Prediction of Stem Biomass of *Pinus caribaea* Growing in the Low Country Wet Zone of Sri Lanka

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Abstract

Forests are important ecosystems as they reduce the atmospheric CO_2 amounts and thereby control the global warming. Estimation of biomass values are vital to determine the carbon contents stored in trees. However, biomass estimation is not an easy task as the trees should be felled or uprooted which are time consuming and expensive procedures. As a solution to this problem, construction of mathematical relationships to predict biomass from easily measurable variables can be used.

The present study attempted to construct a mathematical model to predict the stem biomass of *Pinus caribaea* using the data collected from a 26 year old plantation located in Yagirala Forest Reserve in the low country wet zone of Sri Lanka. Due to the geographical undulations of this forest, two 0.05 ha sample plots were randomly established in each of valley, slope and ridge-top areas. In order to construct the model, stem wood density values were calculated by using stem core samples extracted at the breast height point. Stem volume was estimated for each tree using Newton's formula and the stem biomass was then estimated by converting the weight of the known volume of core samples to the weight of the stem volume. Prior to pool the data for model construction, the density variations along the stem and between geographical locations were also tested.

It was attempted to predict the biomass using both dbh and tree height. Apart from the untransformed variables, four biologically acceptable transformations were also used for model construction to obtain the best model. All possible combinations of model structures were fitted to the data. The preliminary model selection for further analysis was done based on higher R^2 values and compatibility with the biological reality. Out of those preliminary selected models, the final selection was done using the average model bias and modeling efficiency quantitatively and using standard residual distribution qualitatively. After the final evaluation the following model was selected as the best model to use in the field.

$$\sqrt{\mathrm{w}} = 0.736dbh - 44.9(1/h)$$

Keywords: *allometric equations, forest biomass, non-destructive sampling, Pinus caribaea*

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1. Introduction

Global climate change has inspired an increasing interest of scientific and political communities in the study of global carbon storage and of the carbon balance (Landsberg et al., 1995). The estimation of biomass is an essential aspect of studies of carbon storage and carbon balance (Xiao & Ceulemans, 2004).

Forests play an important role in global carbon budget as carbon sinks and throughout emission of CO_2 (Dixon et al., 1994; Sedjo et al., 1997). Carbon is stored in trees as biomass and therefore biomass assessments play a major role in determining carbon storage in forests. Forests hold two third of terrestrial C and as the forest biomass increase over the time, so does the stock of sequestered C in the standing forest and soils.

Estimation of biomass of a sample of trees can be very difficult and expensive. At most, it involves felling the trees, excavating their root systems and drying and weighing the biomass. Such practices may be impossibly expensive and therefore much attention has been paid to the development of techniques to estimate tree biomass from easily measured tree characteristics. These techniques, known generally as allometry, involve relationships between tree above-ground biomass and tree stem diameter and/or height and above-ground biomass (Specht & West, 2003). In 1994, Niklas said that allometry, relating easily measured variable to other structural and functional characteristics, is the most common and reliable method for estimating biomass, net primary production, and biogeochemical budgets in forest ecosystems (Gower et al., 1999; Wang, 2006).

Mostly allometry employs diameter at breast height (dbh) as the only independent variable, and develops an allometric relationship between dbh (Gower et al., 1999). However, such models can further be improved by adding one or more additional independent variables. Therefore some studies proposed to include tree height as the second predictor (e.g. Wang, 2006). The use of allometric relationships yields a non-destructive and indirect measurement of biomass compartments, and is often the preferred approach since it is less time consuming and less expensive than direct measurements (St. Clair, 1993). In addition to that, such methods prevent damaging the forest ecosystems or environment due to felling or excavation of trees.

Among temperate forests, pine stands are considered one of the most productive forests. Mean carbon values for pine stands have been reported to range from 3 to 161 t ha^{-1}, depending on stand age, type and number of carbon pools included in the reported inventory (e.g. Forrest & Ovington, 1970; Kinerson et al., 1977; Johnson et al., 2003).

Pinus caribaea was introduced to the wet zone of Sri Lanka in 1970s to rehabilitate the degraded lands resultant due to deforestation. The other objectives of planning pines in Sri Lanka were to protect the watersheds, control soil erosion, stabilise slopes and to obtain pulp and timber.

However, according to Weerawardene et al. (1998), some of the above mentioned objectives have not been achieved due to various reasons. One reason was the lack of sufficient demand for pine timber and pulp in Sri Lanka due to the low density of wood. The high resin content of the wood adversely affects the pulp production and expensive technology should be used to remove the resins from the wood. Due to this reason, harvesting schedules were delayed probably causing some environmental problems such as over-crowded stands of trees possibly lowering the water table excessively reducing the timber quality, creating a dense mat of pine leaves on the ground etc.

2. Study Area and Sampling

The present study was carried out in the 26 year old *P. caribaea* monoculture plantation of the Yagirala Forest Reserve which is situated in the south-western part of the wet zone in Sri Lanka. The extent of this forest is 2,000 ha and it is located between N $06^0 20^/$-$06^0 22^/$ to E $80^0 10^/$-$80^0 12^/$ in Kalutara Administrative District in the low country wet zone. The area receives 4,000 mm annual rainfall and the mean temperature is about 27-28.5^{0}C.

Yagirala Forest Reserve had extensively been subjected to timber harvesting in 1970s. Due to this reason, large gaps were created and those were replaced by establishing monoculture *P. caribaea* plantations. Among those pine blocks, a 25 ha *P. caribaea* block was selected for data collection for the present study. This area had an undulating ground with valleys, slopes and ridge tops. Although there were no visual growth differences within the selected area, it was decided to use stratified random sampling as two 0.05 ha circular sample plots from each of valley, slope and ridge top. Thereby six sample plots were used for the data collection.

3. Methodology

3.1 Theoretical model structure

Stem of living trees grows both horizontally and vertically. Biomass accumulation also occurs in trees in both directions. The horizontal growth can be measured by the diameter at breast height (dbh) and the vertical growth can be measured by the total tree height. Therefore it was assumed that the biomass was a function of both dbh and total height as shown in equation 1.

$$\text{biomass} = f\ \text{dbh, total height} \qquad (1)$$

The relationship shown in equation 1 was used to construct a model to predict the main stem biomass of *P. caribaea* in this study.

3.2 Samplings and measurements

The 25 ha pine block was divided into three strata as valley, mid-slope and ridge based on the geographical variations. Two circular sample plots of 0.05 ha were randomly laid in each stratum to collect the necessary data.

Dbh and total height of all *P. caribaea* trees in each sample plot were accurately measured using a diameter tape and an altimeter respectively. Newton's formula was used to estimate the precise stem volumes for this study (Philip, 1994; Subasinghe, 1998). In order to apply the Newton's formula, standing trees were divided into sections less than 5 m and base, top and mid diameters and length of each section were accurately measured. Spiegal relescope was used for diameter measurements and an altimeter was used for length measurements in this exercise. Then the volume for each section was separately estimated using Newton's formula. The top most section was assumed as a cone and the volume was estimated accordingly. In order to calculate the total stem volume, the section volumes were added together as shown in equation 2.

$$V_{tot} = \Sigma v_i + v_f \tag{2}$$

where: v_f = volume of the final section (cone), m^3
v_i = volume of the each section, m^3
V_{tot} = total stem volume, m^3

3.3 Estimation of stem biomass

A non-destructive sampling method was used in the present study to estimate the stem biomass. The biomass estimation was therefore done by converting a volume and weight (density) of a core sample extracted by an increment borer at the breast height point in to the stem biomass via stem volume.

The length of the stem core extracted using the increment borer was accurately measured in millimetres. Core diameter was measured for randomly selected core samples and the average was taken because only one increment borer with one extraction tube was used for the entire study. The core samples were oven-dried at 105^0C for 72 hours and then the weight was measured.

3.4 Volume of the core

Shape of the core sample was cylindrical and therefore the equation 3 was employed to estimate the core volume.

$$v_s = \frac{\pi d_s^2 l}{4 \times 10^9} \tag{3}$$

where:
d_s = diameter of the core sample, mm
l = length of the core sample, mm
v_s = volume of the core sample, m^3

3.5 Estimation of the main stem biomass

Dry weight of the core sample was measured in grams using an electronic balance. Stem biomass, i.e., the dry weight of the stem was calculated by using the equation 4.

$$W_{tot} = \frac{w_d \times V_{tot}}{v_s} \tag{4}$$

where:
V_{tot} = total stem volume, m^3
w_d = oven dry weight of the core sample, kg
W_{tot} = total biomass of the stem, kg

3.6 Testing the stem density difference of trees growing in different locations

Although there was no visual growth difference observed in different locations of the selected area, the difference of the stem wood density of the trees growing in different locations, i.e., valley, slope and ridge top was tested using one-way ANOVA at 95% probability level.

3.7 Determination of stem wood density differences along the main stem

Apart from the core samples taken at the breast height point, core samples were extracted at the mid-length of the stems of four randomly selected trees in each plot. The stem wood density was calculated for these core samples taken at the mid-lengths using the method described in section 3.3. Finally the density differences between at the breast height point and at the mid-length of the stems were tested using one sample *t*-test at 95% probability level.

3.8 Construction of relationships between biomass and other variables

Regression analysis was employed to develop the relationship between biomass and the selected explanatory variables, i.e., dbh and total height. Apart from the untransformed variables, it was decided to use four transformations which are biologically accepted, i.e., logarithmic, square root, square and reciprocal to obtain the models with the minimum bias and the highest efficiency. Thereby all possible combinations of variables were tested to obtain the best model to predict the stem biomass.

Coefficient of determination (R^2) was initially used to identify the possible candidate models. Apart from the accuracy of model fitting, the compatibility with the biological reality was tested by employing the following theory (source: Subasinghe, 1998).

If the height of the tree moves to zero ($h \rightarrow 0$), dbh should be zero ($dbh = 0$). In this case, biomass of the stem should also be zero ($W_{tot} = 0$). Therefore the intercept of the selected model should be zero or at least it should not be significantly different from zero. Therefore the preliminary model selection was based on higher R^2 values and insignificant intercepts. Then they were further tested for the bias and modelling efficiency using the equations 5 and 6 and using standard residual distribution.

$$Bias = \frac{\Sigma(\hat{y}_i - y_i)}{n} \tag{5}$$

where:

n = number of data

y_i = measured biomass used for the model building

$\hat{y}_i$ = predicted biomass from the model

$$ME = 1 - \frac{\Sigma(y_i - \hat{y}_i)^2}{\Sigma(yi - \bar{y})^2} \tag{6}$$

where:

ME = modelling efficiency

$\bar{y}$ = mean measured biomass

4. Results

4.1 Plot summary

As described in the methodology, six plots were established in the randomly selected positions to collect data. The summary of the data is given in Table 1.

Table 1: Summary of the collected data.

Site	Plot No	No of trees	Mean dbh, Cm	Mean height, m	Mean volume, m^3	Mean density, kgm^{-3}
Valley	1	34	19.3	18.2	0.287	549.0
Valley	2	22	20.1	20.1	0.306	539.1
Slope	3	14	23.7	23.1	0.457	596.2
Slope	4	27	21.2	21.9	0.367	581.2
Ridge top	5	35	21.5	20.2	0.351	572.5
Ridge top	6	46	19.9	18.7	0.253	571.6

The visual observations of the mean values appeared to be similar irrespective of the location of the plots. However, there was a difference between the numbers of trees in different locations.

4.2 Difference of stem wood density of trees growing in different locations

One-way ANOVA was usd at 95% probability level to investigate the significance of the wood density at breast height of the trees growing in different locations. The results were not significant and it proved that there was no difference of the stem density of the trees growing in different locations (F=2.16 and p=0.061). Due to this reason, it was possible to pool all data for model construction.

4.3 Difference of mid-length density and density at the breast height

According to the results of the two sample *t*-test, there was no significance difference between the stem wood density at the mid-length of the stem and the stem wood density at the breast height (t=1.57 and p=0.130). Therefore the density values calculated by using the core samples taken at the breast height were used as the wood density of the entire stem of *P. caribaea*.

4.4 Model construction to predict stem biomass from other variables

Relationships between stem biomass of *P. caribaea* and other candidate easily measurable variables were developed using regression analysis. As mentioned in section 3.8, other than the untransformed values, the variables were transformed to four biologically accepted forms. The preliminary evaluation of the resultant models was tested using R^2 and compatibility with biological reality as mentioned in section 3.8. The preliminary selected models for further analysis are given in Table 2.

All models listed in Table 2 had non-significant intercepts and high R^2 values. However, apart from model 3 and 4, all other models indicated poor or very poor standard residual distributions. Both models 3 and 4 of Table 2 had the square root transformed response variable, i.e., biomass. Due to the fact that the intercepts of both models were non-significant, it was possible to re-fit them to the same data without intercepts. The resultant models are given in Table 3.

Table 2: Preliminary selected models for further analysis.

Model No	Model	R^2	Residual
1	$\log w = 0.275 + 0.0447dbh + 0.819\ logh$	84.6	Poor
2	$\log w = -0.017 + 0.396\sqrt{dbh} + 0.208h$	86.4	Poor
3	$\sqrt{w} = 3.10 + 0.671dbh - 78.4(1/h)$	86.2	Good
4	$\sqrt{w} = 0.118 + 0.0144(dbh)^2 + 0.318h$	86.2	Good
5	$1/w = -0.0055 + 0.381(1/dbh) - 0.002h$	79.9	Very poor
6	$1/w = 0.0018 + 0.388(1/dbh) - 0.0105logh$	79.6	Very poor
7	$1/w = 0.0017 + 0.375(1/dbh) - 0.0029\sqrt{h}$	80.2	Very poor

Table 3: Results of the re-fitted models 3 and 4 without intercepts.

New Model No	Old No in Table 2	Model	Average model bias	Modelling efficiency
8	3	$\sqrt{w} = 0.736dbh - 44.9(1/h)$	-0.023	86.0%
9	4	$\sqrt{w} = 0.0143(dbh)^2 + 0.324h$	-0.003	86.0%

According to Table 3, both models had insignificant bias and equally high modelling efficiencies. Therefore the selection of the final model was done based on the distribution of standard residuals (Fig. 1 and 2).

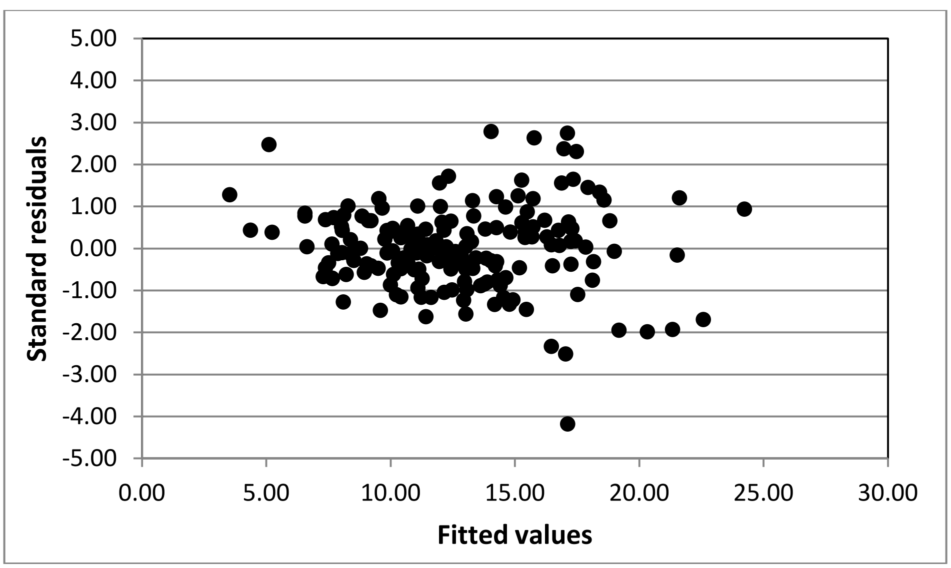

Fig. 1: Standard residual distribution against the fitted values of model 8 of Table 3.

The residual distribution of model 9 of Table 3 (Fig. 2) appeared to be non-random. In fact, the residuals spread diagonally from lower left corner of the graph towards to top right corner. Such a pattern, however, was not observed in model 8 of Table 3 (Fig. 1) and therefore the residuals of model 8 proved random distribution. Therefore based on the standard residual analysis, it was decided that the model 8 given in equation 7 as the best one to use in the field.

$$\sqrt{\mathrm{w}} = 0.736dbh - 44.9(1/h) \quad (7)$$

where: dbh = breast height diameter, cm
h = total tree height, m
w = biomass of the main stem of *P. caribaea*, kg

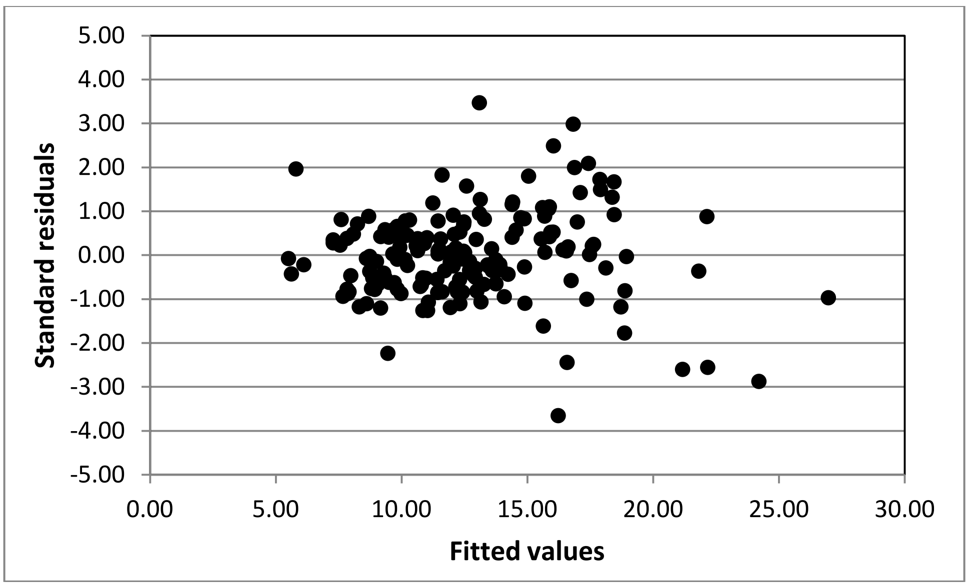

Fig. 2: Standard residual distribution against the fitted values of model 9 of Table 3.

5. Discussion

Forests can be considered as carbon sources and sinks. Therefore the management of the forests can maintain the global carbon cycle and climate change. According Brown et al., (1992), about 50% of the biomass of trees is carbon. However, Subasinghe & Munasinghe (2011) found higher carbon percentages than 50% for all above ground components in their study conducted for *Pinus caribaea* growing in the wet zone of Sri Lanka.

The greatest potential for aboveground biomass and carbon storage in forest ecosystems is usually found within the tree biomass components (stem, branches, and foliage). Biomass of understory and ground vegetation, as well as of dead standing trees and woody debris, may also provide a considerable contribution (Peichl & Arain, 2006). However, being a coniferous tree, *P. caribaea* does not produce large branches or a large amount of leaves. Therefore its main stem contributes most to the above ground biomass and thereby to the carbon storage.

Apart from aboveground vegetation, belowground tree root biomass, forest floor, and mineral soil provide large carbon pools (Johnson et al., 2003; Oliver et al., 2004). However, due to an immense effort required in obtaining a precise estimate of tree root biomass, it is often neglected or estimated from standard root to shoot ratios (Kurz et al., 1996; Cairns et al., 1997).

Most forest biomass studies conducted in the past used destructive sampling to analyse biomass and/or carbon values of different tree components (e.g., Parde, 1980; Guo et al., 2002; Xiao & Ceulemans, 2004; Williams & Gresham, 2006). Use of destructive sampling is not possible for the present study due to the difficulty of obtaining selective harvesting approval from the government forest plantations. Therefore it used a core sample analysis to estimate the biomass of the main stem and therefore much attention has been paid to the development of techniques to estimate tree biomass from easily measured tree characteristics. These techniques, known generally as allometry, involve relationships between tree above-ground biomass and tree stem diameter and/or height and above-ground biomass (Spelcht & West, 2006).

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