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Evaluation of biomass and carbon storage potential of a natural mangrove stand in Muzhappilangad, Kerala, southwest coast of India

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Original Article

Abstract

The present study was envisaged to assess the biomass and carbon stocks of a natural mangrove stand of Muzhappilangad wetland of Kerala, southwest coast of India. The carbon stocks of above-ground, below-ground (root) and sediment carbon pools were assessed to arrive at the total ecosystem carbon stock. The grey mangrove *Avicennia marina* was the predominant species which registered an average tree density of 1,592.31 individuals ha^{-1}. The overall mean above-ground biomass was 260.69 $\pm$ 151.76 t ha^{-1}, while the overall mean root biomass was 102.84 $\pm$ 53.84 t ha^{-1}. The estimated mean C-stocks were 130.34 $\pm$ 75.88, 51.42 $\pm$ 26.92 and 28.68 $\pm$ 10.14 ha^{-1} in the above-ground, root and sediment carbon pools respectively. The carbon stock in the above-ground biomass constituted 61.94%, while the root biomass and sediment constituted 24.43% and 13.63% of C-stock respectively. The total ecosystem carbon stock of Muzhappilangad wetland was 210.44 t C ha^{-1} which is equivalent to 772.32 t CO_2 ha^{-1}. The Muzhappilangad estuarine wetland has a mangrove cover of 8.9 ha and therefore it can be presumed that this small wetland along the southwest coast of India has the potential to sequester and store 1,872.92 t C, equivalent to an estimated 6,873.61 t CO_2.

Keywords: *Carbon sequestration, carbon stock, India, Kerala, mangroves, Muzhappilangad*

Introduction

The forests play a significant role in the global carbon cycle (Vashum and Jayakumar, 2012) as these ecosystems serve as huge receptacles for capture and storage of carbon. Thus conserving the existing forests and horizontal expansion of forest lands would be essential to reduce atmospheric carbon dioxide to a considerably low level. The United Nations Collaborative Programme on Reducing Emissions from Deforestation and forest Degradation (REDD)$^{+}$ insists countries to conserve and expand forest lands in order to reduce greenhouse gas emissions (Anonymous, 2020).

The mangroves are one of the important 'blue carbon ecosystems' as they are known to sequester and store large quantities of carbon in their biomass and sediments. These ecosystems store carbon to the tune of 84 to 233 Tg C yr^{-1} which is higher in comparison to an estimated 180.8 Tg C yr^{-1} uptake by terrestrial forests (Donato *et al.*, 2011; McLeod *et al.,* 2011). The mangroves are important coastal ecosystems that provide invaluable ecological goods and services that render both direct and indirect benefits to humans. Mangroves protect the coasts (Field, 1995) from the vagaries of cyclonic storms, waves and floods. They help in regulating water quality, nutrient cycling, and also support food web in the adjoining coastal ecosystems

(Robertson and Phillips, 1995; Rivera-Monroy *et al.*, 1999; Alongi *et al.*, 2000; Machiwa and Hallberg, 2002; Mumby *et al.*, 2004). Mangroves with their strong network of roots help to stabilize sediments and prevent soil erosion. The mangrove wetlands are storehouses of rich biological diversity, both flora and fauna. They serve as an important breeding and nursery grounds for many fishes and invertebrates, thereby support commercial coastal fisheries (Barbier, 2000; Diele *et al.*, 2005). The significance of mangroves in terms of their economic value have been highlighted by Costanza *et al.* (1998) who stated that the average economic value of mangroves is greater than that of the coral reefs, continental shelves and open sea while the estimated value of mangroves stand second when compared to estuaries and seagrass meadows. The mangrove forests also play an important role in climate change mitigation through capture and storage of carbon (Chen *et al.,* 2012; Kauffman and Donato, 2012; Murdiyarso *et al.,* 2009). Khan *et al.* (2007) and Donato *et al.* (2011) opined that the mangrove forests have the ability to sequester four times more carbon per unit area than the terrestrial forests of the tropics.

Globally, the mangroves are subjected to serious threats, mainly due to many anthropogenic activities and the rate of loss of mangrove cover globally is estimated to be approximately 1 to 2 per cent per year (Valiela *et al.,* 2001; Alongi, 2002; Duke *et al.*, 2007) and approximately 50% of the world's mangrove forests have disappeared in the past 50 years (Giri *et al.,* 2011). Consequently, the coastal ecosystems become more prone to cyclonic storms and erosion (Danielsen *et al.*, 2005, 2006; Das and Vincent, 2009; Kathiresan and Rajendran, 2005; Roy and Krishnan, 2005) and reduction in mangrove forest cover results in loss of potential carbon sinks. The destruction of mangroves and degradation of mangrove soils would result in the reintroduction of large quantities of carbon into the atmosphere which will exacerbate climate change.

The total mangrove cover in the world is 15 million ha (FAO, 2007), which is about 1% of the tropical forests of the world, and distributed in over 123 countries in the tropical and sub-tropical regions. Of the 4,975 sq. km. of mangrove forests in India, 29.66% are categorised as 'very dense', 29.73% as 'moderately dense' and 40.61% as 'open mangroves' (FSI, 2019), the net increase in mangrove cover was 54 sq.km. as compared to the 2017 assessment. Thus the mangrove cover of India which is 3.32% of the total mangrove area of the world is expected to sequester and store a substantial amount of carbon in its biomass and sediments. The Kerala state has been assessed to have 9 sq. km. of mangrove cover (FSI, 2019) of which a maximum area of 6.24 sq.km. lies in the Kannur district of the state. The present study was therefore aimed to estimate the biomass and carbon stocks in a natural mangrove stand of Muzhappilangad in the Kannur district of Kerala, south-west coast of India.

Material and methods

The Muzhappilangad mangrove stand lies very close to the Muzhappilangad drive-in beach in the Kannur district of Kerala. The area is connected to the sea through a narrow channel and the mangrove cover exists as a single large patch in an area of 8.9 ha (Fig. 1).

Fig. 1. Map of Muzhappilangad showing the study area

Field sampling

The study was conducted from April 2019 to December 2019 and a total of 13 sampling plots, each of 10m x 10m size were established. Non-destructive stratified random quadrat sampling technique was conducted to record the species composition of mangroves and to estimate the tree density, biomass and carbon stock. A total of 0.13 ha was covered in the study locale by way of placing the quadrats in 13 sampling plots. The geolocation of each of the sampling plots (Table.1) was recorded using a Global Positioning System (Garmin Montana 680).

Table 1. Geolocations of different stations of the study area at Muzhappilangad

Stations / Quadrats	GPS locations
1	11°47.010" N; 075°27.015" E
2	11°47.019" N 075°27.057" E
3	11°47.011" N 075°27.081" E
4	11°46.099" N 075°27.107" E
5	11°46.975" N; 075°27.150" E
6	11°46.966" N; 075°27.173" E
7	11°46.946" N;075°27.213" E
8	11°46.899" N;075°27.229" E
9	11°46.914" N; 075°27.200" E
10	11°46.930" N; 075°27.172" E
11	11°46.952" N; 075°27.137" E
12	11°46.984" N; 075°27.095" E
13	11°47.025" N; 075°27.036" E

Tree measurements

The tree girth of all the individual mangrove trees in each study quadrat was measured using a measuring tape. The breast height which is 1.3 m above the ground was considered to measure the girth of each individual tree in the quadrat, which was then converted to diameter at breast height (DBH) following the method as outlined in Frontier Madagascar (2005). The saplings and trees which were 1.3 m or more in their total height were measured for the DBH. In *Rhizophora mucronata*, the girth of the trunk at 1 feet above the highest stilt root was measured, which was considered as the DBH value for the individuals of this species (Komiyama *et al.*, 2005). The DBH of all the individual trees lying in the quadrat were measured to calculate the biomass.

The understory vegetation of seedlings and herbs as well as mangrove litter was not considered for ecosystem carbon pools, since it is negligible (Kauffman and Donato, 2012). The 'decay status categories' suggested by Kauffman and Donato (Kauffman and Donato, 2012) was considered for biomass estimation in dead mangrove trees present in the quadrats.

Biomass and carbon stock estimation

The carbon stored in the above-ground biomass, below-ground biomass (root) and sediment were estimated to arrive at the total ecosystem carbon stock. The allometric equations proposed by Komiyama *et al.* (2005) for mangroves of south-east Asia were used for the estimation of above-ground biomass stock (W_{top}) and below-ground biomass stock (W_R). The following are the allometric equations of the above and below-ground biomass:

$$W_{top} = 0.251\rho D^{2.46} \quad (1)$$
$$W_R = 0.199\rho^{0.899} D^{2.22} \quad (2)$$

Where W_{top}, W_R, ρ and D are designated for above-ground biomass (kg), below-ground/root biomass (kg), wood density of the respective species and Diameter at Breast Height respectively. The wood density of different mangrove species available in the World Agroforestry Database (World Agroforestry Centre, 2011) were used in the equation.

The sum of the above-ground and below-ground biomass obtained for all the quadrats were considered to arrive at the total biomass. The values were averaged to obtain the mean total biomass which is then converted to tonnes per hectare (t ha^{-1}). The biomass values were converted to carbon by applying a carbon fraction value of 50% (Komiyama *et al.*, 2005).

Sediment sampling and analysis

One metre long PVC sediment core sampler having an inner diameter of 4 cm was used to acquire the sediment samples from surface to a depth of 30 cm in each study quadrat. The collected sediment samples were analysed for the estimation of organic carbon following the method of Walkley and Black (1934) using the formula:

Sediment organic carbon (t ha^{-1}) = Bulk density (g cm^{-3}) x sediment depth (cm) x organic carbon (%)

Simultaneously, another set of sediment sample was collected from the same quadrat for the estimation of bulk density. These samples were oven-dried and the bulk density was calculated by dividing the dry weight of the sample by the volume of the core.

Results

Floristic composition

A total of four species of mangroves *viz.*, *Avicennia marina* (Family: Avicenniaceae), *Avicennia officinalis* (Family: Avicenniaceae), *Rhizophora mucronata* (Family: Rhizophoraceae), and *Bruguiera cylindrica* (Family: Rhizophoraceae) which belonged to 3 genera and 2 families were found distributed in the mangrove wetland of Muzhappilangad.

Mangrove tree density

Of the four species of mangroves, *A. marina* was the dominant one with an average tree density of 1,592.31 individuals ha^{-1}, followed by *A. officinalis* with an average tree density of 169.23 individuals ha^{-1} and *R. mucronata* with an average tree density of 53.85 individuals ha^{-1} (Table 2). The lowest tree density of 7.69 individuals ha^{-1} was recorded in *B. cylindrica* (*i.e.* only one individual was recorded in the quadrats laid, covering 0.13 ha).

Table 2. Tree density of different species of mangroves in Muzhappilangad wetland

Species	Tree Density (nos./ha)
Avicennia marina	1,592.31
Avicennia officinalis	169.23
Rhizophora mucronata	53.85
Bruguiera cylindrica	7.69

Diameter at Breast Height (DBH)

The average DBH was found to be the highest in *A. officinalis* (13.32 cm), followed by *A. marina* (11.90 cm) and *Rhizophora mucronata* (6.65 cm) (Fig. 2). As mentioned earlier, only one individual plant was recorded in the case of *Bruguiera cylindrica* in the quadrats studied which was less than 1 m in its total height, and therefore the DBH could not be measured.

Biomass and Carbon stock

Table 3 provides a summary of biomass and carbon stocks of mangroves in different quadrats of the study area at Muzhappilangad wetland. The above-ground biomass (AGB) ranged from 16.33 (quadrat 13) to 454.33 t ha^{-1} (quadrat 2), with an overall mean AGB value of 260.69±151.76 t ha^{-1},

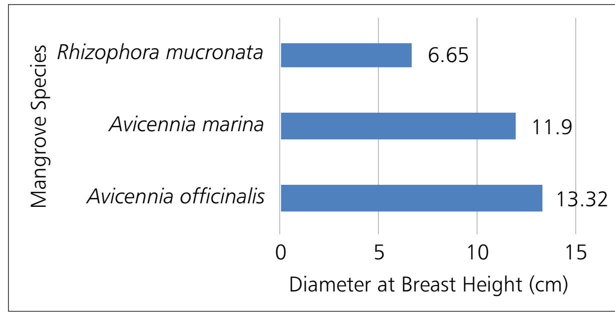

Fig. 2. Average DBH of different species of mangroves in Muzhappilangad wetland

while the above-ground carbon ranged from 9.00 (quadrat 13) to 250.40 t C ha^{-1} (quadrat 2), with an overall mean carbon value of 130.34±75.88 t C ha^{-1}. The values of below-ground biomass (root biomass) ranged from 9.04 to 190.35 t ha^{-1} while the carbon stock of root biomass ranged from 4.52 to 95.17 t C ha^{-1} in different quadrats. The overall mean root biomass was 102.84 ± 53.84 t ha^{-1}, while the overall mean below-ground carbon stock was 51.42 ± 26.92 t C ha^{-1}.

On the stand level, the mangroves of Muzhappilangad wetland had a total mean biomass of of 363.53 ± 205.51 t ha^{-1}, ranging from 27.05 to 691.15 t ha^{-1}. The C-stock of the total biomass

Table 3. Above-ground biomass, below-ground (root) biomass and carbon stocks of mangroves in different stations of the study area.

Stations/ Quadrats	Above-ground biomass (t ha^{-1})	Above-ground carbon stock (t C ha^{-1})	Below-ground biomass (t ha^{-1})	Below-ground carbon stock (t C ha^{-1})	Total biomass (t ha^{-1})	Total carbon stock (t C ha^{-1})
1	222.42	111.21	87.80	43.90	310.22	155.11
2	500.80	250.40	190.35	95.17	691.15	345.57
3	497.40	248.70	182.93	91.47	680.33	340.17
4	219.96	109.98	91.86	45.93	311.82	155.91
5	253.78	126.89	102.81	51.40	356.59	178.29
6	235.87	117.94	94.52	47.26	330.40	165.20
7	262.13	131.07	106.01	53.00	368.14	184.07
8	118.34	59.17	56.67	28.33	175.01	87.51
9	151.90	75.95	68.31	34.16	220.21	110.10
10	453.13	226.56	166.73	83.36	619.85	309.93
11	107.81	53.91	46.64	23.32	154.45	77.23
12	347.39	173.69	133.26	66.63	480.65	240.33
13	18.00	9.00	9.04	4.52	27.05	13.52
Total	3388.94	1694.47	1336.93	668.47	4725.87	2362.94
Overall Mean	260.69	130.34	102.84	51.42	363.53	181.76
S.D	151.76	75.88	53.84	26.92	205.51	102.76

ranged from 13.52 to 345.57 t C ha^{-1} with a mean C-stock value of 181.76 ± 102.76 t C ha^{-1}, which is equivalent to 49.62 to 1,268.24 t CO_2 ha^{-1}, with an average of 667.06 t CO_2 ha^{-1} sequestered and stored in the above-ground and below-ground biomass.

The ratio of above-ground and root biomass (referred to as T/R ratio) ranged from 1.99 to 2.63, with an average value of 2.53. The above-ground biomass constituted 71.71% of the total biomass of Muzhappilangad wetland, while the remaining 28.29% accounted for the roots.

Sediment Carbon stock

The sediment organic carbon pool and the bulk density in the upper 30 cm depth of the sediment in different study quadrats are depicted in Table 4. The percentage of organic carbon ranged from 2.34 to 6.40, with a mean value of 4.75%. The mean sediment bulk density was 0.64 g cm^{-3} with a range of 0.41 to 1.03 g cm^{-3}. The total organic carbon in sediment ranged from 12.02 to 41.74 t C ha^{-1} with a mean value of 28.68 ± 10.14 t C ha^{-1}.

Total Carbon stock

Of the three carbon pools, the above-ground C-stock was the highest (61.94%), followed by the carbon stock of root biomass (24.43%) and the sediment carbon stock (13.63%) (Fig. 3).

Table 4. Percentage organic carbon, soil bulk density and sediment organic carbon stocks of mangroves in different stations of the study area

Stations/ Quadrats	% Organic carbon	Soil bulk density (g/cm^3)	Sediment organic carbon (t/ha)
1	4.16	1.03	41.74
2	4.06	0.51	19.80
3	2.34	0.50	12.02
4	2.99	0.73	25.19
5	6.40	0.64	35.30
6	6.14	0.52	31.23
7	6.03	0.69	39.32
8	3.83	0.64	23.84
9	2.83	0.67	17.29
10	5.12	0.92	41.62
11	5.83	0.69	40.36
12	6.03	0.41	22.59
13	6.03	0.41	22.59
Mean	4.75	0.64	28.68
S.D.	1.45	0.18	10.14

The total ecosystem carbon stock of Muzhappilangad wetland showed that this mangrove wetland stored 210.44 t C ha^{-1} (above-ground 130.34 t C ha^{-1}, root 51.42 t C ha^{-1} and sediment 28.68 t C ha^{-1}), which was equivalent to 772.32 t CO_2 ha^{-1}(above-ground 478.35 t CO_2 ha^{-1}, root 188.71 t CO_2 ha^{-1}and sediment 105.26 t CO_2 ha^{-1}) (Fig. 4).,

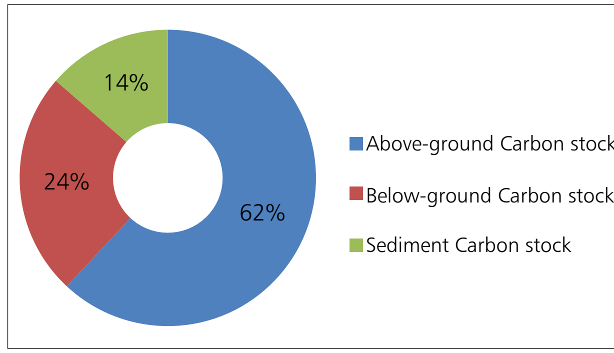

Fig. 3. Percentage contribution of above-ground, below-ground and sediment carbon stocks of mangrove ecosystem in Muzhappilangad wetland.

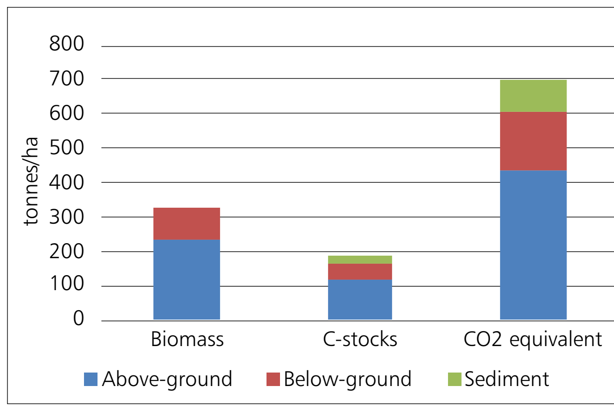

Fig. 4. Biomass, C-Stocks and carbon dioxide equivalent of mangroves in Muzhappilangad wetland.

Discussion

The present study in the Muzhappilangad estuarine wetland in the southwest coast of India have shown that *Avicennia marina* was the dominant species of mangrove and registered an average tree density of 1,592.31 individuals ha^{-1}. This species was also the dominant species in the Mahanadi wetland, east coast of India (Sahu *et al.*, 2016) with a tree density of 1,060 trees ha^{-1}. The tree density of *Avicennia officinalis* obtained in the present study was also higher when compared to the tree density of the same species in Mahanadi wetland reported by Sahu *et al.* (2016). In Thalassery estuary which lies in close proximity to Muzhappilangad, *A. officinalis* was the predominant species with a tree density of 729.37 individuals ha^{-1} followed by *A. marina* which recorded a tree density of 471.43 individuals ha^{-1} (Vinod *et al.*, 2019).

In the present study, the highest diameter at breast height (DBH) value was recorded in *A. officinalis* (13.32 cm) which was found to be high when compared to *A. marina.* (11.9 cm) which was the dominant species. The lowest DBH (6.65 cm) was noted for *Rhizophora mucronata*. When compared to the DBH values of *A. officinalis* and *A. marina* obtained during the present study with the values obtained by Sahu *et al.* (2016) in the Mahanadi estuary, the present values were found to be much lower. However, when compared to the DBH values obtained for *A. officinalis* (10.01 cm) and *R. mucronata* (5.61 cm) in Kadalundi mangrove wetland by Vinod *et al.* (2018) and for *A. officinalis* (9.86 cm) and *R. mucronata* (3.31 cm) in Thalassery estuarine wetland by Vinod *et al.* (2019) along the southwest coast of India, the present study registered higher DBH values for the same species. The higher DBH values indicate the presence of older trees in the ecosystem which are larger in size and contribute substantially to the biomass and carbon stocks.

The overall mean above-ground biomass estimated during the present study (260.69 t ha^{-1}) was found to be much higher than the values obtained by Golley *et al.*(1962) for the *Rhizophora mangle* forest of Puerto Rico which registered 62.9 t ha^{-1}, by Christensen (1978) for *Rhizophora apiculata* mangroves of Thailand (159 t ha^{-1}) and by Woodroffe (1985) for *A. marina* forests in New Zealand (104.1 t ha^{-1}). The estimated above-ground biomass value of the present study was also higher when compared to the value estimated by Loung *et al.* (2017) for the Can Gio mangrove forest of South Vietnam (179.52 Mg ha^{-1}). The present values were also higher compared to those obtained by Muhd-Ekhzarizal *et al.* (2018) for the mangroves of Kuala Sepetang (South) Forest Reserve, Malaysia (133.97Mg ha^{-1}) and by Dezhi Wanga *et al.* (2020) for the northeast Hainan Island mangrove (119.26 Mg ha^{-1}).

Mean above-ground biomass values lesser than the values estimated during the present study was obtained by Khan *et al.* (2009) for the mangrove forests of Manko wetland, Okinawa, Japan (80.5 t ha^{-1}) and Murdiyarso *et al.* (2009) for the North Sulawesi mangroves (61.4 t ha^{-1}). The values were also lesser (116.8 t ha^{-1}) in studies reported by Chandra *et al.* (2011) in the mangals of Sarawak, Malaysia, by Kathiresan *et al.* (2013) for the mangroves in the estuaries along the Bay of Bengal (60 to 117.7 t ha^{-1}), by Sahu *et al.* (2016) for the Mahanadi mangroves (124.91 t ha^{-1}), by Vinod *et al.* (2018) for the mangroves of Kadalundi wetland, India (166.63 t ha^{-1}) and Vinod *et al.* (2019) for the mangrove stands of Thalassery estuarine wetland, India (189.26 t ha^{-1}). However, the value obtained by Kauffman *et al.* (2011) for the Micronesian mangroves at Yap (363 t ha^{-1}) was higher than the mean above-ground biomass estimated during the present study.

Comparison of results of the mean above-ground biomass obtained in the present study with the findings obtained elsewhere within the country as well as across the world indicates that the above-ground biomass varies greatly from region to region. Lugo and Snedaker (1974), Woodroffe (1985) and Knox (1986) attributed several factors like species composition of mangroves, tree density, tree height, stem diameter, growth forms and age of the mangrove stands as responsible factors for the variation in above-ground biomass values. The mangrove stands of Muzhappilangad are well-established population of over four decades, predominantly with *A. marina* which has contributed significantly to the mean above-ground biomass.

The above-ground carbon pool obtained at Muzhappilangad wetland during the present study was 130.34 t C ha^{-1} which was higher than the values obtained for the mangroves of Palau (Kauffman *et al.*, 2011). The above-ground C-stock values obtained during the present study were also higher when compared to the studies of Chen *et al.* (2012) in the mangroves of southern China, Sahu *et al.* (2016) in the mangroves of Mahanadi estuary, Vinod *et al.* (2018) in the mangroves of Kadalundi estuarine wetland and Vinod *et al.* (2019) in the mangroves of Thalassery, India. However, the values obtained for above-ground C-stock by Kauffman *et al.* (2011) for the Micronesian mangroves at Yap was 169.2 t C ha^{-1} which was higher than the overall mean above-ground C-stock of 130.34 t C ha^{-1} estimated during the present study (Table 5).

The overall mean below-ground biomass / root biomass (102.84 t ha^{-1}) and root C-stock (51.42 t C ha^{-1}) obtained for the mangroves of Muzhappilangad during the present study were found to be lower when compared to the values obtained by Kauffman *et al.* (2011) for the mangroves at Yap, which registered root biomass value of 312 t ha^{-1} and C-stock value of 144 t C ha^{-1}. However, the root C-stock of the present study was higher when compared to the values obtained for the mangroves of southern China by Chen *et al.* (2012) who recorded 21.4 t C ha^{-1}, for the mangroves of Tamil Nadu, India by Kathiresan *et al.* (2013) who registered 12.9–18.1 t C $ha^{-1}$and for the mangroves of Mahanadi, India by Sahu *et al.* (2016) who estimated a value of 27.86 t C $ha^{-1}$and 26.69 t C $ha^{-1}$for planted and natural mangroves respectively. The root C-stock values obtained by Vinod *et al.* (2018) for Kadalundi mangrove wetland (34.96 t C ha^{-1}) and Vinod *et al.* (2019) for Thalassery mangroves, India (41.53 t C ha^{-1}) were also lower when compared to the present study.

The average ratio of the above-ground biomass and root biomass (T/R) obtained in the present study was 2.53. The T/R value is consistent with the values of Kauffman *et al.* (2011) for Micronesian mangrove forests (T/R ratio of 1.1 to 4.4). The

Table 5. Carbon stock values obtained for carbon pools in various studies.

Sl. No	Carbon pools	Values	Area of the study	Reference
1	Above ground biomass	104.4 t C ha^{-1}	Micronesian mangrove of Palau	Kauffman *et al.* (2011)
		169.2 t C ha^{-1}	Mangroves at Yap	Kauffman *et al.* (2011)
		94.63 t C ha^{-1}	Mangrove stands of Thalassery estuarine wetland, India	Vinod *et al.* (2019)
		62.45 t C ha^{-1}	Mahanadi mangroves , India	Sahu *et al.* (2016)
		55 t C ha^{-1}	Mangroves of Southern China	Chen *et al.* (2012)
		83.32 t C ha^{-1}	Kadalundi mangrove wetland, India.	Vinod *et al.* (2018)
		130.34 t C ha^{-1}	Muzhappilangad wetland	present study
2	Below ground C-stock	144 t C ha^{-1}	Mangroves at Yap	Kauffman *et al.* (2011)
		21.4 t C	Southern China	Chen *et al.* (2012)
		12.9–18.1 t C ha^{-1}	Mangroves of Tamil Nadu, India	Kathiresan *et al.* (2013)
		27.86 t C ha^{-1}	Mangroves of Mahanadi, India	Sahu *et al.* (2016)
		34.96 t C ha^{-1}	Kadalundi mangrove wetland, India.	Vinod *et al.* (2018)
		41.53 t C ha^{-1}	Mangrove stands of Thalassery estuarine wetland, India	Vinod *et al.* (2019)
		51.42 t C ha^{-1}	Muzhappilangad wetland	present study
3	Sediment carbon	57.3 t C ha^{-1}	Okinawa region of Japan	Khan *et al.* (2007).
		119.5 t C ha^{-1}.	Mangroves at Yap	Kauffman *et al.* (2011)
		57.6 t C ha^{-1}	Mahanadi wetland of India	Sahu *et al.* (2016)
		63.87 t C ha^{-1}	Kadalundi mangroves, India	Vinod *et al.* (2018)
		17.48 t C ha^{-1}	Mangrove of Thalassery estuarine wetland, India	Vinod *et al.* (2019)
		28.68 t C ha^{-1}	Muzhappilangad wetland, India	Present study

present value is also comparable with the results of Sahu *et al.* (2016) for Mahanadi mangrove wetland (2.3), Vinod *et al.* (2018) for Kadalundi mangroves (2.38) and Vinod *et al.* (2019) for Thalassery estuarine wetland (2.28). The T/R values of mangrove forests are generally lower when compared to the T/R values of terrestrial forests owing to the fact that a substantial amount of biomass gets allocated to the root system of mangroves which facilitate the mangrove trees to remain erect in soft and muddy conditions that prevail in the mangrove wetlands.

The average organic carbon in the sediment sample estimated during the present study was 28.68 t C ha^{-1} which was higher when compared to the value of sediment C-stock of Thalassery estuarine wetland of India (Vinod *et al.,* 2019). However, the Muzhappilangad sediment C-stock was much less compared to the sediment C-stock of mangroves in the Okinawa region of Japan (57.3 t C ha^{-1}) obtained by Khan *et al.* (2007). Similarly higher values of sediment C-stock was also obtained for Micronesian mangroves (Kauffman *et al.*, 2011). Sahu *et al.* (2016) obtained a higher sediment C-stock value in Mahanadi wetland of India (57.6 t C ha^{-1}) which was higher when compared to the sediment C-stock value obtained for the Muzhappilangad mangroves. Vinod *et al.* (2018) also reported higher value of sediment C-stock 63.87 t C ha^{-1} in Kadalundi mangroves, India (Table 5).

The C-stock of sediment in Muzhappilangad constituted 13.63% of the total carbon stock (above-ground carbon stock, below-ground carbon stock and sediment carbon stock), which was equivalent to 105.26 t CO_2 ha^{-1}. The present study fully agree with the fact that sediments in a mangrove ecosystem serve as an important carbon pool (Donato *et al.,* 2011; Kauffman *et al.*, 2011; Kauffman and Donato, 2012). The present study although indicative of the potential of mangrove sediments as a carbon reservoir, estimated the C-stock of only the upper 30 cm sediment strata. However, the estimation of carbon at different depths is imperative in view of the blue carbon trading (Nellemann *et al.*, 2009; Lawrence, 2012).

The mangrove forests of Muzhappilangad wetland cover an area of 8.9 hectares. Considering the estimated total C-stock of 210.44 t C ha^{-1}, it can be assumed that this wetland can sequester and store 1,872.92 t C, equivalent to an estimated 6,873.61 t CO_2. The social cost of carbon (SCC) per tonne of CO_2 is estimated to be US $ 220 (Moore and Diaz, 2015) which is equivalent to ₹14,250/- per tonne of CO_2. Thus the estimated SCC for Muzhappilangad is ₹97.95 million. With an estimated total ecosystem carbon stock of 210 t C ha^{-1} at Muzhappilangad, it can be assumed that the mangroves of the south Indian state of Kerala can sequester and store 189,000 t C which would be equivalent to 693,630 t CO_2.

The Muzhappilangad wetland is a pristine environment rendering many ecological services. Although, Muzhappilangad wetland has a mangrove cover of only 8.9 ha, the present study has clearly indicated that this wetland has the potential to sequester and store significant quantity of carbon. Thus it is important to protect and conserve this blue carbon ecosystem in the context of climate change mitigation.

Climate change has been a major concern across the globe and measures for mitigation of climate change is a major challenge faced by man during the last few decades. The enormous potential of mangroves to sequester and store carbon in their biomass and sediments, as evident from the present study as well as from the studies conducted elsewhere undoubtedly signifies the importance of mangrove ecosystems in mitigation of climate change. Mangroves, besides being large store houses of carbon, render numerous ecological services; yet they are fragile and vulnerable to natural and man-made disturbances. Conservation of existing mangroves and restoration of mangroves in degraded habitats is therefore an urgent need to harness the benefits of these blue carbon ecosystems.

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