*Indian Forester,* 142 (1) : 93-101, 2016
http://www.indianforester.co.in
ISSN No. 0019-4816 (Print)
ISSN No. 2321-094X (Online)

# CAPITALIZING ON THE INFORMATION IN ALLOMETRIC EQUATION DATA BASES FOR FOREST BIOMASS ESTIMATION

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ABSTRACT

In many countries, inventory data or biomass or volume equations are often incomplete or unavailable. Either taxonomic information is not accurate at the species level, or else no literature exist compiling particular allometric equations for some species. On the other hand, some species are represented by many alternative equations in the database. The vast quantity of information that allometric equation databases such as Globallometree can provide, can be capitalized to inform other, non-available species from the ranges and distributions of aboveground biomass estimates that other, better known species provide. In this study we provide an alternative method that takes those elements to estimate overall plot aboveground biomass from bootstrapping different equations belonging to a certain ecozone. Using a real inventory plot as an example, we prove that such estimates present error levels similar to those of generalized pantropical equations when a minimum set of rules for quality control has been added. This opens the possibility to establish more adequate quality control protocols that end up providing even better estimates than those published pantropical equations.

*Key words:* Allometric equations, Globallometree, Bootstrap, Aboveground biomass, Forest inventory.

## Introduction

The assessment of forest resources is becoming increasingly important. Forest resources are becoming scarcerat the same time as the forest sector is being recognisedas crucial for mitigating climate change (IPCC, 2014). However, forest resource assessment facesmany challenges. In South Asia alone, forest types range from tropical rainforest to mountain boreal (FAO, 2000). Forest structure, management and floristic composition vary depending on altitudinal gradients, soil types, geographical location, climate, human practices and history (Tabata *et al.,* 1988; Vetaas, 1997, 2000; Wangda and Ohsawa, 2006) making assessment complex. Furthermore, assessment depends on the available data and human, technical and financial capacities (Herold, 2009). With the emerging importance of payments for environmental services which create incentives for forest management and conservation (Wunder, 2007), improving the accuracy of forest biomass and carbon stock estimates becomes essential to ensure system robustness. Under the United Nations Framework Convention on Climate Change (UNFCCC), REDD+ (Reducing Emissions from Deforestation and Forest Degradation) has become one of the key mechanisms for climate change mitigation in developing countries (UNFCCC, 2011). In this context the accuracy and transparency of emission calculations are particularly important.

Different sources of errors in biomass and carbon stock estimates can be identified: (i) Sampling errors arising from landscape heterogeneity and plot number, size and shape; and (ii) Model errorsarising from the differences between the true plot biomass values and the model predictions (Picard *et al.*, 2014). A number of authors report significant differences in forest carbon stock estimates depending on the volume and biomass models used (Kenzo *et al.*, 2009; Melson *et al.*, 2011; Alvarez *et al.*, 2012; Ngomanda *et al.*, 2014). While the optimization of the sampling design tends to minimize the sampling error, the model error can be reduced by improving the selection and use of models.

Tree allometric models are used to predict biomass from tree characteristics (e.g. trunk diameter, height and wood specific gravity). Estimates of biomass per area are calculated as the sum of individual tree biomass across all trees in a plot (Picard *et al.*, 2012). Thus, systematic errors in the allometric models applied at tree level propagate to plot and forest level errors, and then to national estimates (Chave *et al.*, 2004). Improving the accuracy of allometric equations for biomass and volume is valuable for both national biomass assessment and emissions estimates and for individual-tree/plot-level estimates for forest managers, scientists and all stakeholders in the economic sector of timber production.

Simple rules for quality control of allometric equations in a database, linked to a bootstrap procedure, showed model uncertainties similar to those of existing pantropical equations.

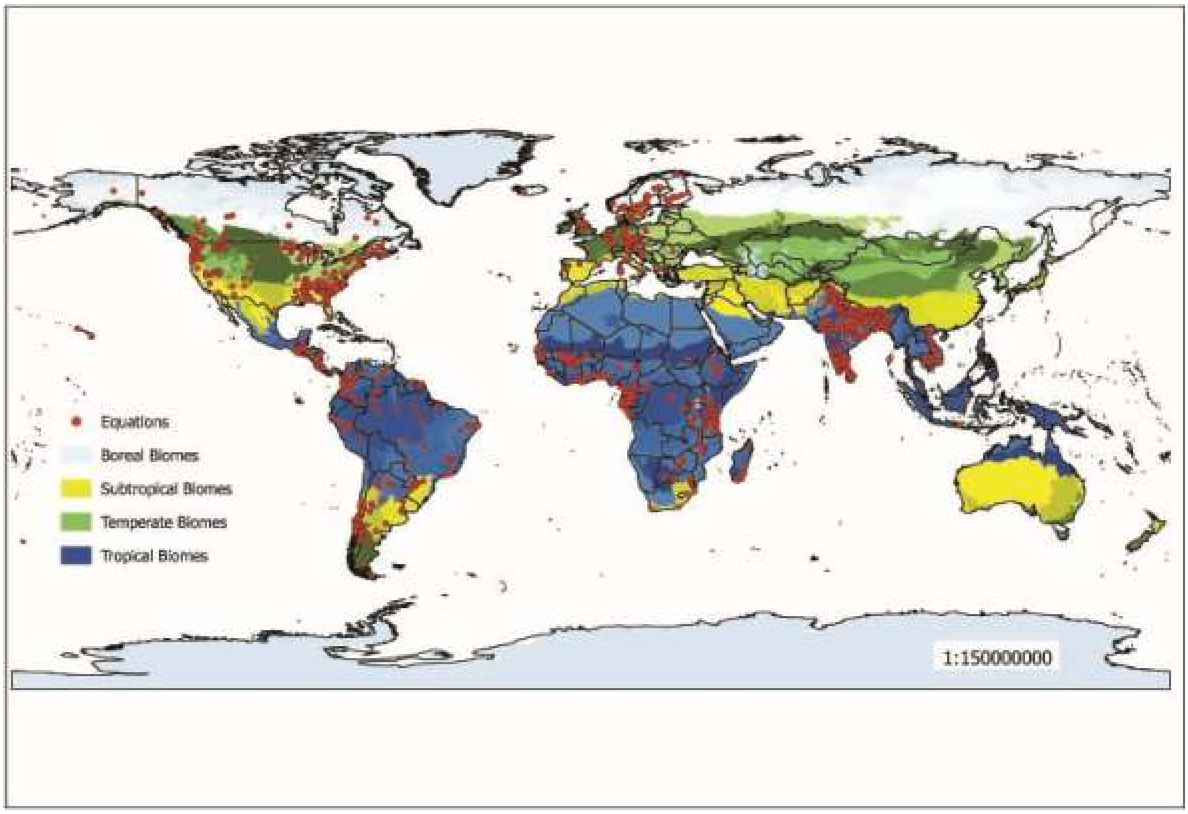


Fig. 1 : Geographic distribution of tree volume and biomass equations in the world (www.globallometree.org)

In 2013 a compilation of the tree allometric equations for biomass and volume that had been produced and made available in South Asia was completed (Sandeep *et al.*, 2013). To estimate total biomass the IPCC proposesa number of methods usingvariously partial volume, wood density and expansion factors (IPCC, 2003). However, the applicability of these methods faces several constraints, one of which is related to the correct identification of species during forest inventories (Lacerda and Nimmo, 2010). When tree species lists are absent or incomplete, the application of species-specific volume and biomass equations becomes problematic. Further, most of the species to be found in inventories in tropical countries lack species-specific allometric equations in the largest existing allometric equation database (Globallometree) or in the literature.The objective of this paper is to present a generalized method to estimate total above-ground biomass based on repeated sampling (bootstrapping) of regional volume and biomass equations.

## Methods

### *Collection of tree volume and biomass equations*

4,604 volume and biomass equations were downloaded from the Glob Allome Tree (Henry *et al.*, 2013; Sandeep *et al.*, 2013) (Fig. 1). The database was filtered in order to select only the equations predicting total biomass (n=75), stem biomass (n=13) and stem volume (n=209), of which 201, 212, 14, 2 and 9 were from Bangladesh, India, Nepal, Pakistan and Sri Lanka respectively.

### *Biomass assessment procedures*

Four different methods are proposed to assess aboveground biomass, all of them species-independent. Hence the covariates for biomass prediction only involved diameter or girth at breast height, tree height, wood density and biomass expansion factor depending on the equation and method used. The four methods are the following:

*Method 1*: two pan tropical equations (Brown, 1997; Chave *et al.*, 2014) are applied;

*Method 2:* 75 total above-ground biomass equations from Glob Allome Tree are applied with a bootstrapping procedure;

*Method 3*: 13 stem biomass equations from Glob Allome Tree are applied with a bootstrapping procedure and total biomass is calculated using a randomized list of Biomass Expansion Factors (BEF).

*Method 4:* 209 stem volume equations from Glob Allome Tree are applied with a bootstrapping procedure and the results expanded and converted to above ground

Table 1 : parameters of the forest structure of the study site

| Variables | Average | Median | Min | Max |
|---|---|---|---|---|
| Dbh (cm) | 42.30 | 38 | 12 | 110 |
| Height (m) | 11.77 | 12 | 8 | 18 |

biomass using wood density values and BEFs (the values are presented in Appendix 2).

*Quality control*

Many equations are reported erroneously in scientific articles and therefore in Glob AllomeTree for several reasons, including using an incorrect approach for model development or formatting problems (Henry *et al.*, 2011). A quality control method was developed to identify the equations that predicted unrealistic values as estimates. Unrealistic values were determined to be: (1) negative estimates, (2) decreasing estimates (output (biomass) values are decreasing with increasing input (diameter) values) and (3) *degree of divergence from a "reference" value*. The reference values used are derived from Brown's biomass model (1997), where acceptable values must fall within a range ($B_{Brown}$ * *t*) where *t= (0.1,10)* is a threshold range. In order to assess the effects of quality control and to detect the deviations from reference pantropical equations, methods 2, 3 and 4 were applied with and without qualitycontrol. Our reference equation is only used in this study as an example to highlight the quality control general protocol. Any other reliable reference generalized equation from the literature may be chosen in the calculations. In any case, a real scenario involving the choice of appropriate allometric equations for national forest assessment will necessarily involve protocols for quality control both in the allometric equation database and the inventory.

*Wood density and biomass expansion factors*

In method 1, a default wood density value of 0.6 was used (Chave *et al.*, 2005). In method 4, wood density values were extracted from the Dryad Global Wood Density Database (Chave *et al.*, 2009; Zanne*et al.*, 2009) which provides wood density values at species and/or genus levels. Biomass was calculated using tree species- or genus-specific wood density values. When regional species-specific wood density values were not available, a regional genus-level average value was used (Appendix 1).In the absence of such a value, a global species-specific average or, subsequently, a global genus-specific average of wood density values was applied (Appendix 1). In methods 3 and 4, the biome-specific BEF values from the IPCC (2003)were used to calculate total biomass.

*Confidence interval*

Biomass estimators and their corresponding 95% confidence intervals were calculated from non-parametric bootstraps with 1000 replicates. Bootstraps were in all cases made with replacement, to characterize the population estimates, and compared to pantropical estimates, used as reference value. Given that some equations are repeated through the database, our bootstraps present weights following proportionality in the representation of the equations on the database. Analyses were coded using R and the package boot (Canty and Ripley, 2011; Team RDC, 2011).

*Study area*

Tree and plot biomass estimates were achieved based on one plot in Bangladesh's Chittagong Division (FAO, 2007). The 2 hectare plot was divided into four 250 x 20 m tracts, and belongs to the FAO biome "Tropical rainforest" (FAO, 2010). In total 31 tree species were inventoried. 9 out of the 31 species in the plot had no associated allometric equations in the database. The forest structure in the example plot is summarized in Table 1.

## Results and Discussion

*Preparation of a database for volume and biomass calculations*

From the 4,604 equations developed for South Asia and available on Glob Allome Tree, 438 equations were identified for stem and total volume and biomass estimations within the ecological zone of the study site. From the 438 equations only 297 (69.4% and 64.2% of volume and biomass equations) met the selection criteria (1), (2) and (3) of the quality control, and were considered as reliable. From the ones not fulfilling the selection criteria, 111 equations respected the criteria in only one part of the interval, while 30 equations (6% of the total) didn't fulfill the requirements in any part of their range. In consequence, the quality of the equations found for South Asia appears to be slightly better than those for Sub-Saharan Africa, where 22% of the equations were reported to be wrong (Henry *et al.*, 2011).

Until very recently, there was no harmonized global repository of allometric equations. With Glob Allome Tree, it is now possible to have access to the equations that have been used and to evaluate their reliability, applicability and robustness. Arbitrating among existing models heterogeneous in quality and complexity is challenging and can lead to mistakes and inaccuracies, especially if information regarding the uncertainty of parameters is not reported (Sileshi, 2014). Many equations are erroneously reported in South Asia, and also in other continents such as Africa (Henry *et al.*, 2011). In consequence, it is important to control the equations for quality before using them for volume or biomass assessment. Many published equations lack basic location descriptions, information on the statistics of the equation and on the method used to construct the allometric model. These missing data limit the usefulness of equations, the assessment of the accuracy of estimates and ultimately scientific progress towards sustainable forestry practices. In order to ensure that equations are adequately developed for tree volume and biomass assessment, scientists are recommended to use guidelines (Cifuentes *et al.*, 2014).

*Assessment of forest biomass using different approaches*

The use of different methods to assess forest biomass results in large differences (Table 2, Fig.1). Using method 1, aboveground biomass estimates ranged 178-462 Mg ha$^{-1}$ when using the equations from Chave *et al.* (2014) and Brown (1997) respectively. When bootstrapping was applied to the whole plot, method 1presented the smallest range of confidence intervals for the estimates, both with and without QC. However, when QC was implemented, biomass confidence intervals were the smallest, ranging between 357.7 and 458 Mg ha$^{-1}$. The largest confidence intervals for the estimates were obtained using method 2. Yet, when quality control was used, the range of estimates drastically decreased for all methods.

When comparing the averages, the estimates obtained using QC equations were always lower than estimates without QC (Table 2). When considering only QC equations, the highest estimate was using method 3 while the lowest using method 1. On the other hand, estimates from method 1 (Brown) and 2 were similar (462, and 406 Mg ha$^{-1}$). Method 4 provided estimates about two times higher (855 Mg ha$^{-1}$) while difference between methods 1 and 3 was up to 11-fold.

*Forest biomass for different diameter classes*

When analyzing the biomass distribution by diameter classes, from Table 2 it appears that the differences between methods are regular. While the differences for lower diameter classes are smaller, the differences increase with diameter size.

*The robustness of biomass expansion factors limits the use of volume equations for biomass estimation*

Method 3 largely overestimates biomass when compared with the other methods. Other authors estimate forest biomass ranging between 307 and 468 Mg ha$^{-1}$ in evergreen forests in Tamil Nadu and semi-evergreen forests in the Eastern Ghats (Swamy, 1989; Baishya and Barik, 2009). In consequence, the methods using BEFs largely overestimate biomass. This can be explained by (1) the BEFs were developed in a different continent and ecological zone, (2) they do not consider the tree size, tree species and biomass density, and (3) the number of BEFs available is very limited. Henry *et al.* (2011) reported similar results where biomass estimates using BEF largely over estimated biomass when comparing to other methods.

In addition, the limited number of equations for method 3 would also impact the robustness of the estimates. It is necessary to have more biomass equations and expansion factors from different authors when using bootstrap methods for producing average estimates (e.g. method 3 used 13 equations from two references).

*Recommendations for forest biomass assessment*

This study proposes a potential approach to estimating biomass when reliability on species identification is limited and when several tree equations exist. In an ideal scenario, species information is reliable because of: (i) the existence of strong technical knowledge among field survey technicians, or (ii) the

Table 2 : Forest biomass estimates using different methods..

| DBH class (cm) | Method 1 | | Method 2: AGB | | Method 3: BEF*Stem biomass | | Method 4: BEF*WD*Volume | |
|---|---|---|---|---|---|---|---|---|
| | Chave *et al.* (2014) | Brown (1997) | QC | without QC | QC | without QC | QC | without QC |
| 10-111 | 178 | 461.8 | 405.7 (358 - 468) | 57531 (4385 - 246866) | 1,995 (1,817 - 2,058) | 2,726 (2,362 - 20,831) | 855 (354 - 973) | 1,725 (686 - 4942) |
| 10 - 20 | 1.9 | 3.1 | 5.7 (4 - 7) | 15 (4 – 4224) | 26 (20 - 26) | 27 (23 - 42) | 2 (2 - 7) | 3 (0.65 - 102) |
| 20-30 | 8.5 | 15.4 | 23 (19- 28) | 4936 (20 - 14,304) | 103 (92 - 111) | 138 (107 - 179) | 16 (12 - 19) | 39 (12 - 310) |
| 30-40 | 14.2 | 28.6 | 43.5 (28 - 44) | 9939 (28 - 25575) | 162 (146 - 181) | 196 (171 - 353) | 27 (21 - 35) | 108 (21 - 482) |
| 40-50 | 27.7 | 63.7 | 74.8 (55 - 80) | 73 (53 - 48601) | 304 (280 - 341) | 350 (341 - 875) | 50 (46 - 76) | 129 (47 - 863) |
| 50-70 | 40.7 | 99.9 | 89.9 (72 - 116) | 15010 (68 - 82,189) | 442 (391 - 493) | 577 (474 - 2969) | 77 (68 - 152) | 620 (69 - 1403) |
| 70-111 | 85.1 | 251.1 | 175.1 (141 - 231) | 137 (113 - 187,969) | 931 (776.4 - 994) | 1484 (948 - 29225) | 505 (159 - 773) | 2105 (157 - 3814) |

Units are in Mg. “QC” stands for quality-controlled allometric equation database

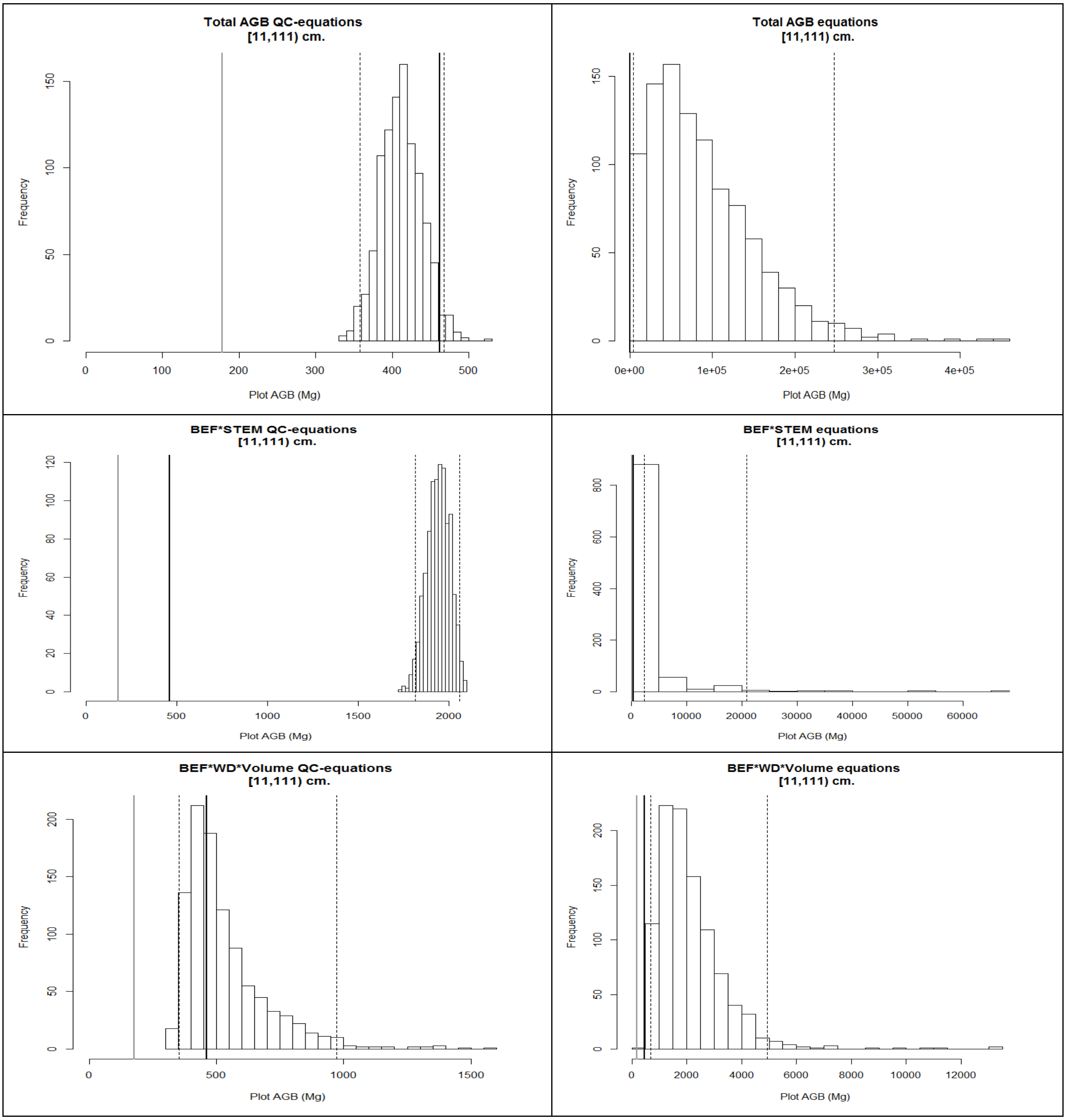


Fig. 2: Aboveground biomass estimates using different methods and equations
A: Biomass estimates using method 2 with QC, B: biomass estimates using method 2 without QC, C: biomass estimates using method 3 with QC, D: biomass estimates using method 3 without QC, E: biomass estimates using method 4 with QC, D: biomass estimates using method 4 without QC.

existence of a rich literature feeding a database with local equations, wood densities and biomass expansion factors for each species. In this context, one recommended decision tree (Fig. 3) would aim to maximize the local information to provide accurate estimations in regards to biomass or volume stocks. A typical scenario where much of the local information is absent consists of the use of pantropical equations, such as those published by Brown (1997) or Chave (Chave *et al.*, 2005; Chave *et al.*, 2014). These tree-based pantropical equations have the advantage of simplicity of calculations, but lack information about the local conditions and often provide very different results between local and/or pantropical equations.

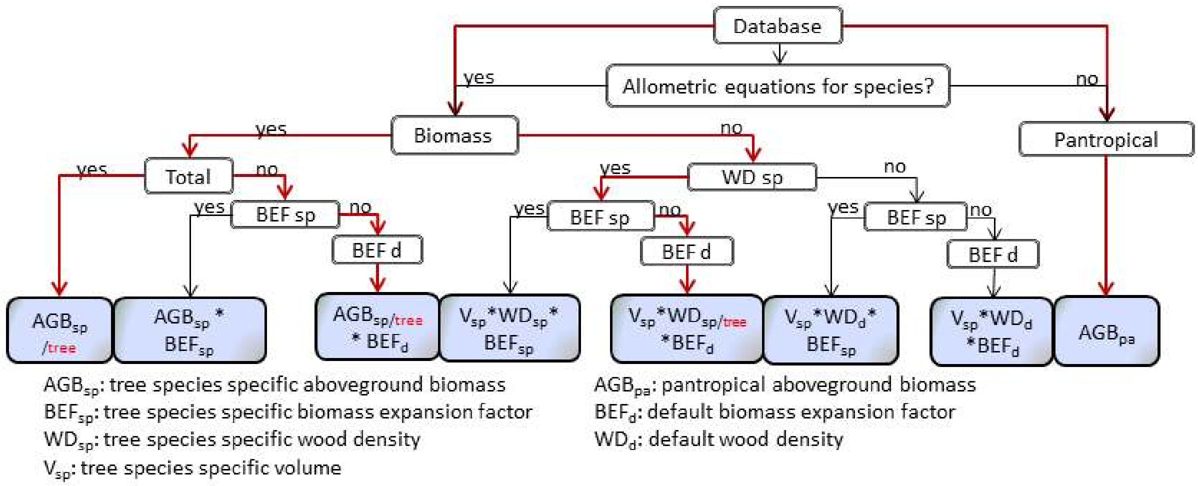


Fig. 3 : Recommended decision tree for the estimation of biomass at the plot level. Each of the branches is dependent on the availability of species-specific equations and wood density or biomass expansion factors. The red arrows show the different species-independent approaches taken in this study.

The bootstrap approach has been used before in Indonesia including height-diameter models as intermediate steps for the calculation of biomass (Rutishauser and Noor'an, 2013), with only 6 available allometric equations. Our results for aboveground biomass measured directly with AGB allometric equations provide similar numbers to those of Rutishauser and Noor'an (2013) in unmanaged forests, but with slightly smaller confidence intervals. While our average AGB/ha doubles that estimated by Chave *et al.* (2005), the confidence intervals for the AGB equations under QC provide smaller confidence intervals (approx. ±60 Mg/ha) than those of Chave *et al.* (2005) (approx. ±87 Mg/ha). Given the fact that the potential scope of allometric equations to choose from is much larger, the improved level of uncertainty in these results is promising. However, volume-based or stem-biomass based equations provide results much larger confidence intervals, or plainly overestimated averages, respectively, at least when compared to both pantropical approaches. In the first case, the selection of default BEF's may be erroneous, and more proper estimations of BEF's at the local level, or based on direct calculations from the ratio between AGB and volume equations might provide a better alternative. In the second case, the low number of equations, linked to the fact that all 10 out of 13 were given by the same study, is likely to introduce a large bias in the bootstrap weights for these equations.

In regards to the bootstraps by diameter class, the results show a slower growth of aboveground biomass in the AGB-based set of selected, quality-controlled equations. This translates in biomass values that are overestimates over Brown's values for the small diameter classes and underestimates for the large trees. For the case of stem volume-based, quality-controlled equations all confidence intervals for all diameter classes include Brown's diameter class estimates. This does not necessarily indicate a better agreement with Brown's estimates, but rather, the fact that the confidence intervals for volume-based equations are very large, largely due to the combined bootstrap of the equations with the randomized lists of BEF's and wood densities. In this respect, it is recommended to use species- or genus-, regional- or even global-specific wood density data from well-representative databases i.e. (Zanne *et al.*, 2009) combined with bootstrapping of equations, and to potentially calculate regional BEF's based on bootstrapping biomass/volume ratio values. Furthermore, it is strongly advisable to expand the wood density databases to cover all species, or otherwise, if randomized lists are to be used, further research is needed to set up prioritization criteria (either taxonomic or on a spatial scale) when species-specific densities are not present.

## Conclusion

We have shown an alternative method of calculating biomass estimates based on the use of large databases of allometric equations. By bootstrapping all existing allometric equations within a biome we have shown that the uncertainty in estimates may be reduced if an appropriate method is used. For the example shown, the choice of previously quality-controlled aboveground biomass equations seems promising in this respect. Hence, as a first step, the use of a quality controlled database is necessary. Large tree model databases contain errors and it is crucial to identify and minimize them. Given the typically exponential or power relationships existing among equations, apparently small errors in a few entries may introduce serious miscalculations of several orders of magnitude that may overestimate the true value of aboveground biomass or the confidence intervals. As a second step, we propose to compare different methods and identify the best one, taking into consideration the number of equations, the range of validity, the number of independent studies, and the number of parameters required. Further research should aim to improve the quality-control algorithmic steps and the quality of biomass expansion factors and develop other methods to improve the statistical robustness of forest biomass estimates.

Acknowledgements

The authors thank S. Sandeep and M. Sivaram for their work in the elaboration of the South Asia allometric equation database as well as the participants of the Regional Workshop on Allometric Equations taking place in the Kerala Forest Research Institute in November 2014.

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Appendix 1 : Wood density values

| Tree species | Genus | Regional level | | | | Global level | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Species-specific | | Genus-specific | | Species-specific | | Genus-specific | |
| | | No. WD values (regional) | Mean species WD (regional) | No. WD values (regional) | Mean Genus WD (regional) | No. WD values (global) | Mean species WD (global) | No. WD values (global) | Mean genus WD (global) |
| *Albizia procera* | *Albizia* | 3 | 0.55 | 26 | 0.56 | 8 | 0.57 | 107 | 0.54 |
| *Alstonia scholaris* | *Alstonia* | 5 | 0.40 | 18 | 0.42 | 10 | 0.38 | 55 | 0.44 |
| *Amaranthus tricolor* | *Amaranthus* | 0 | NA | 0 | NA | 0 | NA | 0 | NA |
| *Anthocephalu schinensis* | *Anthocephalus* | 0 | NA | 0 | NA | 0 | NA | 0 | NA |
| *Aphanamixis polystachya* | *Aphanamixis* | 6 | 0.55 | 8 | 0.56 | 10 | 0.58 | 12 | 0.58 |
| *Artocarpus chaplasha* | *Artocarpus* | 2 | 0.46 | 49 | 0.49 | 2 | 0.46 | 63 | 0.48 |
| *Bombax ceiba* | *Bombax* | 3 | 0.28 | 9 | 0.32 | 4 | 0.31 | 30 | 0.37 |
| *Chukrassia tabularis* | *Chickrassia* | 0 | NA | 0 | NA | 0 | NA | 0 | NA |
| *Cocos nucifera* | *Cocos* | 0 | NA | 0 | NA | 0 | NA | 0 | NA |
| *Costus speciosus* | *Costus* | 0 | NA | 0 | NA | 0 | NA | 0 | NA |
| *Crateva magna* | *Crateva* | 0 | NA | 3 | 0.36 | 0 | NA | 9 | 0.47 |
| *Derris indica* | *Derris* | 0 | NA | 3 | 0.67 | 0 | NA | 7 | 0.67 |
| *Dichopsis polyantha* | *Dichopsis* | 0 | NA | 0 | NA | 0 | NA | 0 | NA |
| *Dillenia indica* | *Dillenia* | 1 | 0.70 | 30 | 0.62 | 1 | 0.70 | 37 | 0.61 |
| *Dipterocarpus turbinatus* | *Dipterocarpus* | 2 | 0.62 | 88 | 0.65 | 2 | 0.62 | 90 | 0.65 |
| *Duabanga grandiflora* | *Duabanga* | 0 | NA | 2 | 0.34 | 2 | 0.38 | 5 | 0.35 |
| *Ficus hispida* | *Ficus* | 2 | 0.38 | 66 | 0.41 | 2 | 0.38 | 153 | 0.41 |
| *Lagerstroemia speciosa* | *Lagerstroemia* | 2 | 0.60 | 20 | 0.60 | 2 | 0.60 | 21 | 0.60 |
| *Lannea coromandelica* | *Lannea* | 1 | 0.34 | 1 | 0.34 | 3 | 0.40 | 11 | 0.42 |
| *Macaranga denticulata* | *Macaranga* | 2 | 0.39 | 42 | 0.37 | 4 | 0.43 | 57 | 0.38 |
| *Mesua nagassarium* | *Mesua* | 0 | NA | 8 | 0.72 | 0 | NA | 8 | 0.72 |
| *Michelia champaca* | *Michelia* | 4 | 0.53 | 18 | 0.48 | 4 | 0.53 | 29 | 0.50 |
| *Phragmites karka* | *Phragmites* | 0 | NA | 0 | NA | 0 | NA | 0 | NA |
| *Schleichera oleosa* | *Schleichera* | 4 | 0.90 | 5 | 0.90 | 4 | 0.90 | 5 | 0.90 |
| *Stereospermum chelonoides* | *Stereospermum* | 0 | NA | 8 | 0.66 | 0 | NA | 11 | 0.66 |
| *Swietenia* | *Swietenia* | 0 | NA | 2 | 0.50 | 0 | NA | 15 | 0.54 |
| *Syzygium cumini* | *Syzygium* | 1 | 0.76 | 12 | 0.64 | 3 | 0.67 | 102 | 0.65 |
| *Terminalia belerica* | *Terminalia* | 0 | NA | 17 | 0.59 | 0 | NA | 179 | 0.55 |
| *Tetrameles nudiflora* | *Tetrameles* | 0 | NA | 0 | NA | 5 | 0.31 | 5 | 0.31 |
| *Toona ciliata* | *Toona* | 0 | NA | 0 | NA | 6 | 0.38 | 12 | 0.40 |
| *Trewia polycarpa* | *Trewia* | 0 | NA | 1 | 0.44 | 0 | NA | 1 | 0.44 |