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Full Research Article

Fractal Branching Model for Non-Destructive Biomass Estimation in *Terminalia chebula* and *Emblica officinalis* Agroforestry Plantations

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Abstract

Fractal branching model is a non-destructive tool for biomass estimation. In the present paper we compared estimates of above ground tree biomass of *Terminalia chebula* and *Emblica officinalis* using usual method of biomass estimates and by employing Fractal Branching Analysis (FBA) model. Allometric equations were developed through FBA for above ground biomass of *Terminalia chebula* ($B=0.1296D^{2.0827}$), branch biomass ($B=0.0103D^{2.5388}$) and leaves+twig biomass ($B=0.0529D^{1.3269}$). Similarly, equations were developed for *Embilica officinalis* for above ground biomass $B=0.0655D^{2.4042}$), branch biomass ($B=0.0007D^{3.35108}$) and for leaves+twig ($B=0.0656D^{1.621}$) (where B is Biomass and D is diameter of tree at breast height). While comparing the biomass estimate of both the methods using different descriptive statistics it was found that biomass equations developed through FBA model can fairly estimate the biomass as Maximum Error (ME) values ranged from 0.1 to 0.385 in *Terminalia* and from 0.068 to 0.289 in *Embilica*. The Coefficient of Residual Mass (CRM) values for both the species were also less than and near to one signifying good prediction by the FBA model. The experiment also showed that the method is fairly accurate and estimation for large number of trees, with different diameters, can be generated through the model thus saving precious time and resources.

1. Introduction

Increase in the earth's average surface temperature have generated interest in measuring and monitoring carbon (C) pools and fluxes to predict future changes in C concentrations and to develop C management strategies (IPCC, 2003, 2006; Terakupisut et al., 2007). Biomass estimates are useful for quantifying net primary productivity, energy pathways, nutrient and C cycles, harvestable biomass yields, and carbon sequestration potential of different land uses (Saglan et al., 2008; Pal and Panwar, 2013; Devi et al., 2013; Koul and Panwar, 2012). For auditing of national C stocks and fluxes, screening of tree species for C sequestration potential in agroforestry systems, and measurement and monitoring of C stocks in reforestation programmes, require collection of credible biomass data (IPCC, 2003). Credible data on tree C stocks are scarce due to unreliable biomass estimation techniques (Brown et al., 2004; Saint-Andre et al., 2005). Periodic destructive harvesting of aboveground biomass is the most precise way to measure and monitor change in C stocks. However, destructive sampling is not feasible for long-term forestry activities and in areas where felling is restricted. Therefore, non-destructive techniques have been developed to determine aboveground biomass of forest and agroforestry tree species (IPCC, 2003; Brown et al., 2004; Saatchi et al., 2007). These methods are based on regression models that relate biomass growth parameters by allometry. Relationships between tree biomass and stem allometric properties vary depending on the age of the tree, management practices, structure of the system, climate, and biophysical characteristics of the site (Lott et al., 2000; Claesson et al., 2001). Foresters have long term experience in scaling trees on the basis of stem diameter at a specified height above the ground (Brown, 1997), but their empirical rules need re- calibration for each tree species and stand density, and cannot be easily applied in mixed species forests or in situations where trees grow in more open conditions rather than in a dense stand (Ketterings et al., 2001).

Aboveground trees, root systems, rivers and road networks share common properties, which have gradually been recognized on the basis of 'fractal' analysis (Mandelbrot, 1983). 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, and depending on the stem anatomy, to a proportional relation the cross- sectional areas of the whole stem (van Noordwijk and Lusiana, 1999). This also ensures mechanical stability which requires each branch to be designed to carry its share of the total weight load (Niklas, 1992). FBA is based on these characteristics of the tree structure.

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. Apart from tree biomass, the model can predict total leaf area; relative allocation of current growth of leaves, branches or stem, number of branches, the transfer coefficient of cross sectional area, an allocation coefficient among branches, and a regression coefficient between diameter and length of links.

The objective of this study was to (1) develop allometric equations of aboveground biomass for two native species on the basis of parameters that can be measured non-destructively; (2) test the validity of FBA model as a non-destructive tool to estimate biomass.

2. Materials and Methods

2.1. Site description

The study area is located in lower Shivalik Himalayan region of India (30^0 45^0 N latitude, 70^0 45^0 E longitude, and 370 m above mean sea level). As per the USDA soil taxonomy, the soil of the study area has been classified as light-textured hyperthermic Udic Ustochrept (Grewal et al., 1996). The soil is sand to sandy loam in texture, well drained, with low water-holding capacity. The area receives 1100 mm of mean annual rainfall, of which 80% occurs during the monsoon season (June to September).

Embilica officinalis and *Terminalia chebula* plots were established in 2001. Uniform and evenly distributed plots were established as per the randomized block design with five replications, in the experimental field of the research farm of Central Soil and Water Conservation Research and Training Institute, Research Centre, Chandigarh. Three trees with normal appearance for each species were selected as the sample for non-destructive measurements of above-ground biomass following the recommendations of van Noordwijk and Mulia (2002).

2.3. Field data collection and FBA model calibration

The FBA protocol needs different kind of information to estimate tree biomass as listed in the input sheet (Table 2; column 1 and 2). Field data of diameter and length of links were measured as seen in Figure 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 leavesof 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).

The prerequisite for the fractal branching model is the independent relation between p and q values and parent diameters. Where transfer coefficient p for the change in total cross- sectional area is,

$p=D^2_{before}/ \Sigma D^2_{after}$

allocation coefficient q for the split of cross- sectional area over the branches is,

$q=maxD^2_{after}/ \Sigma D^2_{after}$

Where D is Diameter of branch or bole. $MaxD^2$=largest diameter square after branching and ΣD^2_{after} is sum of diameter square after branching.

Only if the relation between p and q is weak or negligible (i.e low R^2 value), FBA can be used to estimate the tree biomass.

Woody part of the tree was categorised into: wood, branch and twig. 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. Wood density/specific gravity of every tree component was determined (Devi et al., 2013)

Specific Leaf Area (SLA) was calculated as the surface area of leaves per unit dry weight (cm^2 g^{-1}). For this one hundred leaf samples per tree were collected to determine the average area of a single leaf. Leaf surface area (one side) was measured. Dry weight of leaves was determined by drying the samples in an oven at 80^0C for 24 h.

The usual method of non-destructive method of biomass estimate which is generally used was also employed as described by various workers (Devi et al., 2013; Koul and Panwar, 2008) for comparison with results of FBA. To evaluate how close observations through empirical non-destructive sampling and predicted estimations (using FBA model) statistics of goodness of fit (Loage and Green, 1991) were applied using SAS 9.3 statistical software (Table 1).

3. Results and Discussion

3.1. Testing applicability of FBA for the selected species

The prerequisite for the fractal branching model is the independent relation between p and q values and parent diameters. To test it FBA Help file developed by Rachmat Mulia of Word Agroforestry Center, Bogor, Indonesia (sent to the senior author) was used. Data on Link length, diameter of link at smaller end and larger end and number of leaves per length was entered in FBA help file. In *Embilica officinalis* 209 branching points were observed (minimum of 50 is essential) and in *Terminalia chebula* 130 branching points were observed. The data was processed for both the species to generate p and q. The p and q were plotted against parent diameter (Figure 2). It was found that the R^2 for *Embilica officinalis* was 0.024 for both p and q and for *Terminalia chebula* it was 0.006 and 0.018 for p and q respectively. The R^2 values showed very weak relationship for p and q for both species. This test of scale independence showed an absence of relationships between link diameter and the p or q values, confirming the applicability of fractal branching rules in both the species.

3.2. Generation of biomass allometric equations and comparison of FBA estimation with non-destructive usual method of biomass estimation

Input parameters required for the FBA model was measured from the field. Table 2 provides few input parameters for *Embilica officinalis* and *Terminalia chebula*. On the basis of the input data obtained from the field for FBA model and using random seed generator imbedded in the software, large number of trees having range of initial tree diameters were generated. Allometric equations for total above ground tree biomass as well as for each of the tree components: wood and leaves for both the species were derived (Table 3).

The allometric equation ($B=aD^b$; where B is biomass (kg tree^{-1}), D is diameter (cm) at breast height and 'a' is tree biomass when the diameter is 1 cm, 'b' is allometric scaling power) developed through FBA model for above ground biomass of *Embilica officinalis* was $0.0655\ D^{2.4042}$. Allometric equation for branch biomass had a higher value of b factor then observed in total biomass. The allometric equation for branch biomass was $0.0007\ D^{3.35108}$. The b factor for leaves+twig was lesser then the total biomass and the equation was $0.0656\ D^{1.621}$. Above ground biomass of *Terminalia chebula* was $0.1296D^{2.0827}$. The allometric equation for branch biomass was $0.0103D^{2.5388}$. The b factor for leaves+twig was lesser then the total biomass and the equation was $0.0529D^{1.3269}$.

The relationship between the biomass and the initial diameter for different parameters generated through model for *Embilica officinalis* and *Terminalia chebula* is given in Figure 3.

The stem diameter of trees measured through non-destructive usual methods was used in allometric equations developed through FBA model to predict the biomass of different components. The values for descriptive statistics obtained for comparison between model prediction and non-destructive usual method of biomass estimation is given in Table 4.

3.3. Statistical analysis of fractal variables

The descriptive statistics for comparison between the methods included EF, CD and RMSE. The EF values for *Terminalia* and *Embilica* was close to the value one for wood biomass as compared to branch and twig/leaf. This indicates model performance in prediction of wood biomass is more accurate as compared to other parameters. The CD values for *Terminalia* and *Embilica* ranged from 1.35 to 3.0404 and 1.1 to 1.655 respectively for different components. The CD measures the proportion of the total variance of observed data explained by

Table 1: Statistical criteria for evaluation of FBA model (Loage and Green, 1991)

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

P_i: predicted value; O_i: observed values, n: number of samples and O_{mean}: mean of observed data

Table 2: Input parameters for FBA model in present study

Parameters	Unit	*Embilica officinalis*	*Terminalia chebula*
The lowest dbh to be simulated	cm	0.5	0.5
The highest dbh to be simulated	cm	50	50
Average number of branch per branching point	number	2.29	2.20
Dry weight unit^{-1} volume of twig	g cm^{-3}	0.68	0.65
Dry weight unit^{-1} volume of branch	g cm^{-3}	0.71	0.67
Dry weight unit^{-1} volume of wood	g cm^{-3}	0.8	0.7
Maximum diameter of links to be included as 'twig'	cm	2	2
Maximum diameter of links to be included as 'branch'	cm	10	10
Specific leaf area (surface area (one-sided) unit^{-1} dry weight)	cm^2 g^{-1}	45.70	79.71
Area of a single leaf	cm^2	34.73	150.979
Maximum leaf area index within the tree crown (2-6), for the extreme tree, it might be 1-10	unit less	4	4
Number of iterations to be calculated for each parameter combination	number	10	10

Table 3: Allometric equation ($B=aD^b$) for the species generated through FBA model (output in kg)

Biomass component	*Embilica officinalis*	*Terminalia chebula*
Total biomass diam (a)	0.0655	0.1296
Total biomass diam slope (b)	2.4042	2.0827
Branch biomass diam (a)	0.0007	0.0103
Total biomass diam (b)	3.5108	2.5388
Leaf+twig biomass diam (a)	0.0656	0.0529
Leaf+twig biomass diam (b)	1.6211	1.3269

Table 4: Statistical evaluation results of FBA estimations according to Loage and Green (1991)

	Wood biomass	Branch biomass	Twig/leaf biomass	Total
Terminalia				
ME	0.183	0.162	0.100	0.385
RMSE	46.037	74.150	98.066	60.020
CD	2.474	1.731	3.0404	1.358
EF	-0.61	-10.58	-9.295	-7.320
CRM	0.1437	0.2671	0.2931	0.1584
Embilica				
ME	0.094	0.153	0.068	0.289
RMSE	26.28	73.734	82.986	50.128
CD	1.655	1.500	1.601	1.100
EF	0.668	-6.548	-8.480	-2.364
CRM	0.1238	0.2670	0.2789	0.1486

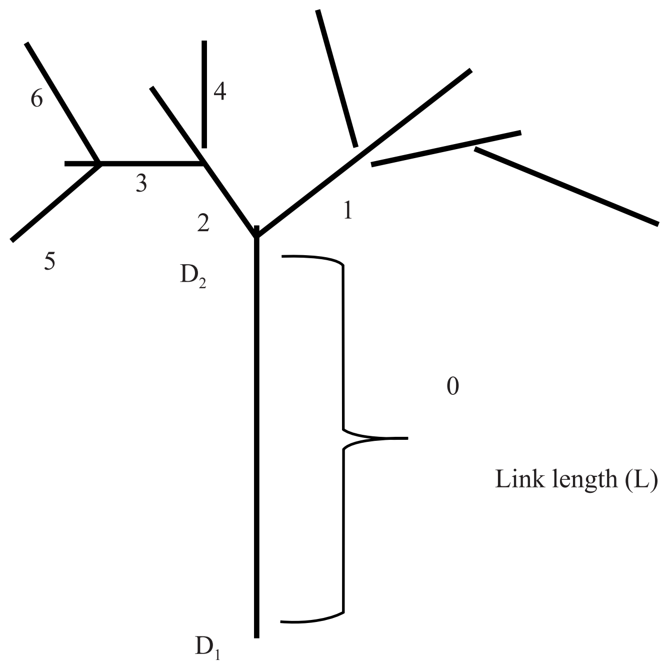
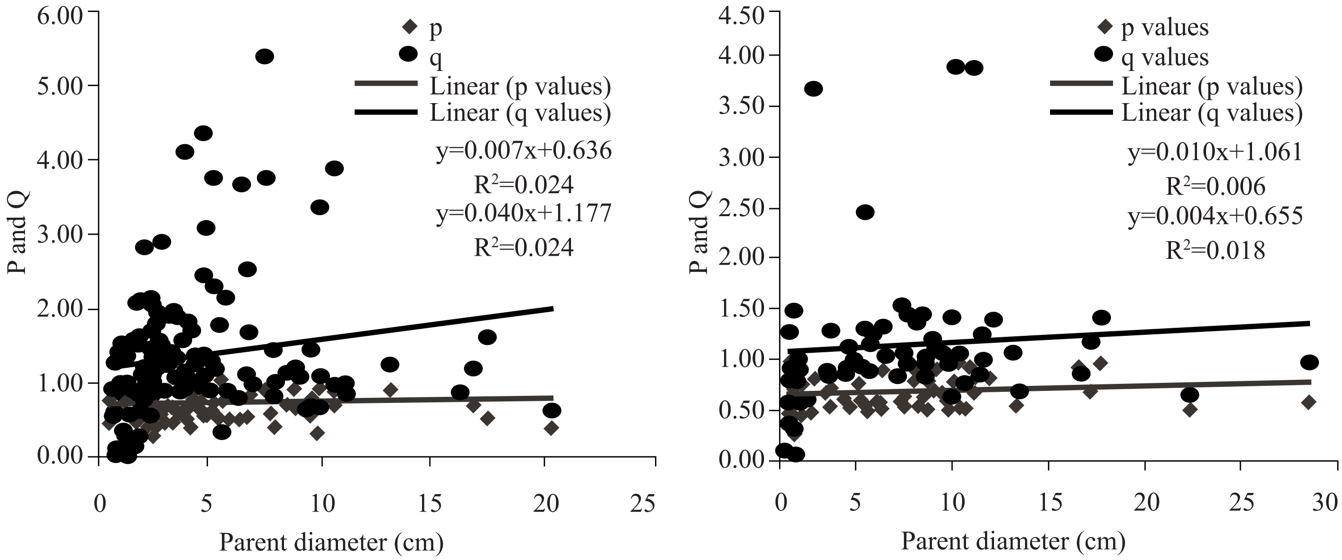


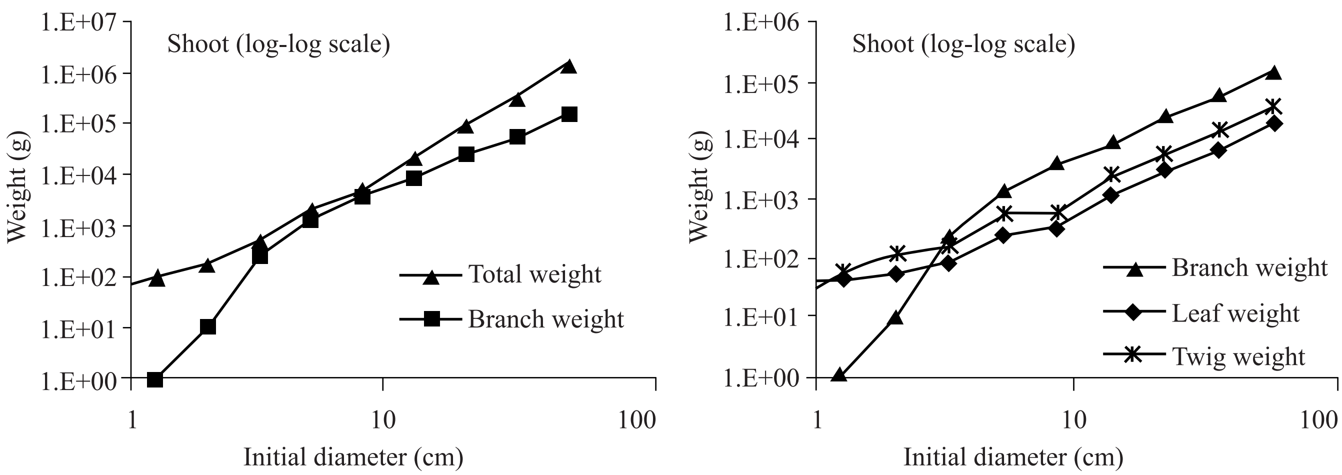
Figure 1: Numbering and measuring of link and branches

predicted data through model; a perfect fit is 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). The results show that there is a small over prediction of biomass estimation by FBA model as compared to the usual method of biomass estimation. However, Martin et al., 2010 had observed that a CD value between 0.5 and 2 was considered necessary. The values of ME ranged from 0.1 to 0.385 in *Terminalia* and from 0.068 to 0.289 in *Embilica*. The ME is the single greatest error between observed and predicted results. The values closer to zero shows lesser differences between the observed and predicted values. CRM values for both the species were also less than and near to one signifying good prediction. Konga, 2012 had also employed FBA model for estimation of above ground biomass. He found that Fractal variables (D10, proximal diameter, and Dfract, and number of branches) described most of the variations in aboveground biomass (stem, wood, and total biomass) with

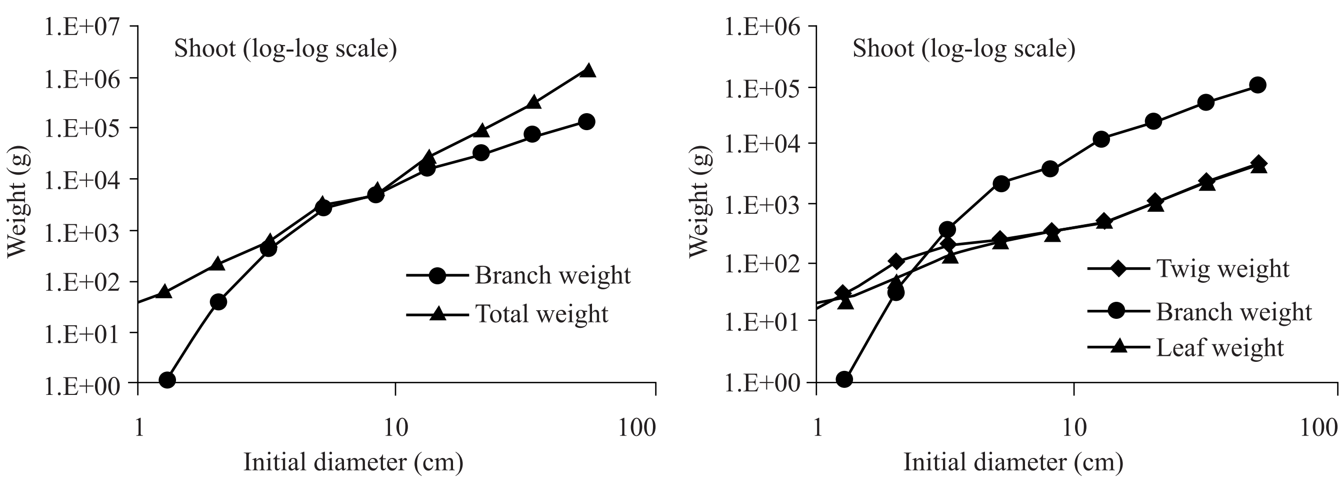


A) *Embilica officinalis* B) *Terminalia chebula*

Figure 2: Relationship between parent diameter and p and q values



A) *Embilica officinalis*



B) *Terminalia chebula*

Figure 3: Relationship between biomass and initial diameter for different parameters

95% confidence.

3.4. Relevance of the technology and scope of application

Agroforestry and other plantations are increasingly gaining importance for amelioration of degraded lands, carbon sequestration, income generation etc. To keep a record on biomass produced and rate of biomass accumulation for valuation of the plantation from time to time, periodic measurement of the growing stock is imperative. FBA technique provides a simple and reliable method of biomass estimation of tree components. To earn carbon credits from plantations and agroforestry, FBA technology being non-destructive and accurate will be handy in its application. Horticultural plantations have not been much studied for carbon sequestration because of their complex branching systems which are difficult to measure non-destructively. Since FBA also accounts for branches, twigs and leaves it will be very helpful in database development of horticultural plantations for carbon sequestration potential.

4. Conclusion

FBA was found to be simple and reliable method to predict above-ground biomass estimation compared to usual method particularly when large numbers of trees, having different ranges of stem diameter, are to be measured for biomass estimation. Further comparisons of FBA, after harvesting trees under different conditions, is required for large scale adoption of the model in India. FBA is fairly accurate and large number of trees with different diameters can be generated thus saving precious time and resources.

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5. References

Brown, J.H., Gillooly, J.H., Allen, A.P., Savage, V.M., West, G.B., 2004. Toward a metabolic theory of ecology. Ecology 85, 1771-1789.

Brown, S., 1997. Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry Paper. 134, Rome Italy.

Claesson, S., Sahlen, K., Lundmark, T., 2001. Functions for bio- mass estimation of young Pinus sylvestris, *Picea abies* and *Betula* spp. from stands in Northern Sweden with high stand densities. Scandavian Journal of Forestry 16,138-146.

Devi, B., Bhardwaj, D.R., Panwar, P., Pal S., Gupta, N.K.., Thakur, C.L., 2013. Carbon allocation, sequestration and carbon dioxide mitigation under plantation forests of north western Himalaya, India. Annals of Forest Research 56(1), 123-135.

IPCC 2003. Good practices guidance for land use, land-use change and forestry for global environmental strategies. IGES, ISBN 4-88788-003-0

IPCC 2006. Guidelines for national greenhouse gas inventories. IGES, ISBN 4-88788-032-4

Kaonga, Martin. L., 2012. Fractal analysis of canopy architectures of *Acacia angustissima, Gliricidia sepium*, and *Leucaena collinsii* for estimation of aboveground bio-mass in a short rotation forest in eastern Zambia. Journal of Forestry Research 23(1), 1-12.

Ketterings, Q.M., Coe R., van Noordiwijk M., Ambagau Y., Plam, C.A., 2001. Reducing uncertainty in the use of allometric equations for predicting aboveground biomass in mixed secondary forests. Forest Ecology and Management 146, 199-209.

Koul, D.N., Panwar, P., 2012. Opting different land use for carbon buildup in soils and their bioeconomics in humid subtropics of West Bengal, India. Annals of Forest Research 55(2), 253-264.

Koul, D.N., Panwar, P., 2008. Prioritizing land-management options for carbon sequestration potential. Current Science 95(5), 658-663.

Loage, K., Green, R.E., 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. Journal of Contaminant Hydrology 7, 51-73.

Lott, J.E., Howard, S.B., Black, C.R., Ong, C.K., 2000. Allometric estimation of above-ground biomass and leaf area in managed *Grevillea robusta* agroforestry systems. Agroforestry System 49, 1-15.

Mandelbrot, B.B., 1983. The Fractal Geometry of Nature. Freeman, New York.

Martin, F., Santos, R.M., Navarro-Cerrillo, R., Mulia, M., van Noordwijk, 2010. Allometric equations based on a fractal branching model for estimating aboveground biomass of four native tree species in the Philippines. Agroforestry System 78, 193-202.

Niklas, K.J., 1992. Plant Biomechanics: an Engineering Ap-proach to Plant Form and Function. University of

Chicago Press, Chicago, London, p. 607.
Pal, S., Pankaj, P., 2013. Interrelationship of Carbon Sequestration, Soil Fertility, and Microbial Indices as Influenced by Long-Term Land Uses in Lower Himalayan Region, India. Communications in Soil Science and Plant Analysis. 44, 869-883.
Saatchi, S.S., Houghton, A., Dos Santos Alvala R.C., Soare, J.V., Yu, Y., 2007. Distribution of aboveground biomass in the Amazon. Global Change Biology 13, 816-837.
Saglan, B., Kucuki, O., Bilgili, E., Durmaz, D., Basal, I., 2008. Estimating fuel biomass of some shrub species (Maquis) in Turkey. Turkish Journal of Agriculture 32, 349-356.
Saint-Andre, L., M'bou Mabiala, A., Mouvondy, W., Jourdan, C., Roupsard, A., Deleporte, P., Hamel, O., Nouvellon, Y., 2005. Age-related equations for above- and below-aground biomass of *Eucalyptus hybrid* in Congo. Forest Ecology and Management 205, 199-214.
Terakupisut, J., Gajaseni, N., Ruankawe, N., 2007. Carbon sequestration potential in aboveground biomass of Thong Pha Phum National Forest, Thailand. Applied Ecology and Environmental Research 5(2), 93-102.
Van Noordwijk, M., 1999. Functional branch analysis to derive allometric equations of trees. In ICSEA No. 6. Modelling global change impacts on the soil environment. International Centre for Research in Agroforestry (ICRAF), Bogor, Indonesia
Van Noordwijk, M., Mulia, R., 2002. Functional branch analysis as a tool for fractal scaling above- and belowground trees for their additive and non- additive properties. Ecological Modelling 149, 41-51.
Van Noordwijk, M., Lusiana, B., 1999. WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. Agroforestry Systems 43, 217-242.