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Biomass and carbon stocks in mangrove ecosystems of Kerala, southwest coast of India

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Abstract

Background: Mangroves are important tropical carbon sinks, and their role in mitigating climate change is well documented across the globe. However, the ecosystem carbon stocks in the mangroves of India have not been studied comprehensively. Data from this region is very limited for providing sufficient insights and authentic evaluation of carbon stocks on a regional scale. In this study, we evaluated the ecosystem carbon stock and its spatial variation in mangroves of Kerala, southwest coast of India.

Results: The mean biomass stored in mangrove vegetation of Kerala is 117.11 ± 1.02 t/ha (ABG= 80.22 ± 0.80, BGB = 36.89 ± 0.23 t/ha). Six mangrove species were found distributed in the study area. Among the different species, *Avicennia marina* had the highest biomass (162.18 t/ha) and least biomass was observed in *Sonneratia alba* (0.61 t/ha). The mean ecosystem carbon stock of mangrove systems in Kerala was estimated to be 139.82 t/ha, equivalent to 513.13 t CO_2 e/ha with the vegetation and soil storing 58.56 t C/ha and 81.26 t C/ha respectively.

Conclusion: The present study reveals that Kerala mangroves store sizable volume of carbon and therefore need to be preserved and managed sustainably, to retain along with the increase in carbon storage. This features the need of broadening mangrove cover as well as restoring deteriorated land in the past 50 years. Although mangrove forests in this region are protected by the Kerala Forest Department, they have been frequently facing illegal encroachment, prawn cultivation, and coastal erosion.

Keywords: Mangrove ecosystem, Biomass, Aboveground carbon, Belowground carbon, Ecosystem carbon stock

Background

The 1997 Kyoto Protocol was framed on the principle that CO_2 from the air can be sequestered in the soil and biomass, a practical way of mitigating climate change. Blue carbon sinks, which encompass vegetated coastal habitats like seagrass meadows, salt marshes, and mangrove forests, rank among the most profound carbon sinks in the biosphere. Recently, these submerged ecosystems have gained much attention as these are among the most carbon-rich forests in the tropic (Duarte et al. 2005; Nellemann et al. 2009a, 2009b).

Mangroves are considered as potential sinks of atmospheric carbon having a significant role in the global carbon cycle (Matsui et al. 2010). Mangrove plants are highly productive (Alongi 2014), and it is estimated that the average annual carbon sequestration rate of mangrove ecosystems averages between 6 and 8 Mg CO_2 e/ha (tons of CO_2 equivalent per hectare) (Murray et al. 2011). These rates are approximately 2 to 4 times higher than global rates observed in mature tropical forests and are considered as one of the largest and productive pools of carbon (Nellemann et al. 2009a, 2009b). However, estimations from regional mangrove carbon sinks are limited due the geographical disparity in their carbon stocks (Kauffman et al. 2011). Currently, management of these carbon sinks are excluded from the international schemes for carbon payment and national carbon inventories and as such are not included in climate change policies.

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Mangrove cover of India is estimated as 4639 km^2, occupying 3% of the global mangroves (FAO 2007; Forest Survey of India 2009). The inventory of carbon stocks in mangrove ecosystems are scanty, and currently only a few studies have reported the ecosystem carbon stocks of these systems in India (Pandey and Pandey 2013; Sahu et al. 2016; Suresh et al. 2017). Kerala lies in the southwestern tip of peninsular India with a shoreline of 590 km and rich mangrove patches. The mangrove areas in Kerala have been dwindling widely in the past few decades from ~ 7000 ha in 1985 to ~ 1095 ha in 1994 and 2502 ha in 2014 (Basha 1991; Kurian 1994; Ramachandran et al. 1985; Vidyasagaran and Madhusoodanan 2014). Even though there were various attempts to estimate the mangrove cover of Kerala, the actual figure is still elusive and such limitations in data restrain insights and authentic evaluation of carbon stocks on a regional scale. The present study evaluated the ecosystem carbon stock and its spatial variation in the mangrove ecosystems of Kerala, India.

Materials and methods
Study area
The Kerala state is located in the southwest corner of India between 10° 51′ 1.8576″ N and 76° 16′ 15.8880″ E with a total area of 38,863 km^2. The region has a long coastal belt of 590 km with rich mangrove ecosystems as narrow strips along the coast. The study was conducted from April 2017 to March 2018. The area experiences a humid climate with annual average rainfall of 2664.9 mm. Recent estimations by the Indian Space Research Organization (ISRO) show the mangrove cover of Kerala state as 6.63 km^2 (SAC 2012). A stratified random sampling was used wherein the entire region was classified into three zones: northern zone (75.280091° to 75.284046° E and 12.020338° to 12.018587° N), central zone (76.062087° to 76.064901° E and 10.547201° to 10.546128° N), and southern zone (76.550405° to 76.560820° E and 8.937838° to 8.934120°N). These zones served as the main strata, and within each zone, substrata were established based on the canopy density classification scheme proposed by the Forest Survey of India (FSI 2013). Three levels of canopy density were considered for sampling using a spherical crown densitometer: (i) canopy density of above 70% (very dense), (ii) canopy density between 40 and 70% (moderately dense), and (iii) canopy density between 10 and 40% (open).

A total of 30 sampling plots (10 plots in each zone) of size of 10 m × 10 m was established for non-destructive determination of biomass and soil carbon stock as well as species composition. The total sampling area covered was 3 ha. According to Sujanapal et al. (2014), there are 18 mangrove species recorded from Kerala. The number of plots in each zone was fixed by plotting species–area curve and selecting the plots by random integer generator function in Microsoft Excel. To mark the exact location of each sampling site, a global positioning system, GPS (Garmin Etrex 10), was used and the spatial location of each quadrant was recorded (Fig. 1).

Aboveground and belowground biomass carbon stocks
All mangrove trees ≥ 10 cm in girth was measured at breast height (GBH, 1.37 m) to the nearest centimeter and identified to the species level. The diameter of the trees were calculated by dividing the girth by π (Brock et al. 2006). Allometric equations developed by Komiyama et al. (2005) for mangrove species in Southeast Asia were used for the estimation of aboveground biomass (W_{top}) and belowground biomass (W_R) as

$$W_{top} = 0.251\rho D^{2.46}$$

$$W_R = 0.199\rho^{0.899} D^{2.22}$$

where ρ is the wood density of the respective species. The wood density of different mangrove species was obtained from the World Agroforestry Database (Chave et al. 2009). The values of aboveground biomass and belowground biomass were summed to get the total biomass for all the plots, and this biomass value was averaged to get mean total biomass (tons/hectare). The carbon content was calculated by multiplying the individual tree biomass with the conversion factor 0.5 (IPCC 2006). Since understory vegetation (seedlings and herbs) is negligible in mangrove systems, they were not considered for ecosystem carbon stock estimations (Kauffman and Donato 2012; Vinod et al. 2018).

Soil sample collection
A PVC core having 60 cm length and 2 cm radius was used for the collection of soil samples from selected plots. The soil samples from were collected from two depths (0–30 cm and 30–60 cm) using the PVC core and stored in clean polythene bags. Bulk density was estimated from the core samples by dividing the dry weight (oven-dried at a temperature of 105 °C to a constant weight) of the soil sample by the volume of core. Simultaneously, bulk soil samples were also collected from each plot using (0–30 cm and 30–60 cm) a Eijkelkamp Dutch auger (Aryal et al. 2018; de Blécourt et al. 2013; Motsara and Roy 2008; Sheikh et al. 2009) for the estimation of organic carbon. It was air dried, powdered, and sieved (2 mm sieve) for further analysis. Three replications of the samples were collected in all cases. Care was taken to select only natural mangrove systems, and planted systems were avoided to minimize the bias that would have happened during selection of the species in planted mangrove systems.
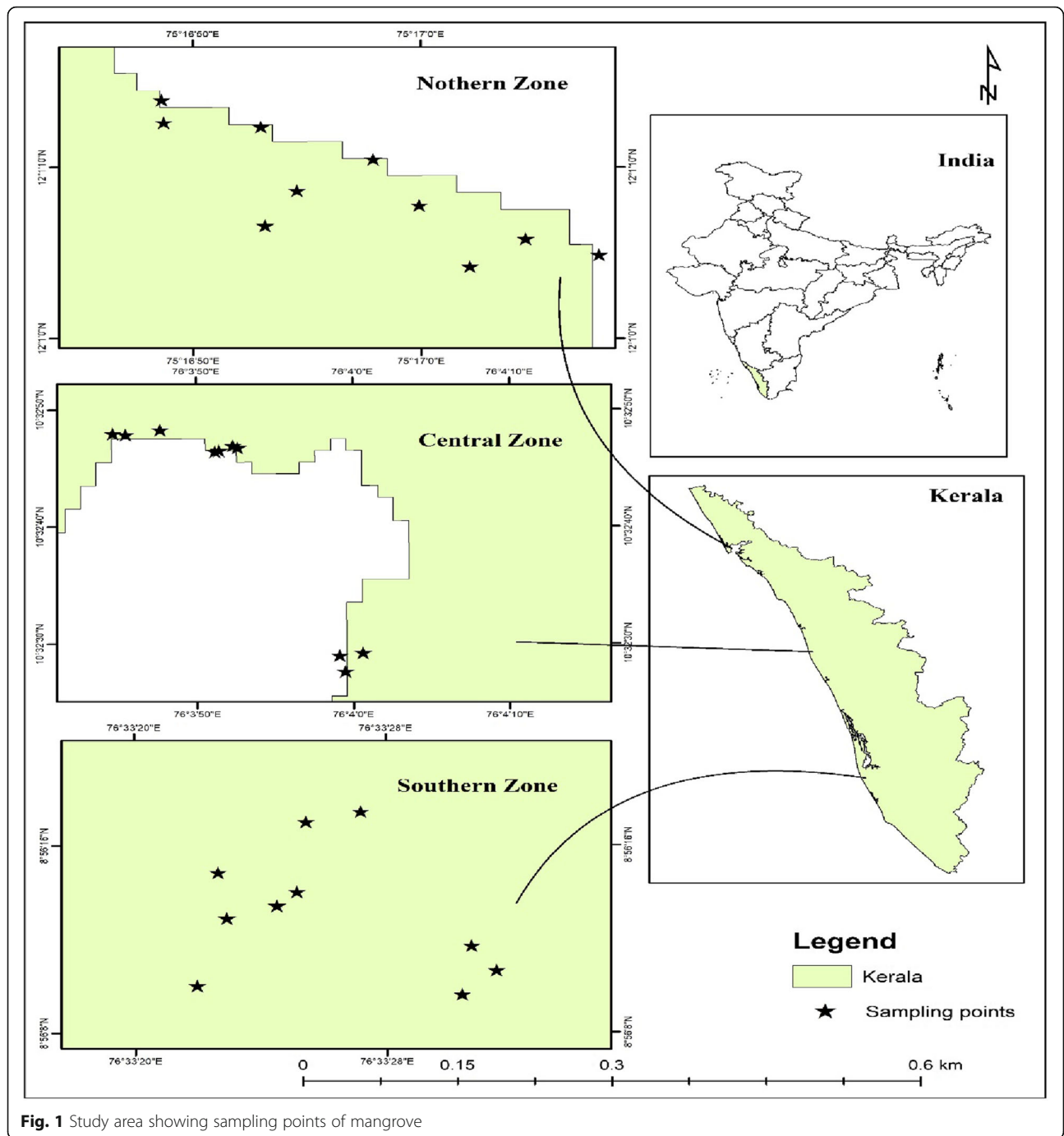
Fig. 1 Study area showing sampling points of mangrove

Soil analysis

Organic carbon in the samples were determined by sulfuric acid and potassium dichromate wet digestion method using ferroin as indicator (Walkley and Black 1934).

Soil carbon stocks

Soil carbon stocks (SCS) in each layer was determined as:

$$SCS \left(kg\, C/m^2 \right) = C \times T \times BD$$

where C is organic carbon concentration (%), T is the layer thickness (m), and BD is the bulk density (kg m^{-3}).

The total carbon stock was estimated as:

Total carbon stock (t/ha) = $C_{treeAGB} + C_{treeBGB} + C_{soil}$

This total carbon stock was converted into CO_2 equivalents by multiplying with the factor 3.67. The factor was derived as the ratio of molecular weight between

Results and discussion

Floristic composition

A total of 6 species, i.e., *Avicennia officinalis*, *Rhizophora mucronata*, *Avicennia marina*, *Bruguiera cylindrica*, *Rhizophora apiculata*, and *Sonneratia alba*, from 3 families and 4 genera were recorded from the selected zones. A total of 628 individuals over 10 cm GBH were enumerated from the 30 (10 × 10 m) plots in 3 zones. Among them, 36.62% were found to be of a single species, *A. marina*. *R. mucronata*, *A. officinalis*, and *B. cylindrica* were the other major species occupying 28.66%, 17.65%, and 15.76% respectively of the total species recorded from the region. The remaining 1.27% was collectively represented by *R. apiculata* and *S. alba* (Fig. 2). A study by Sujanapal et al. (2014) has reported 18 true mangrove species from Kerala. But the distribution of most of the species was limited to certain estuarine pockets indicating very less diversity for most of the species in the region. Usually, an increase in the number of the plant species is an index of ecosystem health in wetlands. But in the case of mangroves, their species distribution is restricted by competition, salinity, and other physical factors (Hogarth 2007).

Vegetation characteristics

Tree height and GBH in the 3 zones showed a significant variation among them with the values ranging from 1.35 to 16.5 m height with a mean height of 5.06 ± 0.11 m and GBH of 10 cm to 228 cm with a mean girth of 21.24 ± 0.70 cm. The maximum height (2.3 to 16.5 m) was observed in the mangrove systems of northern zone of Kerala and lowest in the southern zone (1.69 to 7.9 m). In central Kerala, the height of the mangrove trees was found to be similar to northern mangrove patches (1.35 to 15 m). Considering overall zone-wise mean height, the highest average height with 7.72 ± 1.6 m was recorded in northern patches followed by central and southern Kerala with an average height of 3.35 ± 0.11 m to 3.49 ± 0.06 m respectively (Table 1).

Among the 6 mangrove species generally found along the Kerala coast, *R. mucronata* was found to have the maximum GBH (girth at breast height) (25.74 ± 1.03 cm) and height (8.28 ± 0.18 m). Lowest height and GBH was recorded in *A. officinalis* (3.36 ± 0.22 m) and *B. cylindrica* (17.90 ± 1.10 cm) respectively (Table 2). Based on the overall GBH, height, and plant density from each zone, it could be concluded that the mangrove stands of northern Kerala seem to be older than central and southern patches (Table 1).

Biomass

The mean biomass of mangroves in Kerala was found to be 117.12 ± 1.02 t/ha (Table 4), and there were considerable variations in the biomass between different species (range 13.89–548 t/ha; SD = 121.24 t/ha). Comparing the biomass of the mangrove species in different regions of Kerala, the northern zone was found to have the maximum biomass with 246.56 t/ha with a recruit density of 2380 trees/ha. The lowest biomass was observed in central Kerala (48.55 t/ha) with a recruit density of 1690 trees/ha. The southern zone had a mean biomass of 56.25 t/ha with a recruit density of 2210 trees/ha. Earlier studies by Vinod et al. (2018) have reported 236.56 t/ha of biomass from Kadalundi mangroves (Northern Kerala) and 132.83 ± 97.5 t C/ha from the central zone (Suresh et al. 2017). Such mismatches in the biomass values indicated a very high variability across different patches in different zones.

The average aboveground biomass of the study area was estimated to be 80.23 ± 15.95 t/ha, and the average belowground biomass was 36.90 ± 6.23 t/ha. The results are similar to the reported aboveground biomass values from East Sumatra and Sri Lanka (Amarasinghe and
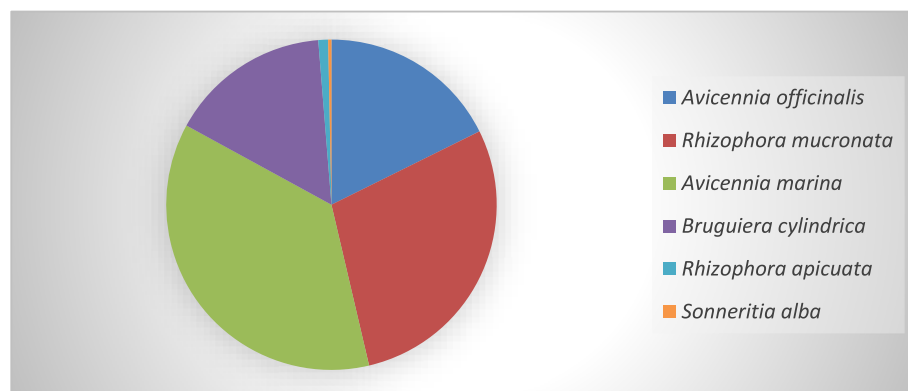

Fig. 2 Mangrove species density in the study area

Table 1 Zone-wise height and GBH

Zone	Height (m)	GBH (cm)	Tree density (per ha)
Northern zone	7.72 ± 0.17	30.34 ± 1.66	2380
Central zone	3.35 ± 0.11	15.74 ± 0.40	1690
Southern zone	3.49 ± 0.06	15.61 ± 0.28	2210

Table 3 Soil organic carbon stock in each zone

Zone	OC	BD	Depth	kg C/ha	Average kg C/ha
Central 1	2.43 ± 0.28	0.91	0–30	124.99	100.80 ± 14.81
	1.48 ± 0.31	1.32	30–60		
Central 2	2.55 ± 0.42	0.90	0–30	103.51	
	1.25 ± 0.10	0.93	30–60		
Central 3	1.70 ± 0.12	0.79	0–30	73.90	
	1.34 ± 0.13	0.84	30–60		
Northern 1	1.66 ± 0.35	1.17	0–30	104.02	90.96 ± 7.11
	1.31 ± 0.29	1.17	30–60		
Northern 2	1.54 ± 0.24	1.08	0–30	89.31	
	1.10 ± 0.24	1.20	30–60		
Northern 3	1.75 ± 0.21	0.88	0–30	79.54	
	1.20 ± 0.16	0.93	30–60		
Southern 1	1.24 ± 0.17	1.04	0–30	66.26	52.04 ± 8.55
	0.77 ± 0.13	1.21	30–60		
Southern 2	0.73 ± 0.16	0.95	0–30	53.13	
	0.94 ± 0.30	1.16	30–60		
Southern 3	0.88 ± 0.15	0.83	0–30	36.71	
	0.44 ± 0.04	1.13	30–60		

Balasubramaniam 1992; Kusmana et al. 1992). The range of overall aboveground biomass in the study plots (8.87–397.03 t/ha) was commensurate with what has been reported from Guadeloupe, Puerto Rico, Japan, Australia, Senegal, Thailand, Florida, and Sundarbans estuarine delta along the Bay of Bengal but lower than the studies conducted in Indonesia, Malaysia, Sri Lanka, Andaman Islands, and the Philippines.

The average biomass values reported from the mangroves in Kerala was greater than the values from the tropical dry forests of Kerala (Padmakumar et al. 2018). Komiyama et al. (2008) indicated that the biomass gradient in different mangrove zones will be influenced by the distance from the sea to the mangrove systems. Accordingly, the aboveground biomass values tend to be relatively low in the mangrove systems near the sea. In the present study, the northern zone mangroves are placed relatively farther from the sea when compared with the other two zones.

Among the different species, the highest biomass of 108.23 t/ha was recorded in *Avicennia marina* (above ground biomass = 82.22 ± 1.55 t/ha, root biomass = 25.99 ± 0.037 t/ha) located in the northern zone of Kerala and lowest biomass in *Sonneratia alba* having 0.61 t/ha in the southern zone. In northern region, biomass of other species such as *Avicennia officinalis*, *Bruguiera cylindrica* and *Rhizophora mucronata* were, 33.62 t/ha, 21.22 t/ha, 83.48 t /ha biomass respectively.

In the southern region, *Avicennia marina* was found to have 53.96 t/ha and was the highest reported biomass from the southern plots for a single species. In the central region, the maximum recorded biomass was 15.27 t/ha *for Avicennia officinalis*, and the minimum biomass was recorded from the southern region and central region in *Sonneratia alba* and *Bruguiera cylindrica* (0.04 t/ha and 9.72 t/ha respectively). The biomass recorded was specific for each species, which may be due to adaptabilities of these species to environmental variables. The accumulation of biomass is primarily influenced by species, age of tree, climate, management regime, proximity to water channel, and nutrient sediment that

supplement mangrove productivity (Kairo et al. 2008; Fatoyinbo et al. 2008).

The aboveground biomass (AGB) and belowground biomass (BGB) contributed 68.49% and 31.51%, respectively, to the total mangrove biomass, and this is almost equal to the mangrove systems in the oligohaline zones of Sundarbans, Bangladesh (Kamruzzaman 2017). The ratio of AGB to BGB was found to range from 1.5 to 2.6 with an average of 2.17 and was comparable with that of the mangroves in Mahanadi Delta, India, having an average of 2.3 (Sahu et al. 2016), and studies conducted in global scale (Komiyama et al. 2008). However, the biomass estimation from upland forests from different parts of the world has shown that the AGB to BGB ratio of mangrove forests was relatively lower than upland forests. The lower AGB to BGB ratio for mangroves indicates a large amount of biomass allocation in the belowground root system that can be considered a requisite adaptation for mangroves to stand firmly in muddy conditions.

Vegetation carbon stock

The average vegetation carbon stock of Kerala mangroves was found to be 58.56 ± 0.51 t C/ha (Table 4).

Table 2 Species-wise height and GBH

	Avicennia marina	Avicennia officinalis	Bruguiera cylindrica	Rhizophora apiculata	Rhizophora mucronata	Sonneratia alba
GBH (cm)	20.28 ± 1.46	19.35 ± 1.65	17.90 ± 1.10	16.52 ± 1.72	25.74 ± 1.03	19.68 ± 5.63
Height (m)	3.81 ± 0.11	3.36 ± 0.22	4.09 ± 0.13	4.04 ± 0.49	8.28 ± 0.18	5.05 ± 2.05

Species contribution of the different mangrove species to the average carbon stock was in the order of *A. marina* > *R. mucronata* > *A. officinalis* > *B. cylindrica* > *R. apiculata* > *S. alba* (Fig. 3).

The biomass carbon stock of the northern region of Kerala was estimated to be 123.28 ± 1.36 t C/ha and was found to be the most carbon-rich mangrove region indicating a positive correlation between tree density and biomass and carbon storage. According to Syamani and Susilawati (2012), the increase in biomass was mainly due to the photosynthetic activities resulting in horizontal and vertical growth. Chanan (2012) stated that each expansion of biomass substance will be trailed by increment in carbon stock.

In the southern region, the total carbon stock estimated was 28.13 ± 0.10 C/ha, and species such as *A. marina*, *R. apiculata*, and *S. alba* contributed 26.98 t C/ha, 0.85 t C/ha, and 0.31 t C/ha respectively to the total estimated stocks. The central zone was the least carbon-rich area with a total carbon stock of 24.28 ± 0.08 t C/ha. The contribution of species to the carbon stock in this region was in the order of *A. officinalis* > *B. cylindrica* > *R. mucronata*. The difference in the carbon stocks in the vegetation biomass of mangrove systems in different zones may be attributed to the structural peculiarities of the stands in each region (Kasawani et al. 2007).

Soil carbon stock

The general trend in soil bulk density and organic carbon in different mangrove zones is summarized in Table 3. The bulk density and organic carbon storage in the mangrove systems were found to be inversely correlated. The soil carbon content in the top 30 cm was comparatively higher than the lower layers. Soil organic carbon stored in the upper 60 cm depth of the mangrove sediment was estimated to be in the range of 36.71–124.99 t C/ha with an average soil carbon stock of 81.26 ± 10.16 t C/ha. It was comparable with that

of the studies in Bahamas, Saudi Arabia (Atwood et al. 2017) but lower than the values obtained by Micronesian mangroves (Kauffman et al. 2011) and higher than that of Mahanadi Mangrove Delta, India (Sahu et al. 2016). Among the different zones, the highest soil organic carbon (SOC) was recorded from the central zone (100.80 ± 14.81 t C/ha) of Kerala and lowest from southern zone (52.04 ± 8.55 t C/ha). Statistical analysis showed that the SOC of central and southern zone varied significantly ($F = 5.82$). Studies have showed that there can be significant variation in soil carbon stocks across different mangrove forests and sometimes with in the same mangrove forests (Adame et al. 2015; Jardine and Siikamäki 2014; Kauffman et al. 2011). The soil in the mangroves is considered as one of the major carbon pool (Donato et al., 2011, b; Kauffman et al. 2011), and it has been proven that sediment carbon stock accounts for 58% of total carbon stock in these systems.

It was observed that canopy cover had significant influence on soil carbon stocks. Accordingly, the central zone "1" (124.99 t C/ha), northern zone "1" (104.02 t C/ha), and southern zone "1" (66.26 t C/ha) had the highest soil carbon stock, and the lowest carbon stocks were found in the open category in each zone. The highest carbon stock recorded from the densely covered plots may be due to the higher litter production that was added to the soil as carbon input. The mangrove litter added to the soil could decompose and get incorporated in to the underlying mineral soil layer thereby affecting the soil carbon dynamics (Niu et al. 2019). The soil carbon in the upper layers contents are usually the most vulnerable owing to the direct interaction with atmosphere and erosional forces. The higher carbon contents in the mangrove systems compared to forest (55.40 t C/ha), rubber (43.73 t C/ha), home gardens (37.78 t C/ha), coconut (26.42 t C/ha), and rice paddy (17.74 t C/ha) indicated the higher potential of mangrove soils to act as a
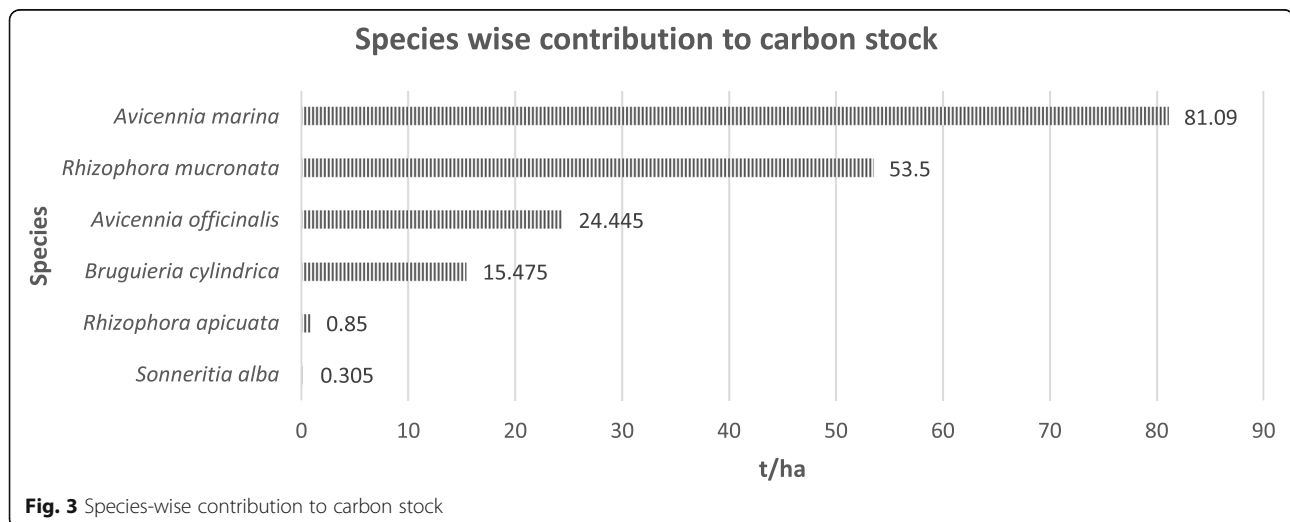
Fig. 3 Species-wise contribution to carbon stock

(Chart: Species wise contribution to carbon stock; t/ha on x-axis)

Species	t/ha
Avicennia marina	81.09
Rhizophora mucronata	53.5
Avicennia officinalis	24.445
Bruguieria cylindrica	15.475
Rhizophora apicuata	0.85
Sonneritia alba	0.305

Table 4 Zone wise Biomass, Vegetation carbon stock, Soil carbon stock, Ecosystem carbon stock, CO_2 equivalent

Zone	Biomass (t/ha)	Vegetation carbon stock (t C/ha)	Soil carbon stock (t C/ha)	Ecosystem carbon stock (t C/ha)	CO_2 equivalent (t CO_2/ha)
North	246.56 ± 2.71	123.28 ± 1.36	90.96 ± 7.11	214.24 ± 8.47	786.25
Central	48.55 ± 0.16	24.28 ± 0.08	100.80 ± 14.81	125.08± 14.90	459.03
South	56.25 ± 0.2	28.13 ± 0.10	52.04 ± 8.55	80.16 ± 8.65	294.19
Average	117.11 ± 1.02	58.56 ± 0.51	81.26 ± 10.16	139.82± 10.67	513.13

better carbon reservoir than other common land uses in the region (Saha et al. 2010).

Ecosystem carbon stock

The mean ecosystem carbon stock of Kerala was estimated to be 139.82 ± 10.67 t C/ha (Table 4). However, the ecosystem carbon values in the mangrove systems of Kerala was found to be much lesser than the 332–2205 t C/ha reported for natural and replanted mangroves in Southeast Asia (Alongi 2012) and the global mean carbon stocks in mangroves (885 t C/ha) reported by Kauffman and Bhomia (2017). The mean carbon stock of northern, central, and southern zones of mangrove were 214.24 ± 8.47 t C/ha, 125.08 ± 14.90 t C/ha, and 80.16 ± 8.65 t C/ha respectively. The mean C stock in the northern region was higher than that of the other two zones which may be due to the higher tree density, GBH, and height of mangroves in this zone. The distribution of carbon stock in mangroves was 42% and 58% in the vegetation and soil respectively. Studies have shown that soil organic carbon is the largest component of total carbon stock, especially in areas that have lost their natural vegetation or not naturally forested (Scharlemann et al. 2014). There exists a possibility of underestimating the SOC in the present study as carbon contents were estimated only up to 60 cm due to water level restricting sampling depth whereas in reality, it would extend up to several meters (Fujimoto 2004; Kauffman et al. 2011). The average estimated CO_2 equivalent of Kerala mangroves was 513.13 t CO_2/ha (Table 4). This value was interpreted as an indicative value rather than a prognosis and helps to highlight the importance of mangrove conservation and estimation of mangrove ecosystems in the world (Donato et al. 2011; Kauffman et al. 2014).

Conclusion

A comprehensive assessment of the C stocks in the mangrove systems of Kerala, southwestern tip of India, shows that this region has a capacity to sequester 139.82 t C/ha within this specific ecosystem. Among the different mangrove zones of Kerala, the northern part of Kerala was found to store relatively more carbon because of its higher tree density, soil carbon content, and biometric peculiarities (tree height and GBH). The allocation of C stock in the mangrove ecosystems of the region was 42% in vegetation and 58% in the soil pools. The findings of the present study add to the present knowledge gap in the ecosystem functioning dimensions of a major mangrove system in India and contribute to reliable and informed decision-making in their management.

Authors' contributions

Harishma K M designed and drafted the manuscript with the help of S Sandeep. V B Sreekumar contributed to the revision of the first draft. All authors have read and approved the final manuscript.

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