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Carbon Partitioning and Allometric Relationships between Stem Diameter and Total Organic Carbon (TOC) in Plant Components of *Bruguiera gymnorrhiza* (L.) Lamk. and *Lumnitzera racemosa* Willd. in a Microtidal Basin Estuary in Sri Lanka

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Abstract The capacity of plants to sequester carbon depends on net primary productivity and pattern of biomass/carbon partitioning within the plant which is not well understood for mangroves. Above (A) to below (B)-ground carbon ratio (A/B) of both *Bruguiera gymnorrhiza* (L.) Lamk. and *Lumnitzera racemosa* Willd. from where micro-tidal conditions prevail, Negombo estuary, Sri Lanka (7°11′42.18″N- 79°50′47.50″E) was approximately 3, and more closely resembles that of terrestrial plants than mangroves in macro-tidal environments. Relatively low inundation frequency, duration and depth apparently promote aerial growth than root production. Wet oxidation without external heating, followed by colorimetric method was adopted to determine total organic carbon (TOC) of plant components. Except for leaves of *L. racemosa*, nearly half the biomass of all other components of the two species was composed of TOC. Statistically significant allometric relationships exist among TOC and dbh (diameter at breast height) of trees. It was found that 96.5% of TOC in *L. racemosa* was in sequestered form (in the wood) compared to *B. gymnorrhiza* which only accumulated 78.7% in sequestered form. Profuse branching of *L. racemosa* contributes to the higher carbon sequestration capacity.

Keywords Allometric relationships, Carbon sequestration, Organic carbon; Mangroves

1 Introduction

1.1 Mangrove ecosystems

Mangrove forests are considered to be a unique and complex components of coastal zones in the tropical and sub-tropical regions. Their primary productivity is characteristically high when compared to other terrestrial plant communities (Alongi, 2002; Amarasinghe and Balasubramaniam, 1992a; Kathiresan, 2007; Suratman, 2008 Khan et al., 2009) and contribute substantially to all organic carbon sequestration in marine ecosystems (Breithaupt et al., 2012). Carbon that accumulates in the above-ground components such as leaves, smaller branches and non-woody aerial roots decomposes rapidly (i.e., labile carbon) and is quickly returned to the atmosphere. Carbon that remains away from atmosphere within plants for considerably a long time, i.e. carbon in wood (stems and large branches) and woody roots, both below-ground and aerial, contributes to the carbon sequestration function of the mangrove ecosystems.

1.2 Carbon sequestration capacity of mangroves

Carbon sequestration capacity of mangrove plants depends on biomass/carbon partitioning pattern which is characteristic to the species. Contribution of mangrove plant species for carbon sequestration may vary from species to species, for their inherent capacities of primary production, storage pattern and environmental conditions (Twilley et al., 1992). The ratio between above to below ground biomass reflects the distribution of biomass and carbon within the plant and hence it provides a pragmatic measure of carbon partitioning and sequestration capacity of respective mangrove species. Carbon stored in below-ground components are of significance in terms of sequestration, as anaerobic conditions prevailing in the soils due to frequent flooding reduces its oxidation and limits release into the atmosphere as CO_2.

Total of 20 true mangrove species, belong to 11 plant families were identified in Sri Lanka (Jayatissa et al., 2002). Rhizophoraceace, Combretaceae, Euphorbiaceae and Avicenniaceae are abundant in Sri Lanka. *Bruguiera gymnorrhiza,* which belong to the family Rhizophoraceace and is one of the most distributed pantropical families in the world (Tomlinson, 1986), and *Lumnitzera racemosa,* which belongs to family Combretaceae, were selected for the study. *Rhizophora mucronata* and *Avicennia maria* are the dominant species in mangrove areas of the Negombo estuary and the allometric relationship between biomass and dbh (diameter at breast height) of these species has already been determined (Amarsinghe and Balasubramaniam, 1992b). Nevertheless, investigations of TOC on mangroves in Sri Lanka are non-existent.

1.3 Aims and objectives of the study

Present study is the first of this kind conducted on Sri Lankan mangrove species with the objectives of determining the pattern of total organic carbon (TOC) distribution within the plant components, including below ground components, through allometric relationships between organic carbon in biomass of plant components (stem, roots, leaves) and diameter at breast height (dbh) of *B. gymnorrhiza* and *L. racemosa.* Allometry has proven to be a useful method not only to estimate total organic carbon sequestration capacity of plant species, but also that of mangrove ecosystems comprised of these species.

2 Results

2.1 Distribution of TOC among plant components

Except for the organic carbon in leaves of *L. racemosa*, approximately half the biomass of all components in the two species in the present study is composed of organic carbon. Average organic carbon in woody components (stems and branches) of *B. gymnorrhiza* was (10.17±4.52) kg/plant and it accounts for 53.5% of total carbon available in the plant and this is lower than that of *L. racemosa* (18.5±6.15 kg/plant) that accounts for 71% of the total carbon in the whole plant (Table 1). Although leaves of *L. racemosa* accumulate a relatively low amount of carbon (0.79±0.2 kg/plant) and account only for 3.5% of the total carbon in *B. gymnorrhiza* accumulates a comparatively high amount of carbon in leaves (i.e. (4.05±1.78) kg/plant and 21.3% of the total carbon in the plant), revealing that *L. racemosa* accumulates carbon predominantly in the sequestered form in stems, branches and roots, and not as labile carbon in the leaves (Table 1). Quarter of organic carbon in both the species is accumulated in roots (under-ground and below-ground together). The amount of organic carbon retained in the above ground plant components is about three times greater than that in below-ground parts (Table 1).

Figure 1 presents the distribution of TOC among plant components of trees with varying dbh. Although a similar propensity in percentage TOC of stems, branches and roots of *B. gymnorrhiza* observed with increasing dbh, leaves showed a decrease with increasing dbh values. Percentage TOC in branches of *L. racemosa* recorded a greater increase with increasing dbh and decreasing values was recorded in stem and roots with similar variations of dbh.

Relatively smaller trees (lower dbh) of *B. gymnorrhiza* accounted for a higher above (A) to below (B) ground total organic carbon (TOC) ratio (A/B) and this was observed to decrease with increasing dbh. On contrary, *L. racemosa* was revealed to account an A/B, that was lower in smaller trees and it increases with tree dbh (Figure 2).

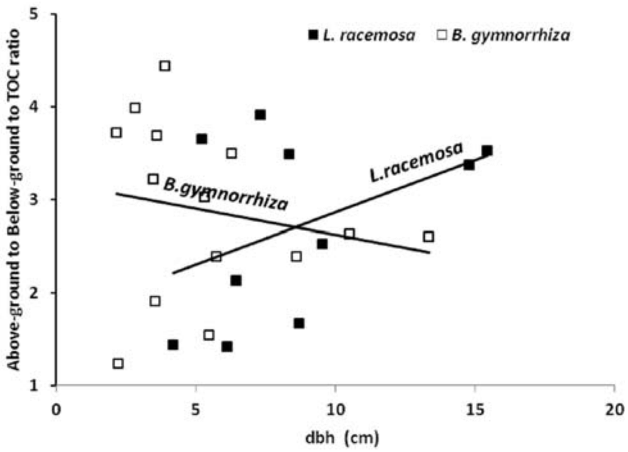

Figure 2 Relationship between dbh and above-ground to below-ground ratio (A/B)

Table 1 Total organic carbon (TOC) content in the biomass of plant components of sample trees of *Bruguiera gymnorrhiza* and (n=14) *Lumnitzera racemosa* (n=10).

		Total organic carbon (TOC) content (kg/kg dry weight)				Ratio of above to below ground TOC
		Wood (stems + branches)	Leaves	Roots (above + below ground)	Total (mean)	
Bruguiera gymnorrhiza	Mean TOC content (kg C per kg biomass)	0.54±0.003	0.51±0.002	0.52±0.003	0.52±0.002	2.96
	Percentage TOC	53.50	21.30	25.20	–	–
Lumnitzera racemosa	Mean TOC (kg C per kg biomass)	0.55±0.001	0.44±0.002	0.54±0.003	0.54±0.002	2.90
	Percentage TOC	71.00	3.50	25.50	–	–

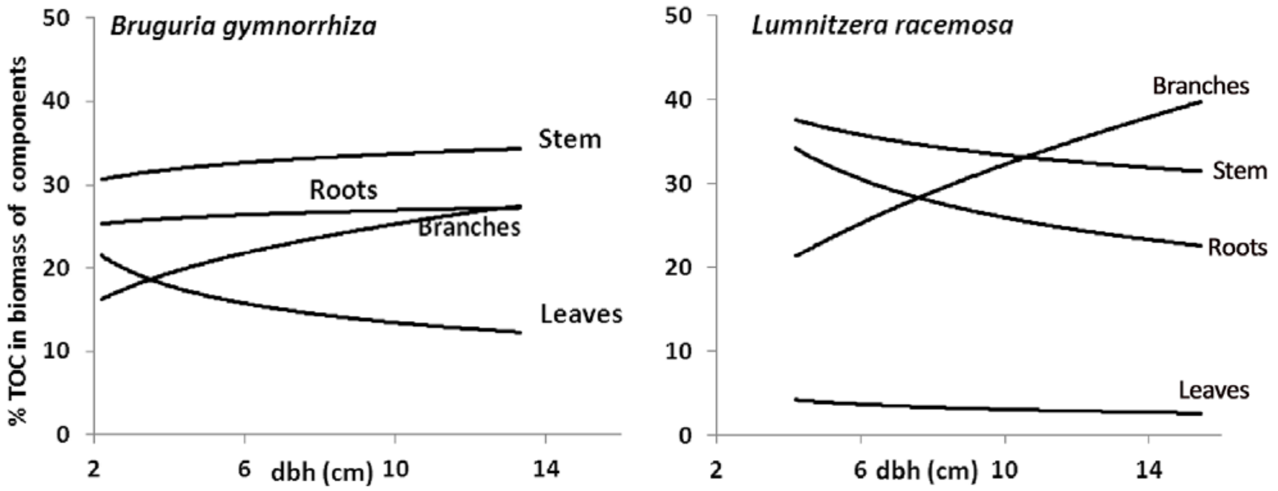

Figure 1 Percentage TOC in biomass of plant components varied in different stem diameters of sample trees of *B. gymnorrhiza* and *L. racemosa*.

Although average TOC per tree was greater in *B. gymnorrhiza* than in *L. racemosa,* in most of stem diameter classes available, percentage potentially sequestered carbon content per tree in the same diameter classes was higher in *L. racemosa* than of *B. gymnorrhiza* (Figure 3).

2.2 Development of allometric relationship between dbh and TOC, and estimated the accuracy

A positive correlation ($p<0.01$) with leaner relationship was revealed between log-transformed values of TOC content in biomass of plant components and dbh with $r^2>0.80$ (coefficient of determination), except for leaves of the two species (Figure 4). The allometric equations were in the form, $\log_{10}(TOC)=B_0 + B_1 \log_{10}(dbh)$, B_0 and B_1 are the regression coefficients (Table 2).

2.3 Accuracy of organic carbon estimation using the allometric relationships

Accuracy of developed allometric relationships was tested with one real data set which not used for developing the equation. Similarly, each equation was tested with more than 10 sets of real data obtained from the study. Difference between actual and estimated values of organic carbon content in biomass of each plant components negligibly low and are presented in Table 3.

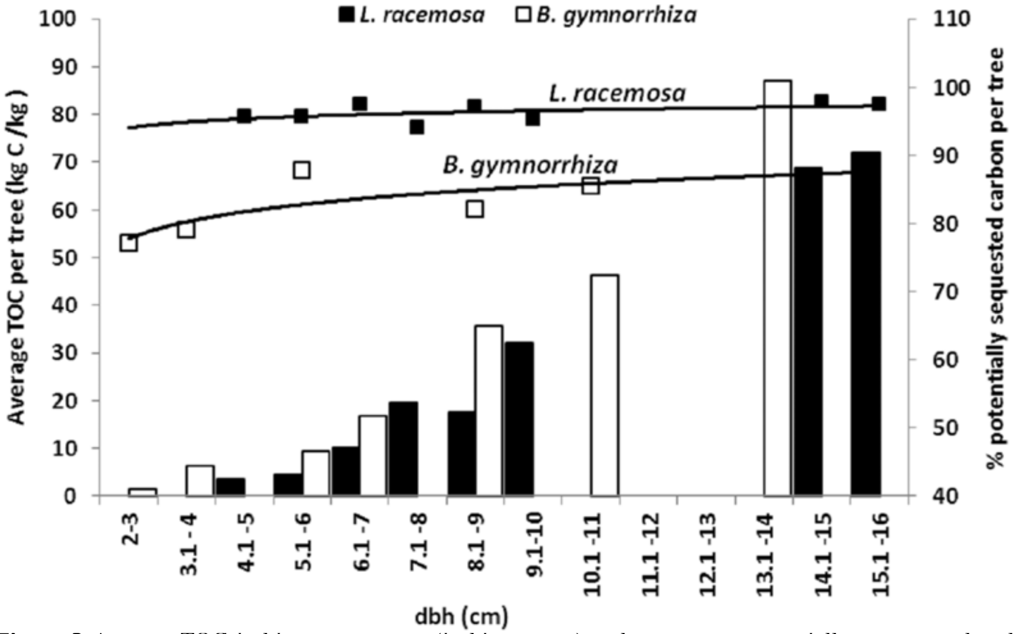

Figure 3 Average TOC in biomass per tree (in histograms) and percentage potentially sequestered carbon per tree (line graph) of stem diameter classes used in the present study for *B. gymnorrhiza* and *L. racemosa*

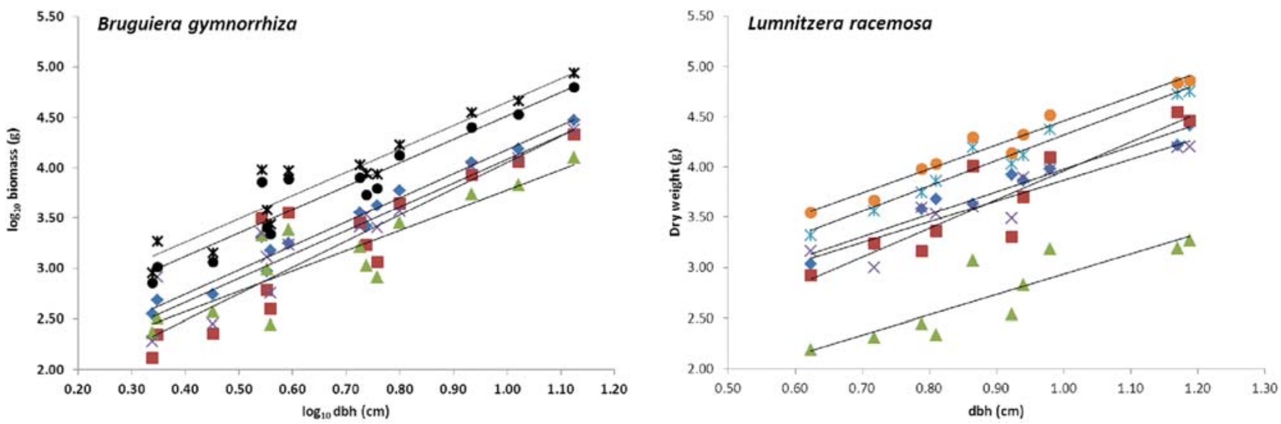

Figure 4 Relationship between dbh and organic carbon content in plant components and TOC of *B. gymnorrhiza* and *L. racemosa*.

Table 2 Allometric equations derived for estimating TOC ($\log_{10}$) content of separate plant components and total plant of *B. gymnorrhiza* and *L. racemosa*

Plant components	*B. gymnorrhiza*	r^2	Std_{error}	*L. racemosa*	r^2	Std_{error}
Stem	$1.794 + 2.386 \log_{10}$ (dbh)	0.971	0.233	$1.734 + 2.244 \log_{10}$ (dbh)	0.946	0.237
Leaves	$1.766 + 2.014 \log_{10}$ (dbh)	0.780	0.611	$0.921 + 2.011 \log_{10}$ (dbh)	0.761	0.497
Root	$1.718 + 2.364 \log_{10}$ (dbh)	0.882	0.496	$1.805 + 2.063 \log_{10}$ (dbh)	0.855	0.376
Above-ground fraction	$2.183 + 2.332 \log_{10}$ (dbh)	0.907	0.427	$1.788 + 2.529 \log_{10}$ (dbh)	0.960	0.227
Total tree/plant	$2.329 + 2.323 \log_{10}$ (dbh)	0.911	0.415	$2.073 + 2.381 \log_{10}$ (dbh)	0.958	0.219

Note: * r^2 is the coefficient of determination and Std_{error} is the stranded error of estimate

Table 3 Difference between actual and estimated TOC per kg of plant biomass for each plant component and total plant of *Bruguiera gymnorrhiza* and *Lumnitzera racemosa*

	Component	Total organic carbon (kg TOC /kg plant biomass)		
		Actual	Estimated	Difference
Bruguiera gymnorrhiza	Stem	5.74	5.75	+0.01
	Leaves	2.70	2.34	-0.36
	Root	4.71	4.61	-0.10
	Above-ground	12.70	12.58	-0.12
	Total tree	19.02	19.36	+0.34
Lumnitzera racemosa	Stem	8.31	8.78	+0.47
	Leaves	1.48	1.47	-0.01
	Root	6.10	6.14	+0.04
	Above-ground	19.04	18.89	-0.15
	Total tree	25.89	26.83	+0.94

3 Discussions

3.1 Distribution of TOC among plant components

Half the biomass of *B. gymnorrhiza* (0.52 kg/kg biomass) as well as of *L. racemosa* (0.54 kg/kg biomass) is composed of organic carbon and the values are compatible with that for other mangrove species reported by Suratman (2008). *L. racemosa,* however, contains more carbon (96.5%) in stems, large branches and roots than *B. gymnorrhiza* (78.7%), hence is a species more capable in sequestering carbon. Percentage carbon content in mangroves is also similar to that of tropical and sub-tropical woody plants (0.47~0.49 kg/kg biomass) (Hughes et al., 2000; McGroddy et al., 2004; Aalde et al., 2006) and it signifies that the carbon sequestration capacity of mangrove plants equals that of tropical and subtropical terrestrial plants.

Nearly 25% of the carbon in both the species is accumulated in the aerial and underground roots and thus the above ground carbon accumulation of these species is three times greater than that of the roots. Reported data on biomass partitioning of some mangrove species indicate that above:below ground biomass is low, indicating relatively high biomass in the roots relative to above-ground parts (Komiyama et al., 2008). The present study reveals that approximately half the biomass is accounted by carbon and thus the above and below-ground carbon partitioning represents a ratio of 3.0. This may slightly change when the biomass of aerial roots are excluded from the root fraction. An contrary observation (i.e. above:below ground biomass ratio of 2.0), has been reported by Hoque et al (2010) from Okinawa island, Japan, where the tidal amplitude is 1.5~2.0 m. Comley and McGuinness (2005) report above:below ground biomass ratio of 0.75~2.0 for four mangrove species in Darwin Harbour, Australia, under macro-tidal conditions where the amplitude ranges up to 8 m. In upland forests below ground fraction become less compared with above ground portion and the ratio ranges between 3.9 and 4.5 (Cairns et al., 1977). The two mangrove species subjected to present study that occupy an intertidal habitat with an average tidal range which does not exceed 50 cm (relatively low inundation depth, duration and frequency) results in plants with a above:below ground biomass/TOC that resembles plants living under terrestrial conditions, (i.e. relatively low below ground than the above ground biomass and hence carbon content).

Besides, inundation and consequent anaerobic edaphic conditions, above:below ground biomass appears to vary with salinity. According to the observations documented by Saintilan (1997) with four mangrove species in south-eastern Queensland, under low salinity (upstream) conditions above:below ground biomass lies greater than 2 and this ratio decreases to 1.1~0.65 in saline conditions at the estuary and further declines to 0.3 in hyper-saline environments. These results reveal that increasing salinity reduces above-ground growth, may be as a result of energy expenditure for salt exclusion and thus leads to a lower above:below biomass as well as TOC ratio. Furthermore, greater number of knee roots was observed in *L. racemosa* plants that were found to occur in inundated areas than in others, indicating that inundation also may induce biomass diversion to below-ground parts to expand air passage and storage volume, thus contributing to declining above:below biomass/carbon ratio.

Results reveal that stems and branches contributed the most components to TOC in both *B. gymnorrhiza* and *L. racemosa* (Figure 1). Carbon retention of larger trees of *L. racemosa* was found mostly in branches. Inherently profuse branching pattern and tree architecture of *L. racemosa* may contribute to accumulation of carbon in the branches more than even in the main stem. Even though similar pattern of TOC was found to occur in leaves of two species with age/dbh, magnitude of contribution by *L. racemosa* with its low volume of fleshy leaves is much lower than that of *B. gymnorrhiza* which possesses larger and thick leaves. TOC partitioning among the plant components are highly species specific and also appears to depend on habitat conditions such as aridity and soil salinity (Clough et al., 1997).

Gradual decline of A/B (biomass) of *B. gymnorrhiza* with dbh (Figure 2) is analogous to observations recorded by Matusui (1998) with B/A (biomass) changes with dbh of *Rhizophora stylosa* in Iriomote island, Japan. Root development, especially the radial roots and negatively geotropic roots such as the knee roots of *B. gymnorrhiza,* that takes place with age, may contribute to slightly higher magnitude of below-ground biomass or carbon accumulation, when compared to that of above carbon accumulation. *L. racemosa* plants most often occur in less inundated landward areas of the mangrove stands in the Negombo estuary and do not develop many knee roots (which are characteristically much less in diameter) unlike *B. gymnorrhiza* that occupies more inundated terrain of the mangrove areas and forms greater numbers of large knee roots. Increasing below ground biomass/carbon in *B. gymnorrhiza* relative to *L. racemosa* may have resulted the opposing patterns of A/B (TOC) with age (dbh) of the two species, indicating magnitude, period and frequency of inundation influences the biomass/carbon distribution in mangrove plants.

Moreover, TOC/ plant in *L. racemosa* (mean dbh = 8.62 cm) is greater (25.90 ± 8.04 kg/plant) than that of *B. gymnorrhiza* (19.02±8.42 kg/plant) of which the mean diameter is 5.5 cm. Profuse branching of *L. racemosa* makes an important contribution in carbon sequestration capacity of the species. Percentage potentially sequestered carbon stock in any girth/age class of *L. racemosa* was greater than that of *B. gymnorrhiza,* revealing that *L. racemosa* is superior in carbon sequestration in all age/girth classes. This provides useful knowledge in selecting mangrove species for replanting and maintaining mangrove plantations for carbon assimilation purposes. Moreover, destruction of *L. racemosa* may contribute significantly to loss of sequestered carbon in a mangrove ecosystem.

3.2 Development of allometric relationships between dbh and TOC

Estimation of organic carbon content in mangrove plants presents a pragmatic measure to determine the carbon sequestration capacity of individual plants, species and communities. Although allometric relationships have been developed between dbh and biomass for a number of mangrove species, (Amarasinghe and Balasubramaniam, 1992b; Comley and McGuinness, 2005; Chave et al., 2005; Komiyama et al., 2005) allometric relationships between dbh and TOC for mangrove species is sparse. This is the first study of this nature conducted in Sri Lanka that probed into allometry of total organic carbon in mangrove biomass and it assists in estimating carbon emission from mangrove deforestation.

4 Materials and Methods

4.1 Selection of sample trees

The dbh of *B. gymnorrhiza* plants in the study area ranged between 2 cm and 14 cm and the height from 2.0~9.5 m. Fourteen plants that represent the above ranges were harvested to determine biomass and TOC. Likewise, 10 *Lumnitzera racemosa* plants that represent the natural range of dbh from 4~16 cm and tree height from 4.0~10.0 m were selected from Kadolkele mangrove area in Negombo estuary, Sri Lanka (7°11′42.18″N ~ 79°50′47.50″E) to measure the biomass and TOC of plant components.

4.2 Determination of mangrove plant biomass

Each sample tree was cut at ground level using a saw and separated manually into trunk, branches, leaf fractions and reproductive parts. The trunk diameters of each sample tree were measured at ground level (D_0), 1 m above ground level (D_1) and 1.3 m above ground level/dbh level ($D_{1.3}$). Roots of each sample tree were excavated and washed with pressurized water (Comely and McGuinnes, 2005, Komiyama, 2005).

Total fresh weight of stems, branches, leaves, reproductive parts and roots of each plant was measured in the field with an electronic balance of 1.0 g accuracy. Samples from each component were oven-dried at 65℃ to constant weight. Fresh to dry weight ratios of each plant component of the two species were used to estimate biomass of plant components and thus of the total plant.

In the present study, stems, branches and leaves were considered as above ground plant components while below-ground roots and knee roots were considered as below-ground plant components.

4.3 Determination of total organic carbon (TOC) content of mangroves

Samples from woody stems, leaves and roots of *B. gymnorrhiza* and *L. racemosa,* were taken in triplicates from five sample trees that represent the respective ranges of dbh, to measure TOC. Fresh samples were initially air dried and subsequently oven dried at 60℃ until constant weight and then ground with an electric grinder and sieved through 150 µm mesh. Roots, both above and below-ground, were considered as one component. Wet oxidation method without external heating procedure followed by colorimetric method based on absorbance at 600 nm, using a UV- visible spectrophotometer (Anderson and Ingram, 1998; Schumacher, 2002) was adopted to estimate the TOC in each plant component.

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