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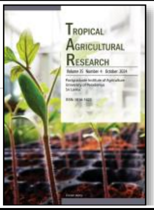

RESEARCH

Allometric Models for Estimating Above-Ground, Below-Ground and Total Biomass of Tea (*Camellia sinensis* (L.) O. Kuntze) Plants Grown in Uva and Up Country, Sri Lanka

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ABSTRACT

This study was conducted to identify the dendrometric variables highly correlating with above-ground (AGB), below-ground (BGB) and total (TB) biomass of tea grown in Uva and Up Country Sri Lanka, develop allometric models to estimate AGB, BGB and TB of tea plants, and to investigate the applicability of already developed allometric models in other countries to Sri Lanka. Twelve experimental plots from TRIORCON field experiment at Tea Research Institute of Sri Lanka, and 18 farmer fields in Uva region, Sri Lanka were selected as the study sites. Representative tea plants were uprooted from the selected sites and seven dendrometric variables were measured. Fresh and dry AGB and BGB of the tea plants were determined. The best allometric models to predict AGB, BGB and TB using dendrometric variables were developed using multiple linear and non-linear regression analyses. Non-linear allometric models fitted best when predicting AGB and TB. Over 64% of total variability of AGB and TB was explained by these models using collar diameter at the soil level. Linear allometric fitted best when predicting BGB. Over 92% of total variability of BGB was explained by linear regression models using collar circumference, main-stem circumference, mean length and circumference at end of the primary branches. Leave-one-out cross validation showed strong positive (AGB and TB) and moderate positive (BGB) correlations between observed and predicted biomass values. Developed linear allometric models in comparison to those in literature showed better fit to data collected under Sri Lankan conditions and precisely estimated AGB, BGB and TB.

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INTRODUCTION

Tea (*Camellia sinensis* (L.) O. Kuntze) is a perennial evergreen beverage crop cultivated mainly in Asia, Africa and the Near East (Kalita et al., 2015). Tea crop is maintained as a plant for continuous harvesting of shoots. Harvested shoots are used for the production of made tea which is a popular beverage in the world.

Accurate estimation of biomass paves path for better understanding of biomass dynamics, net primary productivity, yield, nutrient cycling and budgeting for research purposes in a given ecosystem (Hossain et al., 2008; Litton and Kauffman, 2008; Mahmood et al., 2019). Allometric models are commonly used for estimating plant biomass (Segura and Kanninen, 2005; Litton and Kauffman, 2008; Vieilledent et al., 2012; Chave et al., 2014). Allometric model refers to a mathematical relationship which predicts biomass based on easily measurable dendrometric variables such as diameter at breast height, total height and wood density (Sileshi, 2014). Global allometric equations applicable for any plant species were initially developed to estimate biomass (José Návar, 2010; Sileshi, 2014; Latifah et al., 2021). However, with the advancement of data availability and science and technology, allometric equations have been developed for individual species(species-specific or generic allometric equations) or multiple species covering local and regional scales to estimate biomass in more precise manner (Fayolle et al., 2013; Xiang et al., 2016; Salmona et al., 2018; Abich et al., 2019; Daba and Soromessa, 2019).

Existing allometric models to predict standing biomass have been developed for naturally grown trees characterized by a single principal stem well-developed in height. However, tea is a perennial, which is being subjected to pruning once in 3-5 years at a height of 0.40 -0.55 m above the ground level for easy harvesting. Natural growth of tea plant is further affected by continuous, almost weekly harvesting, during which the young shoots containing the apical bud and 2-3 adjoining young leaves are removed. Therefore, allometric models available in the literature may not be directly applied to estimate biomass of tea plants which are being subjected to continuous modification. Despite these limitations, a few attempts have been made to develop allometric equations for tea in India (Kalita et al., 2015; 2016) and Thailand (Sasaki et al., 2020).

The applicability of the allometric equations present in the literature have not been explored to estimate biomass of tea plants grown in Sri Lanka due to the variations in the climatic conditions, cultivars, pruning patterns, and other agronomic practices. Moreover, some of the allometric equations developed are based on age of the tea plants (Kalita et al., 2015), although there are many other simplified dendrometric variables to be considered. Therefore, this study was conducted to (i) investigate the dendrometric variables highly correlated with the biomass of tea, (ii) investigate the applicability of the already developed allometric models in other countries to Sri Lanka, and (iii) develop best allometric relationships to estimate the above ground, below ground and total biomass of tea plants in grown in Sri Lanka.

METHODOLOGY

Selection of study site

In order to develop generic allometric models for tea, data were collected from tea fields representing diverse crop management options, i.e., from tea plants cultivated under both organic or conventional systems for the last 25 years (TRIORCON field experiment) at the Tea Research Institute (TRI), Talawakelle of Sri Lanka and 18 selected farmers' fields in Uva region (under different management systems for 6-65 years), Sri Lanka. The organically managed plots were selected from the certified organic farmers. Details of the selected tea plants are shown in Table 1.

Analyses on uprooted tea plants

Seven dendrometric variables were measured in each tea bush selected for uprooting. Collar region, main stem and primary branches are the most undisturbed, long-standing plant parts of tea plants. Therefore, the selected variables were, collar circumference at soil surface (CCSL), main stem circumference at 6 cm height from soil surface (CCSH), height from soil surface to the beginning of primary branch (HSLPB), Number of primary branches (NPB), mean length of primary branches (LPB), mean circumference at the beginning (CBPB) and the end (CEPB) of primary branches. These variables were expected to correlate with tea biomass since they are the measurements related to long-standing biomass of tea plants. Age of the tea plants uprooted (AGE) also were recorded.

Uprooting and biomass assessment of tea plants

Biomass assessment was carried out using a destructive method. Total of 64 representative healthy, vigorously grown, and single stem tea plants were uprooted from the selected plots/fields as shown in Table 1. First, the above ground portion was separated by cutting the plant at the soil level of the collar using a hand-saw, and all the roots were carefully recovered from the soil. Saw dust was also collected and added to the biomass. Plant parts in each uprooted tea bush were separated into Above Ground biomass (AGB) and Below Ground biomass (BGB) as shown in Figure 1 a and g. Both fresh and dry weights of separated plant parts were measured. Description of each step is given in the following sections.

Table 1. Characteristics of selected tea plots and number of uprooted tea plants

Location	Input management	Size category and management	Number of selected plots	Number of uprooted tea plants
Uva region (Tea fields in Welimada, Bandarawela, Diyathalawa and Haputhale areas)	Organic	Smallholder farmer	8	8
		Large-scale estate plantation	3	9
	Conventional	Smallholder farmer	5	5
		Large-scale estate plantation	2	6
Up Country (TRIORCON long-term experimental area, Talawakelle)	Organic	experimental tea plots	9	27
	Conventional	experimental tea plots	3	9
				64

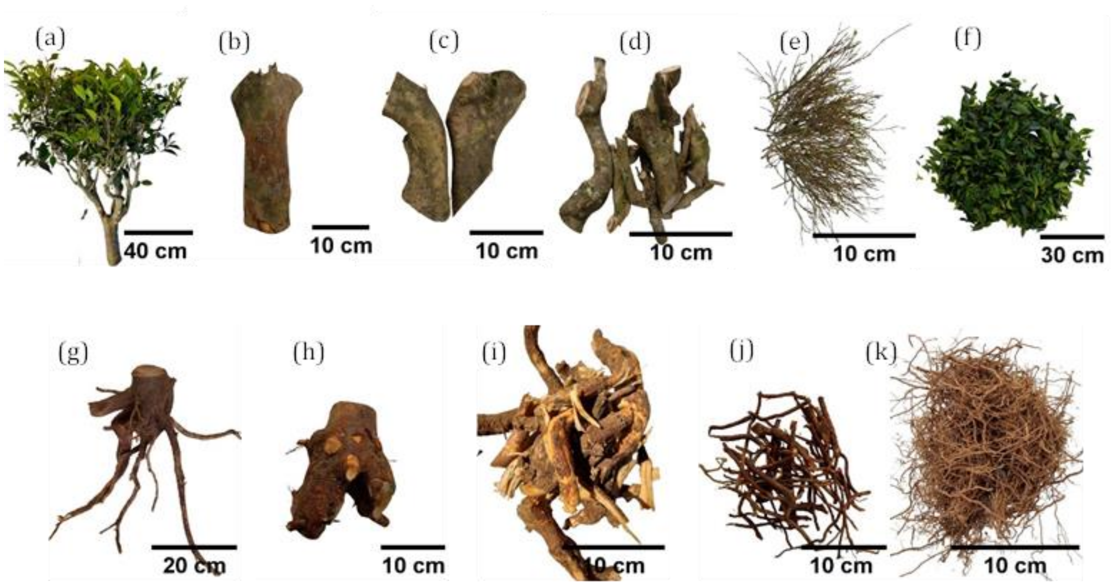

Figure 1. (a) Above ground biomass and its portioned plant parts i.e., (b) main stem, (c) primary branch, (d) secondary branches, (e) tertiary branches and (f) leaves (1st row) and (g) below ground biomass and its portioned parts i.e., (h) root balls, (i) larger roots, (j) medium roots and (k) smaller roots (2nd row).

Portioning of plant parts in uprooted tea plants

Above ground biomass of tea plants was further portioned into 5 parts (i.e., main stem, primary branches, secondary branches, tertiary branches and leaves) (Figure 1b to 1f). The branches arising from the main stem were considered as primary branches, branches arising from the primary branches were considered as secondary branches, and all the branches arising from the secondary branches were considered as tertiary branches. Similarly, belowground biomass was portioned into 4 plant parts [i.e., root ball, larger roots (> 1 cm dimeter), medium roots (0.2-1 cm diameter) and smaller roots (<0.2 cm diameter) (Figures 1 h to k)]. The fresh weight of each plant part was measured using a top loading balance with the accuracy of 0.1 g.

Oven-drying and weighing of samples

Portioned plant parts of uprooted tea plants were packed in hard paper bags and oven-dried at 60 °C for 96 hours, until a constant weight was obtained. Dry weight of each sample was taken using a top loading balance with the accuracy of 0.1 g.

Statistical analysis

Correlations between AGB, BGB and TB of tea plants with dendrometric variables were tested using Pearson's correlation analysis. The box and whisker plots and histograms were used to identify the outliers in the biomass and the dendrometric variable datasets. The observation that are more than 1.5*interquartile range (IQR) below quartile1 (Q1) or more than 1.5*IQR above quartile3 (Q3) were considered be an outlier corresponding to Tukey's original definition of boxplot. However, the extreme outliers (the values more than 3*IQR below Q1 or more than 3* IQR above Q3) were only removed from the datasets if they were highly influenced to regression analyses in this study. Multicollinearity among the selected dendrometric variables were checked using a matrix of Pearson's bivariate correlations.

When developing the best suited models to estimate AGB, BGB and TB using linear regression approach, CCSL, CDSL, CCSH, CDSH, HSLPB, NPB, LPB, CBPB, DBPB, CEPB, DEPB and AGE were considered as explanatory variables. Here, step-wise model fitting procedure was used under multiple regression analysis.

Non-linear models used to predict AGB, BGB and TB based on the diameter at breast height (DBH) of different plant species reported in the literature are presented in Table 2. The non-linear allometric models of which DBH has been used as the only variable to estimate biomass were selected for this study. Collar diameter at the soil level (CDSL) was used as the dendrometric variable resembling DBH, as it was highly correlated with AGB, BGB and TB under Pearson's correlation analysis. Collar diameter at soil surface (CDSL was calculated based on CCSL assuming a circular cross-section of the stem.

Table 2. Non-linear allometric models used to estimate above ground biomass (AGB), below ground biomass (BGB) and total biomass (TB) of different plant species reported in literature

Model	Model allometric equation	References
1	$B = a + b(DBH) + c(DBH)^2$	Brown *et al.* (1989)
2	$B = a(DBH)^b$	Brown *et al*. (1989)
3	$B = a + b(DBH)^2$	Mugasha *et al.* (2016)
4	$B = a (DBH +1)^b$	Madgwick (1979)
5	$B = (a + b \times DBH)^2$	Sharifi *et al.* (2013)
6	$B = a+ b \times \ln(DBH)$	Segura (2005)
7	$B = \exp [a +b \times (DBH)^2]$	Segura (2005)
8	$B = \exp [a + b \times \ln(DBH)]$	Segura (2005)
9	$B = a. \exp (b \times DBH)$	Kusmana *et al.* (2018)
10	$B = \exp [b \times \ln(DBH)] + a$	Basuki *et al.* (2009); Ketterings *et al*. (2001)

B=above-ground or below-ground (in kg) or total biomass and DBH= Diameter at breast height (cm)

Evaluation and comparison of the predicted allometric models

Coefficient of determination (R^2), mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) were used when comparing different allometric models.

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{n}(B_{obs,i}-B_{est,i})^2}{\sum_{i=1}^{n}(B_{obs,i}-B_o)^2}\right)$$

$$ME = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(B_{est,i} - B_{obs,i})}$$

$$MAE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|(B_{est,i} - B_{obs,i})\right|}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(B_{est,i} - B_{obs,i})^2}$$

where $B_{obs,i}$ = observed biomass in g , $B_{est,i}$ = estimated biomass in g, n = number of observations, B_0 is mean biomass of observed biomass in g.

Akaike information criterion (AIC), was used to choose the best fitted model (Akaike, 1981). The best allometric models to predict AGB, BGB and TB were validated using leave-one-out cross validation technique.

RESULTS AND DISCUSSION

Summary statistics of dendrometric variables and age of uprooted tea plants

Variations of the measured dendrometric variables of uprooted tea plants are shown in Figure 2. The CCSL was 24.5±4.4 cm and the percentage of coefficient of variation (CV%) of CCSL was 18%. The CCSH was 24.1±4.8 cm and the CV% of CCSH was 19%. Moreover, HSLPB of the uprooted tea plants was 19.1±6.1 cm. The CV% of HSLPB was 31%. The CBPB and CEPB were 16.0±3.5 cm and 16.4±4.3 cm, respectively. The CV% of CBPB and CEPB were 22% and 26%, respectively. Furthermore, LPB of the uprooted tea plants and its CV% were 13.0±4.2 cm and 32%, respectively. The NPB of the uprooted tea plants and its CV% were 3±1 and 32%, respectively. Ages of the uprooted tea plants and its CV% were 25±11 years and 45%, respectively.

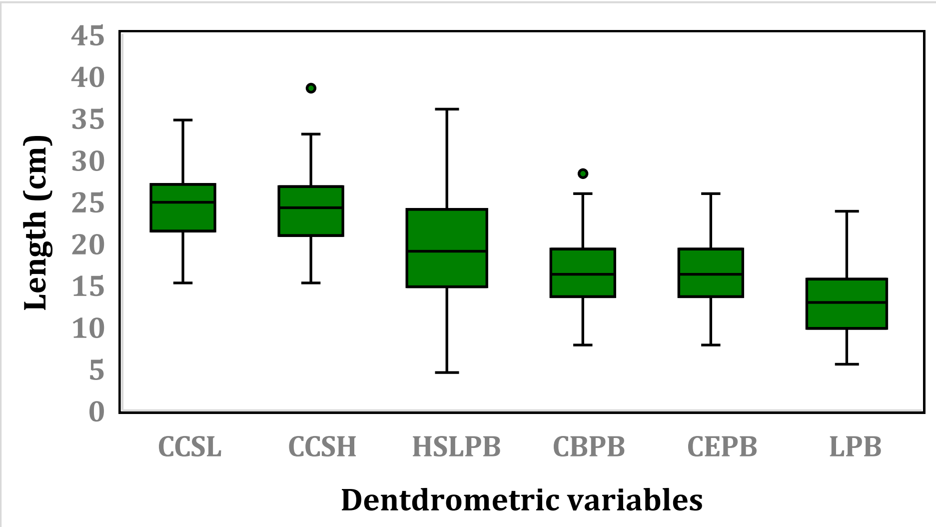

Figure 2. Box and whisker plots showing the variations of observed dendrometric variables (i.e., CCSL: Collar circumference at soil level (CCSL), CCSH: Main stem circumference at 6 cm height (CCSH), NPB: Number of primary branches, HSLPB: Mean height from soil surface to the beginning of primary branches, CBPB: Mean circumference at the beginning of primary branches, CEPB: Mean circumference at the end of primary branches and LPB: Mean length of primary branches) of the uprooted tea plants.

Summary statistics of biomass of uprooted tea plants

Variation of the biomass of the uprooted tea plants is shown in Table 3. In the present study, the contributions of AGB and BBG to TB were 66% and 34%, respectively. Handavu *et al.* (2021) reported that BGB accounts for 20-26% of TB in naturally growing trees. Continuous disturbances to the tea bush in terms of pruning in 3-5 years intervals and regular plucking may result in higher contribution of BGB to TB in tea plants in comparison to naturally grown plant species. The AGB, BGB and TB of the uprooted tea plants were 2596±1187.0 g per plant, 1332±523.6 g per plant and 3927±1543.2 g per plant, respectively. The CV% value of each biomass category ranged between 30-46% indicating higher variability in biomass of the uprooted tea plants.

Similarly, fresh AGB, BGB and TB were 5225±2332.6 g per plant, 2856±1091.7 g per plant and 8081±3017.7 g per plant. The moisture contents of fresh AGB, BGB and TB were 49.4±4.8%, 46.7±5.5% and 48.3±4.4%, respectively. The CV% values of fresh AGB, BGB and TB were 44.6%, 38.2% and 37.3%, respectively, indicating higher variability in fresh biomass of the uprooted tea plants. Biomass of tea plants is greatly attributed by both plant inherent characteristics (i.e., cultivar and age of plants) and external characteristics (e.g., climatic conditions, land characteristics, agronomic practices and input management systems) (Barman and Saikia, 2005; Kalita et al., 2015).

Investigation of dendrometric variables highly correlating with the above-ground, below-ground and total biomass

Pearson correlations of measured dendrometric variables with AGB, BGB and TB are shown in Table 4. According to the correlation coefficient classification proposed by Mukaka (2012), AGB and TB showed high positive correlations (0.9 > r > 0.7) with CCSL, CDSL, CCSH and CDSH. However, in the present study, BGB showed moderately positive correlations (0.7 > r > 0.5) with CCSL, CDSL, CCSH, CDSH possibly due to BGB which may not have been fully extracted, although a considerable effort was made to extract all the roots from the soil. Moreover, AGB, BGB and TB showed moderately positive correlations with CBPB, DBPB, CEPB and DEPB. All other measured variables showed moderate to low correlations (0.5 > r) with AGB, BGB and TB. These results revealed that collar circumference and dimeter of collar at soil level were the dendrometric variables best correlating with AGB, BGB and TB.

Investigation of multicollinearity among the selected dendrometric variables and age of the uprooted tea plants

The matrix of Pearson's bivariate correlations among all independent variables and age is shown in Table 5. The strong positive correlations (0.8 < r < 1) were observed between CCSH vs CCSL and CBPB Vs CEPB. Moreover, this indicated the presence of multicollinearity among these variables. However, there should not have any multicollinearity between the independent variables used for multiple linear regression (Shrestha, 2020).

Investigation of the applicability of the already developed allometric models in other countries to predict biomass of tea grown in Sri Lanka

Two attempts to develop allometric models for tea were found in the literature. Kalita *et al.* (2015) have developed the allometric models to predict AGB, BGB and TB of Tea grown in Barak Valley, Assam, North East India. Sasaki *et al.* (2020) have developed the allometric equations to estimate AGB of Tea grown in Miang tea gardens in Northern Thailand. The application of the allometric equation developed by Kalita *et al.* (2015) to our condition is shown in Table 6, with r, mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) when using these allometric models to estimate biomass of the uprooted tea in the present study.

Moderate correlation (0.5 < r < 0.7) was observed between predicted and actual dry AGB and BGB according to the correlation coefficient classification proposed by Mukaka (2012). However, lower correlation (0.5 > r) was observed between predicted and actual dry TB showing the lesser applicability of the allometric models to estimate biomass of tea grown in Sri Lanka. The ME values were between -374.9 and -1003.7, respectively. The MAE and RMSE values were over 640.5 and 817.9, respectively. These values revealed a considerable error when applying these allometric models to estimate biomass of tea grown in Sri Lanka.

Table 3. Summary statistics of above-ground (AGB), below-ground (BGB) and total (TB) dry and fresh biomass (g per plant) of the uprooted tea plants.

Biomass category	Minimum	Maximum	Average	Standard Deviation	CV%
Dry AGB	752.7	5943.8	2596.1	1187.0	46
Fresh AGB	1782.0	12610.0	5224.7	2332.6	45
Dry BGB	359.5	2499.0	1331.5	523.6	39
Fresh BGB	710.7	5158.7	2856.3	1091.7	38
Dry TB	1398.8	7853.0	3927.6	1543.2	39
Fresh TB	3275.2	16743.0	8081.0	3017.7	37

Number of uprooted plants were 64, AGB = Above Ground biomass, BGB = Below Ground Biomass and TB = Total Biomass and CV% = Percentage of coefficient of variation

Table 4. Pearsons's correlation coefficient of measured dendrometric variables and age with above-ground (AGB), below-ground (BGB) and total (TB) biomass

	AGB	BGB	TB
CCSL	0.798	0.623	0.825
CCSH	0.773	0.538	0.777
NPB	0.309	-0.071	0.213
HSLPB	0.135	0.314	0.21
CBPB	0.54	0.642	0.633
CEPB	0.491	0.67	0.605
LPB	0.231	-0.275	0.084
AGE	0.124	0.308	0.199

AGB= Above ground biomass, BGB= Below ground biomass, TB=Total biomass, CCSL = Collar circumference at soil level, CCSH= Main stem circumference at 6 cm height from soil level, NPB = Number of primary branches, HSLPB = Mean height from soil surface to the beginning of primary branches, CBPB = Mean circumference at the beginning of primary branches, CEPB = Mean circumference at the end of primary branches and LPB = Mean length of primary branches

Table 5. The matrix of Pearson's bivariate correlations among all independent variables and age

	CCSL	CCSH	NPB	HSLPB	CBPB	CEPB	LPB	Age
CCSL	1	0.927	0.247	0.044	0.593	0.622	0.114	0.335
CCSH	0.927	1	0.256	-0.008	0.560	0.557	0.136	0.397
NPB	0.247	0.256	1	-0.130	-0.380	-0.357	0.349	0.031
HSLPB	0.044	-0.008	-0.130	1	0.189	0.199	-0.124	0.164
CBPB	0.593	0.560	-0.380	0.189	1	0.870	-0.191	0.174
CEPB	0.622	0.557	-0.357	0.199	0.870	1	-0.158	0.194
LPB	0.114	0.136	0.349	-0.124	-0.191	-0.158	1	0.072
Age	0.335	0.397	0.031	0.164	0.174	0.194	0.072	1

CCSL = Collar circumference at soil level, CCSH= Main stem circumference at 6 cm height from soil level, NPB = Number of primary branches, HSLPB = Mean height from soil surface to the beginning of primary branches, CBPB = Mean circumference at the beginning of primary branches, CEPB = Mean circumference at the end of primary branches and LPB = Mean length of primary branches

The application of allometric equation developed by Sasaki *et al*. (2020) to our condition is shown in Table 7. In this study, allometric models have been developed separately for predicting branch and stem biomass (BSB) as well as leaves biomass (LB). The summation of these two components were considered to be AGB. Table 7 shows *r,* ME, MAE and RMSE when using these allometric models to AGB of the uprooted tea in the present study.

The *r* value was 0.769 indicating moderate correlation between actual and predicted AGB. The ME, MAE and RMSE values showed a considerable error (> 569 g) when using these allometric models to estimate biomass of tea grown in Sri Lanka.

Development of allomeric models to predict above-ground, below-ground and total tea biomass

Linear regression models

Stepwise multiple linear regression analysis resulted in one best fitted regression models to predict AGB. The model consisted of only CCSH (Table 8). The model predicted 91.1% of total variability of AGB. This highlights that CCSH has the highest contribution to explain the variability of AGB. Kalita *et al*. (2015) also showed that AGB of tea plants in Barak Valley, Assam, Northeast India was highly correlated with collar diameter at 5 cm height from soil and over 95% of total AGB variability was explained by this variable.

Step-wise multiple linear regression analysis resulted in three linear regression models to predict BGB. The model 1 predicted BGB with only one variable i.e., CEPB. Over 92.0% of total BGB variability was predicted by CEPB. The model 2 predicted BGB with only two variables i.e., CEPB and CCSL. These two variables explained 93% of total variability of BGB. The model 3 predicted BGB with three variables i.e., CEPB, CCSL and LPB. Model 3 predicted 94.2% of total variability of BGB. The linear relationship between collar diameter and BGB in tea plant has been reported previously (Kalita et al., 2015). However, the relationships between BGB and CEPB were not reported in the literature. Raj and Raj Kumar (2017) observed a strong positive linear correlation between AGB and BGB (R^2=0.936). Primary branches are one of the major plant parts of above ground standing biomass. Therefore, circumference and length of primary branches (volume of primary branches) may be highly correlated with BGB.

Step-wise multiple regression analysis resulted the best fitted regression model to predict TB. This regression model predicted TB only with one variable i.e., CCSL. This model predicted 94% of total variability of TB. Kalita *et al.* (2015) also reported a strong positive correlation between collar diameter and TB (R^2=0.970).

Table 7. Summary statistics results in applying the allometric models developed by Sasaki *et al.* (2020) to predict dry AGB of the uprooted tea plants.

Biomass category	Model allometric equation	*r*	ME	MAE	RMSE
AGB	$BSB = 0.03012 \times (D^2H)^{0.9342}$ $LB = 0.01814 \times (D^2H)^{0.7633}$	0.769	-569.0	729.2	967.3

AGB =above-ground biomass (in kg), BSB = Branch and stem biomass (in kg), LB = Laves biomass (in kg), D = Diameter at 6 cm height (in cm), r = Pearson's correlation, ME = Mean Error, MAE = Mean Absolute Error and RMSE = Root Mean Square Error.

Table 8. Summary statistics of multiple linear regression models developed using step-wise linear regression procedure to predict dry above-ground (AGB), below-ground (BGB) and total (TB) tea biomass

Biomass category	Model allometric equation	R^2	ME	MAE	RMSE	AIC
AGB	1. AGB = 110.9 × CCSH	0.911	75.8	678.1	844.3	1040.4
BGB	1. BGB = 81.2 × CEPB	0.926	-0.9	288.9	385.7	948.1
	2. BGB = 52.8 × CEPB + 19.4×CCSL	0.932	15.1	286.8	373.6	946.2
	3. BGB = 41.5×CEPB + 46.2×CCSL – 36.3×LPB	0.944	5.5	267.5	337.1	935.3
TB	1. TB = 164.5 × CCSL	0.940	97.2	861.3	1026.1	1073.3

AGB = Above ground biomass, BGB = Below ground biomass, TB =Total biomass, CCSL = Collar circumference at soil level, CDSL = Collar diameter at soil level, CCSH = Mean main stem circumference of primary branches at 6 cm height from soil level, CEPB = Mean circumference at the end of primary branches, LPB = Mean length of primary branches, R^2 = Coefficient of determination, ME = Mean Error, MAE = Mean Absolute Error, RMSE = Root Mean Square Error and AIC = Akaike information criterion

Nonlinear regression models

In general, non-linear models are best fitted to estimate biomass of tea plant. Therefore, applicability of non-linear models for precise estimation of biomass of tea plant individuals was further investigated. Summary statistics of non-linear regression analysis is given in Table 9. Coefficient of determination of developed models ranged between 0.303-0.674. Moreover, ME, MAE, RMSE of developed models ranged between -1.2-41.3, 302.2-775.4 and 392.4-955.9, respectively. Akaike information criterion of developed models ranged between 954. 0-1064.6. The best fitted non-linear models to predict AGB, BGB and TB in tea plants are highlighted in Table 9. The model 5 was the best model to predict AGB based on AIC (Table 9). The R2 of the model was 0.643. This revealed that 64.3% of total variability of AGB was predicted by CDSL. Moreover, AIC value of AGB predicting non-linear model 5 in comparison to the respective linear regression model was lower indicating that the non-linear model was the best model to predict AGB. Similarly, MAE and RMSE values of the non-linear AGB predicting model in comparison to the respective linear regression model were lower.

Non-linear regression model 6 was the best fitted model to predict BGB based on AIC (Table 9). However, both AIC and R2 values of this model were lower in comparison to the respective linear regression models. When comparing MAE (306.5) and RMSE (398.3) of BGB predicting non-linear model 6, those were higher with the respective linear regression models 267.6<MAE<288.9 and 337.1<RMSE<385.7) showing lower capabilities to predict BGB accurately.

Non-linear model 2 & 8 were the best fitted models to predict TB based on AIC values (Table 9). Lower AIC, R2, MAE and RMSE values were observed in these two models (AIC = 1054.3, R2 < 0.674, MAE < 698, RMSE = 871.8) in comparison to the respective linear model (AIC =1073.3, R2 = 0.940, MAE= 861.3, RMSE=1026.1) to predict TB. This revealed that the prediction accuracies of non-linear models were higher though they were lesser fitted to predict TB.

Above results revealed that linear allometric models were best fitted to predict BGB and non-linear models were best fitted to predict AGB (nonlinear model 5) and TB (non-linear model 2 and 8). In comparison to the allometric models developed by Kalita *et al.* (2015) and Sasaki *et al.* (2020) (Table 6 and 7), the best allometric models developed to dry biomass in this study showed lesser MAE and RMSE (Table 8 and 9). This revealed higher precisions of the newly developed allometric models in predicting biomass of the uprooted tea plants. Moreover, the newly developed allometric models showed higher R^2 values showing better fit to the dataset.

Figure 3 showed the scatter plots showing the relationship between observed versus predicted AGB, BGB and TB values resulted by the best fitted allometric models. The scatter plots of AGB, BGB and TB showed that most of the data points were scattered close to the middle lines of the respective plot (Figure 3). This indicated that actual and predicted AGB, BGB and TB values were comparable.

Table 9. Summary statistics of non-linear allometric models developed to estimate above-ground (AGB), below-ground (BGB) and total (TB) dry biomass based on main stem diameter at 6 cm height (CDSH)

Model	Biomass Category	Coefficients			R^2	ME	MAE	RMSE	AIC
		A	b	c					
1	AGB	-23.2	-27.0	45.2	0.643	-0.7	542.3	699.8	1028,1
	BGB	-2724.1	830.2	-38.5	0.433	-0.4	302.2	392..4	954.1
	TB	-2747.2	803.1	6.7	0.679	-1.2	693.0	865.0	1055.3
2	AGB	34.3	2.1		0.643	-0.5	542.9	699.9	1026.2
	BGB	95.6	1.3		0.382	3.5	323.9	409.6	957.6
	TB	**96.4**	**1.8**		**0.674**	**5.8**	**697.9**	**871.8**	**1054.3**
3	AGB	-126.0	43.5		0.643	-0.7	542.2	699.9	1028.1
	BGB	436.7	14.3		0.357	-0.2	330.7	418.0	960.2
	TB	310.7	57.8		0.671	-0.9	701.4	876.1	1054.8
4	AGB	15.3	2.3		0.642	2.2	543.9	700.5	1026.2
	BGB	58.0	1.4		0.379	5.1	325.3	410.8	958.0
	TB	48.1	2.0		0.673	10.3	701.6	874.3	1054.6
5	**AGB**	**-2.6**	**6.8**		**0.643**	**-0.5**	**542.3**	**699.8**	**1026.1**
	BGB	12.7	3.0		0.370	2.4	327.4	413.7	958.8
	TB	5.8	7.2		0.673	3.4	700.1	874.0	1054.6
6	AGB	-7313.2	4868.4		0.599	-1.0	586.5	741.5	1033.5
	BGB	**-2311.9**	**1790.0**		**0.416**	**-0.4**	**306.5**	**398.3**	**954.0**
	TB	-9625.0	6658.4		0.663	-1.4	729.4	886.3	1056.4
7	AGB	6.9	0.014		0.602	19.2	573.5	738.2	1033.0
	BGB	6.6	0.009		0.303	41.3	347.6	437.1	965.2
	TB	7.5	0.012		0.609	-19.0	775.4	955.9	1065.9
8	AGB	3.5	2.1		0.643	0.2	542.9	699.9	1026.2
	BGB	4.6	1.3		0.382	3.5	323.9	409.6	957.6
	TB	**4.6**	**1.8**		**0.674**	**6.0**	**698.0**	**871.8**	**1054.3**
9	AGB	362.5	0.2		0.630	11.9	555.7	712.2	1028.4
	BGB	400.4	0.152		0.346	5.4	337.1	421.5	961.2
	TB	719.5	0.213		0.649	18.3	730.4	904.6	1058.9
10	AGB	1063.4	3.5		0.621	0.5	559.2	720.9	1029.9
	BGB	787.2	3.0		0.312	-0.4	346.5	432.1	964.4
	Total	2009.4	3.6		0.617	1.2	762.1	944.9	1064.6

AGB = Above ground biomass, BGB = Below ground biomass, TB =Total biomass, R^2 = Coefficient of determination, ME = Mean Error, MAE = Mean Absolute Error and RMSE = Root Mean Square Error.

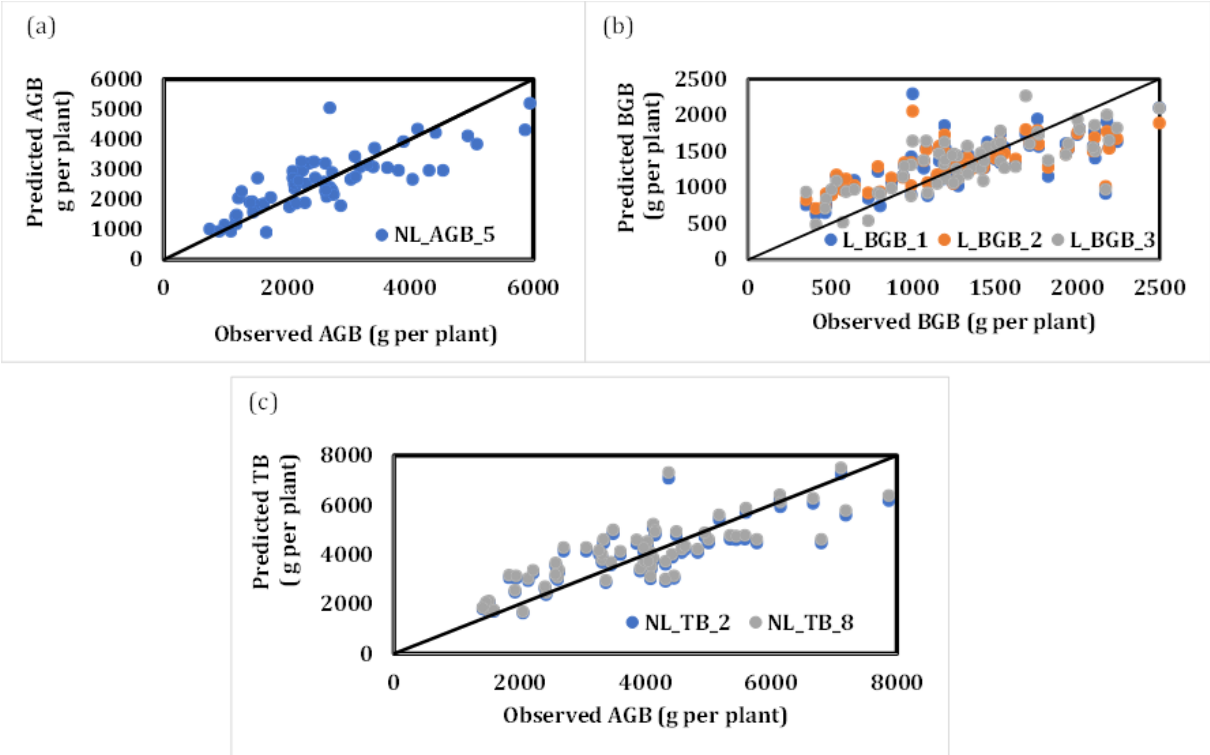

Figure 3. Scatterplots of the predicted versus observed (a) above ground biomass (AGB), (b). below ground biomass (BGB) and (c). total Biomass (TB). The predicted AGB, BGB and TB values were estimated by the best fitted allometric models for the respective biomass category i.e., AGB by non-liner model 5 (NL_AGB_5), BGB by linear BGB model 1 (L_BGB_1), 2 (L_BGB_2) and 3 (L_BGB_2), TB by non-linear model 2 (NL_TB_2) and 8 (NL_TB_8).

Leave-one-out cross-validation results revealed strong agreement (r = 0.803) between actual and predicted AGB values by non-linear allometric model 5. Similarly, leave-one-out cross-validation showed strong positive correlations were observed between actual and predicted TB values by non-linear allometric models 2 (r = 0.843) and 8 (r = 0.843). However, leave-one-out cross-validation showed moderately positive correlation positive correlations were observed between actual and predicted BGB by linear BGB models 1 (r = 0.624), 2 (r=0.669), and 3 (r = 0.706).

CONCLUSION

Biomass and measured dendrometric variables of uprooted tea plants had a high variability. This revealed a wide applicability of the dataset to be used for developing allometric models for tea plants grown in both Uva and Up country, Sri Lanka. Collar diameter at soil level had the highest correlation with biomass since it belongs to longest standing undisturbed plant part of a tea pant. Non-linear allometric model 5 was the best model to predict AGB and non-linear allomeric models 2 and 8 were the best models to predict TB based on AIC values. Over 64% of the variability of AGB and TB was explained by these non-linear regression models using CDSL. Linear allometric models in comparison to the selected non-linear allomeric models fitted best when predicting BGB based on AIC values. Over 92% of the variability of BGB was explained by linear regression models using CCSH, CCSL, CEPB and LPB. Developed non-linear allometric models in comparison to those in the literature were better fitted to our data and precisely estimate AGB, BGB and TB data generated in this study. Leave-one-out cross-validation techniques revealed the strong positive agreement ($r > 0.8$) between actual and predicted AGB (predicted by non-linear model 5) and TB (predicted by non-linear models 2 and 8) values. However, cross-validation results revealed the moderate positive correlation between actual and predicted BGB (predicted by linear BGB models 1, 2 & 8) values. Furthermore, the developed allometric models need to be validated by independent datasets prior to use them in future studies.

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