperature (^{0}C)	30 ± 0.70^a	28.2 ± 0.44^b	30 ± 0.73^a	30.8 ± 0.44^a	28.8 ± 0.40^b	30 ± 1.00^a	30.2 ± 0.45^a	28.4 ± 0.54^b	29 ± 0.45^b
pH	6.76 ± 0.11^a	6.56 ± 0.15^b	6.64 ± 0.11^a	6.88 ± 0.04^d	6.52 ± 0.15^b	6.26 ± 0.21^c	7.62 ± 0.13^f	6.54 ± 0.05^b	6.94 ± 0.15^e
Redox potential (mV)	-173 ± 27^a	-140 ± 26^b	-121 ± 27^b	-469 ± 38^c	-448 ± 37^c	-316 ± 26^d	-278 ± 121^d	-151 ± 24^a	-76 ± 37^b
Salinity (PSU)	27 ± 1.22^a	8.6 ± 0.54^b	12 ± 0.71^c	35.2 ± 0.45^d	6.4 ± 1.14^e	11.4 ± 1.13^c	11.8 ± 0.84^c	5.0 ± 1.00^f	6.2 ± 1.30^e
Sand (%)	79.6 ± 2.97^a	75.6 ± 2.30^a	77.8 ± 4.76^a	58 ± 4.32^b	44.6 ± 2.70^c	49.2 ± 4.49^d	68 ± 1.58^e	64.2 ± 3.70^e	70.2 ± 1.92^f
Silt (%)	16.5 ± 2.55^a	18.4 ± 2.97^a	20.2 ± 1.79^a	38 ± 3.20^b	40.4 ± 3.51^b	35 ± 3.39^b	21.2 ± 2.86^a	20.2 ± 4.09^a	18 ± 2.92^a
Clay (%)	3.9 ± 3.75^a	6 ± 3.54^b	2 ± 5.61^a	4.6 ± 7.09^b	15 ± 5.34^c	15.8 ± 5.31^c	10.8 ± 4.44^d	15.6 ± 6.50^c	11.8 ± 4.15^d
OrganicCarbon(mg/g)	23.91 ± 1.37^a	19.65 ± 1.23^b	21.73 ± 1.22^c	19.14 ± 1.41^b	11.93 ± 0.29^d	16.25 ± 0.64^e	51.89 ± 0.56^f	11.92 ± 0.40^d	32.88 ± 1.79^g
Bulkdensity(g/cm^3)	0.43 ± 0.05^a	0.41 ± 0.04^a	0.42 ± 0.05^a	0.65 ± 0.05^b	0.61 ± 0.06^b	0.63 ± 0.10^b	0.79 ± 0.05^c	0.72 ± 0.06^c	0.74 ± 0.04^c
Total Nitrogen (mg/g)	1.67 ± 0.38^a	1.37 ± 0.09^b	1.54 ± 0.17^b	2.72 ± 0.33^c	1.68 ± 0.08^a	2.01 ± 0.14^d	3.55 ± 0.23^e	0.77 ± 0.04^f	1.53 ± 0.21^b

*the values with different superscript letters in a row are significantly different ($p < 0.05$), Pre mon *Pre Monsoon season*, Mon *Monsoon season* Post mon *Post monsoon season*

higher total vegetation carbon ($p < 0.05$). The significant differences in the vegetation carbon stock between sites could be attributable to the variability in the structural characteristics of mangrove stands (Kasawani et al. 2007). The contribution of vegetation to total ecosystem C stocks in site 1, site 2 and site 3 were 90.59%, 95.01% and 45.89% respectively. The study revealed a significant negative correlation between pH and vegetation carbon (r = -0.625, $p < 0.05$), while a positive correlation between pore water salinity and vegetation carbon (r = 0.709, $p < 0.05$). Higher vegetation carbon stock was observed in site 2 (Table 2) which showed higher salinity (17.33 ± 15.5psu) and lower vegetation carbon was found in site 3 with lower salinity(7.67 ± 3.79psu).

In site 1, *Rhizophora mucronata* had the highest vegetation carbon stock (242.20MgCha^{-1}) and *Avicennia officinalis* (74.39 MgCha^{-1}) had the lowest, whereas in site 2, *Avicennia marina* had the highest vegetation carbon stock (781.21 MgCha^{-1}) and *Lumnitzera racemosa* (18.77 MgCha^{-1}) had the lowest. While, in site 3, maximum carbon stock was represented by *Avicennia officinalis(*48.66 MgCha^{-1}), and minimum by *Bruguiera cylindrica* (5.05 MgCha^{-1}) as shown in Table 1; Fig. 2.

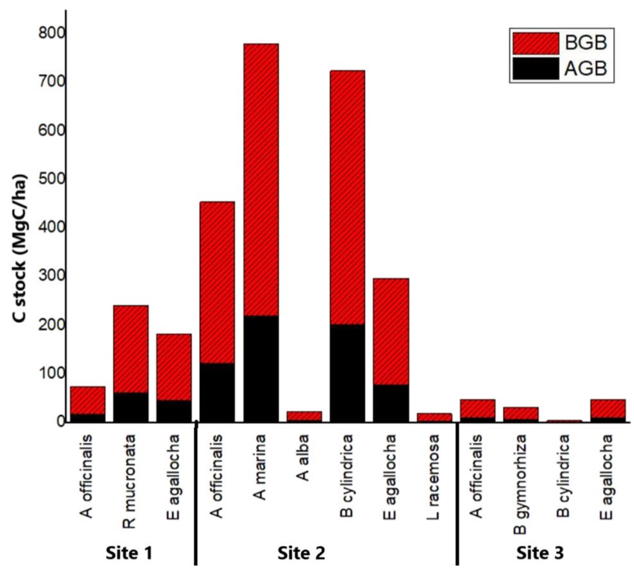

Fig. 2 Vegetation carbon stock of different species in the study area during the study period

Downed Wood Carbon Stock

The mean downed wood carbon stock in the mangrove ecosystems of Kerala was 3.03 ± 3.26 Mg C ha^{-1}. Maximum downed wood carbon was recorded in site 2 (5.02 ± 4.75 Mg C ha^{-1}) followed by site 1 (3.04 ± 1.91 Mg C ha^{-1}) and site 3 (1.04 ± 1.08 Mg C ha^{-1}) as shown in Table 3. However, there were no significant variations in downed wood carbon between stations (Table 4). The contribution of downed wood carbon to the total ecosystem carbon stock appeared negligible, (1.68% in site 1, 1.24% in site 2, and 1.49% in site 3). Large rotten wood made up 46% of the downed wood carbon stock whereas

Table 3 Downed wood carbon stock recorded in the sites during the study period

Quadrats	Downed wood C Stocks (MgC/ha)		
	Site1	Site 2	Site 3
Q1	4.52	6.52	0.98
Q2	0	8.46	1.84
Q3	2.76	10.11	0
Q4	3.12	0	0
Q5	4.8	0	2.39
Mean	3.04	5.018	1.042
SD	1.911439	4.753748	1.075788

Table 4 Carbon stocks recorded in the sites during the study period

Sites	Carbon stocks in various ecosystem compartments (Mg C ha^{-1})				
	Above-ground biomass	Below - ground biomass	Downed wood	Soil (0-100 cm)	Total ecosystem (Tree + Downed wood + soil)
Site 1	41.25 ± 23.65^a	122.89 ± 65.25^a	3.04 ± 1.91^a	13.72 ± 2.26^a	180.90
Site 2	105.61 ± 614.64^b	279.04 ± 239.71^b	5.02 ± 4.75^a	14.96 ± 3.75^a	404.63
Site 3	7.42 ± 4.72^c	25.94 ± 15.77^c	1.07 ± 1.08^a	36.99 ± 20.73^b	71.42
Entire study sites	51.42 ± 49.87	142.61 ± 127.67	3.03 ± 3.26	22.52 ± 13.70	218.98 ± 169.86

* the values with different superscript letters in a column are significantly different ($p < 0.05$)

medium and small wood only constituted 30% and 24% of the carbon pool, respectively.

Soil Carbon Stock

The mean depth of the mangrove soils across the sites was 1 m. However, the soil organic carbon stock ranged from 9.98 to 66.20 Mg C ha^{-1} with a mean value of 22.52 ± 13.70 Mg C ha^{-1} (Table 4). The amount of carbon is determined by the size of the soil particles. Fine silt and clay particles have greater carbon retention capacity due to their larger surface area than sand particles (Kauffman and Bhomia 2017; Kathiresan et al. 2021). Thus, the sandy nature of the soil in all the sites attributed to the relatively low carbon stock. A significant positive correlation (r = 0.648, $p < 0.05$), was found between the bulk density and organic carbon stock in the study sites while a significant negative correlation was observed for pH (r = -0.693, $p < 0.05$) and salinity (r = -0.715, $p < 0.05$) with the soil organic carbon stocks demonstrating that relatively low pH and salinity benefits the accumulation of organic matter.

Earlier reports revealed that mangrove ecosystems are important carbon sinks and that the soil OC pool accounts for the majority of ecosystem OC stock (Twilley et al. 1992; Donato et al. 2011; Murdiyarso et al. 2015; Rovai et al. 2018). However, in this investigation, samples were obtained from the top 1 m of the soil, resulting in much lower estimates of soil carbon stocks. Murdiyarso et al. (2015) found that soil OC density did not vary significantly with depth in mangrove habitats and that the drop in soil OC concentration with depth was compensated by the increased bulk density. Further, the top 1 m soil OC stock in this study (9.98–66.20 Mg C ha^{-1}), was within the range recorded in other mangrove wetlands of India (Table 5). The mean soil organic carbon content recorded in the present study (23.26 mgg^{-1}) was found to be greater than the global mean value (20 mgg^{-1}) for mangroves (Kristensen et al. 2008), demonstrating that Kerala mangroves have a significant soil carbon stock. Further, Donato et al. (2011) found that estuarine sites have relatively lower soil carbon content (with a mean of 7.9%) than oceanic sites (with a mean of 14.6%) when comparing the soil OC stock of different mangrove ecosystems in the tropics.

Stable Isotopic Signatures of Soil Organic Carbon Sources

Earlier reports revealed that the majority of organic matter in undisturbed mangrove soils comes from autochthonous sources, as determined by carbon (δ13C) and nitrogen (δ15N) stable isotope signatures (Ranjan et al. 2011; Stringer et al. 2016; Xiong et al. 2018; Li et al. 2018) as well as the ratio of total organic carbon to total nitrogen (C/N ratio) (Lamb et al. 2006), but if considerable rates of input from riverine or tidal sources are present, allochthonous organic matter may become more important (Jennerjahn and Ittekkot 2002). C3 plants such as mangroves have a δ13C signature ranging from −32 to −21‰ (Bouillon et al. 2008b), whereas C4 plants, as well as marine sources such as seagrass, and algae have a δ13C signature ranging from −25 to −8‰ (Lamb et al. 2006; Kennedy et al. 2010). The typical δ15N signature of mangrove biomass ranges from 0 to 11‰ (outliers: −10 to 20‰, Bouillon et al. 2008a; Ranjan et al. 2011), whereas the δ15N values of seagrass and marine microalgae are 6–12‰ and 0–4‰ respectively.

In the present study, site 1 and 3 had the lowest δ 13 C values (-26.81 ± 2.14 and -28.47 ± 0.29 respectively) and higher C/N ratios (14.34 ± 0.07 and 14.98 ± 0.35

Table 5 Mean stable isotope & C/N ratio of soil samples of Kerala mangroves during the study period

Stations	δ 13 C (‰)	C%	δ 15 N (‰)	N%	C:N	Remarks
Site 1	-26.81 ± 2.14	2.17 ± 0.30	3.24 ± 1.03	0.15 ± 0.02	14.34 ± 0.07	Mangrove origin
Site 2	-23.09 ± 0.91	1.55 ± 0.51	1.11 ± 0.05	0.22 ± 0.07	7.07 ± 0.008	Marine origin
Site 3	-28.47 ± 0.29	3.19 ± 2.83	4.49 ± 0.09	0.21 ± 0.19	14.98 ± 0.35	Mangrove origin

respectively) indicating mangrove litter as the potential organic carbon sources (Table 5). However, site 2 exhibited the highest δ 13 C value (-23.09 ± 0.91), and the lowest C/N value (7.07 ± 0.008) indicating a marine input as this site was found close to the Arabian sea. The exchange of organic matter and nutrients in this site is attributed to the frequent tidal flushing. The δ 15 N values (1.11 ± 0.05) were also quite low in this site and appeared to be similar to the isotopic signatures of phytoplankton. The mean C/N, δ13C and δ15N values for phytoplankton were 6.67 ± 0.33, -25.83 ± 1.37‰ and 1.57 ± 1.18‰, respectively (Costa et al. 2021).

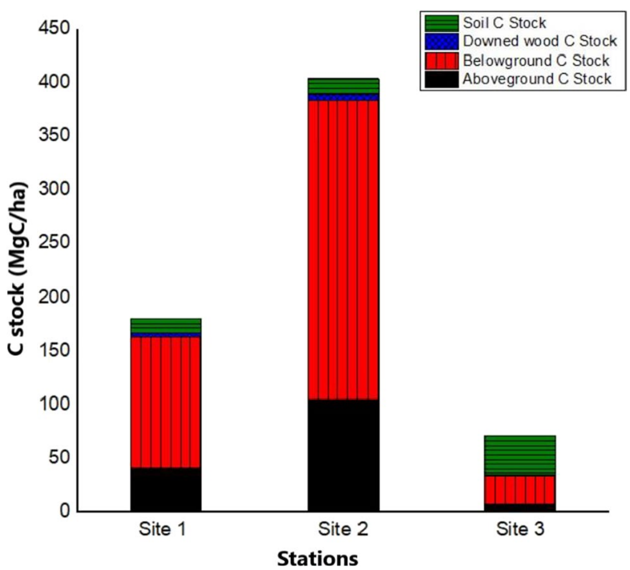

Fig. 3 Distribution of carbon stock in different compartments of the ecosystem in the study sites

Total Ecosystem Carbon Stock

The total ecosystem carbon stock was found to be highest in site 2 (404.63 Mg C ha^{-1}) and lowest in site 3 (71.42Mg C ha^{-1}) as shown in Table 4; Fig. 3. The mean ecosystem carbon stock of Kerala mangroves was estimated to be 218.98 ± 169.86 Mg C ha^{-1}, which is higher than that of other mangrove habitats of India (Table 6). A wide range of total ecosystem carbon stocks in mangrove ecosystems of different nations has been reported, with values ranging from 54.3 $MgCha^{-1}$ in Cochin, Kerala to 1396.9 $MgCha^{-1}$ in Bintuni, Indonesia. On a global scale, mangrove forests in tropical countries at low latitudes have significantly more biomass than those in temperate zones (Komiyama et al. 2008). In the present study, the contribution of vegetation and soil carbon stocks to the total ecosystem carbon stock was 88% and 22% respectively. Furthermore, the belowground carbon stock accounted for 65% of the ecosystem carbon stock. Our results corroborate with the findings of Sanders et al. (2016) and Kauffman et al. (2020) that the belowground C stocks accounted for ~ 85% of the total ecosystem carbon stock in mangroves especially in medium and low-stature mangroves. However, the average estimated CO_2 equivalents of the ecosystem carbon stocks was 805.78 ± 621.47 Mg CO_2 ha^{-1} and the social cost of carbon contributed by the mangroves of the study area was US $53447.05.

Table 6 Comparison of carbon stocks of Kerala with other mangroves of world

Mangroves	Carbon stocks (MgC/ha)			Reference
	Tree biomass	Soil	Ecosystem	
Global	-	-	856.10	Kauffman et al. 2020
Global	-	-	738.90	Alongi 2020
Bintuni, Indonesia	382.10	1014.80	1396.90	Murdiyarso et al. 2015
Mui Ca Mau National park, Vietnam	140.00	623.00	762.00	Tue et al. 2014
Sulawesi, Indonesia	139.00	2064.00	2203.00	Donato et al. 2011
Sulawesi, Indonesia	8.30	15.40	23.70	Shunyang et al. 2018
Mozambique	59.00	160.00	219.00	Sitoe et al. 2014
Sundarbans, Bangladesh	-	-	159.50–360.00	Rahman et al. 2014
Sundarbans, India	53.20	18.50	71.70	Ray et al. 2013
Mahanadi, India	90.60	60.90	151.50	Sahu et al. 2016
Bhitarkanika, India	143.61	5.46	149.07	Banerjee et al. 2020
Cochin, Kerala, India	-	-	54.30	ShyleshChandran et al. 2020
Vellar estuary, India	36.75	23.52	60.27	Kathiresan et al. 2021
Kerala, India	58.56	81.26	139.82	Harishma et al. 2019
Kerala, India	194.03	22.52	219.56	Present study

Conclusions

Indian mangroves, particularly Kerala mangroves are under tremendous development pressures despite the fact that sustainable mangrove management could contribute substantially to reduce national GHG emissions. However, as compared to other mangroves across the world, Kerala's mangroves had a substantial amount of ecosystem carbon stock. Site 1 has a carbon stock of 180.90 Mg C ha^{-1}, while site 2 showed the highest carbon stock (404.63 Mg C ha^{-1}) whereas a carbon stock of 71.42 Mg C ha^{-1} was estimated from site 3. The findings suggested that in site 2, the trapping of particulate organic matter from the adjacent coastal waters contributed more to the mangrove carbon sinks than the actual production of the mangrove trees, whereas the carbon sinks in the other two sites received the organic matter from autochthonous sources. The continuous tidal flushing in site 2, resulted in higher vegetation carbon stock but lower soil organic carbon stock, as demonstrated by stable isotopic studies and salinity range. The study also revealed that structural characteristics, salinity, soil pH and bulk density were the major factors influencing the carbon stock in the study sites.Therfore, considering the importance of mangroves as global carbon sinks, the disproportionate GHG emissions they produce when disturbed, and other vital ecological services they offer, they should be conserved, restored, and included in climate change adaptation and mitigation strategies. Being a state with a high risk of flooding and sea level rise, Kerala can adopt mangrove carbon sequestration as a key 'climate change mitigation program' in the future. Further, the estimation of the large C stocks of Kerala mangroves is important for policy formulation as per the guidelines of The United Nations Framework Convention on Climate Change (UNFCCC) to develop appropriate adaptive measures to deal with the climate change trends and to generate country- or region-specific data on C stocks and emission factors from various land-use activities in mangroves.

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Author Contribution SL, BN & HK developed the research; SL, SK and RH performed the field work, collected and analysed the data, SL wrote the manuscript, SL, HK, BN, SK & RH reviewed and approved the manuscript.

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Data Availability The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Code Availability Not applicable.

Declarations

Consent for Publication Everybody entitled so gave their consent for this research being published.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

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

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