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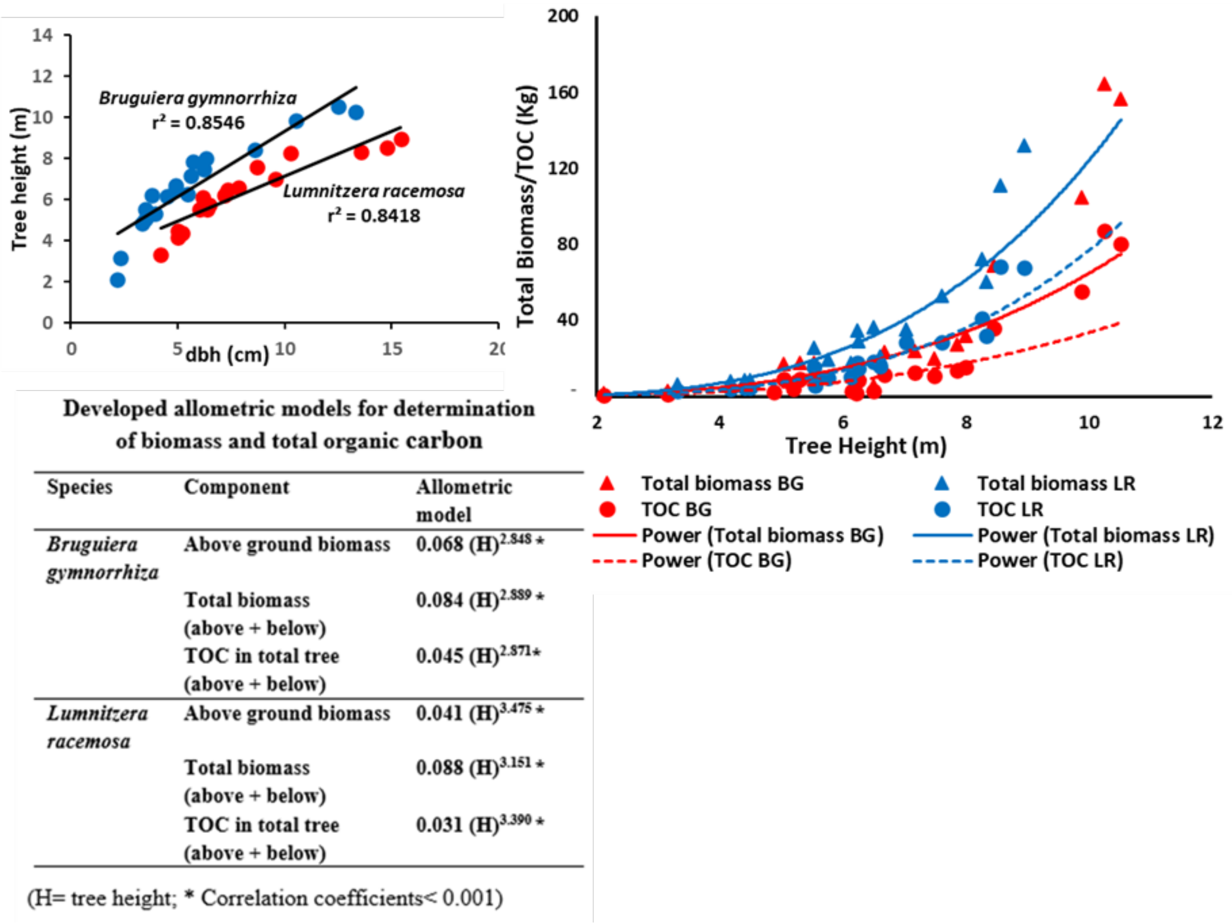
RESEARCH ARTICLE

Potential of using tree height as a surrogate variable to estimate biomass and total organic carbon (TOC) of mangrove trees

K.A.R.S Perera and M.D. Amarasinghe



Developed allometric models for determination of biomass and total organic carbon

Species	Component	Allometric model
Bruguiera gymnorrhiza	Above ground biomass	$0.068\ (H)^{2.848\,*}$
	Total biomass (above + below)	$0.084\ (H)^{2.889\,*}$
	TOC in total tree (above + below)	$0.045\ (H)^{2.871*}$
Lumnitzera racemosa	Above ground biomass	$0.041\ (H)^{3.475\,*}$
	Total biomass (above + below)	$0.088\ (H)^{3.151\,*}$
	TOC in total tree (above + below)	$0.031\ (H)^{3.390\,*}$

(H= tree height; * Correlation coefficients< 0.001)

Highlights

- In allometric models, tree height can be used as a quantifiable variable instead of dbh
- Two common mangrove species, *Bruguiera gymnorrhiza* and *Lumnitzera racemosa* were used in the study
- A total of 12 allometric models were developed to estimate biomass/total organic carbon (TOC) with tree height
- These models can be used to estimate biomass/TOC in mangroves with low accessibility

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RESEARCH ARTICLE

Potential of using tree height as a surrogate variable to estimate biomass and total organic carbon of mangrove trees

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Abstract: Estimation of biomass and total organic carbon (TOC) content in mangrove plants/species presents a realistic measure of the carbon sequestration capacity of plants/species in these communities. Allometric models are widely used for estimating biomass and TOC, and are considered sufficiently a reliable tool in tree biomass estimation. Although diameter at breast height (dbh) is the commonly used quantifiable variable to develop allometric models to estimate biomass, it requires accessing each individual plant to measure the dbh, which often can be a cumbersome task, particularly when it has to be performed in a muddy and waterlogged conditions in a remote location. Twenty-one (21) individuals of *Bruguiera gymnorrhiza,* and 20 individuals of *Lumnitzera racemosa* trees were selected to represent the range of dbh of the respective species that occurred in the mangroves at Kadolkele in Negombo estuary, Sri Lanka. A statistically significant relationship ($p<0.001$) was revealed between the tree height and dbh of both species. TOC content embedded in biomass was calculated using published data. Allometric relationships were developed between biomass/TOC and height of *B. gymnorrhiza* and *L. racemosa.* The accuracy of estimated biomass of allometric relationships was compared with the actual data set and revealed more than 95% and 93% of reliability for above-ground biomass and below-ground biomass, respectively. Instead of dbh, tree height, which is measurable from distance with suitable remote sensing tool, may be used reliably to estimate the stand biomass of mangroves that cannot be accessed easily on foot.

Keywords: mangroves, allometry, tree height, biomass, total organic carbon

INTRODUCTION

Mangrove forests are defined as unique and complex ecosystems of coastal zones in tropical and subtropical regions. Their primary productivity is characteristically high when compared to other terrestrial plant communities (Donato *et al*., 2011) and they possess great potential in contributing to the carbon sequestration function of these coastal ecosystems (Amarasinghe and Balasubramaniam, 1992; Alongi, 2002; Kathiresan, 2007; Suratman, 2008 Khan *et al*., 2009; Perera *et al*., 2012). It has been proven that mangroves contribute substantially to organic carbon sequestration in marine ecosystems (Breithaupt *et al*., 2012) and that they represent a potentially important carbon, thus have been ranked among the most carbon-dense forests in the tropics, partly due to their deep organic-rich soil and dense vegetation (Fujimoto *et al*., 1999; Donato *et al*., 2011; Kauffman *et al*., 2011).

Biomass studies on mangroves are important to reveal information on successional changes, individual and site productivity, nutrient cycling, carbon retention capacity, predicting future change with climate changes and managing them in a sustainable manner (Komiyama *et al*., 2008; Mahmood, 2014; Hossain *et al*., 2016). Recently, biomass estimations have become important to determine the carbon sequestration capacity of vegetation and understanding the impacts of vegetation changes on carbon fluxes (Cole and Ewel, 2006; Heryati *et al*., 2011; Addo-Fordjour and Rahmad, 2013). There are three methods frequently used to estimate tree biomass, i.e. area harvest method, mean-tree method and allometric method (Golley *et al*., 1975; Ketterings *et al*., 2001). In the harvesting method, uprooting trees is impracticable with cost and time-consuming. In addition to that, it may conflict with legal barriers including conservation rules and regulations at local as well as global levels. Allometry is a simple but powerful as well as non-destructive technique for estimating tree biomass from independent variables such as stem diameter and tree height which is easily quantifiable. The basic theory of allometric relationships is that the growth rate of one part of the tree is proportional to that of others. The stem diameter or tree height of an individual could be expected to have a strong correlation with stem weight (Komiyama *et al*., 2008). Allometric equations for mangroves have been developed for several decades to estimate biomass, growth and organic carbon content embedded in the biomass (Tami *et al*., 1986; Fromard *et al*., 1998; Clough and Scott, 1989; Komiyama et al., 2005; Perera *et al*., 2012; Perera *et al*., 2013). Most of the equations have been derived for single-stem trees. Certain mangrove species such as *Rhizophora, Excoecaria and Lumnitzera* are multi-stemmed or like with *Avicennia*, the main stem is branched closer to the ground. Clough *et al*. (1997), showed that allometric relationships can be used for stems in a multi-stemmed tree as well as for dwarf mangrove trees with very short stems. Clough *et al*. (1997), found different relationships in the same species grown in different sites and on the contrary, Ong *et al*. (2004), have observed that *Rhizophora apiculata,* from two different sites have similar relationships. Amarasinghe

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& Balasubramaniam (1992) observed a similar situation with *Rhizophora mucronata* and *Avicennia marina* in fringe and riverine mangrove areas on the northwestern coast of Sri Lanka. Baberjee *et al*. (2013) reported species-specificity of allometric models for three mangrove species under different salinity regimes. It appears therefore that to increase reliability, it is appropriate to develop allometric equations not only for separate species but also for each locality in which they naturally occur.

Due to issues related to both site-specificity and species-specificity of mangrove allometry, Chave *et al*. (2005) and Komiyama *et al*. (2005) proposed common allometric models for mangrove biomass with quantifiable variables such as tree dbh and wood density. The common allometric models are based on the pipe model of Shinozaki *et al*., (1964) and the static model of plant form by Oohata & Shinozaki (1979). Reviewing allometric equations published on mangrove biomass during the last two decades, dbh (diameter at breast height) is the most used independent/quantifiable variable (Chave *et al*., 2005; Komiyama *et al*., 2005; Perera *et al*., 2012; Hossain *et al*., 2015). However, collecting dbh data from individual mangrove trees is time-consuming and cumbersome, especially in unfamiliar remote areas with waterlogged and muddy condtions. Therefore, the present study was conducted to develop allometric models to estimate biomass and the total organic carbon content of two mangrove species, *Bruguiera gymnorrhiza* and *Lumnitzera racemosa* using tree height as the quantifiable variable.

MATERIALS AND METHODS

Study area

Trees of *Bruguiera gymnorrhiza* and *Lumnitzera racemosa* were selected for biomass estimation from mangrove areas at Kadolkele, Negombo estuary (between 7^0 6' – 7^0 12' N and 79^0 40' – 79^0 53' E) located in the west coast of Sri Lanka. Being a micro-tidal basin estuary, the average tidal range is less than 50 cm and the maximum depth of the estuary recorded 2 -3 m. The salinity varies between 1 -15mg l^{-1} and pH from 5 -8. Surface water temperature fluctuates between 26.0 – 34.1^o C. (Kotagama *et al*., 1989; Gammanpila *et al*., 2009). The annual rainfall of the area is approximately 2,025 mm (Perera and Amarasinghe, 2016).

Selection of sample trees

A preliminary survey was carried out to find out the range of height and dbh (diameter at breast height) of individual trees of each of the two species present in the study area. Twenty-one (21) trees of *Bruguiera gymnorrhiza,* of which the height ranged between 2.12 – 10.52 m and dbh between 2.18 -13.33 cm, and 20 trees of *Lumnitzera racemosa,* with height ranging from 2.82 – 8.95 m and dbh from 4.20 – 15.43cm were selected for harvesting.

Harvesting and field measurements

Each selected sample tree was cut from the ground level using a handsaw or a chainsaw depending on the diameter of the tree. The major above-ground plant components, i.e. stem, branches and leaves were separated manually. For all sample trees, trunk diameters were recorded at ground level (D_0), at 1.3 m above ground level ($D_{1.3}$) and at each 1 m interval ($D_{2.3}$, $D_{3.3}$ …) of the main stem of the tree. Total tree height and height to the lowest living branch were recorded with a common measuring tape as described by Comely and McGuinnes, (2005) and Komiyama *et al*., (2005).

Below ground components of each sample tree were investigated. Root balls were excavated by mechanical devices and washed with a pressured water jet to remove mud and small/ young roots were washed on a mesh, to collect all the broken parts during washing. Extended radial roots were excavated by cutting trenches. All radial roots and feeder roots (as far as possible) were collected.

Determination of biomass

The fresh weight of stems, branches, leaves, reproductive parts and roots was recorded with an electronic balance with 1.0 g accuracy in the field. Fresh weight (0.1 g accuracy) representative sub-samples from plant components were obtained and oven dried at 65 - 75^{0}C to constant weight. Fresh to dry weight ratio of samples was used to calculate the total dry weight/ biomass of each plant component.

Total organic carbon (TOC) in biomass

Standing stock of total organic carbon (TOC) content in biomass was calculated with the help of percentage TOC content in wood, leaves and roots of *B. gymnorrhiza* and *L. racemosa* as reported by Perera and Amarasinghe in 2016 (Table 1).

Development of allometric equations

Regressions and curve estimates were used to determine the relationship between dependent variables of biomass (above ground, below ground and total biomass) and TOC (above ground, below ground and total TOC) with the independent variable as tree height. Different regression relationships i.e. linear, logarithmic, power etc. were used with statistical software SPSS Ver.21 to determine the best-fitted allometric model for biomass of each plant component with total tree height. Selection of the best fitted

Table 1: Total organic carbon content (TOC) in biomass of main plant components of *Bruguiera gymnorrhiza* and *Lumnitzera racemosa* (Source: Perera and Amarasinghe, 2016).

Species	Total organic carbon content (kg/kg biomass)		
	Wood	Leaves	Root
Bruguiera gymnorrhiza	0.549±0.003	0.512±0.002	0.529±0.003
Lumnitzera racemosa	0.557±0.001	0.441±0.002	0.543±0.003

allometric models was performed by considering the values of coefficient of determination (r^2), level of probability (*p*) value and mean standard error of sample data.

RESULTS

Distribution of biomass and total organic carbon (TOC) content

Sample trees were categorized into frequency classes with respect to height measurements. Accordingly, five frequency classes for *B. gymnorrhiza*, (2.0-4.0 m, 4.1 – 6.0 m, 6.1 – 8.0 m, 8.1 -10.0 m and 10.1 – 12.0 m) and four frequency classes for *L. racemosa* (2.0-4.0 m, 4.1 – 6.0 m, 6.1 – 8.0 m, and 8.1 -10.0 m) were noted. Total biomass of the sample trees were ranged between 2.22-160.7 kg and TOC content between 1.17-83.68 kg of *B. gymnorrhiza* (Table 2). Total biomass of *L. racemosa* was ranged between 6.02-94.17 kg, while TOC ranged between 2.56-52.39 kg (Table 3). Biomass and TOC content in above-ground plant components of both species was 2 – 4 times greater than that of the below-ground components. In *B. gymnorrhiza,* above-ground/ below-ground (A:B) ratio was revealed to be higher (3.5- 3.9) in smaller trees than that was recorded in larger trees (2.5-2.9).

Relationship between tree height and diameter at breast height (dbh)

A statistically significant ($p<0.001$) relationship was revealed between tree height and dbh of *B. gymnorrhiza* and *L..racemosa* (Figure 1).

$$\text{Tree height}_{(B.\ gymnorrhiza)} = 0.636\ (\text{dbh}) + 2.9847$$

$$\text{Tree height}_{(L.\ racemosa)} = 0.437\ (\text{dbh}) + 2.7567$$

Table 2: Mean values of biomass and total organic carbon (TOC) of above- and below-ground plant components of *Bruguiera gymnorrhiza* trees under each height classes.

Height class (m)	dbh range (cm)	Mean aboveground biomass (kg)	Mean below ground biomass (kg)	Mean total biomass (kg)	Mean aboveground TOC (kg)	Mean below ground TOC (kg)	Mean total TOC (kg)
2–4	2.1-2.3	1.76 (1.3-2.7)	0.45 (0.3-0.5)	2.22 (1.7-2.7)	0.93 (0.7-1.1)	0.24 (0.1-0.2)	1.17 (0.9-1.4)
4-6	3.3-3.9	10.06 (3.3-14.6)	2.80 (0.8-4.2)	12.87 (4.1-17.8)	5.33 (1.7-7.7)	1.46 (0.4-2.2)	6.79 (2.2-9.4)
6-8	3.5-6.2	13.53 (1.9-24.7)	3.98 (1.1-7.0)	17.51 (5.1-31.8)	6.91 (1.0-11.9)	2.07 (0.5-3.6)	8.98 (1.8-15.6)
8-10	8.6-10.5	64.71 (48.7-80.6)	21.97 (19.9-24.0)	86.68 (68.6-104.6)	33.94 (25.3-42.5)	10.74 (8.9-12.5)	45.36 (35.6-55.0)
10-12	12.5-13.3	115.89 (112.8-118.9)	44.83 (43.8-45.7)	160.7 (156.7-164.7)	60.36 (57.2-63.4)	23.33 (22.8-23.8)	83.68 (80.1-87.2)

Table 3: Mean values of biomass and total organic carbon (TOC) of above- and below-ground plant components of *Lumnitzera racemosa* trees in each height classes.

Height class (m)	dbh range (cm)	Mean aboveground biomass (kg)	Mean below ground biomass (kg)	Mean total biomass (kg)	Mean aboveground TOC (kg)	Mean below ground TOC (kg)	Mean total TOC (kg)
2 – 4	3.3-4.1	3.55 (3.2-3.8)	2.47 (2.2-2.6)	6.02 (5.5-6.5)	1.33 (1.2-1.4)	1.23 (1.1-1.3)	2.56 (2.3-2.7)
4 - 6	4.9-6.3	10.37 (6.6-13.3)	3.4 (1.8-6.3)	13.57 (8.1-19.66)	5.63 (3.2-6.7)	1.71 (0.8-3.1)	7.33 (4.3-9.9)
6 - 8	6.4-9.5	27.95 (12.5-43.1)	8.78 (5.9-14.5)	32.46 (17.5-52.8)	14.58 (6.5-22.5)	4.56 (2.9-7.8)	19.14 (10.2-28.7)
8 - 10	10.2-15.4	81.39 (55.6-102.91)	21.32 (11.2-29.4)	94.17 (60.5-132.3)	41.29 (24.5-53.4)	11.10 (6.5-15.6)	52.39 (32.1-68.2)

Allometric models of biomass and TOC with tree height

Among others, power curve was determined to be the most fitted for the data sets of the two species and therefore allometric equations were derived from power curves. A strong positive correlation ($p < 0.001$) and a higher coefficient of determination with non-linear relationships were observed for biomass and TOC content with tree height of both *B. gymnorrhiza* (Table 4 and Figure 2) and *L. racemosa* (Table 5 and Figurs 3).

Allometric models developed between tree height (H) with biomass (above ground, below ground and total biomass) and TOC content (above ground, below ground and total TOC) of *B. gymnorrhiza* and *L. racemosa* (Table 6).

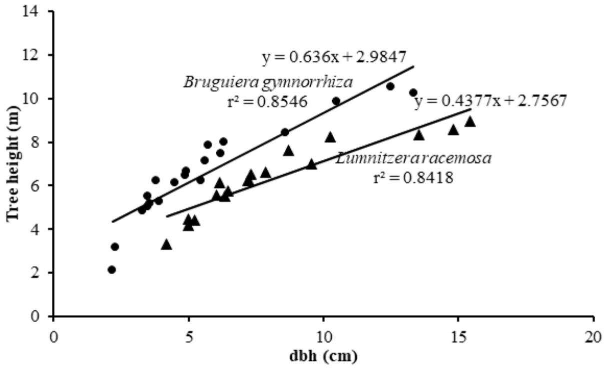

Figure 1: The relationship between tree height and dbh of *Bruguiera gymnorrhiza and Lumnitzera racemosa*

Table 4: Regression results for data fit to the power curve in each tree component with total tree height for *Bruguiera gymnorrhiza.*

Component	B_0	B_1	r^2	MS_{error}	*p*	*n*
Above ground biomass	0.068	2.848	0.889	0.757	< 0.001	21
Below ground biomass	0.015	3.026	0.866	0.712	< 0.001	21
Total biomass (above + below)	0.084	2.889	0.894	0.718	< 0.001	21
Above ground TOC	0.037	2.822	0.891	0.753	< 0.001	21
Below ground TOC	0.008	3.009	0.864	0.706	< 0.001	21
TOC in total tree (above + below)	0.045	2.871	0.888	0.716	< 0.001	21

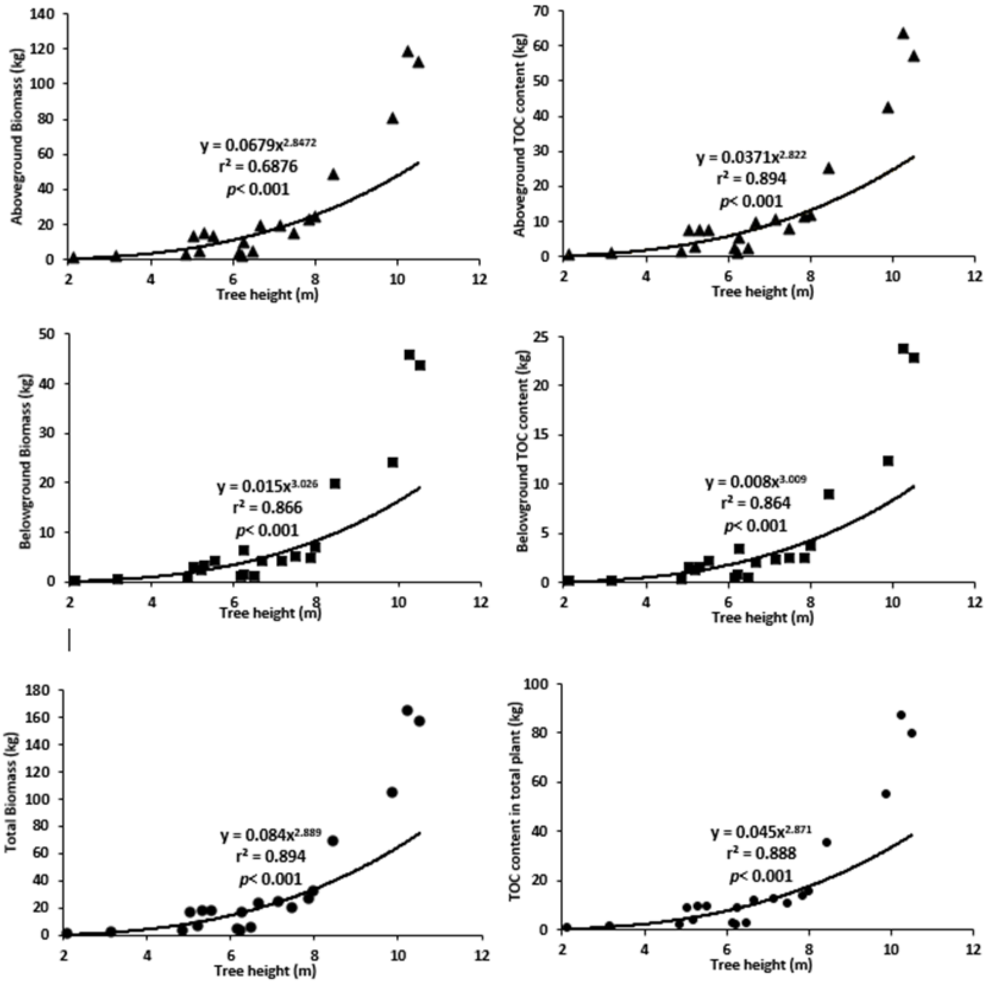

Figure 2: Relationship between tree height with biomass (above, below and total) and total organic carbon (TOC) content of *Bruguiera gymnorrhiza* (r^2 – coefficient of determination, p – Pearson correlation coefficient).

Table 5: Regression results for data fit to the power curve in each tree component with total tree height for *Lumnitzera racemosa.*

Component	B_0	B_1	r^2	MS_{error}	p	n
Above ground biomass	0.041	3.475	0.918	0.296	< 0.001	20
Below ground biomass	0.032	2.952	0.841	0.382	< 0.001	20
Total biomass (above + below)	0.088	3.151	0.891	0.310	< 0.001	20
Above ground TOC	0.017	3.578	0.896	0.292	< 0.001	20
Below ground TOC	0.014	3.026	0.849	0.382	< 0.001	20
TOC in total tree (above + below)	0.031	3.390	0.894	0.287	< 0.001	20

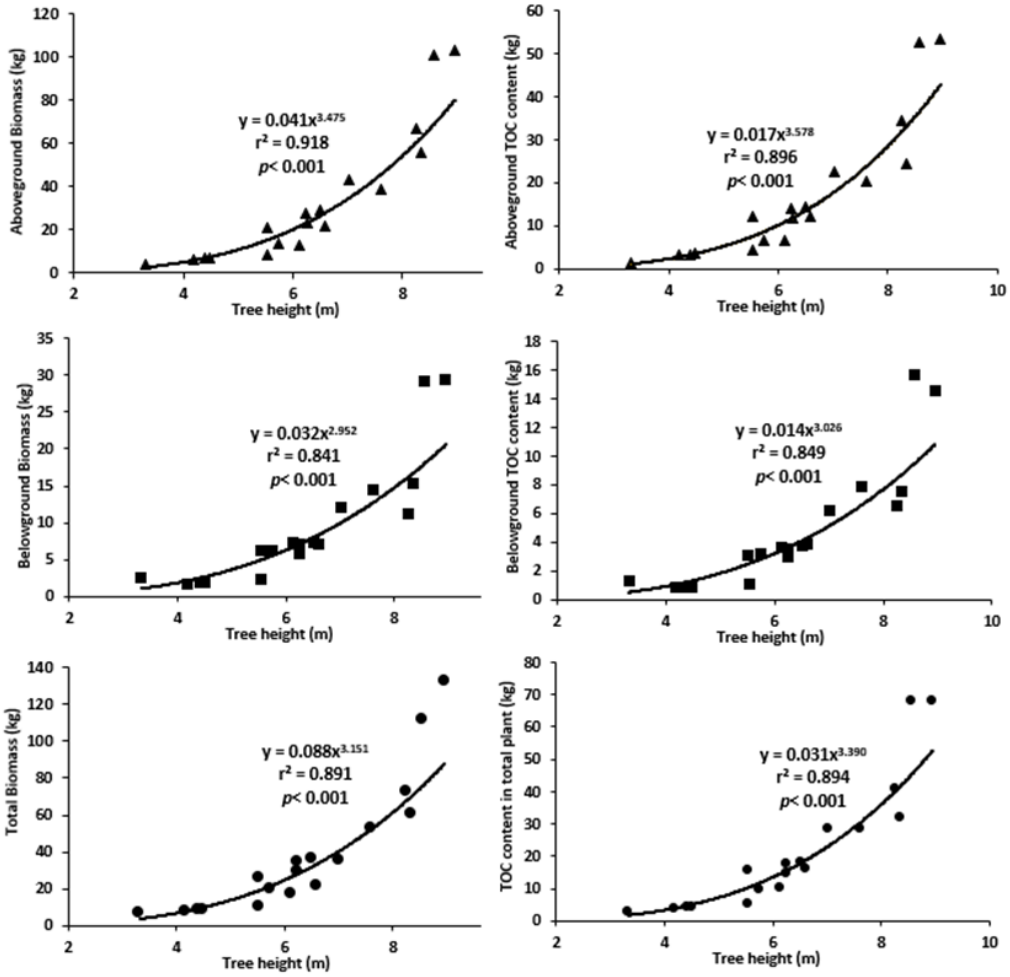

Figure 3: Relationship between tree height with biomass (above, below and total) and total organic carbon (TOC) content of *Lumnitzera racemosa* (r^2 – coefficient of determination, p – Pearson correlation coefficient).

Table 6: Developed allometric models for determination of biomass and total organic carbon (TOC) of each plant component of *Bruguiera gymnorrhiza* and *Lumnitzera racemosa.*

Species	Component	Allometric model
Bruguiera gymnorrhiza	Above ground biomass	$0.068\ (H)^{2.848}$ *
	Below ground biomass	$0.015\ (H^{\ 3.026}$ *
	Total biomass (above + below)	$0.084\ (H)^{2.889}$ *
	Above ground TOC	$0.037\ (H)^{2.822}$ *
	Below ground TOC	$0.008\ (H)^{3.009}$ *
	TOC in total tree (above + below)	$0.045\ (H)^{2.871}$*

*Lumnitzera racemos*a	Above ground biomass	0.041 $(H)^{3.475}$ *
	Below ground biomass	0.032 $(H)^{2.952}$ *
	Total biomass (above + below)	0.088 $(H)^{3.151}$ *
	Above ground TOC	0.017 $(H)^{3.578}$ *
	Below ground TOC	0.014 $(H)^{3.026}$ *
	TOC in total tree (above + below)	0.031 $(H)^{3.390}$ *

(H= tree height; * Correlation coefficients (Pearson)< 0.001)

Accuracy of biomass estimation using developed allometric models

Estimated values of biomass using the developed allometric models were compared with actual data and other common allometric models proposed by Komiyama (2005), in which, diameter at breast height (dbh) is the quantifiable variable. The percentage differences between actual and estimated values of *B. gymnorrhiza* and *L.racemosa* were found to be less than 5% for above-ground biomass and less than 7% for below-ground biomass (Table 7). This actual data set was compared with allometric models of Komiyama (2005), and found to be less than 3% and 6% for above- and below-ground biomass, respectively (Table 7). The outcomes indicate a high reliability of using these developed allometric models to estimate biomass of these two plant species.

DISCUSSION

Despite relatively a small area under mangroves, Sri Lanka boasts 22 true mangrove plants species, of which *Bruguiera gymnorrhiza* and *Lumnitzera racemosa* are commonly found in all climatic zones of the island (Amarasinghe and Perera, 2017). Total organic carbon (TOC) values of wood of *Lumnitzera racemosa* (55.7% of the biomass) and *Bruguiera gymnorrhiza* (54.9% of the biomass) were relatively higher than that of other mangrove species in the island (Perera and Amarasinghe, 2016).

Relatively higher total organic carbon (TOC) contents were noted in above-ground components than that of in below-ground components of both mangrove species, *B. gymnorrhiza* and *L. racemosa.* This observation was common to all height classes (2- 20 m) of *L. racemosa*, with an average of above-ground: below-ground ratio of 2.6 (1.4-3.8). It was 3.2 (2.5-3.9) for *B. gymnorrhiza* trees with height range between 2-12 m. Komiyama *et al.* (2008) reported that this ratio for mangroves is generally between 2.0 - 3.0 as mangrove plants maintain bottom-heavy tree forms due to maintain the stability in typical muddy and anaerobic substratum, with a large proportion of biomass/ organic matter accumulated in their below-ground components, compared to other terrestrial plants/ trees. Extent of biomass accumulation in individuals of *B. gymnorrhiza* with comparable dbh in Australian mangroves (Twilley *et al*, 1992) revealed that above-ground biomass per tree in micro-tidal Negombo estuary is approximately twice as that has been estimated for individuals in macro-tidal Australian mangroves. This highlights the significance of the contribution of mangroves in countries belongs to lower latitudes for global carbon sink and the importance of their conservation.

A strong positive correlation ($p<0.01$) and a high coefficient of determination ($r^2>0.80$) were observed for diameter at breast height (dbh) and total tree height of the two species, *B. gymnorrhiza* and *L .racemosa* (Figure 1). Similar observations were reported by Aheto *et al*., (2011), Fu and Wu (2011) and Aleamyehu *et al*., (2014) for mangroves as well as in other terrestrial plant species (Mugasha *et al*., 2013 and Buba, 2013). The relationship between tree height and dbh (h-dbh) is often used to characterize forest stands. The height-dbh models for the tropical forests have been developed by Tewari and Van Gadow, (1999),

Table 7: Accuracy of estimated biomass of *Bruguiera gymnorrhiza* and *Lumnitzera racemosa* using the derived allometric equations and compared with common allometric models proposed by Komiyama (2005).

	Percentage differences between actual values	
B. gymnorrhiza	New allometric models	Allometric models by Komiyama *et al*., 2005
Above-ground biomass	4.90 (95.10)	2.74 (97.26)
Below-ground biomass	5.02 (94.98)	3.27 (96.73)
L. racemosa		
Above-ground biomass	4.11(95.89)	2.86 (97.14)
Below-ground biomass	7.00 (93.00)	5.85 (94.15)

(Percentage of reliability are given within parentheses)

Sharma (2009), and these relationships vary between tree species, age classes and localities (Poorter *et al*., 2006 and Mugasha *et al*., 2013) and therefore of restricted utility value. The accuracy of estimated biomass of developed allometric relationships was compared with the actual data set and revealed more than 95% of reliability for above-ground biomass and 93% of reliability for below-ground biomass (Table 7). Less than 2% of deviation was observed in comparing the new allometric relationships with the dbh allometric models introduced by Komiyama (2005).

The carbon accounting schemes such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation and Enhancing Carbon Stocks) has created widespread interest in determining carbon biomass in mangrove vegetation. Tree allometry is a widely used non-destructive method of estimating biomass and TOC. Statistically significant relationships of rates of growth between two components of a tree are the base for deriving allometric models. All the available allometric relationships of mangrove species (Amarasinghe and Balasubramaniam, 1992, Comley and McGuinness, 2005; Komiyama *et al*., 2005) are between biomass and dbh which require reaching each individual to take stem measurements. Typically, mangroves occurred in waterlogged and muddy substratum that cannot be accessed easily on foot. The present study revealed that tree height in place of dbh can reliably be used to estimate the biomass of trees (Table 6). As such, tree height, which can be measured from distance adopting methods using laser beams and remote sensing methods such as light detection and ranging (LiDAR) could overcome this issue by allowing the determination of tree heights to some extent of accuracy. Therefore, this can be employed conveniently to estimate the stand biomass of inaccessible mangroves.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no competing interests

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