

# Allometric equations based on a fractal branching model for estimating aboveground biomass of four native tree species in the Philippines

F. Santos Martin · R. M. Navarro-Cerrillo ·  
R. Mulia · M. van Noordwijk

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**Abstract** Fractal branching models can provide a non-destructive and generic tool for estimating tree shoot and root length and biomass, but field validation is rarely described in the literature. We compared estimates of above ground tree biomass for four indigenous tree used on farm in the Philippines based on the WanFBA model tree architecture with data from destructive sampling. Allometric equations for the four species varied in the constant (biomass at virtual stem diameter 1) and power of the scaling rule ( $b$  in  $Y = aD^b$ ), deviating from the value of  $8/3$  that is claimed to be universal. Allometric equations for aboveground biomass were  $0.035 D^{2.87}$  for *Shorea contorta*,  $0.133 D^{2.36}$  for *Vitex parviflora*,  $0.063 D^{2.54}$  for *Pterocarpus indicus* and  $0.065 D^{2.28}$  for *Artocarpus heterophyllus*, respectively. Allometric equations for branch biomass had a higher  $b$  factor than those for total biomass (except in *Artocarpus*); allometric equations for the leaf + twig fraction a lower  $b$ . The performance of the WanFBA model was significantly improved by introduction of a tapering factor

“ $\tau$ ” for decrease of branch diameter within a single link. All statistical tests performed on measured biomass versus biomass predicted from the WanFBA results confirm the viability of the WanFBA model as a non-destructive tool for predicting above-ground biomass equations for total biomass, branch biomass and the leaf + twig fraction.

**Keywords** Above-ground biomass · Native tree species · Allometric equations · Tree architecture

## Introduction

Lack of scientific information on lesser known tree species constrains the utilization and promotion of those species for tree domestication. Scaling rules for tree biomass with stem diameter are an essential characteristic that has to be measured for understanding the ecological dynamics related to nutrient cycling, energy flow and ecosystem productivity (Parresol 1999). Available data that classify trees by their broad climate requirements and types of use are generally not precise enough to guide local choice, especially for some native tree species in early stages of domestication (Roshetko and Evans 1999). It is therefore imperative to have appropriate methods and tools for estimating tree biomass and other important tree properties and parameters (van Noordwijk 1999).

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F. Santos Martin (✉) · R. M. Navarro-Cerrillo  
Department of Forestry Engineering, University  
of Cordoba, Avenida Menendez Pidad s/n,  
14004 Cordoba, Spain  
e-mail: santosmartinfer@gmail.com;  
fsmartin@ucdavis.edu

R. Mulia · M. van Noordwijk  
World Agroforestry Centre South-East Asia  
(ICRAF-SEA), P.O. Box 161, Bogor 16001, Indonesia

Tree biomass can be estimated by either destructive or non-destructive methods. The former methods are laborious and expensive because they involve cutting down trees and measuring the dry weight of their components (Araujo et al. 1999). To reduce the need for destructive sampling, biomass can be estimated from an easily measured property such as stem diameter, by using ‘allometric’ scaling equations (Brown et al. 1995). A substantial number of allometric equations have been developed for trees in various climatic zones, forest types and tree species, using a variety of algebraic forms and parameter values (Ketterings et al. 2001). Details of the equations vary with environmental conditions of tree growth (Nelson et al. 1999), and these differences matter. For example, Nogueira et al. (2007) argued that on the basis of an overestimate of wood density and allometric coefficients for forests in Brazil, national CO<sub>2</sub> emissions had been overestimated by 10%. Biomass of trees varies depending on the site conditions such as soils, vegetation, over storey structure (mean height and diameter) and nutrient impoverishment.

Anybody who wishes to use any of the available equations for a new situation is faced with a difficult choice among the various types of equations. The most commonly used functions are polynomials and power models (van Noordwijk 1999). Although polynomials (usually quadratic or cubic equations) may provide good fits with the measurement range, their inherent shape is non-natural and extrapolation outside of the range of the original model calibration is risky (Ketterings et al. 2001). The power function form is widely found within biology (Huxley 1932) and has some attractive interpretations for scaling. The allometric power equation generally used in estimating aboveground tree biomass is:

$$B = aD^b \quad (1)$$

where  $B$  is biomass (kg/tree) and  $D$  is diameter (cm) measured at breast height (standardized at 1.3 m), and  $a$  and  $b$  are parameters that indicate ( $a$ ) tree biomass when the diameter is 1 cm and ( $b$ ) the allometric scaling power. Parameters  $a$  and  $b$  can be determined by linear regression of log-transformed  $B$  and  $D$  (Fownes and Harrington 1991) or by direct model fitting, with greater weight for errors at larger stem diameters. Empirical relationships have to be taken at face value, unless models of tree architecture

provide a ‘logic’ for relationships between the different parts of a plant across the range of diameter values. West et al. (1999) provided a biomechanical interpretation for a supposedly universal 8/3 (=2.67) allometric scaling rule for all trees. The forestry literature, however, suggests a substantial variation in the  $b$  factor that requires specific attribution and, if possible, a relationship with visual attributes of the trees to assist in selecting of appropriate values.

The Functional Branch Analysis (FBA) model was designed by van Noordwijk and Mulia (2002) to generate allometric equations on the basis of easily observed properties of branched systems (above or belowground), in order to allow a more informed choice among empirical equations for specific tree species or even for individual trees in a sampling area. Apart from tree biomass, the model can predict total leaf area; relative allocation of current growth of leaves, branches or stem, number of branches  $n$ , the transfer coefficient of cross sectional area  $p$ , an allocation coefficient among branches  $q$ , and a regression coefficient between diameter and length of links. The term “link” refers to a section of stem or branch between two branching points; links can thus be larger than internodes. For each link a length, volume and number of “end structures” are calculated on the basis of its diameter, and these data are stored in various summation parameters. If such an algorithm for constructing branching patterns is applied many times to trees of different initial diameters,  $D_o$ , a range of properties of the tree as a whole can be related to  $D_o$ , for example by fitting a power-type allometric equation to the data (Mulia et al. 2001).

Fractal branching models make use of self-repeating properties in applying simple rules consistently across a range of scales (van Noordwijk et al. 1994). In trees above as well as below-ground branching follows a simple logic that the amount of transport tissue (functional xylem) where two branches split (or come together, depending on perspective) has to be able to transport the same amount of water before and after the branching point. This consistency leads to the requirement of a near-constant cross-sectional area of xylem (assuming that the maximum size of metaxylem elements is determined by the risk of embolism; Tyree and Sperry 1989), and depending on the stem anatomy, to a proportional relation the cross-sectional areas of the whole stem (van Noordwijk

1999). Any branching point can be described by a transfer coefficient  $p$  for the change in total cross-sectional area

$$p = D_{\text{before}}^2 / \sum D_{\text{after}}^2 \quad (2)$$

an other allocation coefficient  $q$  for the split of cross-sectional area over the branches

$$q = \max D_{\text{after}}^2 / \sum D_{\text{after}}^2 \quad (3)$$

and one ( $n$ ) for the number of branches between the axes before and after branching. Direct measurements of diameter change at branching points and statistical analysis to test the independence of these parameters from the diameter can establish the validity of the model assumptions and the viability of the fractal model (van Noordwijk and Mulia 2002). If the empirical range of parameter values in allometric equations can indeed be accounted for on the basis of easily observable, non-destructive parameters, such parameters (at least for the more extreme values) can be included in standard tree inventories to improve the reliability of biomass estimates and carbon stock accounting. Additionally, the allometric equations as derived with the WanFBA module can be directly used in the WaNuLCAS model (van Noordwijk and Lusiana 1999) for exploration of biophysical performance in agroforestry scenarios (Santos-Martin and van Noordwijk 2009).

Thus, the overall objective of this study was to develop a tree database of tree architecture parameters that will allow further analysis for selected trees. More specifically this study was designed to (1) develop allometric equations of aboveground biomass for four native species on the basis of parameters that can be measured non-destructively; (2) test the validity of WanFBA model as a non-destructive tool to estimate biomass and describe tree architecture in terms of branching properties.

## Materials and methods

### Tree selection and sample

WanFba model was used for this study because the allometric scaling relations as derived from the model can be directly used in the WaNuLCAS model, which allow the assessment of possible agroforestry

scenarios using native timber trees (Santos-Martin and van Noordwijk 2009).

Four native timber tree species commonly found in a farmer's fields and planted under different types of agroforestry systems were selected for the study based on farmer's preferences and lack of existing scientific information: *Shorea contorta* Vid. (Dipterocarpaceae), *Vitex parviflora* Juss. (Verbenaceae), *Pterocarpus indicus* Willd. (Fabaceae) and *Artocarpus heterophyllus* Lam. (Moraceae). Four trees with normal appearance for each species were selected as the sample for destructive and non-destructive measurements of above-ground biomass following the recommendations from van Noordwijk and Mulia (2002).

### Field data collection

The WanFBA protocol needs four kind of information to estimate tree biomass as listed in the input sheet (Table 1) information on tree size, information on branching pattern, information on woody parts and information on the final structures (leaves and others) of the tree.

The prerequisite for the fractal branching model is the independent relation between  $p$  and  $q$  values and parent diameters. It is suggested that before using the WanFba program, users should check first the relation between  $p$  and  $q$  parameters with the parent diameter. Users can employ the output of the Inputfba program which lists  $p$  and  $q$  values with the associated parent diameters, and test the relation using the regression technique. Only if the relation is weak or negligible (as indicated by a low  $R^2$  value), will the basic assumption of 'fractal branching' or scale independence at process level hold and can WanFba be used to estimate the tree biomass.

### Tree size and branching pattern

Field data of diameter and length of links were measured as seen in Fig. 1. The diameter was measured twice, cross-wise, at the middle of the link. The stem or link number and the parent number of that stem were also recorded as follows: the main stem was given link number 1, its offspring were number 2 and 3, and therefore, the number of the parent of the main stem is zero. The number of leaves

**Table 1** Tree parameters by WanFBA model automatically processed from field input data

Tree parameter	Definition
Nsub	Average number of branching points
$p$ (transfer coefficient)	Ratio between sum of diameter square before branching and sum of diameter square after branching
$q$ (allocation coefficient)	Ratio between the largest diameter square after branching and sum of diameter square after branching
Mean_ $p$	Average of $p$
Mean_ $q$	Average of $q$
STDev_ $p$	Standard deviation of $p$
STDev_ $q$	Standard deviation of $q$
Lbaretip	Length of bare tip on final links
Dmaxfin	Link diameter still having the maximum leaf density
Dzerofin	Link diameter where leaf density reaches zero
Maxfindens	Number of leaves per centimetre of link before leaf fall has occurred
DwperVwood, DwperVbranch and DwperVtwig	Total dry weight of shoot classified as twig, branch or wood
Tot_Sholength	Total shoot length
Tot_Showeigh	Total shoot weight
DW_leaves	Total dry weight of leaves
Leafarea and LWR	Total leaf area and leaf weight ratio (relative to total shoot weight)
MinCrownRad	Minimum radius of tree crown
Leaf/(Leaf + twig)	Leaf weight ratio in twig category
T_BiomDiam1 and T_BiomDiamSlope	$a$ and $b$ for the equation $Tot\_Showeigh = a(Diam_0)^b$
T_BranchDiam1 and T_BranchDiamSlope	$a$ and $b$ for the equation $DW\_Branch = a(Diam_0)^b$
T_LeafTwigDiam1 and T_LeafTwigDiamSlope	$a$ and $b$ for the equation $(DW\_leaves + DW\_Twig) = a(Diam_0)^b$
T_CumLit1 and T_CumLitSlope	$a$ and $b$ for the equation $Cumulative\ Litterfall = a(Diam_0)^b$
T_CrownRad1 and T_CrownRadSlope	$a$ and $b$ for the equation $MinCrownRad = a(Diam_0)^b$
Ndstep	Sets the number of initial tree diameters
LinorLog	Selects a linear or logarithmic approach to the allometric regressions
Ncal	Sets the number of replicates per initial tree diameter
Randseed	Provides a seed value to the random generator

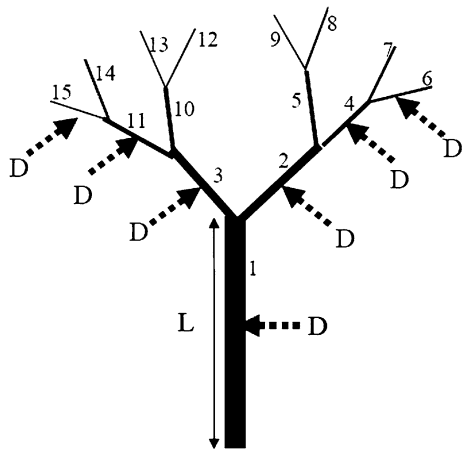
of each link was also recorded. For reliable estimates of the fractal branching parameters, minimum number on 100 branching points were collected for each tree sample as recommended by van Noordwijk and Mulia (2002).

#### Dry weight estimation

WanFBA classifies the woody part of the tree into three categories: wood, branch and twig. The classification follows the diameter of the link. Twigs were defined for this study as any link with a diameter of less than 2 cm; links between 2 and 10 cm were

classified as branch, and links above 10 cm diameter as wood.

Dry weight per volume of wood (wood density) was estimated by taking two sub-samples (in between 200 and 500 g) of every tree component and determining volume by scale measurements. Sub-samples of all fractions were collected from the field and stored in sealed plastic bags to prevent loss of moisture. Wet weights were recorded immediately upon arrival at the laboratory and dry weights were determined by drying those samples in an oven at 80°C until a constant weight was reached (Padrón and Navarro-Cerrillo 2004).



**Fig. 1** Schematic of stem length ( $L$ ) and diameter ( $D$ ) measurement process used for data collection in WanFBA model

#### *Measuring the final tree structures (leaves)*

One hundred leaf samples per tree were collected to determine the average area of a single leaf. Leaf surface area (one side) was measured using WinFO-LIA computer software (Regent Instruments Inc., [www.regentinstruments.com](http://www.regentinstruments.com)) over the scan images of leaf samples. Based on this information Specific Leaf Area (SLA) is defined as the surface area of leaves per unit dry weight ( $\text{cm}^2/\text{g}$ ). Dry weight of leaves was determined by drying the samples in an oven at  $80^\circ\text{C}$  for 24 h.

#### Adjustments to the published version of the model

As the observations on the trees suggested that links deviate from cylinders by having a degree of tapering modifications were made to the WanFBA model to incorporate this concept. A tapering coefficient  $\tau$  was introduced to describe the ratio between up and downstream link diameter. Total observed biomass of trees were well predicted with  $0 < \tau < 0.1$ . Following the pipe stem theory that a branch section always has  $\tau = 0$  (i.e. pipe-shaped) unless self or mechanical pruning has taken place, the difference between total biomass with  $\tau = 0$  and  $0 < \tau < 0.1$  reflects potential cumulative litterfall of the observed trees (van Noordwijk and Mulia 2002).

The assumption of a linear relationship between link diameter and link length was not satisfactory and

an option was included (and used) that employs a diameter-independent average link length for each branch category (twig, branch, and wood).

#### Destructive tree sampling

A total number of ten trees per species in the diameter range from 2 to 30 cm dbh were cut down direct measurement of tree biomass and biomass components (Ola-Adams 1997; Nelson et al. 1999).

Each tree was separated into four fractions: leaves, twigs, branches, and all wood rest. Fresh biomass measurements from each fraction were recorded in the field immediately after cutting down the tree using conventional scales. Dry weight per volume of wood (wood density) was estimated by taking two sub-samples of every tree component. The coefficient  $f$  (dimensionless) is the average relation between the dry and fresh weight of each sub-sample for every tree component.

#### WanFBA calibration

A linear regression between empirical results (destructive sampling) and predicted estimations (using the WanFBA model) was performed to evaluate how close these two observations were to linear relationships. Additional statistics of goodness of fit (Loage and Green, 1991) were also applied (Table 2).

#### WanFBA evaluation

The descriptive statistics of the models included EF, CD and RMSE, EF indicates model performance in prediction with a value of one indicating a perfect one-to-one relationship and any negative values indicating that the model, adjusted for degrees of freedom, is worse at predicting observed data than the mean of observed values. CD is similar to  $R^2$  as it measures the proportion of the total variance of observed data explained by predicted data, a perfect fit also being one with a lower limit of zero and upper limit of infinity. It tells us whether the model is over predicting (a value under one) or under predicting (a value over one). RMSE is the root of the mean square error expressed as a percentage of the observed mean i.e. the average error of predicted results and the ME

**Table 2** Statistical criteria for evaluation of model results according to Loage and Green (1991)

$P_i$  predicted values,  $O_i$  observed values,  $n$  number of samples and  $O_{\text{mean}}$  is the mean of the observed data

Criterion	Symbol	Calculation formula	Range	Optimum
Maximum error	ME	$\text{Max} P_i - O_i _{i=1}^n$	$\geq 0$	0
Root mean square	RMSE	$\left(\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}\right)^{\frac{1}{2}} \times \frac{100}{O_{\text{mean}}}$	$\geq 0$	0
Coefficient of determination	CD	$\frac{\sum_{i=1}^n (O_i - O_{\text{mean}})^2}{\sum_{i=1}^n (P_i - O_{\text{mean}})^2}$	$\geq 0$	1
Modeling efficiency	EF	$\frac{(\sum_{i=1}^n (O_i - O_{\text{mean}})^2 - \sum_{i=1}^n (P_i - O_i)^2)}{\sum_{i=1}^n (O_i - O_{\text{mean}})^2}$	$\leq 1$	1
Coefficient of residual mass	CRM	$\frac{(\sum_{i=1}^n O_i - \sum_{i=1}^n P_i)}{\sum_{i=1}^n O_i}$	$\leq 1$	0

is the single greatest error between observed and predicted results. In accordance with Rykiel (1996), for the simulations to be accepted an  $R^2$  value for calibration and validation of 0.9 was considered necessary to indicate a good relationship between predicted and observed values. A CD value between 0.5 and 2 was considered necessary and, although sought, an EF value above zero was not considered necessary as a satisfactory relationship between observed and predicted results does not require absolute prediction accuracy.

## Results

### Biomass allometric equations

The WanFBA model in the first round of analyses provided summary values for the tree branching parameters for each tree species (Table 3), based on a minimum of 400 branching points per species. Tests of scale independence showed an absence of relationships between link diameter and the p or q values, confirming the applicability of fractal branching rules.

**Table 3** Input parameters values by species used for WanFBA model

Input parameters	<i>Shorea contorta</i>	<i>Vitex parviflora</i>	<i>Pterocarpus indicus</i>	<i>Artocarpus heterophyllus</i>	FBA's default
Nsub	2.14	2.12	2.15	2.07	2.20
Mean_p	1.00	1.05	1.06	1.03	1.00
Mean_q	0.87	0.77	0.80	0.88	0.75
STDev_p	0.19	0.29	0.28	0.24	0.40
STDev_q	0.13	0.16	0.15	0.11	0.30
Lbaretip (cm)	1.00	1.00	1.00	1.00	1.00
Dmaxfin (cm)	1.80	1.80	1.80	1.80	0.80
Dzerofin	2.00	2.00	2.00	2.00	1.60
Maxfindens	0.50	0.40	0.40	0.40	0.40
Av. twig length (cm)	95.6	95.5	82.3	76.9	–
Av. branch length (cm)	20.9	72.4	43.0	21.7	–
Av. wood length (cm)	123.3	172.6	147.2	100.4	–
Av. wood density ( $\text{g cm}^{-3}$ )	0.48	0.73	0.74	0.45	0.50
Av. branch density ( $\text{g cm}^{-3}$ )	0.42	0.60	0.61	0.51	0.60
Av. twig density ( $\text{g cm}^{-3}$ )	0.46	0.81	0.61	0.52	0.70
Specific leaf area ( $\text{m}^2 \text{g}^{-1}$ )	50.2	34.9	369.7	32.2	95.0
Av. leaf area ( $\text{cm}^2$ )	71.0	116.9	265.8	55.2	50.0
Leaf area index	6.03	1.09	6.27	2.55	3.00

**Table 4** WanFBA allometric equations ( $Y = aD^b$ ) for total aboveground biomass and tree components (branch and leaf)

	<i>Shorea contorta</i>	<i>Vitex parviflora</i>	<i>Pterocarpus indicus</i>	<i>Artocarpus heterophyllus</i>
T_BiomDiam1 (a)	0.035	0.133	0.063	0.065
T_BiomDiamSlope (b)	2.870	2.360	2.540	2.282
T_BranchDiam1(a)	0.007	0.046	0.025	0.018
T_BranchDiamSlope (b)	3.326	2.679	2.819	1.671
T_LeafTwigDiam1 (a)	0.055	0.179	0.084	0.110
T_LeafTwigDiamSlope (b)	2.224	1.582	1.721	1.440

Based on these summary statistics, the WanFBA model reconstructed a large number of replicate trees with a range of initial tree diameters, as the basis for allometric equations for total above ground tree biomass as well as for each of the tree components: wood and leaves (Table 4). The resulting allometric equations suggested a substantial variation among tree species for the “b” factor around the claims of a universal value of 8/3.

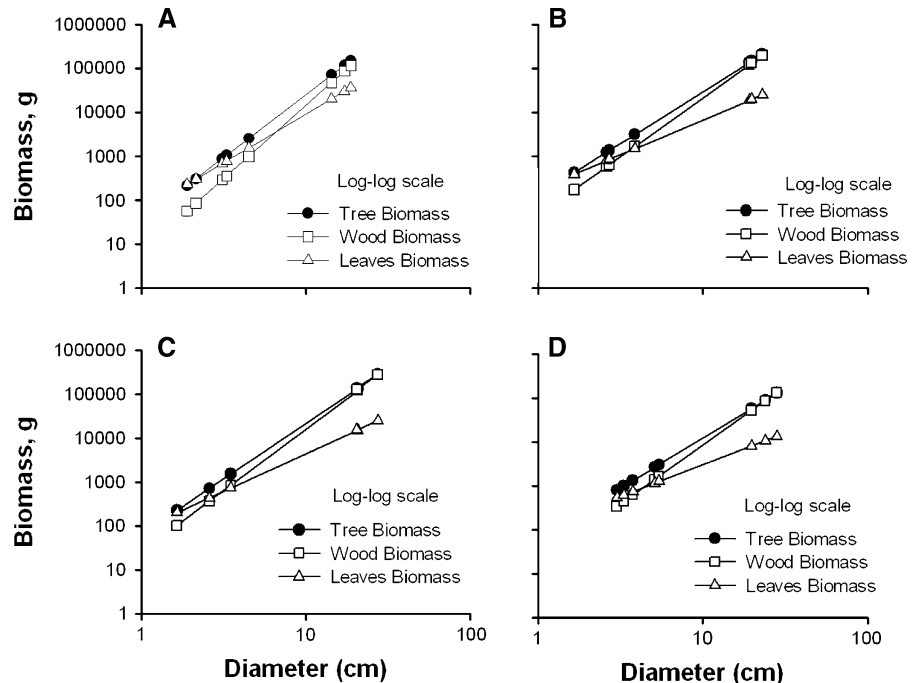
To complete the outputs, WanFba gives a graph that shows relation between the biomass and the initial diameter (Fig. 2). As these graphs were built in log–log scale, straight lines on log–log plot of stem diameter against tree biomass, they confirm the validity of allometric power equations within the relations used in the model.

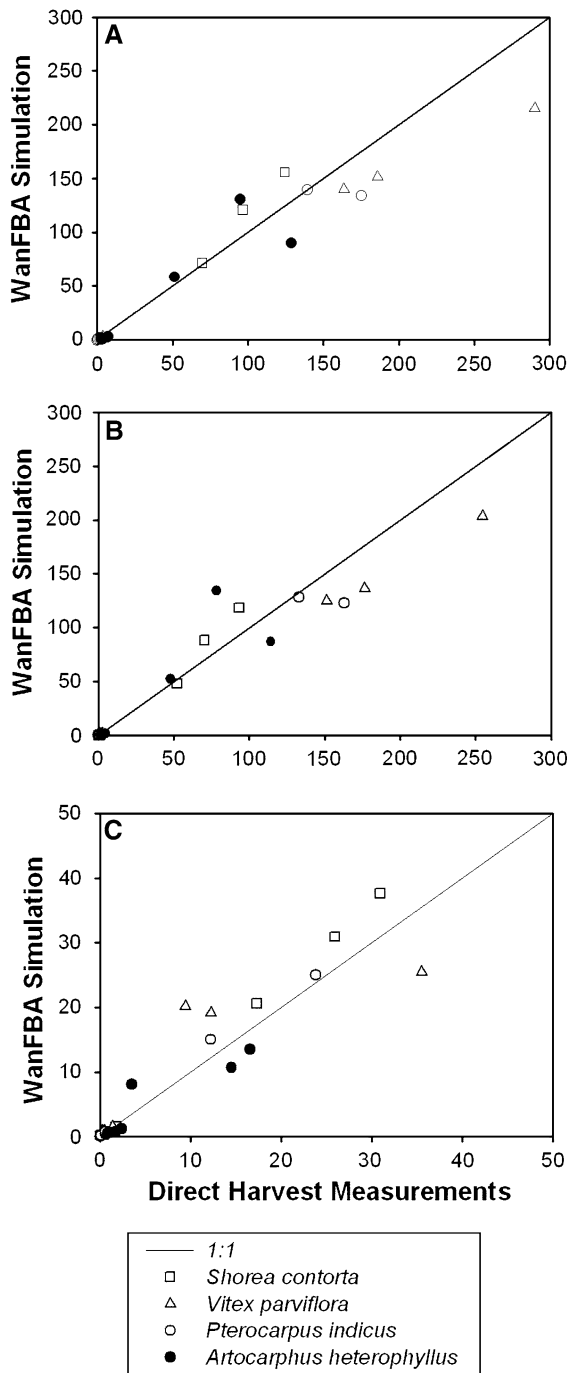
WanFBA calibration and evaluation results

For each of the stem diameters of trees with destructive biomass measurements, a predicted biomass was derived from the allometric equation for the given species. Direct comparison of measured and predicted values (Fig. 3) showed general correspondence with the 1:1 line for total above-ground tree biomass (Fig. 3a), and relatively larger deviations for woody biomass (Fig. 3b) and leaf + twig biomass (Fig. 3c), but no systematic difference in the degree of fit between the species.

Statistical test analysis also confirmed the viability of the WanFBA model for all tree species. Indeed, all tests performed on WanFBA results indicated that the model is applicable and provides an acceptable

**Fig. 2** WanFba output results: relation between tree biomass and initial diameter. These graphs are built in log–log scale, so straight lines confirm the validity of allometric power equations within the relations used in the model. **a** *Shorea contorta*, **b** *Vitex parviflora*, **c** *Pterocarpus indicus*, **d** *Artocarpus heterophyllus*





**Fig. 3** Evaluation results: comparison of WanFBA and Direct harvest biomass values for all tree species: **a** tree biomass (kg), **b** wood biomass (kg) and **c** leaf biomass (kg)

approximation for total aboveground biomass estimation as well as for the tree components (wood and leaf) (Table 5). The largest discrepancies were found

**Table 5** Statistical evaluation results of WanFBA estimations according to Loage and Green (1991)

	Tree biomass	Wood biomass	Leaf biomass
<i>Shorea contorta</i>			
$R^2$	0.96	0.94	0.96
ME ( $0, \geq 0$ )	19.52	27.19	66.48
RMSE ( $0, \geq 0$ )	21.04	51.30	331.29
EF ( $1, \leq 1$ )	0.95	0.69	-11.87
CRM ( $0, \leq 1$ )	-0.07	0.45	-2.55
CD ( $1, \geq 0$ )	0.86	0.73	0.96
<i>Vitex parviflora</i>			
$R^2$	0.971	0.985	0.925
ME ( $0, \geq 0$ )	41.61	112.15	107.78
RMSE ( $0, \geq 0$ )	22.63	61.33	505.91
EF ( $1, \leq 1$ )	0.95	0.67	-24.25
CRM ( $0, \leq 1$ )	-0.03	0.46	-3.55
CD ( $1, \geq 0$ )	0.88	0.87	0.93
<i>Pterocarpus indicus</i>			
$R^2$	0.973	0.957	0.97
ME ( $0, \geq 0$ )	45.63	80.59	103.15
RMSE ( $0, \geq 0$ )	31.56	64.21	580.13
EF ( $1, \leq 1$ )	0.92	0.67	-26.53
CRM ( $0, \leq 1$ )	-0.06	0.46	-3.68
CD ( $1, \geq 0$ )	0.99	0.98	1.00
<i>Artocarpus heterophyllus</i>			
$R^2$	0.984	0.999	0.809
ME ( $0, \geq 0$ )	21.97	43.00	49.16
RMSE ( $0, \geq 0$ )	22.60	61.63	527.75
EF ( $1, \leq 1$ )	0.97	0.76	-7.61
CRM ( $0, \leq 1$ )	-0.13	0.41	-4.03
For all species			
$R^2$	0.9715	0.964	0.902
ME ( $0, \geq 0$ )	45.63	112.15	107.78
RMSE ( $0, \geq 0$ )	27.27	66.76	495.40
EF ( $1, \leq 1$ )	0.95	0.71	-19.27
CRM ( $0, \leq 1$ )	-0.06	0.45	-3.33
CD ( $1, \geq 0$ )	0.90	0.88	1.02
CD ( $1, \geq 0$ )	0.79	0.79	1.41

ME maximum error, RMSE root mean square error, EF model efficiency, CRM coefficient of residual mass, CD coefficient of determination

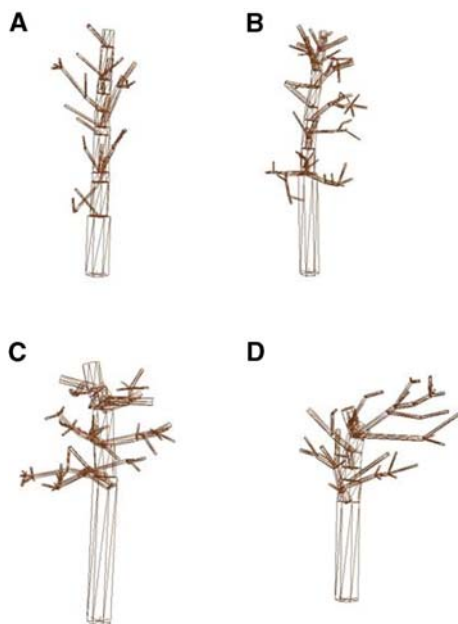
for *Vitex parviflora* and *Pterocarpus indicus*, probably because for these two species trees with a larger stem diameter were included in the measurements than for *Shorea contorta* and *Artocarpus heterophyllus*.



## Discussion

Experience with the WanFBA from this study shows that the mean values of transfer coefficient ( $p$ ), the branch allocation coefficient ( $q$ ), and the relationship between diameter and link length all had a strong influence on the final allometric equation, especially on the scaling rule or  $b$  factor.

The parameters of the branching process differed between the tree species and can be meaningfully entered in databases as characteristic of the species at the site tested. As mentioned by Mulia et al. (2001), the fact that the major parameters (at least in their more extreme values), can be visually recognized should lead to more confidence in the use of the method. With the purpose of visually validating outputs from the model, WanFBA model includes an additional tool to visualize tree branch data (3D Virtual Branch 1.0.3). Figure 4 shows visualisation results of tree shapes and branching pattern for all four tree species, and its relation with WanFBA estimated allometric equation ( $b$  factor).



**Fig. 4** Visualisation results of tree shapes and branching pattern for all four tree species using 3D Virtual Branch 1.0.3. This tool of WanFBA model is used with the purpose of visually validate outputs from the model. **a** *Shorea contorta* ( $b = 2.870$ ), **b** *Vitex parviflora* ( $b = 2.360$ ), **c** *Pterocarpus indicus* ( $b = 2.540$ ), **d** *Artocarpus heterophyllus* ( $b = 2.282$ )

Although the 8/3 for allometric scaling of trees has a biomechanical interpretation that may appear to be generic (West et al. 1999), results from this study suggest that scaling rules in the range 2.3–2.9 are consistent with tree shapes and branching pattern for individual tree species. Thus, the fractal branching analysis offers promise for a better understanding of why, when and how to modify allometric scaling relations from the generic “default” values recommended in the forestry literature (van Noordwijk 1999).

Implementing WanFBA software to predict tree biomass (only above-ground) proved to be easier and cheaper than destructive methods. However, further comparisons between these two methods under different conditions may still be needed and may lead to further improvement of WanFBA model. Significant adjustments to the published version of WanFBA model were made during the study, i.e. the inclusion of a tapering coefficient. Although results from this study justify the inclusion of a tapering coefficient into the model further studies and field data are still needed.

Applicability of WanFBA outputs depends primarily on whether or not the assumptions underlying the fractal (scale-independent) process are met. The basic assumptions have been tested and found to be applicable an acceptable first approximation for a wide of tropical trees, although a number of extensions of the theory have been suggested for various situations (Pages et al. 2000; Ozier-Lafontaine et al. 1999; Rowe 1999; Smith 2001). Actually, WanFba is a simplification of the FBA (Functional Branch Analysis) program which is also available in excel format. The full FBA model contains more complex approaches especially in estimating the below ground biomass. WanFba was made/created especially because the allometric scaling relations as derived from WanFBA model can be directly used in the WaNuLCAS model (van Noordwijk et al. 2004), which allow the assessment of possible agroforestry scenarios utilizing new tree species included in its tree library (Santos-Martin and van Noordwijk 2009).

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