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Biomass and carbon stocks in mangrove stands of Kadalundi estuarine wetland, south-west coast of India

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ABSTRACT

Mangroves are keystone ecosystems which provide numerous environmental services. Mangroves assume significance as standing stores of sequestered atmospheric carbon and are therefore, important in the light of climate change mitigation. In this study, we attempted to assess the biomass of mangroves in the Kadalundi wetland, south-west coast of India and evaluated the potential of these mangroves to sequester and store carbon. The C-stocks of above-ground and root biomass were 83.32±11.06 t C ha^{-1} and 34.96±4.30 t C ha^{-1} respectively, while the C-stock in sediment was estimated to be 63.87±8.67 t C ha^{-1}. The estimates of mean combined C-stocks in the mangrove biomass and sediment of Kadalundi shows that this estuarine mangrove wetland stored 182.15 t C ha^{-1}, which was equivalent to 668.48 t CO_2 ha^{-1}. The mangroves which cover an area of 13.23 ha in the Kadalundi wetland is assumed to have a potential to sequester and store a substantial quantity of 2,409.84 t C which is equivalent to 8,844.11 t CO_2. The study underscores the importance of these intertidal forests for climate change mitigation and stresses the importance of protecting the mangroves which provide many other important ecosystem services that benefit communities.

Keywords: Carbon sequestration, Carbon stocks, Mangroves, Tree biomass

Introduction

Mangroves are keystone ecosystems providing numerous environmental services and critical ecological functions. They thrive along the coastlines in most of the tropical and sub-tropical regions. These ecosystems are highly productive and rich in floral and faunal biodiversity. They are home to many aquatic species and it is well known that most of the commercially important fin and shellfish species spend at least part of their life cycle in these ecosystems which serve as an important breeding and nursery ground. Mangroves play an important role in supporting coastal food webs and nutrient cycles in the adjacent coastal ecosystems (Robertson and Phillips, 1995; Rivera-Monroy *et al*., 1999; Alongi *et al*., 2000; Machiwa and Hallberg, 2002; Mumby *et al*., 2004). These ecosystems contribute to coastal protection (Field, 1995), commercial fisheries (Barbier, 2000; Diele *et al.*, 2005) and are also highly valued for their aesthetics and ecotourism.

Worldwide, there is an increased awareness among the communities on climate change and its effects. In this context, the forests, including mangroves, assume immense significance as reservoirs of sequestered atmospheric carbon. Murdiyarso *et al*. (2009), Chen *et al*. (2012) and Kauffman and Donato (2012) have highlighted the potential role of mangroves in sequestering atmospheric carbon dioxide and to store the sequestered carbon in its biomass as well as in sediments.

The tropical forests are important component in the global carbon cycle and represent ~30-40% of the terrestrial net primary production (Malhi and Grace, 2000; Clark *et al*., 2001). Although only a mere 0.7% of tropical forests of the world is contributed by the mangrove forests (Giri *et al*., 2011), they have the potential to store up to 20 billion t C, which is much higher than the mean carbon stock in tropical upland, temperate and boreal forests (Donato *et al*., 2011). The mangrove forests also contribute remarkably to the carbon biogeochemistry in coastal oceans, by virtue of their exchange with coastal waters (Twilley *et al*., 1992). Thus, mangroves sequester four times more carbon per unit area than tropical terrestrial forests (Khan *et al*., 2007; Donato *et al*., 2011).

Although mangroves have enormous significance, they are one of the most threatened ecosystems, mainly due to human-induced pressures. The reduction in mangrove area leads to loss of potential carbon sinks.

Also, destruction of these habitats might lead to greater emissions of carbon dioxide back into the air and ocean, which may be much higher than it occurs from terrestrial habitats.

The mangrove carbon pools in the Indo-Pacific region are very high and are more than twice of those of most upland tropical and temperate forests (Kauffman and Donato, 2012). India has a total mangrove cover of 4627.63 sq. km (FSI, 2013) which is 0.15% of the country's land area and 3% of the global mangrove area (Sahu *et al*., 2016). Considering the potential and area of occurrence in India, substantial amounts of atmospheric carbon dioxide is expected to be sequestered and stored by the mangroves.

The mangroves of Kadalundi forms a part of the Kadalundi-Vallikunnu Community Reserve which is the first Community Reserve of Kerala, India, declared in 2007 and spread across 1.5 sq. km. The study aims to estimate the above-ground and root biomass and C-stocks to understand the blue carbon potential of the mangroves of the Kadalundi wetland in the south-west coast of India.

Materials and methods

The Kadalundi mangrove wetland comprises five small islands, of which mangrove vegetations are present in four. Hence, the study zone was divided into four sectors, namely, i) Sector I: Balathuruthi I, Sector II: Balathuruthi II, Sector III: Mannanthuruthi and Sector IV: Western side of the railway bridge; all of these sectors have sparse to dense mangrove vegetation (Fig. 1).

Field sampling

The study was conducted from April 2016 to January 2017. A total of 24 sampling plots (4 in sector I, 5 in sector II, 11 in sector III and 4 in sector IV) each of 10 m x 10 m size were established through a non-destructive stratified random quadrat sampling technique to determine the composition of mangroves, tree density and carbon stock. The total sampling area covered was 0.24 ha. To mark the exact location of each sampling site, a Global Positioning System, GPS (Garmin GPSmap 76CSx) was used and the spatial location of each quadrat was recorded (Table 1).

Tree measurements

All the mangrove plants/trees of each study quadrat were measured for their tree girth. The tree girth measurements were taken at breast height, which is approximately 1.3 m above the ground; and the girth measurements were converted into diameter at breast height (DBH) measurement by dividing by π (Frontier Madagascar, 2005). All adult trees as well as saplings greater than 1.3 m height were considered for measurement of DBH (Fig. 2a). The plants were classified as adults, saplings and seedlings depending on their total height and girth at breast height. The plants greater than 4 cm girth at breast height and taller than 1 m were classified as adults. The plants lesser than 4 cm girth at breast height but taller than 1 m were classified as saplings while the plants less than 1 m tall were classified as seedlings (Frontier Madagascar, 2005). In the case of *Rhizophora mucronata*,

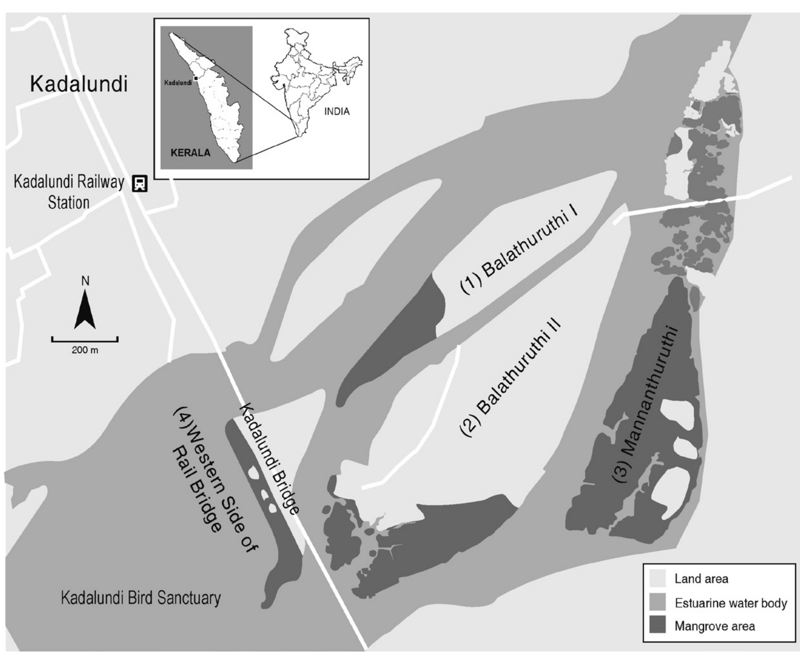

Fig. 1. Map of Kadalundi Estuary showing the study area

Table 1. Study stations and their geo-spatial locations

Sectors	Stations/ Quadrats	GPS locations
Sector I Balathuruthi-I	1	11°07'52.86"N; 75°50'2.28"E
	2	11°07'52.20"N; 75°50'0.84"E
	3	11°07'51.42"N; 75°49'58.80"E
	4	11°07'50.64"N; 75°49'59.52"E
Sector II Balathuruthi-II	1	11°07'38.70"N; 75°50'2.22"E
	2	11°07'40.86"N; 75°50'4.50"E
	3	11°07'39.48"N; 75°49'56.88"E
	4	11°07'36.78"N; 75°49'58.80"E
	5	11°07'39.30"N; 75°49'57.90"E
Sector III Mannanthuruthi	1	11°07'39.66"N; 75°50'13.32"E
	2	11°07'39.48"N; 75°50'14.10"E
	3	11°07'41.52"N; 75°50'13.98"E
	4	11°07'44.64"N; 75°50'15.60"E
	5	11°07'44.04"N; 75°50'17.10"E
	6	11°07'46.98"N; 75°50'17.34"E
	7	11°07'39.18"N; 75°50'16.86"E
	8	11°07'53.52"N; 75°50'21.42"E
	9	11°07'48.90"N; 75°50'22.08"E
	10	11°07'39.12"N; 75°50'19.44"E
	11	11°07'45.36"N; 75°50'21.06"E
Sector IV Western side of railway bridge	1	11°07'46.74"N; 75°49'49.50"E
	2	11°07'45.18"N; 75°49'50.28"E
	3	11°07'39.42"N; 75°49'52.62"E
	4	11°07'38.64"N; 75°49'52.74"E

(*e.g.* seedlings and herbs) is generally negligible in mangroves and its measurement for ecosystem carbon pools need not be considered (Kauffman and Donato, 2012). Also, litter being a small component of the total ecosystem, carbon stock is not usually sampled (Kauffman and Donato, 2012). All the dead trees were also taken into consideration and the biomass of standing dead trees were estimated based on the decay status categories following the methods suggested by Kauffman and Donato (2012).

Estimation of biomass and carbon stock

Three pools of carbon were taken into consideration for the measurement of carbon stored in mangrove ecosystem *viz*., i) above-ground biomass, ii) below-ground biomass (root) and iii) sediment. The allometric equations developed by Komiyama *et al.* (2005) for mangroves of south-east Asia were used for the estimation of above-ground biomass (W_{top}) and below-ground biomass (W_R). The allometric equations are:

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

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

where W_{top} is the above-ground biomass (kg), W_R is the below-ground biomass (root), ρ is the wood density of the respective species and D is the diameter at breast height (DBH).

(a)

(b)

Fig. 2. DBH measurements of (a) *Avicennia officinalis* - 1.3 m from the ground and (b) *Rhizophora mucronata* - 30 cm above the highest prop root

which is characterised by the presence of prop roots, the trunk diameter at 30 cm above the highest prop root was measured (Komiyama *et al*., 2005) (Fig. 2b).

All the adult trees lying in each quadrat were considered for measurement of above and below ground biomass as well as carbon stock. The understory vegetation

The wood density of different mangrove species was obtained from the World Agroforestry Database (WFC, 2011).

The value of above-ground and below-ground biomass was summed up to get the total biomass for all the plots which were then averaged to get the mean total biomass and finally converted to tons per hectare. The carbon values were estimated as 50% of the biomass (Komiyama *et al*., 2005).

Soil sampling and analysis

The soil samples were collected from each quadrat using a PVC core having a length of 1 m and radius of 2 cm. The soil samples from surface to 30 cm depth were collected from each core sampling and stored in clean polythene bags for the estimation of organic carbon. Simultaneously, another set of core sample was collected from the same plot for estimating the sediment bulk density. The bulk density was calculated using dry weight (oven-dried) of the core sample divided by the volume of core. The organic carbon in soil samples were estimated following the method of Walkley and Black (1934). The soil organic carbon per hectare was determined using the formula:

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

Results

Floristic composition

A total of six species of mangroves *viz*., *Avicennia officinalis* (Family: Avicenniaceae), *Rhizophora mucronata* (Family: Rhizophoraceae), *Sonneratia alba* (Family: Lythraceae), *Bruguiera cylindrica* (Family: Rhizophoraceae), *Excoecaria agallocha* (Family: Euphorbiaceae) and *Acanthus ilicifolius* (Family: Acanthaceae) which belonged to 6 genera and 5 families were recorded from the Kadalundi mangrove wetland. The composition of mangrove species in different sectors of the study area is given in Table 2.

Fig. 3. Dominant *Avicennia officinalis* in Kadalundi mangrove wetland

Sector I, Balathuruthi-I: is a small island with patchy to dense mangroves dominated by *A. officinalis* and fringed by *A. ilicifolius* in the peripheral region. This island has mangrove vegetation in 1.59 ha and the rest of the area has coconut plantations and residential houses. The mangroves were also found to extend towards some of the coconut planted areas.

Sector II, Balathuruthi-II: The total mangrove area of Balathuruthi-II is 3.22 ha with *A. officinalis* being the predominant mangrove species. This sector was characterised by a dense patch of *R. mucronata* along the western side (Fig. 4). This island has maximum number of inhabitants with over one hundred houses spread from the mid to the eastern part of the island.

Table 2. Floristic composition of mangroves in different sectors of the study area

Species	Sectors			
	Sector I	Sector II	Sector III	Sector IV
	Balathuruthi I	Balathuruthi II	Mannanthuruthi	West of the railway bridge
Avicennia officinalis	√	√	√	√
Rhizophora mucronata	x	√	√	√
Bruguiera cylindrica	√	x	√	x
Sonneratia alba	x	x	x	√
Excoecaria agallocha	x	x	√	√
Acanthus ilicifolius	√	√	√	√

√ - Present; x - Absent

Among the six species, *A. officinalis* was the predominant species in terms of number as well as in terms of coverage of area (Fig. 3). *S. alba,* which is a planted vegetation, formed only a small patch near the railway bridge (sector IV). *A. ilicifolius* formed a fringe in some islands, but also formed dense patches in other areas. *B. cylindrica* and *E. agallocha* occurred in less numbers and in small areas in the entire Kadalundi mangrove ecosystem.

Sector III, Mannanthuruthi: This island is the largest with an approximate mangrove area of 7.39 ha. Except for *S. alba,* all other mangrove species recorded in the Kadalundi mangrove wetland during the present study were found in this sector. However, the dominant species of this sector was *A. officinalis*. There were three small patches of coconut plantations; however, there are no inhabitants in Mannanthuruthi.

Fig. 4. Dense patch of *Rhizophora mucronata* in Balathuruthi Island

Sector IV, Western side of Railway Bridge: Patchy to dense mangroves occur in this small area of 1.03 ha which lies very close to the estuarine bar mouth. The mangrove *A. officinalis* occupied about 50% of the area and the remaining 50% comprised of *S. alba* of different sizes. In this sector, *A. officinalis* is a natural mangrove while *S. alba* is a planted one and in between, *A. ilicifolius* is also found.

Tree density and diameter at breast height (DBH)

A total of 694 individual stems (662 live and 32 dead) were recorded and studied from 0.24 ha of sampling area. In the case of *A. officinalis*, the average tree density was the highest (1300 individuals ha^{-1}). The density of *R. mucronata* and *B. cylindrica* were 220 and 270 individuals ha^{-1}, respectively, while that of *S. alba* was 146 individuals ha^{-1}. *E. agallocha* showed the lowest density of 42 individuals ha^{-1} (Fig. 5).

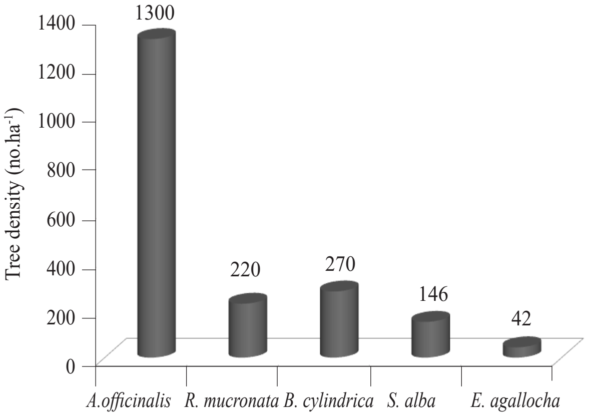

Fig. 5. Mangrove tree density in the Kadalundi Estuary

DBH of different mangrove species ranged from 3.89±2.26 (*B. cylindrica*) to 10.01±7.07 cm (*A. officinalis*). DBH of *E. agallocha* was 6.09±5.14 cm, while that of *R. mucronata* and *S. alba* were 5.61±2.15 and 4.59±2.15 cm respectively (Fig. 6).

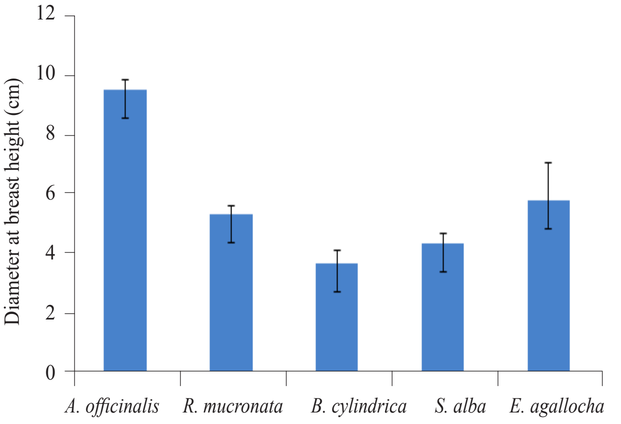

Fig. 6. Average diameter at breast height (DBH) of different mangrove species in the Kadalundi Estuary (Vertical bars denote SE)

Biomass and C-stock

Table 3 shows species-wise comparison of the mean above ground biomass (AGB), root biomass and the total biomass. The highest biomass of 196.48±31.69 t ha^{-1} (AGB of 140.05±23.25 t ha^{-1} and root biomass of 56.43±8.51 t ha^{-1}) was recorded in *A. officinalis*, being the dominant species of the Kadalundi mangrove wetland, while the lowest biomass of 1.67±1.10 t ha^{-1} was recorded in *B. cylindrica*.

Among the Kadalundi mangroves, the species that contributed most to the total carbon was *A. officinalis* (98.24±15.85 t ha^{-1}), followed by *R. mucronata* (17.01 t ha^{-1}). The total carbon share of *S. alba* (1.21±0.86 t ha^{-1}), *E. agallocha* (0.98±0.72 t ha^{-1}) and *B. cylindrica* (0.84±0.55 t ha^{-1}) were less due to their sparse distribution and less density in Kadalundi (Table 4).

Table 5 provides the summary of biomass and carbon stocks of mangroves in different sectors of the study area at Kadalundi. The AGB ranged from 89.39 (sector IV) to 283.15 t ha^{-1} (sector I), with an overall mean AGB value of 166.63 t ha^{-1}, while the above-ground carbon ranged from 44.69 (sector IV) to 141.58 t C ha^{-1} (sector I), with an overall mean carbon value of 83.32 t C ha^{-1}. The range in estimates of mean root biomass was 37.21±18.28 t ha^{-1} (sector IV) to 105.66±20.53 t ha^{-1} (sector I) and the C-stock of root biomass ranged from 18.60±9.14 t C ha^{-1} to 52.83±10.26 t C ha^{-1} in different sectors of the study area. The overall mean root biomass was 69.92±8.61 t ha^{-1}, with a carbon stock of 34.96±4.30 t C ha^{-1}.

On the stand level, the Kadalundi mangroves has a total mean biomass of 236.56 t ha^{-1} ranging from 126.59 to 388.81 t ha^{-1}. The total biomass C-stock varied from 63.30 to 194.41 t C ha^{-1} with a mean of 118.28 t C ha^{-1}. This was equivalent to 232.31 to 713.48 t CO_2 ha^{-1} with an average of 434.09 t CO_2 ha^{-1} which was sequestered and

Table 3. Biomass of different mangrove species of Kadalundi wetland (overall mean of stations with standard error)

Species	Biomass (t ha^{-1})		
	Above Ground Biomass	Root Biomass	Total Biomass
Avicennia officinalis	140.05 ±23.25	56.43 ± 8.51	196.48 ± 31.69
Rhizophora mucronata	22.59 ± 15.91	11.44 ± 8.01	34.03 ± 23.92
Bruguiera cylindrica	1.08 ± 0.70	0.59 ± 0.40	1.67 ± 1.10
Sonneratia alba	1.58 ± 1.12	0.85 ± 0.60	2.43 ± 1.72
Excoecaria agallocha	1.34 ± 1.01	0.62 ± 0.44	1.96 ± 1.45

Table 4. Carbon stock of different mangrove species of Kadalundi wetland (overall mean of stations with standard error)

Species	Carbon (t ha^{-1})		
	Above Ground Carbon	Root Biomass Carbon	Total Carbon
Avicennia officinalis	70.02±11.62	28.22 ±4.26	98.24 ±15.85
Rhizophora mucronata	11.29 ±7.95	5.72 ±4.01	17.01 ±11.96
Bruguiera cylindrica	0.54 ±0.35	0.30 ±0.20	0.84 ±0.55
Sonneratia alba	0.79±0.56	0.42 ±0.30	1.21 ± 0.86
Excoecaria agallocha	0.67 ±0.50	0.31 ±0.22	0.98 ±0.72

stored in the above ground and root biomass. The ratio of above-ground biomass and root biomass (referred to as T/R ratio) ranged from 2.22 to 2.68, with an average value of 2.38. In the case of the Kadalundi mangrove wetland, the above-ground biomass constituted 70.44% of the total biomass while the remaining 29.56% accounted for the roots.

Sediment C-stock

Table 6 summarises the sediment bulk density and the organic carbon pool in the upper 30 cm depth of the mangrove sediment in different study stations. The mean percentage organic carbon obtained in the present study was 2.62 (range of 1.74 to 3.31%). The total soil organic carbon ranged from 40.13±12.31 to 76.37±6.50 t C ha^{-1}.

Total C-stock

The estimates of mean combined C-stocks in the mangrove biomass and sediment of Kadalundi showed that this estuarine mangrove wetland stored 182.15 t C ha^{-1} (above ground 83.32 t C ha^{-1}, root 34.96 t C ha^{-1} and sediment 63.87 t C ha^{-1}), which was equivalent to 668.48 t CO_2 ha^{-1} (above-ground 305.78 t CO_2 ha^{-1}, root 128.30 t CO_2 ha^{-1} and sediment 234.40 t CO_2 ha^{-1}) (Fig. 7). Of the three carbon pools, the above-ground C-stock was the highest (45.74%), followed by the carbon stock of sediment (35.06%) and the carbon stock of root biomass (19.20%).

Discussion

Avicennia officinalis was the dominant mangrove species in Kadalundi wetland; the average tree density (1300 individuals ha^{-1}) and the DBH (10.01±7.07 cm) values were also the highest in this species. When we compare the DBH

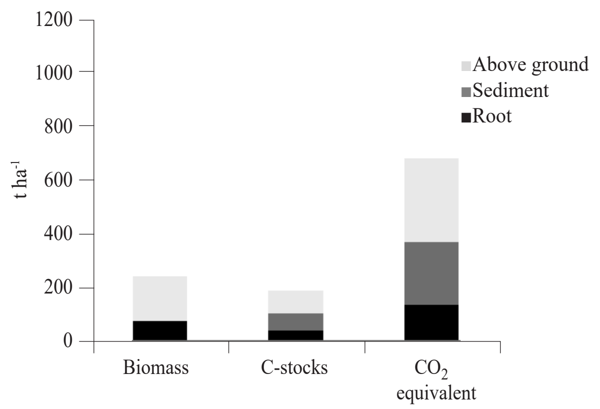

Fig. 7. Biomass, C-stocks and CO_2 equivalent potential of the Kadalundi mangrove wetland

values obtained by Sahu *et al*. (2016) for *A. officinalis*, *B. cylindrica* and *E. agallocha* in the Mahanadi mangrove wetland along the east coast of India, our values for the same species were found to be much less. The higher above ground biomass (140.05±23.25 t ha^{-1}) and root biomass (56.43±8.51 t ha^{-1}) obtained in *A. officinalis* can also be attributed to the dense stem density when compared to other species recorded in the study area.

The overall mean AGB recorded during the study (166.63 t ha^{-1}) was much higher than that of the values obtained for the *Rhizophora mangle* forest of Puerto Rico (62.9 t ha^{-1}, Golley *et al*., 1962), the forests of *Avicennia marina* var. *resinifera* in a flooded explosion crater in New Zealand (taller mangroves 104.1 t ha^{-1}, low stunted mangroves 6.8 t ha^{-1}; Woodroffe, 1985), the Manko Wetland, Okinawa, Japan (80.5 t ha^{-1}, Khan *et al*., 2009), North Sulawesi (61.4 t ha^{-1}, Murdiyarso *et al.*, 2009), the Sarawak Mangrove

Table 5. Biomass and carbon stock of mangroves in different study stations along the Kadalundi Estuary

Sectors	Stations	Above ground		Below ground (Root)		Total	
		Biomass (t ha^{-1})	Carbon (t ha^{-1})	Biomass (t ha^{-1})	Carbon (t ha^{-1})	Biomass (t ha^{-1})	Carbon (t ha^{-1})
Balathuruthi I	1	378.31	189.16	141.34	70.67	519.65	259.83
	2	425.35	212.68	141.06	70.53	566.41	283.21
	3	165.97	82.99	71.92	35.96	237.90	118.95
	4	162.97	81.49	68.33	34.17	231.30	115.65
Mean		283.15	141.58	105.66	52.83	388.81	194.41
SE		69.19	34.60	20.53	10.26	89.56	44.78
Balathuruthi II	1	212.84	106.42	91.84	45.92	304.67	152.34
	2	192.35	96.18	74.87	37.44	267.23	133.61
	3	344.46	172.23	173.02	86.51	517.48	258.74
	4	237.84	118.92	94.84	47.42	332.67	166.34
	5	181.82	90.91	92.51	46.26	274.33	137.17
Mean		233.86	116.93	105.42	52.71	339.28	169.64
SE		29.26	14.63	17.27	8.64	46.05	23.02
Mannanthuruthi	1	162.45	81.22	64.72	32.36	227.17	113.58
	2	20.82	10.41	10.22	5.11	31.05	15.52
	3	82.05	41.02	36.70	18.35	118.75	59.38
	4	124.01	62.00	53.94	26.97	177.95	88.97
	5	37.09	18.55	20.09	10.04	57.18	28.59
	6	116.35	58.17	53.66	26.83	170.01	85.00
	7	102.09	51.05	50.46	25.23	152.55	76.28
	8	257.76	128.88	104.24	52.12	361.99	180.99
	9	194.44	97.22	81.63	40.82	276.08	138.04
	10	99.01	49.51	44.38	22.19	143.40	71.70
	11	143.64	71.82	59.59	29.79	203.23	101.61
Mean		121.79	60.90	52.69	26.35	174.49	87.24
SE		20.40	10.20	7.91	3.96	28.29	14.14
West of railway bridge	1	97.87	48.93	39.10	19.55	136.97	68.48
	2	220.02	110.01	88.23	44.12	308.25	154.12
	3	23.34	11.68	12.22	6.11	35.58	17.79
	4	16.31	8.15	9.27	4.64	25.58	12.79
Mean		89.39	44.69	37.21	18.60	126.59	63.30
Standard error		47.29	23.64	18.28	9.14	65.57	32.78
Overall mean		166.63	83.32	69.92	34.96	236.56	118.28
Standard error		22.12	11.06	8.61	4.30	30.53	15.26

Forest, Malaysia (116.8 t ha^{-1}, Chandra *et al.,* 2011) and the estuarine complex along the Bay of Bengal, India (60 to 117.7 t ha^{-1}, Kathiresan *et al.,* 2013). The present AGB values were almost comparable with the mean AGB values obtained for *Rhizophora apiculata* mangroves in Thailand (159 t ha^{-1}, Christisen, 1978) and for the mangrove forests of Mahanadi Mangrove Wetland, India (natural mangrove stands 124.91 t ha^{-1}, plantation mangrove stands 125.55 t ha^{-1}; Sahu *et al.*, 2016). The findings in the Kadalundi wetland was lower than the above-ground biomass obtained for the Micronesian mangroves (363 t ha^{-1} at Yap, 225 t ha^{-1} at Palau; Kauffman *et al.*, 2011). While comparing the results of the Kadalundi wetland with other mangrove areas, it is evident that the above-ground biomass varies greatly from region to region. The biomass is determined by various factors such as species composition, tree density, growth forms, tree height, stem diameter and age of the mangrove stands (Lugo and Snedaker, 1974; Woodroffe, 1985; Knox, 1986). The mangrove stands of Kadalundi has well established 30 to 40 year-old predominant population of *A. officinalis* which has contributed significantly to the mean above-ground biomass of 166.63 t ha^{-1}.

Table 6. Soil organic carbon pools of the Kadalundi mangrove wetland

Sectors	Stations	Bulk density (g cm^{-3})	Percentage sediment organic Carbon	Sediment organic Carbon (t ha^{-1})
Balathuruthi I	1	0.75	2.90	65.25
	2	1.19	0.57	20.35
	3	0.59	1.00	17.70
	4	0.60	3.18	57.24
Mean		0.78	1.91	40.13
SE		0.14	0.66	12.31
Balathuruthi II	1	0.65	4.32	84.24
	2	0.85	3.84	97.92
	3	0.69	3.26	67.48
	4	0.96	2.43	69.98
	5	0.76	2.73	62.24
Mean		0.78	3.31	76.37
SEE		0.06	0.35	6.50
Mannanthuruthi	1	0.90	1.52	41.04
	2	1.20	2.19	78.84
	3	0.52	4.06	63.34
	4	1.00	1.22	36.60
	5	0.83	2.86	71.21
	6	0.73	2.64	57.82
	7	0.75	3.37	75.83
	8	0.69	4.03	83.42
	9	0.84	3.03	76.36
	10	1.03	2.98	92.08
	11	1.08	3.78	122.47
Mean		0.87	2.88	72.64
SE		0.06	0.29	7.16
West of railway bridge	1	1.01	2.18	66.05
	2	1.14	2.61	89.26
	3	1.45	1.08	46.98
	4	1.91	1.10	63.03
Mean		1.38	1.74	66.33
SE		0.20	0.39	8.71
Overall Mean		0.95	2.62	63.87
SE		0.12	0.22	8.67

The carbon pools of AGB estimated by Kauffman *et al.* (2011) in the Micronesian mangrove forests (104.4 t ha^{-1} at Palau and 169.2 t ha^{-1} at Yap) was much higher than the above-ground carbon pools of the present study (83.32 t C ha^{-1}). The present values of above-ground C-stock were, however, higher when compared to the values estimated by Chen *et al.* (2012) in Southern China (55 t ha^{-1}) and by Sahu *et al.* (2016) in the natural stands of the Mahanadi Mangrove Wetland, India (62.45 t ha^{-1}).

The overall mean root biomass (69.92±8.61 t ha^{-1}) and C-stock of root biomass (34.96±4.30 t C ha^{-1}) obtained for the Kadalundi mangrove wetland were found to be less when compared to the values obtained in Yap (root biomass of 312 tha^{-1} and C-stock of 144 t C ha^{-1}; Kauffman *et al.*, 2011). However, the present study showed comparatively higher C-stock than the mangroves of southern China (21.4 t C ha^{-1}, Chen *et al.*, 2012), Tamil Nadu, India (18.1-12.9 t C ha^{-1}, Kathiresan *et al.*, 2013) and the Mahanadi Mangrove Wetland, India (27.86 26.69 t C ha^{-1} for natural stands and 27.86 t C ha^{-1} for plantation stands; Sahu *et al.*, 2016).

In the present study, the ratio of above-ground biomass and root biomass was 2.38 (average). The results obtained in Kadalundi was consistent with the values of Komiyama *et al.* (2008) which varied from 1.1 to 4.4. The present values were also comparable with that of the mangroves of Mahanadi, India (T/R ratio of 2.3; Sahu *et al.* 2016). Komiyama *et al.* (2008) concluded that the

T/R ratio of mangroves is significantly lower than the terrestrial forests, since a large amount of biomass gets allocated to the root system of the mangroves which helps the mangrove trees to stand upright in soft and wet muddy conditions.

The average sediment organic carbon (63.87±8.67 t C ha^{-1}) obtained for Kadalundi wetland was lower than the values obtained for the same depth in the Micronesian mangroves (Palau 128.1 t C ha^{-1}, Yap 119.5 t C ha^{-1}; Kauffman *et al.,* 2011), but higher than the Mahanadi Mangrove Wetland, India (57.6 t C ha^{-1}; Sahu *et al.,* 2016). Our findings were also substantially higher compared to the sediment C-stock values obtained at 1 m depth in Okinawa, Japan (57.3 t C ha^{-1}; Khan *et al.*, 2007), but much lower than the value obtained for the sediment collected from 1.22 m depth in North Sulawesi, Indonesia (Murdiyarso *et al.*, 2009).

The sediments in a mangrove area serve as an important carbon pool (Donato *et al.*, 2011; Kauffman *et al.*, 2011; Kauffman and Donato, 2012) and this has been proven in the Kadalundi wetland also as the estimated sediment C-stock was 35.06% of the total C-stock. The mean sediment C-stock obtained in the present study was equivalent to 234.40 t CO_2 ha^{-1}. The present study, which estimated the sediment C-stock in the upper 30 cm depth, is only indicative of the potential of mangrove sediments to act as carbon reservoirs. However, studies on the presence of carbon at different sediment depths are important in view of the blue carbon trading (Nellemann *et al.*, 2009; Lawrence, 2012).

The mangroves in the Kadalundi wetland cover an area of 13.23 ha and we assume that this area has a potential to sequester and store a substantial quantity of 2,409.84 t C, equivalent to an estimated amount of 8,844.11 t CO_2. Moore and Diaz (2015) computed the social cost of carbon (SCC) as US $ 220 per ton of CO_2 which corresponds to ₹ 14,250 per ton. The estimated SCC for the Kadalundi wetland is ₹126.02 million. The present study, thus, underscores the importance of these intertidal forests in the light of climate change mitigation and stresses the importance of protecting mangroves which also provide many other important ecosystem services and functions that benefit the communities. Worldwide, attention is now paid for the protection and restoration of mangroves, realising their importance in storing carbon in their plant parts as well as in sediment, thereby acting as blue carbon sink.

Being a part of the community reserve, the mangroves of Kadalundi are well protected from anthropogenic destructions as the communities living along the Kadalundi wetland have a deep concern for the protection of mangroves. However, accretion of sand on the western edge of this wetland, close to the bar mouth, has been a serious threat to the mangrove stands, resulting in the smothering of roots and consequent death of some trees of *S. alba* and *A. officinalis* (Fig. 8). For the rehabilitation of mangrove areas affected by sand accretion, Ellison (1998) suggested that elevation changes must be assessed in the selection of species for replanting where the disturbance was a past event and field trials are required in areas where rapid accretion is an ongoing problem. We found that sand accretion is an ongoing process in the Kadalundi wetland; particularly near the bar mouth and therefore, more studies are suggested to tackle this problem. Suitable management measures need to be adopted to protect the rich mangrove wealth of the Kadalundi wetland, coupled with mangrove plantation efforts in suitable areas in order to sequester and store more carbon.

Fig. 8. Accretion of sand resulting in wilting of *Sonneratia alba* in the western side of the estuarine wetland

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