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Allometric Modelling of the Vegetative Carbon Content in *Avicennia Marina* in a Tropical Mangrove Ecosystem

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Abstract: Mangrove ecosystems play an important role in managing global climate change by sequestering carbon and mitigating the concentration of atmospheric carbon dioxide. This study constructed allometric equations to evaluate the carbon sequestration capacity of the stems, leaves, and above-ground roots of *Avicennia marina*, a prevalent species in a distinctive mangrove ecosystem in northern Sri Lanka. This study examined the allometric relationships between the carbon content of leaves (C_L), stems (Cs), and above-ground roots (C_R) and specific, measurable tree parameters of *Avicennia marina*, such as diameter at breast height (DBH), merchantable stem height (MSH), crown height (CH), leaf area (LA), total tree height (TH), above-ground root height (RH), and above-ground root diameter (RD). Stepwise regression modelling with backward elimination was used to develop these relationships in SPSS Version 26 statistical software. The allometric equations derived from the models for carbon content of stems (Ln Cs = -0.922 + 0.72 Ln DBH + 0.17 Ln LA), leaves (Ln C_L = -0.647 + 0.335 Ln LA), and above-ground roots (Ln C_R = -5.5 + 0.463 Ln RD) showed a reliability of 84.9%, 89.9%, and 62.5%, respectively. These models were identified as the best fit

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for predicting the respective carbon contents. They permit unrestricted reuse, distribution, and reproduction provided that the original article is properly cited. Based on the model bias value, modelling efficiency value, p-value, and residual plot, these models were identified as the best fit to predict the respective carbon contents of *Avicennia marina*. The allometric models developed in this study will be useful for monitoring the annual carbon sequestration potential of mangrove ecosystems in the Jaffna Lagoon in Sri Lanka. These models will also provide insight for assessing tradeable carbon credits in alignment with the REDD+ and Blue Carbon frameworks.

Keywords: Carbon sequestration; Jaffna lagoon; Sri Lanka

1. Introduction

Mangroves are highly adapted plant species that grow in the brackish water and saltwater wetlands in the tropical and subtropical regions of the world. Mangroves account for approximately 1% of tropical forest cover [1,2]. Recent studies have found that mangrove ecosystems can store atmospheric carbon at rates up to ten times higher than tropical forests [3,4]. Mangroves are the only blue carbon forests and account for high rates of carbon sequestration, making them significant contributors to mitigating climate change [5–7].

Approximately 7% of the world's mangrove forests are located in the South Asian region, where there is a high abundance of mangroves along the coastlines of India, Bangladesh, Pakistan, and Sri Lanka [8]. As an island nation, Sri Lanka has a rich diversity of mangroves, which are distributed in discontinuous patches along the coast and are restricted to estuarine and lagoon ecosystems [9,10]. In Sri Lanka, mangrove forests are primarily found along the northern coast, including the Jaffna, Vadamarchchi, and Thondiamannar lagoons; Trincomalee; Kathiraveli; Valaichenai; Batticaloa; and Pothuvil on the eastern coast [11]. Mangroves can also be found on the southern coast in Weligama, Gintota, Balapitiya, and Bentota and on the western and northwestern coasts in Negombo, Chilaw, Puttalam Lagoon, and Mannar [12]. These are highly diverse ecosystems containing true mangrove species and associates. Mangrove ecosystems in Sri Lanka are vital for stabilizing the coast. Additionally, they provide habitats, control pollution, and sequester carbon [13,14]. The potential level of carbon sequestration by mangroves depends heavily on the species of trees and environmental characteristics [15,16].

The Jaffna Peninsula, located in the northernmost region of Sri Lanka, has unique climatic and soil characteristics and contains large areas of undisturbed mangrove forests [17]. Mangroves are the primary forest type in the area, and seven species of true mangroves have been recorded there [18]. *Avicennia marina* is the dominant species, distributed throughout the southern and western parts of Jaffna and its surrounding islands [19]. However, the diversity, environmental importance, economic importance, and carbon sequestration potential of mangroves in this region of Sri Lanka have been poorly studied due to the three-decade-long armed conflict that prevailed in northern Sri Lanka. Following the conclusion of the conflict, some researchers assessed the diversity and distribution of mangrove species in the Jaffna Peninsula [18,19]. However, the carbon sequestration potential of the mangrove forests in this region has yet to be quantified. Due to the stressful environmental conditions in this area, destructive approaches to assessing carbon sequestration are not applicable, as they could further destroy the sensitive mangrove ecosystems. Therefore, this study aimed to develop allometric equations to assess the vegetative carbon sequestration capacity of mangrove forests on the Jaffna Peninsula in Sri Lanka, with a specific focus on the dominant species, *Avicennia marina*.

2. Methodology

2.1. Study Area and Selection of Sampling Sites

The map of the sampling sites is given in Figure 1. Sampling was conducted in five study sites, specifically, Site A: Ariyalai East (9°37′07.9″ N, 80°05′55.3″ E), Site B: Thanankilappu (9°37′56.2″ N, 80°08′53.7″ E), Site C: Navali South (9°41′38.4″ N, 79°58′22.6″ E), Site D: Mandaitivu Islands (9°37′15.8″ N, 80°00′10.0″ E), and Site E: Allaipiddy (9°61′47.41″ N, 79°96′32.27″ E), all of which are located in the Jaffna lagoon (Figure 1).

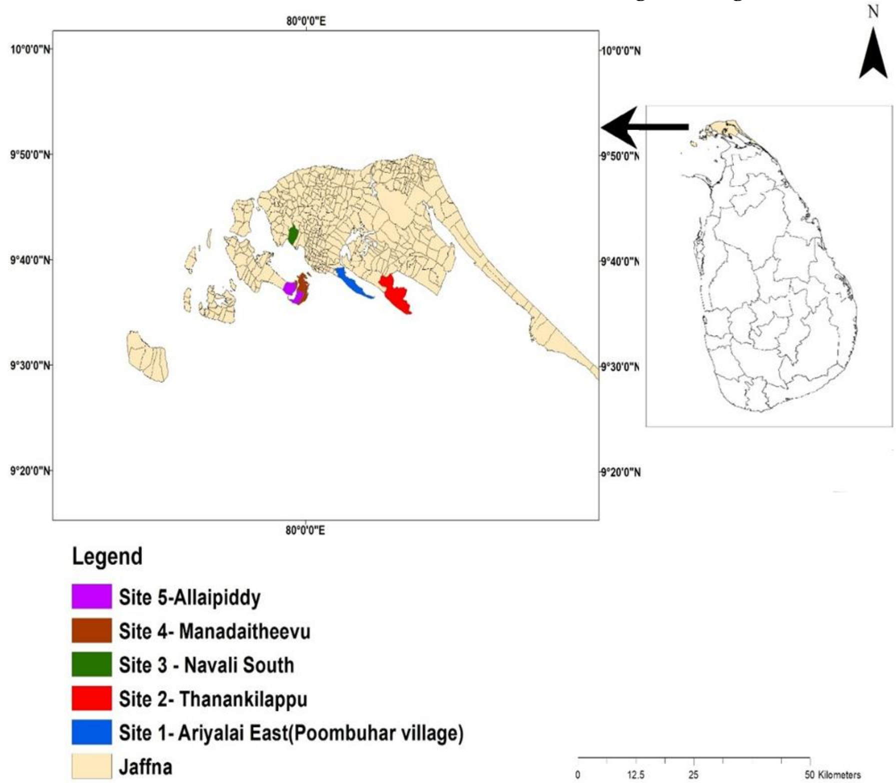

Figure 1. Map of the study area showing the sampling sites.

2.2. Sample Collection and Measurable Tree Parameters

Undisturbed mangrove patches were selected from each study site. Thirty mature *Avicennia marina* plants were sampled from each site using purposive sampling. The sampled trees' diameters at breast height (DBH) ranged from 5 to 12 cm. Damaged trees and leafless trees were excluded from the sample.

The diameter tape was used to measure the DBH of each sampled tree, and a clinometer method was used to estimate the total tree height, merchantable stem height, and crown height. Five above-ground roots from each sampled tree were selected, and the diameter tape was used to measure the diameter and the root height of each aerial root. Using an increment borer, a 2 cm core sample was collected from each tree at breast height and from the above-ground roots 15 cm from the ground, causing relatively minor injury to the trees. The initial volumes of the trunk and root samples were measured using Archimedes' displacement principle [20].

Seventy-five mature, undamaged leaves were randomly selected from each tree. The ImageJ software was used to assess the mean leaf area, which was then multiplied by the number of leaves on one branch and by the total number of branches on one tree. The core and leaf sample extraction procedures were repeated for all sampled trees at each site.

2.3. Determination of the Fixed Carbon Content in the Stem, Root and Leaf Samples

The organic matter content of the root and stem core samples and leaves was determined using the loss-on-ignition method described by Guendehou and Lehtonen (2014) [21].

The core and leaf samples were oven-dried at 105°C until they reached a constant weight. The weight of the oven-dried samples (W1) was then measured using an electronic balance. Then, the samples were ignited at 450°C in a muffle furnace for 24 hours. After cooling to room temperature, the final ash weight (W2) was measured using the same balance. All of the samples described above were placed in a pre-weighted crucible (W0) during the experiment. This procedure was repeated for all the core samples [22]. The amount of organic matter in the sample was calculated using the formula described by Sabin (2008) [23]:

$$\mathrm{OM} = (\mathrm{W1} - \mathrm{W0}) - (\mathrm{W2} - \mathrm{W0})$$

The Van Bemmelen factor (1.724) was used to divide the amount of organic matter in the sample and estimate the amount of carbon [23].

2.4. Model Construction, Evaluation, and Validation

Stepwise regression analysis with backward elimination was used to develop the allometric models to estimate the carbon content of the stems, leaves, and above-ground roots of *Avicennia marina*. These models were based on the DBH, total tree height, merchantable stem height, crown height, leaf area, root height, and root diameter. We used the statistical software IBM SPSS Statistics Version 26 for this analysis. 75% of the data were used to construct the model, and the remaining 25% were used to validate the model based on a random split [20]. The regression model for the stem carbon content of *Avicennia marina* used DBH, total tree height, crown height, merchantable stem height, and leaf area as the independent variables. The regression model for leaf carbon content used the same variables. The regression model for above-ground root carbon content used DBH, total tree height, root height, and root diameter as independent variables.

The data were tested for normality using the Anderson-Darling test. The non-normalized data were then transformed using the natural logarithm (Ln). Multicollinearity among the independent variables was tested at the 95% level of significance, and variables with significantly high multicollinearity were excluded from model construction.

The best-fit models for stem, leaf, and above-ground root carbon content were selected based on model bias, modelling efficiency, p-value, and R^2 value. Residual plots were observed for each constructed model, as described by Subasinghe and Haripriya (2014) and Wijeyaratne and Liyanage (2022) [20,24]. Model validation was performed using data not used for model construction. We validated the selected best-fit models based on the random distribution of residual values and by comparing the predicted and actual carbon contents using a two-sample t-test at the 95% level of significance.

3. Results and Discussion

Table 1 summarizes the measured parameters of *Avicennia marina* sampled from the five study sites.

The mean total height, crown height, and aboveground root diameter of *Avicennia marina* sampled from different study sites did not differ significantly from each other. However, the DBH of *Avicennia marina* in sites A and E was significantly lower than in the other sites at the 95% level of significance. *Avicennia marina* sampled from site B had a significantly higher mean merchantable stem height and a significantly lower mean root length and diameter compared to the other sites at the 95% level of significance. *Avicennia marina* from sites D and E had significantly higher leaf area than other sites. Site C had significantly lower leaf area than other sites ($p < 0.05$, ANOVA, Tukey’s pairwise comparison, Table 1).

3.1. Model Construction and Evaluation

Separate allometric models were developed to predict the carbon content of the stems, leaves, and above-ground roots of *Avicennia marina* using measurable tree parameters. The best-fit model was selected based on each model's variance inflation factor (VIF) and R^2 value. VIF measures the multicollinearity between the variables used in the model. A VIF greater than 5 indicates high multicollinearity, while a VIF between 1 and 5 indicates moderate multicollinearity. A VIF of 1 indicates no multicollinearity between the explanatory variables; thus, the models with these variables were selected as the best-fit models for prediction [5]. Additionally, models with a p-value lower than the level of significance (0.05) and an R^2 value greater than 0.65 can be considered best-fit.

3.2. Allometric Models to Predict the Stem Carbon Content of Avicennia Marina

The best-fit model to predict the stem carbon content of *Avicennia marina* was constructed using the following independent variables: Ln DBH, Ln total height (TH), Ln merchantable stem height (MSH), Ln crown height (CH), and Ln leaf area (LA). The p-values and R^2 values of the models used to predict the stem carbon content of *Avicennia marina* in the Jaffna lagoon are presented in Table 2. Table 3 shows the variance inflation factors for the tree parameters of each model.

The backward elimination regression process resulted in four models that predict stem carbon content in *Avicennia marina* (Table 2). Based on VIF, p-value, and R^2 values (Table 3), the following model was selected as the best model for predicting stem carbon content in *Avicennia marina* in the Jaffna lagoon in Sri Lanka:

$$\text{Ln Cs} = -0.922 + 0.72 \text{ Ln DBH} + 0.17 \text{ Ln LA}$$

Where Cs is the stem carbon content, DBH is the diameter at breast height, and LA is the leaf area.

Table 1. Descriptive statistics of tree parameters of *Avicennia marina* sampled from study sites in the Jaffna lagoon. Data are presented as mean ± standard deviation. Values in parentheses indicate the range of each parameter. Means with different superscript letters within a row are significantly different from each other (one-way ANOVA, Tukey's pairwise comparison, $p < 0.05$, $n = 25$ for each site).

	Site A	Site B	Site C	Site D	Site E
Diameter at breast height (cm)	3.04 ± 0.54^{a}	4.91 ± 2.42^{b}	4.31 ± 1.16^{b}	4.02 ± 1.25^{b}	2.92 ± 0.60^{a}
Total height (m)	2.19 ± 0.54^{a}	2.61 ± 0.91^{a}	2.34 ± 0.61^{a}	2.39 ± 0.53^{a}	2.53 ± 0.82^{a}
Merchantable stem height (m)	1.19 ± 0.40^{a}	6.42 ± 0.82^{b}	1.43 ± 0.62^{a}	1.45 ± 0.46^{a}	1.2 ± 0.51^{a}
Crown height(m)	1.44 ± 0.38^{a}	$1.67 \pm .93^{a}$	1.61 ± 0.53^{a}	1.53 ± 0.40^{a}	1.52 ± 0.55^{a}
Leaf area (m^2)	23.73 ± 9.67^{a}	28.77 ± 6.25^{a}	11.76 ± 2.61^{b}	34.25 ± 6.51^{c}	39.02 ± 5.6^{c}
Root height (cm)	38.18 ± 3.59^{a}	2.68 ± 0.63^{b}	37.62 ± 4.65^{a}	45.09 ± 6.25^{c}	36.52 ± 7.02^{a}
Root diameter (cm)	1.72 ± 0.23^{a}	0.83 ± 0.23^{b}	1.68 ± 0.22^{a}	1.74 ± 0.29^{a}	1.52 ± 0.23^{a}

Table 2. The p-values and R^2 values of the constructed models to predict the stem carbon content of *Avicennia marina* in the Jaffna lagoon.

Model	R^2 value	Excluded variables	p-value
Ln Cs = -0.898 + 0.743 Ln DBH + 0.034 Ln TH + 0.054 Ln MSH + 0.35 Ln CH + 0.144 Ln LA	0.626	-	0.189
Ln Cs = -0.886 + 0.798 Ln DBH + 0.060 Ln MSH + 0.051 Ln CH + 0.14 Ln LA	0.626	TH	0.125
Ln Cs = -0.898 + 0.72 Ln DBH + 0.668 Ln MSH + 0.16 Ln LA	0.624	TH, CH	0.089
Ln Cs = -0.922 + 0.72 Ln DBH + 0.17 Ln LA	0.849	TH, CH, MSH	0.000

DBH: Diameter at breast height; TH: Total height; MSH: Merchantable stem height; CH: Crown height; LA: Leaf area.

Table 3. The VIF values and p-values for each tree parameter of the constructed models to predict the stem carbon content of *Avicennia marina* in the Jaffna lagoon.

Tree parameter	VIF	p-value
Model 1: Ln Cs = -0.898 + 0.743 Ln DBH + 0.034 Ln TH + 0.054 Ln MSH + 0.35 Ln CH + 0.144 Ln LA		
Ln DBH	1.25	0.000
Ln TH	15.23	0.897
Ln MSH	8.52	0.507
Ln CH	5.23	0.767
Ln LA	6.12	0.149
Model 2: Ln Cs = -0.886 + 0.798 Ln DBH + 0.060 Ln MSH + 0.051 Ln CH + 0.14 Ln LA		
Ln DBH	1.85	0.000
Ln MSH	21.21	0.530
Ln CH	20.45	0.600
Ln LA	15.11	0.141
Model 3: Ln Cs = -0.898 + 0.72 Ln DBH + 0.668 Ln MSH + 0.16 Ln LA		
Ln DBH	1.45	0.000
Ln MSH	12.56	0.462
Ln LA	8.56	0.910
Model 4: Ln Cs = -0.922 + 0.72 Ln DBH + 0.17 Ln LA		
Ln DBH	1.00	0.000
Ln LA	1.00	0.023

DBH: Diameter at breast height; TH: Total height; MSH: Merchantable stem height; CH: Crown height; LA: Leaf area.

3.3. Allometric Models to Predict the Leaf Carbon Content of Avicennia Marina

We used Ln DBH, Ln total height (TH), Ln merchantable stem height (MSH), Ln crown height (CH), and Ln leaf area (LA) as independent variables to construct the best-fit model for predicting the leaf carbon content of *Avicennia marina*. The p-values and R^2 values of the models used to predict leaf carbon content of *Avicennia marina* in the Jaffna lagoon are presented in Table 4. Table 5 shows the variance inflation factors for the tree parameters of each model.

Five models were developed to predict the leaf carbon content of *Avicennia marina* (Table 5). Based on the p-value, R^2 value, and VIF (Table 6), the following model was identified as the best fit:

$$\text{Ln } C_L = -0.647 + 0.335 \text{ Ln LA}$$

where C_L is the leaf carbon content and LA is the leaf area.

3.4. Allometric Models to Predict the Above-Ground Root Carbon Content of Avicennia Marina

We used Ln DBH, Ln total tree height (TH), Ln root diameter (RD), and Ln root height (RH) as independent variables to construct the best-fit model for predicting the above-ground root carbon content of *Avicennia marina*. Table 6 presents the p-values and R^2 values of the constructed models to predict the above-ground root carbon content of *Avicennia marina* in the Jaffna lagoon. Table 7 shows the variance inflation factors for the tree parameters of each constructed model for leaf carbon content.

The backward elimination regression resulted in four models for predicting above-ground root carbon content in *Avicennia marina* (Table 6). The VIF, p-value, and R^2 value of the models (Table 7) suggest that the following model is the best fit to predict above-ground root carbon content in *Avicennia marina* in the Jaffna lagoon:

$$\text{Ln } C_R = -5.5 + 0.463 \text{ Ln RD}$$

where C_R is the above-ground root carbon content and RD is the root diameter.

Table 4. The p-values and R^2 values of the constructed models to predict the leaf carbon content of *Avicennia marina* in the Jaffna lagoon.

Model	R^2 value	Excluded variables	p-value
Ln C_L = -0.805 + 0.163 Ln DBH + 0.030 Ln TH - 0.029 Ln MSH - 0.006 Ln CH + 0.326 Ln LA	0.525	-	0.526
Ln C_L = -0.803 + 0.165 Ln DBH - 0.036 Ln TH + 0.029 Ln MSH + 0.325 Ln LA	0.546	CH	0.245
Ln C_L = -0.809 + 0.153 Ln DBH - 0.633 Ln MSH + 0.323 Ln LA	0.552	TH, CH	0.235
Ln C_L = -0.790 + 0.132 Ln DBH + 0.320 Ln LA	0.649	TH, CH, MSH	0.089
Ln C_L = -0.647 + 0.335 Ln LA	0.869	TH, CH, MSH, DBH	0.000

DBH: Diameter at breast height; TH: Total height; MSH: Merchantable stem height; CH: Crown height; LA: Leaf area.

Table 5. The VIF values and p-values for each tree parameter of the constructed models to predict the leaf carbon content of *Avicennia marina* in the Jaffna lagoon.

Tree parameter	VIF	p-value
Model 1: Ln C_L = -0.805 + 0.163 Ln DBH + 0.030 Ln TH - 0.029 Ln MSH - 0.006 Ln CH + 0.326 Ln LA		
Ln DBH	11.25	0.458
Ln TH	12.85	0.856
Ln MSH	18.42	0.326
Ln CH	15.11	0.458
Ln LA	5.28	0.000
Model 2: Ln C_L = -0.803 + 0.165 Ln DBH - 0.036 Ln TH + 0.029 Ln MSH + 0.325 Ln LA		
Ln DBH	11.32	0.532
Ln MSH	13.20	0.538
Ln TH	15.45	0.689
Ln LA	4.56	0.000
Model 3: Ln C_L = -0.809 + 0.153 Ln DBH - 0.633 Ln MSH + 0.323 Ln LA		
Ln DBH	11.45	0.635
Ln MSH	14.25	0.642
Ln LA	3.45	0.000
Model 4: Ln C_L = -0.790 + 0.132 Ln DBH + 0.320 Ln LA		
Ln DBH	8.52	0.075
Ln LA	1.45	0.000
Model 5: Ln C_L = -0.647 + 0.335 Ln LA		
LA	1.00	0.000

DBH: Diameter at breast height; TH: Total height; MSH: Merchantable stem height; CH: Crown height; LA: Leaf area.

Table 6. The p-values and R^2 values of the constructed models to predict the above-ground root carbon content of *Avicennia marina* in the Jaffna lagoon.

Model	R^2 value	Excluded variables	p-value
$\ln C_R = -4.7 - 0.16 \ln DBH - 0.023 \ln TH - 0.178 \ln RH + 0.52 \ln RD$	0.245	-	0.865
$\ln C_R = -4.75 + 0.172 \ln DBH - 0.176 \ln RH + 0.52 \ln RD$	0.346	TH	0.323
$\ln C_R = -5.2 - 0.095 \ln DBH + 0.462 \ln RD$	0.421	TH, RH	0.125
$\ln C_R = -5.5 + 0.463 \ln RD$	0.625	TH, RH, DBH	0.000

DBH: Diameter at breast height; TH: Total height; RH: Root height; RD: Root diameter.

Table 7. The VIF values and p-values for each tree parameter of the constructed models to predict the above-ground root carbon content of *Avicennia marina* in the Jaffna lagoon.

Tree parameter	VIF	p-value
Model 1: Ln C_R = -4.7 - 0.16 Ln DBH - 0.023 Ln TH - 0.178 Ln RH + 0.52 Ln RD		
Ln DBH	19.63	0.331
Ln TH	17.89	0.878
Ln RH	15.23	0.252
Ln RD	1.12	0.000
Model 2: Ln C_R = -4.75 + 0.172 Ln DBH - 0.176 Ln RH + 0.52 Ln RD		
Ln DBH	13.26	0.235
Ln RH	14.75	0.250
Ln RD	1.45	0.000
Model 3: Ln C_R = -5.2 - 0.095 Ln DBH + 0.462 Ln RD		
Ln DBH	12.63	0.459
Ln RD	1.25	0.000
Model 4: Ln C_R = -5.5 + 0.463 Ln RD		
Ln RD	1.00	0.000

DBH: Diameter at breast height; TH: Total height; RH: Root height; RD: Root diameter.

3.5. Model Evaluation

The best-fit models were evaluated based on quantitative and qualitative evaluations.

3.5.1. Quantitative Evaluation

The suitability of the model to predict the carbon content was evaluated based on the calculated model bias and modelling efficiency values. Table 8 shows the model bias and efficiency values for the best-fit models.

Table 8. The model bias and the modelling efficiency value of the best-fit model selected to predict the carbon content of the stem, leaf, and above-ground root of *Avicennia marina*.

Model	Model bias value (MB)	Modelling efficiency value (ME)
Stem: **Ln Cs = -0.922 + 0.72 Ln DBH + 0.17 Ln LA**	0.039985	0.644284
Leaf: **Ln C_L = -0.647 + 0.335 Ln LA**	-0.0271	0.784613
Above ground root: **Ln C_R = -5.5 + 0.463 Ln RD**	-0.00214	1.000303

A model bias value closer to 0 and a model efficiency value closer to 1 indicate a good fit and the predictive ability of a model, respectively. The model bias values for the allometric equations developed to predict the carbon content of the stem, leaf, and above-ground root of *Avicennia marina* in the Jaffna Lagoon were 0.0399, 0.027, and 0.021, respectively, and the model efficiency values were 0.82, 0.78, and 1.00, respectively, indicating that these models are suitable for predicting the carbon content of different plant parts (Table 8).

Furthermore, the constructed models were used to predict the carbon content of the stems, leaves, and above-ground roots of *Avicennia marina* based on the measured tree parameters of the remaining 25% of the data set. Table 9 shows the mean values of the measured and predicted carbon contents for the stems, leaves, and above-ground roots of *Avicennia marina* based on the best-fit models.

The results of the two-sample t-tests showed that the actual carbon content of *Avicennia marina* sampled from the Jaffna lagoon does not differ significantly from the predicted values based on the best-fit allometric equations selected (Table 9). Cohen's d values for the t-test were less than 0.2, indicating a small effect size. Thus, the results confirm that the developed allometric models can successfully predict the carbon content of the stem, leaf, and above-ground root of *Avicennia marina* sampled from the Jaffna lagoon.

Table 9. The mean values of the measured carbon contents and the predicted carbon contents based on the best-fit models for the stems, leaves, and above-ground roots of *Avicennia marina* in the Jaffna Lagoon. The data are presented as mean ± standard deviation. Similar superscripts in each row indicate no significant difference between the measured and predicted values at the 95% level of significance using a two-sample t-test.

Part of the tree	Measured carbon content	Predicted carbon content	p-value	Cohen's d
Leaves	1.491±0.114[a]	1.4642±0.0552[a]	0.831	0.12
Stems	1.788±0.129[b]	1.748±0.172[b]	0.853	0.15
Above-ground roots	0.01342±0.00109[c]	0.01556±0.00193[c]	0.341	0.21

3.5.2. Qualitative Evaluation

We used the residual plots of the best-fit models for a qualitative evaluation of the models. Figure 2, Figure 3, and Figure 4 show the residual plots of the best-fit models for predicting stem, leaf, and above-ground root carbon content, respectively. The residual diagram of the best-fit model for the stem carbon content shows a random distribution of residuals between 0.5 and -0.5, with two outliers (Figure 2). The residual diagram of the best-fit model for leaf carbon content shows a random distribution between 0.25 and -0.5 with two outliers (Figure 3). The residual diagram of the best-fit model for the above-ground root carbon content shows a random distribution between 1.0 and -1.0 with a single outlier (Figure 4). These random patterns indicate that these models can be used to predict the corresponding carbon contents using real data [20].

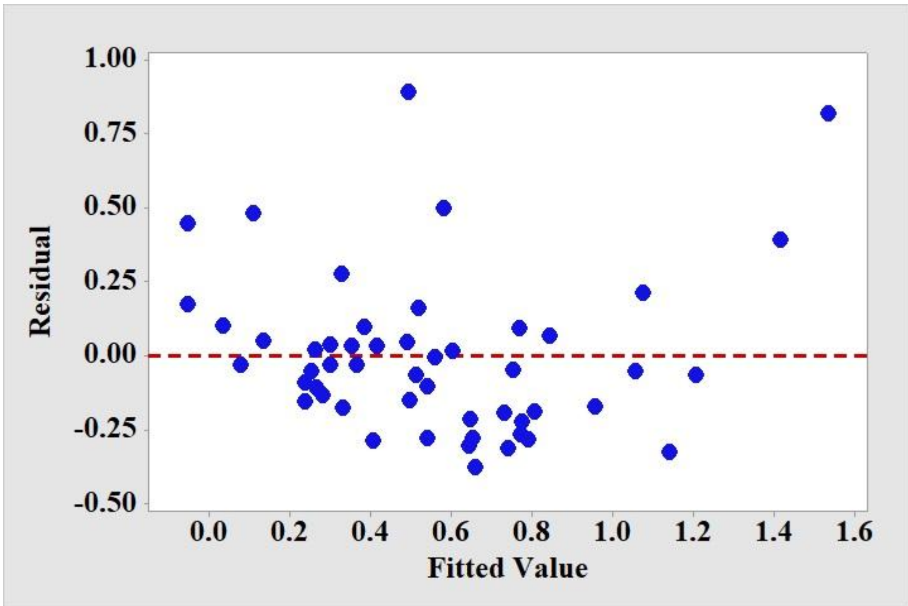

Figure 2. The residual diagram for the residual versus actual values for the stem carbon content of *Avicennia marina*.

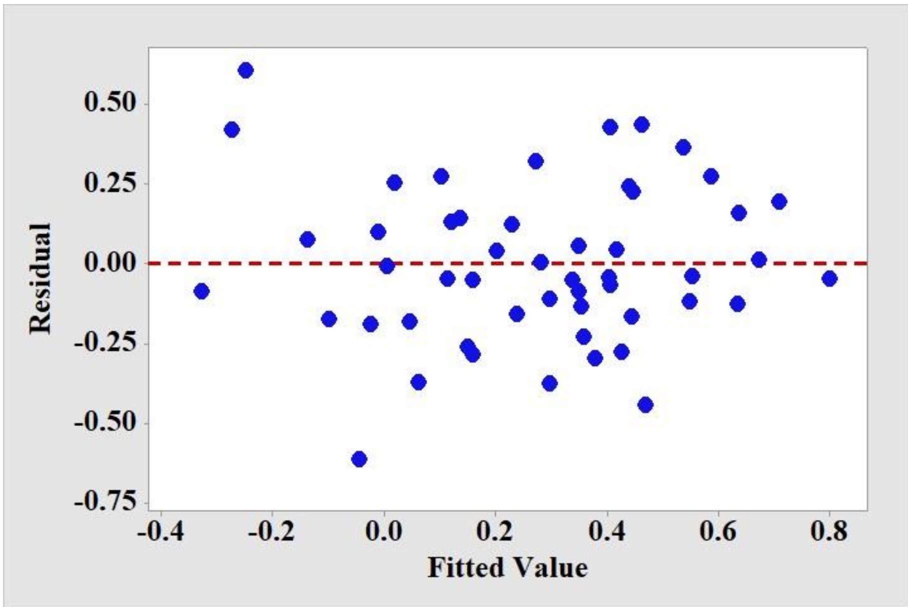

Figure 3. The residual diagram for the residual versus actual values for the leaf carbon content of *Avicennia marina*.

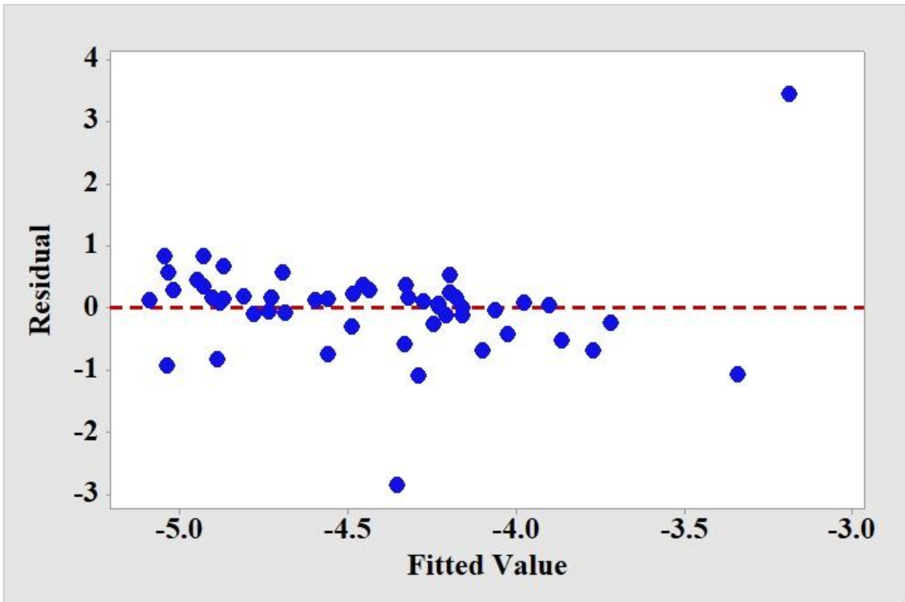

Figure 4. The residual diagram for the residual versus actual values for the above ground root carbon content of *Avicennia marina*.

Researchers have increasingly turned to allometric modelling to identify potentially useful mangrove species for restoration programs that mitigate the impacts of climate change [25]. Many studies have used allometric models to quantify the aboveground biomass of mangrove forests worldwide [26]. Non-destructive methods of estimating stem carbon content have the advantage of using simple, measurable tree parameters. These methods are also more environmentally friendly because they do not involve removing trees. Furthermore, the results can be used to predict the stem carbon content of a large number of similar trees [20].

Allometric models developed for mangrove species in recent decades have demonstrated species- and site-specificity [27–29].

The capacity of mangroves to sequester carbon can vary geographically due to variations in temperature, sunlight, and water quality [30]. Furthermore, studies have suggested that high salinity can significantly impact the growth rate of mangrove plants, thereby indirectly affecting the potential of different plant parts to sequester carbon. Soil temperature variations can increase evaporation, which raises soil salinity. Increased salinity slows the growth rate of mangroves. Increased salinity slows the growth rate of mangroves. Tidal activity can also impact the long-term carbon sequestration potential of mangroves [31]. Incoming tidal fluxes support the mangrove forest by bringing in nutrient-rich allochthonous material and carrying away high-salinity waters. Insufficient freshwater input can cause increased salinity concentrations, which can lead to physiological stress in mangrove trees. This results in the trees expending more energy on osmotic regulation and less energy on growth and carbon sequestration [32,33].

Furthermore, climate change affects forest growth and productivity because warming temperatures can extend the growing season [34]. Mangrove growth is highest in nutrient-rich soils with no water limitations, decreasing with lower fertility and water supply [35]. The occurrence of short-term and long-term disturbances can also affect the carbon sequestration potential of mangrove trees [36]. Disturbances can interact with one another and affect the carbon sequestration capacity. Some disturbances, such as droughts, can reduce the capacity for carbon sequestration [20]. These factors may explain the differences in mangrove carbon sequestration capacity observed by researchers in different geographical locations at different times.

The structural development and architecture of trees are often related [37]. Allometric models used to predict above-ground carbon biomass in mangrove forests have limitations related to species-specific measurable tree parameters. Therefore, when developing species- and site-specific allometric models, it is important to consider the spatial scales of the structural variability of mangrove forests. Standardizing environmental conditions and successional stage is critical for precise allometric models [38]. The authors should also mention these criteria so that the developed model can be used for the same species in other forests with similar environmental conditions [29].

4. Conclusion

This study identified three allometric equations that can be used to predict the carbon content of the stems, leaves, and above-ground roots of *Avicennia marina* sampled from a unique mangrove ecosystem in northern Sri Lanka. These findings can be used to evaluate the carbon storage capacity of mangrove ecosystems in this area and could inform carbon stock valuation and trading under the United Nations' REDD+ (Reducing Emissions from Deforestation and Forest Degradation, Conservation and Enhancement of Carbon Stocks, and Sustainable Management of Forests) Blue Carbon initiatives. These results can also encourage rational decision-making regarding the conservation and management of mangrove areas due to their capacity for carbon sequestration and potential to mitigate predicted climate changes.

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