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Scaling Aboveground Biomass from Small Diameter Trees

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ABSTRACT. *Forest inventory data is a source of data to determine the aboveground biomass estimates, which are required to assess the carbon stored and cycled in forest ecosystems. Forest inventories are conducted mainly for commercial purposes to determine the stand volume of trees. They are large scale operations and hence, limited to commercially harvestable trees excluding trees below a certain minimum diameter. These small diameter trees, missing from the inventory, lead to underestimate the forest biomass when forest inventory data are used. Objectives in this study were to (a) describe a generic approach to estimate the total aboveground biomass of a forest including small (missing) diameter trees, and (b) apply the proposed methodology to a large dataset to determine the uncertainty. Data were obtained from a detailed inventory conducted in Sri Lanka. Appropriate models for the basal area and stand density for small diameter trees were selected using R^2 and residual analysis though non-linear estimation. These models were back extrapolated to estimate the basal area and stand density for small diameter trees and their contribution to the total aboveground biomass was estimated using an allometric equation. Uncertainty associated with the omission of smaller diameter trees was also estimated. Results showed that small diameter trees contained 12–49 % of the total aboveground biomass depending on the yield potential of the forests in Sri Lanka. This omission can be recovered using statistical models with midpoint diameter of a diameter class as an independent variable to estimate the basal area and stand density of a forest stand.*

Keywords: *Aboveground biomass, forest inventory data, diameter, Sri Lanka, uncertainty*

INTRODUCTION

The biomass in forests is an important source of data from a national, international and scientific perspective. Nationally it is necessary to determine the carbon budget, forest management and national development planning. Internationally, understanding the consequences of global warming require the assessment and contribution of forest lands, particularly in the tropics, to the global carbon cycle. The forest ecosystems are the largest terrestrial systems, which are the subject of scientific studies to determine their productivity, energy, nutrient flows and cycling, requiring an accurate estimate of the biomass available in the forests.

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Two major sources of data for biomass estimation in forests are: (i) Permanent Sampling Plots (PSPs) established by forest ecologists, and (ii) Forest Inventory Data (FID) collected by foresters. The PSPs are for specific purposes to study nutrient cycling, productivity of forests and other research interests (Gillespie *et al*., 1992) where data are carefully collected and spatially limited to plot sizes from less than one ha to 50 ha. For commercial purposes of timber harvesting, foresters and logging companies conduct extensive surveys to assess the stand volume of trees for logging, which can also be used to estimate aboveground biomass (AGB; Brown and Lugo, 1984). The large scale operation limits the data collected to commercially harvestable trees (above a minimum diameter) and type of data collected on the diameter at breast height (dbh) and height estimations are limited to commercial timber volumes. While lacking in detail, FID are extensive and methodologies have been developed using allometric equations to determine their biomass (Brown and Lugo, 1984; Brown *et al.*, 1989; Chave *et al.*, 2005; Gibbs *et al.*, 2007; Maniatis *et al.*, 2011). The minimum diameter of sampled trees in many tropical forest inventories is usually greater than 10 cm (Brown *et al*., 1989) and often greater than 35 cm, which is unacceptable for biomass estimation without taking into account the missing trees (Gillespie *et al*., 1992). Although the smaller trees may have less volume than larger trees, they often contain relatively more trees thereby resulting in an underestimation of the biomass (Haripriya, 2002). As FID are a major source for estimating the biomass, and considering the need for including data on smaller diameter trees for biomass estimation of forests,, Gillespie *et al.* (1992) estimated the frequency of small diameter stems based on the stem frequencies in the larger diameter classes. They found that 10 -12 % of reduction in error which is always less than the error incurred by omission of small diameter stems. Similarly, Haripriya (2002) estimated the missing number of trees using forest inventories of Indian forests from the frequency of stems in the higher diameter classes and concluded that the omission of small trees was nearly 30% of the total stand biomass. These findings suggest that small diameter trees that have been excluded in the inventory data could have contributed substantially to the forest biomass, depending on the forest category. In Sri Lanka the only comprehensive forest inventory was conducted in the late 1950's by the Hunting Survey Corporation of Canada which provide the stand and stock (Andrews, 1961).

In tropical forest inventories, the dbh is often measured and it is strongly correlated with AGB (Chave *et al.*, 2004). The Midpoint Diameter (D_i) of each dbh class (*e.g.* 15 cm for the dbh class 10 – 20 cm) is a consistent measure for any tree stand and the dbh is correlated with other stand parameters such as height, wood specific gravity, Basal Area (BA) and Stand Density (SD) (Chave *et al.*, 2004; Haripriya, 2002; Fang and Bailey, 1998). Chave *et al.* (2004) reported that there is a significant decrease in wood density across dbh size classes (p <0.001, r^2 = 0.97). The AGB in a dry forest can be estimated using the basal area as an independent variable in an allometric model. The SD and BA of missing small diameter trees could be predicted using an exponential function of D_i, provided the forest extent is large and all the tree species in the forest are considered. In statistical models, the D_i can be used as an independent variable to predict other stand parameters. The benefit of using D_i would be the wider range of applicability as it is an arbitrarily determined variable. However, many tropical forest inventories do not record the maximum dbh for the highest dbh class (Brown *et al.*, 1989) and therefore, D_i for the highest dbh class is unpredictable.

The objectives of this study were to develop a methodology to estimate the total AGB of a forest including the missing small diameter trees to reduce the uncertainty associated with tree inventories and to apply the proposed methodology to the forest inventory dataset on the dry zone forest of Sri Lanka.

METHODOLOGY

Data and study sites

The data for this study were extracted from the forest inventory conducted in Sri Lanka from 1958-1960 (Andrews, 1961). The data were recorded as stand (number of trees/acre), stock (volume in cubic feet/acre), and basal area (square feet/acre). The inventory covered an extent of 452,195 ha from 3,690 plots of varying sizes in eight forests. The original records in imperial units were converted to the metric scale. The forests were stratified into three yield categories based on the commercial value of timber in the selected forests namely, medium yield, low yield and non productive (Andrews, 1961) and the present study also followed the same stratification. A summarized description of these forest categories are given in Table 1. The frequency tables of the forest inventory recorded the basal area and stand density classified by the dbh classes from 10 cm – 90 cm at 10 cm intervals and the last dbh class was greater than 90 cm. The detailed site characteristics of the 8 forests selected for the study are summarized in Table 2.

Table 1. Properties of selected forest yield categories found within the dry zone of Sri Lanka

Forest yield category	Total tree height	Merchantable length	Remarks
Medium yield	> 18 m	12 m	Occurs along streams or other places where ground moisture is plentiful
Low yield	12 – 18 m	6 – 12 m	Occupies extensively flat and slightly rolling areas of the dry zone
Non productive	> 6 m	*	Occurs naturally on sides and tops of rocky areas or where soils are shallow

* stems in this yield category were not merchantable due to small size and fluted stems. Source: Andrews (1961)

Estimation of stand parameters

Non-linear regression equations were developed for each of the three forest yield categories to predict the basal area (m^2/ha), and the stand density (number of stems/ha) for tropical dry forests. The Pearson's correlation matrix was determined with D_i (the mid-point diameter) as the independent variable and the basal area and stand density as dependent variables. The models obtained are presented as Equations 1 and 2.

$$\ln BA = b_0 + b_1 D_i + b_2 D_i^2 + b_3 D_i^3 \qquad \text{Eq. 1}$$

$$\ln SD = b_0 + b_1 D_i + b_2 D_i^2 + b_3 D_i^3 \qquad \text{Eq. 2}$$

Table 2. Location, climate, extent and total number of inventory plots in selected forests

Description		Forests[a]							
		HR	KB	PK	KN	MU	PN	TO	ONR
Location	Latitude	8°13' N	6º45' N	7º39' N	8° 30' N	8º59' N	7 º 00' N	9 º15' N	7º 30' N 7º 40' N 6 º 25' N
	Longitude	80°49' E	81º40' E	80º25' E	81° 00' E	80º00' E	81º 42' E	80º 35' E	81º 30' E 81º 20' E 80º 50' E
Average altitude –(m amsl)		122	61	152	61	61	61	45	61 – 91
Mean annual rainfall (mm/year)		1524 – 1651	1701	1270 –1900	1714	1016 – 1651	1701	1558	2131 2131 1548
Mean annual temperature (°C)		28	27	27	28	28	27	27	27
Total forest area (ha)		24,936.7	26,664.7	14,762.9	47,218.7	142,671.9	37,611.5	38,396.6	55,004.48 43,742.47 4200.64
Total no. of plots		522	261	453	270	928	327	247	682

[a] HR – *Hurulu,* KB – *Kumbukkan,* PK – *Pallekelle,* KN – *Kantalai,* MU – *Madhu,* PN – *Panama,* TO – *Terravil-Oddusuddan*, O – *Omunagala*, N – *Nuwaragala*, R– *Ratkarrawwa*. The three forests ONR are given as single group in the forest inventory and properties in the last column refers to them. Source: Andrews (1961).

where BA is basal area in m^2/ha, SD is stand density in number of stems per hectare, D_i is midpoint diameter of the i^{th} class in cm, *ln* is the natural logarithm and, b_1, b_2 and b_3 are model parameters.

The models were evaluated using R^2 and residual analysis and back extrapolated to estimate the relevant BA and SD values for each forest yield category. Statistical models were developed using STATISTICA version 8.0 (StatSoft, Inc., 2007). A Quadratic Mean Diameter (QMD) is proposed to use for the highest dbh class instead of D_i in model development and the estimated BA and SD were used to find the QMD for each yield category (Equation 3).

$$QMD = \sqrt{\left(\frac{40000}{\pi}\right)\left(\frac{BA}{SD}\right)} \qquad \text{Eq. 3}$$

Using QMD for the missing diameter class (i.e. 0 – 10 cm), the AGB was estimated with a allometric equation (Eq. 4; Brown *et al.,* 1989);

$$\hat{Y} = 34.4703 - 8.0671(QMD) + 0.6586\,(QMD^2) \qquad \text{Eq. 4}$$

where Ŷ is the total AGB in Mg/ha. The estimates for each forest yield category were used to estimate the error due to the omission of small dbh trees from a previous study by the present authors (unpublished) for tropical dry forests in Sri Lanka. The AGB for the 0 – 10 cm dbh class of trees for each forest yield category was estimated using Equation 4 and multiplied with the SD of the respective yield categories to give the AGB. The observed values were plotted and using the models, the equations were back extrapolated to estimate the 0 – 10 cm dbh class for each of the three yield categories.

RESULTS AND DISCUSSION

The estimated model parameters (using Equations 1 and 2) for basal area and stand density for the forest categories (see Table 1) are presented in Table 3. The total variance accounted by the models for BA was 0.89 – 0.94 and for SD was 0.95 – 0.97 as shown by the R^2 values. The random distribution errors in residual value plots, without any systematic pattern, justified the assumption that the frequency distribution of the residuals were normally distributed as shown in Figures 1(r), 1(u), 2(r), 2(u), 3(r) and 3(u). The fitted models for BA [Fig. 1(p), 2(p), and 3(p)], and for SD [Fig. 1(s), 2(s), and 3(s)] for the three forest types followed a similar pattern. The BA and SD estimated for each diameter class using the same models are shown in Table 4 along with the observed values for each forest yield category.

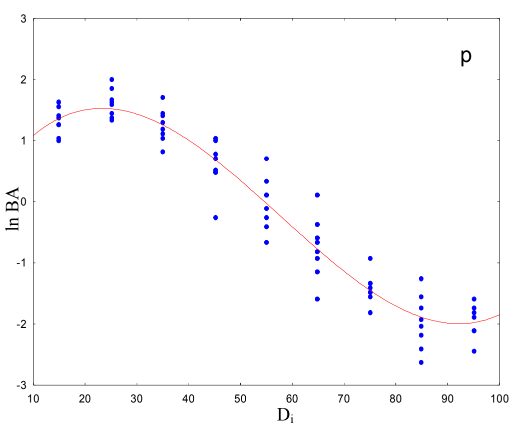
Table 3. Estimated model parameters and number of observations for three forest yield categories

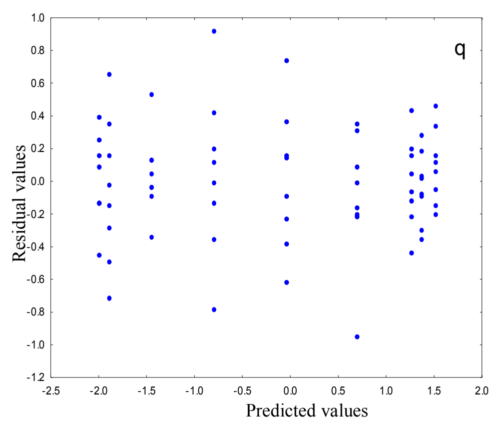
Forest yield category	Dependant variable	R^2	b_0	b_1	b_2	b_3	n
Low yield	lnBA	0.94	0.045908	0.139078	0.003744	0.000022	71
	lnSD	0.97	6.634376	-0.05929	0.001103	0.000009	70
Medium yield	lnBA	0.89	0.132419	0.134539	0.003278	0.000019	43
	lnSD	0.97	6.479111	0.063365	-0.00066	0.000007	42
Non productive	lnBA	0.90	1.749381	0.015516	0.001968	0.000014	28
	lnSD	0.95	7.865098	0.132043	0.000591	0.00001	28

Table 4. Observed and estimated values of basal area and stand density for three forest yield categories

Yield category	Variable	0 -10	20 -30	20 -30	30 -40	40 -50	50 - 60	60 -70	70 - 80	80 -90	>90
Low yield	BA_{obs}	-	3.87	5.30	3.81	2.10	1.10	0.58	0.25	0.15	0.13
	BA_{est}	1.91	3.91	4.6	3.56	2.07	1.03	0.51	0.27	0.18	0.19
	SD_{obs}	-	238	124	43	12	5	2	1	*	*
	SD_{est}	551	251	100	36	13	5	1	1	*	*
Mediu-m yield	BA_{obs}	-	3.45	5.06	4.31	2.64	1.9	1.26	0.61	0.46	0.49
	BA_{est}	1.58	3.36	4.39	3.95	2.76	1.67	0.98	0.63	0.49	0.52
	SD_{obs}	-	223	117	49	17	9	4	2	1	1
	SD_{est}	467	222	99	43	19	9	4	3	2	2
Non product ive	BA_{obs}	-	4.49	4.17	1.79	0.98	0.27	0.17	0.13	0.07	0.05
	BA_{est}	5.92	4.88	3.08	1.62	0.77	0.36	0.18	0.1	0.08	0.08
	SD_{obs}	-	342	100	21	7	1	*	*	*	*
	SD_{est}	1328	325	77	19	5	2	1	*	*	*

where BA_{obs} (in m^2/ha) and SD_{obs} (in trees/ha) are observed values for basal area and stand density and BA_{est} and SD_{est} refer to estimated basal area and stand density, * SD values lesser than one were omitted. The observed values are mean values from the eight forests for each dbh class.





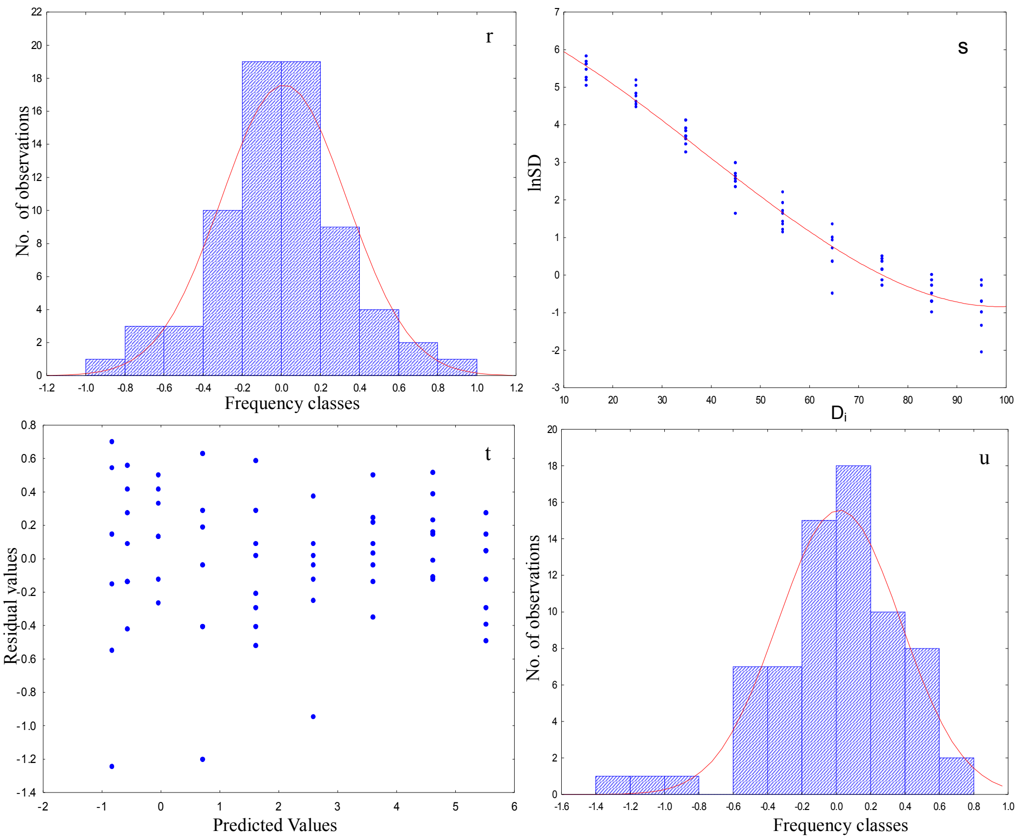
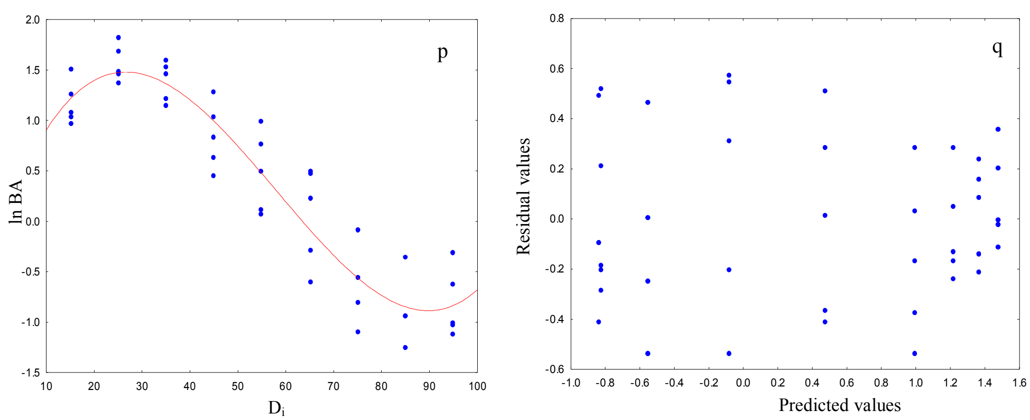


Fig. 1. **Developed models for low yield forests and their residual analyzes: (p) natural logarithm of basal area (lnBA) by midpoint diameter (D_i in cm), (q) residual plot of the BA model, (r) frequency distribution of residuals in the BA model, (s) natural logarithm of stand density (lnSD) by midpoint diameter (D_i in cm), (t) residual plot of the SD model, (u) frequency distributions of residuals in the SD model.**



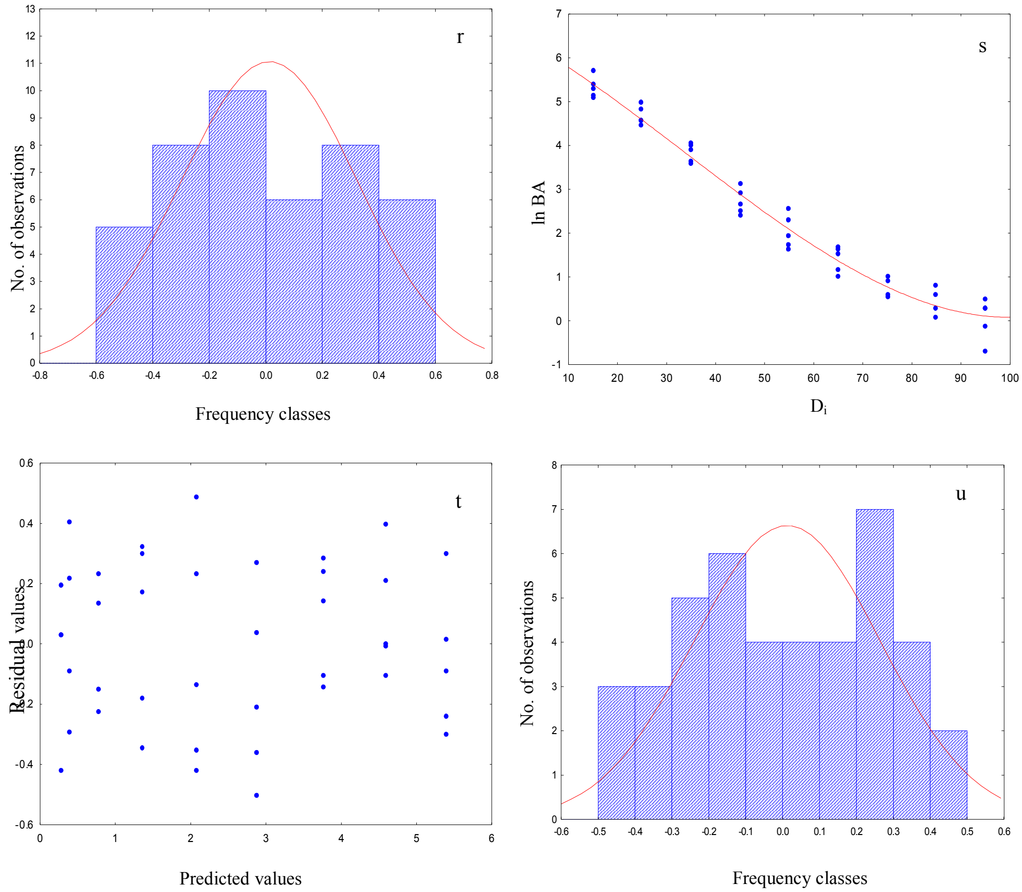
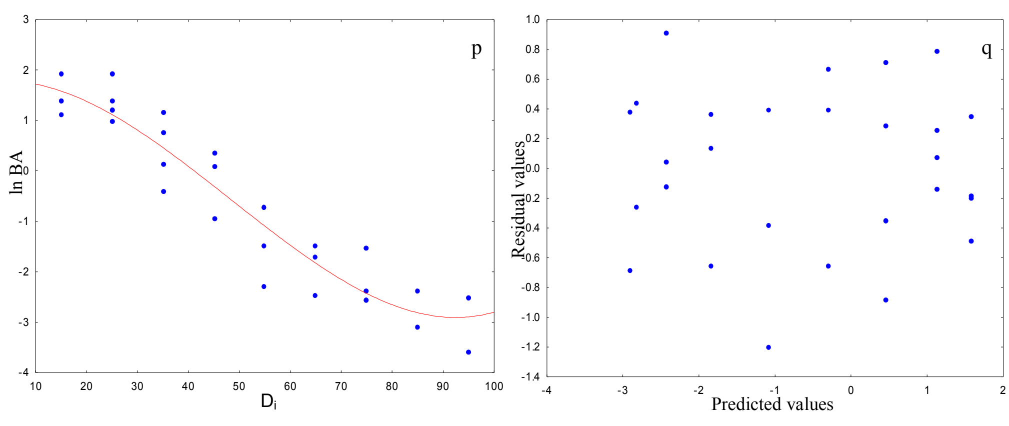


Fig. 2. Developed models for medium yield forests and their residual analyzes: (p) natural logarithm of basal area (lnBA) by midpoint diameter (D_i in cm), (q) residual plot of the BA model, (r) frequency distribution of residuals in the BA model, (s) natural logarithm of stand density (lnSD) by midpoint diameter (D_i in cm), (t) residual plot of the SD model, (u) frequency distributions of residuals in the SD model.



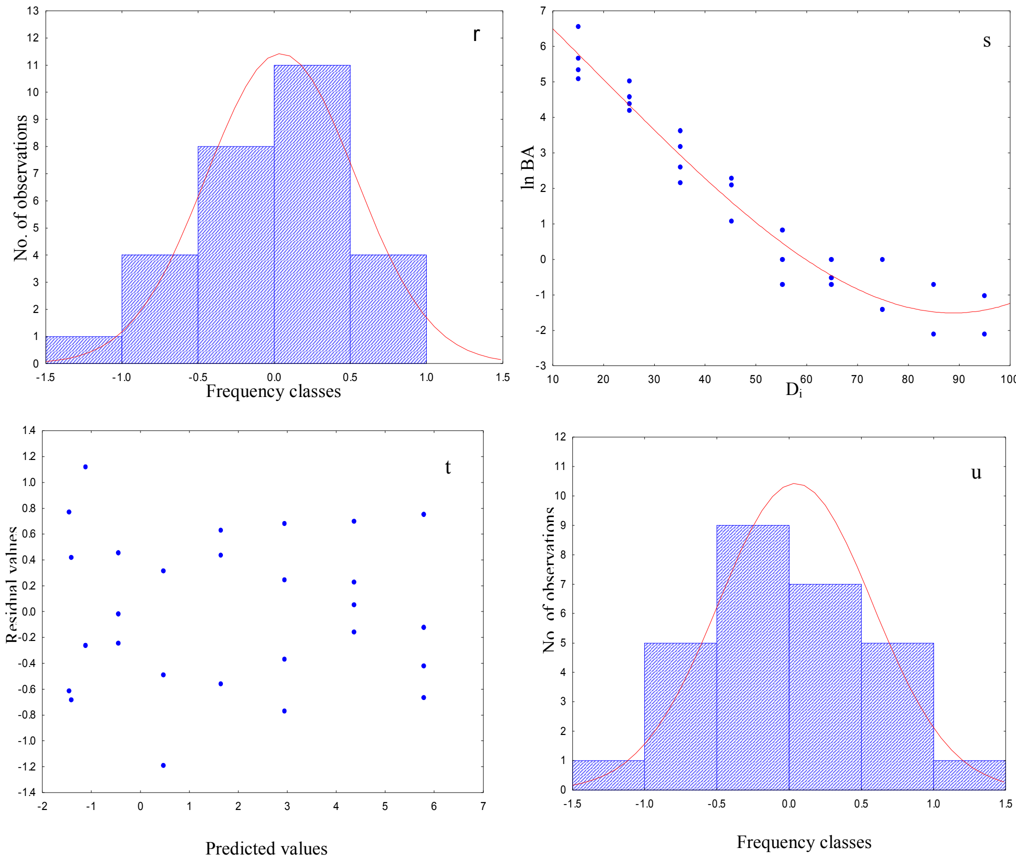


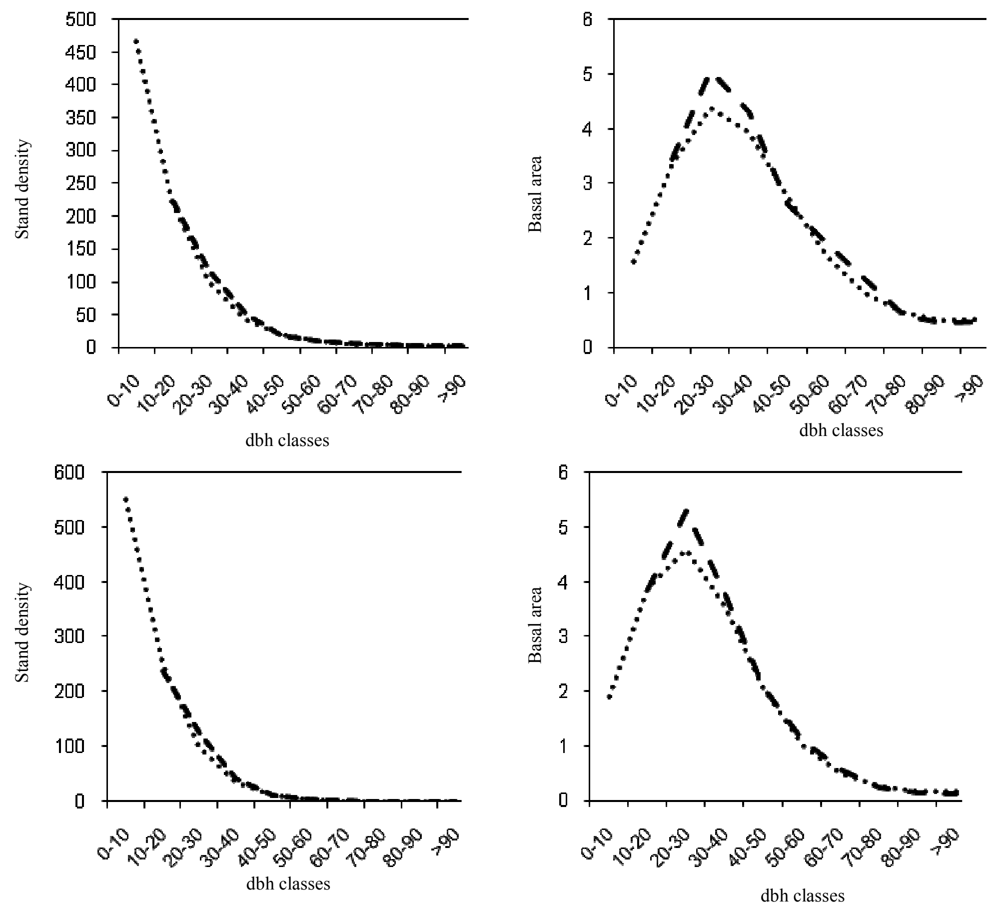
Fig. 3. Developed models for non-productive forests and their residual analyzes: (p) natural logarithm of basal area (lnBA) by midpoint diameter (D_i in cm), (q) residual plot of the BA model, (r) frequency distribution of residuals in the BA model, (s) natural logarithm of stand density (lnSD) by midpoint diameter (D_i in cm), (t) residual plot of the SD model, (u) frequency distributions of residuals in the SD model.

The non-productive forest category had the highest SD in the 0 – 10 cm dbh class of 1328 trees, more than twice the stand density in the low yield and medium yield forests (Table 4). It also had the highest stand density in the 20 – 30 cm dbh class but none beyond 60 cm. The BA followed a similar pattern.

The QMDs for the 0 – 10cm dbh class (Equation 3) were 6.65, 6.57, and 7.53 for the low yield, medium yield and non-productive forest yield categories, respectively (Table 5). The AGB for the 0 – 10 cm dbh class of trees for each forest yield category is shown in Table 5. The medium yield forests had the highest AGB for >10 cm dbh trees (117 Mg/ha) mainly due to the higher stand density of trees in the dbh class of >20 cm. The non-productive forest category in the 0 – 10cm dbh gave an estimated AGB of approximately 45 Mg/ha, about threefold that of medium and low yield forests (Table 5). This biomass is unaccounted in estimations from FID, resulting in a large error of 48.68% due to the omission of <10 cm dbh trees from the total AGB. The correspondence of the observed and estimated values for BA and SD are illustrated in Fig. 4. The BA showed a near exact correspondence while the SD showed a smaller deviation.

Table 5. Estimated quadratic mean diameter, aboveground biomass and percent errors due to omission of trees lesser than 10 cm diameter at breast height

Forest catego -ry	BA and SD		QMD (cm)	AGB of a basal area tree (Mg/ha)	AGB (Mg/ha) < 10 cm dbh	AGB (Mg/ha) > 10 cm dbh	Total AGB (Mg/ha)	% error due to omission of 0 -10 cm dbh class
LY	BA (m^2/ha)	1.91	6.65	33.92	18.69	34.2	52.89	35.34
	SD (trees/ha)	551						
MY	BA (m^2/ha)	1.58	6.57	33.94	15.86	117.1	132.96	11.93
	SD (trees/ha)	467						
NP	BA (m^2/ha)	5.92	7.53	33.87	44.97	47.4	92.37	48.68
	SD (trees/ha)	1328						



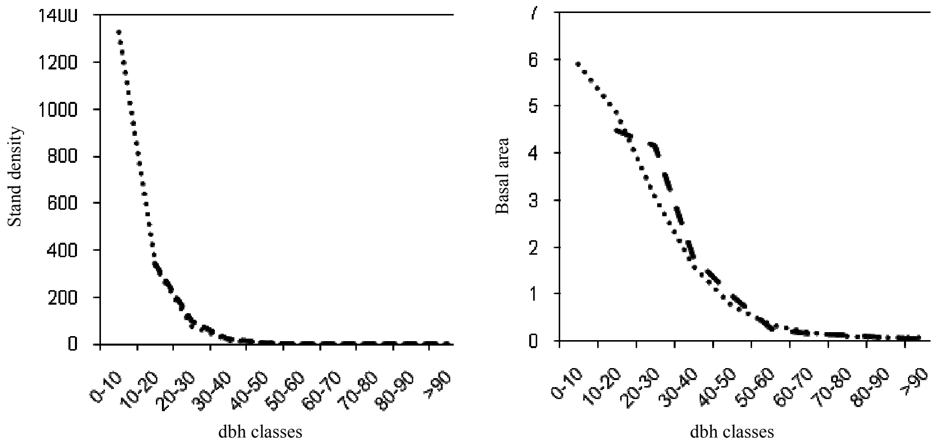


Fig. 4. **Observed (dashed line) and estimated (dotted line) basal area (m^2/ha) and stand density (trees/hectare): (p) – basal area by dbh classes for medium yield forests, (q) – stand density by dbh classes for medium yield forests, r – basal area by dbh classes for low yield forests, (s) – stand density by dbh classes for low yield forests, (t) – basal area by dbh classes for non productive forests and, (u) – stand density by dbh classes for non productive forests.**

Forest inventory data are collected to assess the commercial exploitation of forests. As FIDs are extensive and requires a high input of labour resources, the data collection is restricted to commercially-important species and tree sizes. This results in that the tree sizes <35 cm are omitted from the stand and stock tables (Brown and Lugo, 1992) and diameters <10 cm are invariably excluded. Thus, the biomass estimates based on FID are usually an underestimation (Johnson and Sharpe, 1983) and could vary from nearly 30% (Haripriya, 2002) to 25 – 45% (Gillespie *et al.*, 1992). In a study of the changes in the biomass of an Amazon forest in Brazil, Keller *et al.* (2001) used forest survey data for trees with dbh >35 cm and found that the uncertainties related to the biomass of trees with dbh <35cm dominated the error terms in their estimate.

Natural forests are unevenly-aged containing trees of all sizes and age classes The basis for objectively estimating stem frequencies in small diameter classes in the present study was based on that the stem frequencies in the larger diameter classes is only applicable to inventories that report all the species present in the forest and not limited to a sub-set of commercially important species (Gillespie *et al.*, 1992). The FID in this study recorded all the species in the eight dry forests in Sri Lanka (Andrews, 1961). Different methods have been developed to estimate the small diameter classes in forest inventories. Gillespie *et al.* (1992) used the de Liocourt quotient in their model to estimate the number of small diameter stems. According to this model, the number of stems in the adjacent diameter classes is nearly constant and the quotient is determined for the two lowest size classes in the dbh stand table. Haripriya (2002) used the frequency of stems in the higher diameter classes to estimate the frequency of smaller stems.

In the dry forests of Sri Lanka, the non-productive yield category dominated the 0 -10 cm dbh class with an estimated stand density of 1328 trees/ha. These forests had a low canopy density and the soil was shallow and dominated by rocky ground and scrub jungle (Andrews, 1961). Although these trees make a substantial contribution to the AGB, in forest inventories such commercially useless trees are not inventorized. This is in accordance with the findings of Brown *et al.* (1989), which in dry forest formations or secondary forests, a larger proportion of the biomass are in the smaller diameter trees. In the medium and low yield categories the forests have higher stand density of large trees due to relatively higher soil moisture, the canopy is wide and thick and carries less ground vegetation.

In an extensive study of Indian forests, Haripriya (2002) found that the error of omission in estimating forest biomass was substantial on an individual species basis ranging from 4% to 55% due to the non-inclusion of the small trees in the estimations. An additional investment to include the small diameter trees less than 5 cm dbh would substantially increase the accuracy and value of FID towards biomass estimation, which is becoming increasingly important in the context of carbon flux assessments, particularly in the tropical forests.

This study has developed a simple generic method to account for the missing small-diameter trees from the FIDs, thereby improving the biomass estimation in tropical forests. The basic prerequisites are that the forest inventories should include all the species and the inventoried area should be sufficiently large (Gillespie *et al.*, 1992). The variable parameters necessary are BA and SD, which are invariably recorded in inventories. The model parameters should be determined using non-linear methods to establish regression equations. These should be back-extrapolated to determine the SD classes of trees. This method develops a new model to predict SD and BA from the FID itself. Previous models developed by Haripriya (2002) and Gillespie *et al.* (1992) employed pre-assumed exponential functions. It should also be noted that, although estimating the biomass of <10 cm dbh is not as accurate as direct observation of stem frequencies, they are better than ignoring trees below some large commercial limit of the inventory (Haripriya, 2002).

CONCLUSIONS

The omission of small diameter trees from forest inventories could result in a substantial underestimation of AGB, dependent on the productivity of the forest. This underestimation can be corrected using non-linear methods to establish regression equations, using BA and SD as variables. The underestimation of AGB in the Sri Lankan forest inventory of 1961 ranged from 12% in medium yield forests to as much as 49% in non-productive forests.

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