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Allometric equations for biomass and carbon stock estimation of small diameter woody species from tropical dry deciduous forests: Support to REDD+

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ABSTRACT

In order to assess the contribution to the overall carbon stock and generate carbon credits under REDD+, it is essential to have an accurate estimation of biomass of different forest components. Forest cover in India is gradually increasing due to the active restoration of degraded land and plantation on waste and barren lands leading to an increase in the abundance of small diameter woody species. However, these were not included in biomass studies due to the non- availability of adequate allometric equations and low carbon stocks compared to mature individuals. We have harvested 589 individuals belonging to 23 woody species at the seedling and sapling stage from a tropical dry deciduous forest and developed species specific allometric equation and general allometric equation for aboveground biomass estimation. Further, the belowground biomass equation of 9 species were also developed using above ground biomass and root to shoot ratio as predictor variable. In the case of general equation, the combination of diameter with height and diameter, height and wood specific gravity exhibited highest adjusted R^2 value. In case of species-specific allometric equations, combination of diameter with height predicts above ground biomass more precisely as compared to the diameter and wood specific gravity. Since the estimation of wood specific gravity requires destruction of lower diameter individuals, usage of diameter and height for biomass estimation would help protecting regeneration as both methods yield same results. All the equations developed in the present study for below ground biomass predicts biomass precisely. We suggest use of species specific allometric model developed with diameter and height for estimation of biomass. Further, general models consisting of height and diameter may be used for biomass estimation in case of non-availability of species specific equations without destroying the regeneration.

1. Introduction

Global climate change is accepted as the largest threat to all life forms on earth and its severity is increasing day by day despite several efforts. Recently, REDD+ (Reducing Emissions from Deforestation and Forest Degradation) was developed under the UN Framework Convention on Climate Change (UNFCCC) for forest restoration and conservation by placing a value on the capacity of forests to sequester carbon (Pothong et al., 2021). It aims at forest conservation, restoration and sustainable management for the enhancement of carbon sequestration (Mardiatmoko et al., 2019; Pothong et al., 2021). Quantification of carbon emissions or avoided emissions requires information on the rate of deforestation and the carbon stocks at a given time (Gibbs et al., 2007). To generate carbon credits under the REDD+, reliable estimates of forest carbon stocks are the prerequisite.

Destructive or harvesting method is the most precise method for biomass estimation. However, it leads to the loss of trees. On the other hand, remote sensing method requires validation of data from field. Therefore, non-destructive allometric equation based approach is one of the best options for biomass and carbon stock estimation, as inputs are only the measurable parameters like diameter, height and wood specific gravity (WSG). The main source of error in the estimation of biomass and carbon stock is the choice of the allometric equation (Chave et al., 2004, 2005, 2014; Molto et al., 2013). Forest biomass is often calculated

Abbreviations: D, diameter; H, height; WSG, wood specific gravity; AGB, aboveground biomass; BGB, below ground biomass; REDD+, reducing emission from deforestation and forest degradataion; DBH, diameter at breast height; RSR, root to shoot ratio; MPE, mean percentage error; RMSE, root mean square error.

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using a standard general allometric equation which is applied over a large region (Houghton, 2003; Chaturvedi and Raghubanshi, 2013). Tropical forests vary with physiogeography, climatic conditions and species composition (Daba and Soromessa, 2019a). Therefore, the biomass in the tropics is affected by topography, climatic condition and woody species composition along with other factors like natural and anthropogenic disturbances. A considerable uncertainty exists in the spatial distribution of biomass (Goodale et al., 2002; Fang et al., 2006; Chaturvedi and Raghubanshi, 2013). However, errors in biomass estimation can be minimized by employing site-habitat-specific allometric equation (Litton and Kauffman, 2008; Djomo and Chimi, 2017; Wang et al., 1995; Chaturvedi and Raghubanshi, 2013). Further, the error in biomass estimation can also occur if the equations are applied for diameter ranges outside the one used for their formulation (Fonseca et al., 2012). It could be minimized by using separate equations for different diameter range classes. The use of WSG in allometric equation contribute to increase accuracy in biomass estimation (Chaturvedi and Raghubanshi, 2013; Chaturvedi et al., 2012; Chave et al., 2005; 2014; Basuki et al., 2009; Fayolle et al., 2013; van Breugel et al., 2011; Pothong et al., 2021).

Measurable parameters like diameter at breast height (DBH), height and WSG are the common variables that individually or in combination explain biomass (Chave et al., 2005). WSG is a direct reflection of the amount of carbon present in the forest as biomass (Woodcock and Shier, 2003) and it is strongly correlated with carbon density per unit volume (Fearnside, 1997; Mani and Parthasarathy, 2007). It is known to be the second best predictor of tree biomass (Chave et al., 2005; Vieilledent et al., 2012, 2014) and is an important parameter for converting forest volume into biomass (Fearnside, 1997). However, a number of factors like soil fertility, rainfall, seasonality, temperature, precipitation, geographic range, climatic condition and management practice may affect WSG variation (Ketterings et al., 2001; Sheikh et al., 2011; Mani and Parthasarathy, 2007). Hence, in addition to tree size, WSG is incorporated as a factor into allometric equation to explore the variation at regional scale in biomass estimates (Chaturvedi and Raghubanshi, 2013; Nelson et al., 1999; Baker et al., 2004; King et al., 2006; Basuki et al., 2009; Chaturvedi et al., 2012).

Due to their high production potential, tropical forests (old growth forests, trees outside forests and secondary forests) play a prominent role in lowering green house gas concentrations in the atmosphere by sequestering a large percentage of global atmospheric carbon. They act as a barrier against the effects of climate change (Aryal et al., 2014; Ngo et al., 2013).

In India, forest restoration and conservation together with plantation programmes increased the forest cover area by 3976 sq km (0.56% of forest cover) in the last two years (FSI, 2019). National Mission for Green India (GIM) aims to increase its forest cover up to 33% of its total land to reduce 2.5 to 3 billion tons of carbon dioxide equivalents to combat the present day crisis of climate change. Plantation on barren land and restoration of forests (i.e. secondary forests) with increased natural regeneration would increase the abundance of smaller size individuals. According to Sagar and Singh (2005), 85% of individuals in the dry tropical forests are at juvenile stage at any given time. The structure, composition, traits and biomass allocation of trees during early stages of forest succession and/or restoration of disturbed lands differ significantly as compared to mature forests due to the higher density of young individuals. Further, coppicing is common in tree stumps, especially in regenerated forests (Fukushima et al., 2008; McNicol et al., 2015). In India, most of the studies (Salunkhe et al., 2014a, 2016; Raha et al., 2020; Devi et al., 2021; Mohanta et al., 2020; Nath et al., 2021) did not consider smaller size woody individuals for estimation of biomass due to the non-availability of adequate allometric equation. Thus, ignoring low carbon stock individuals. Although a few studies (Salunkhe et al., 2014b; Gogoi et al., 2021; 2022; Meena et al., 2019) have estimated biomass of herbs and small diameter trees using destructive approach. A number of allometric equations exist for different parts of India but habitat-site-specific allometric equations for biomass estimation especially for younger individuals are still lacking.

In the present study, we have harvested 23 woody species at seedling and sapling stage from tropical dry deciduous forest of central India and developed species specific and general allometric equation for non-destructive estimation of above ground biomass (AGB) using alone or in combination of diameter (D), height (H) and WSG. Models for below ground biomass (BGB) were also developed, considering AGB and root to shoot ratio (RSR) as predictor variables for nine species having an intact root system. Further, we have compared the present best-fit general equation with a few reported equations to observe the usefulness.

2. Material and methods

2.1. Study site

Present study was carried out during July 2021 to September 2021 in semi-natural forests (23°49’ N and 078°46’ E) in central India (Fig. 1). This area is a part of lower Vindhyan range of Central India, at an average altitude of 420 m msl. The forest is classified as tropical dry deciduous type (Champion and Seth, 1968). Climate of the study area is monsoonal with well defined summer, rainy and winter seasons. Summer is hot and dry with maximum temperature of 45°C during April to mid June. Rainy season begins from the month of late June up to September with an average annual rainfall of 1187 mm. Winter is mild with a minimum temperature of 5°C during the month of January. The predominant tree species of study site are *Gliricidia sepium, Butea monosperma, Diospyros melanoxylon, Lagerstroemia parviflora* and *Holoptelia integrifolia*. Most of the vegetation of the study area is found on west facing slope with a thin layer of soil derived from basalt formation. The general conditions of the area are dry for seven to nine months in a year.

2.2. Field sampling

We have harvested 25 to 30 lower diameter individuals (saplings and

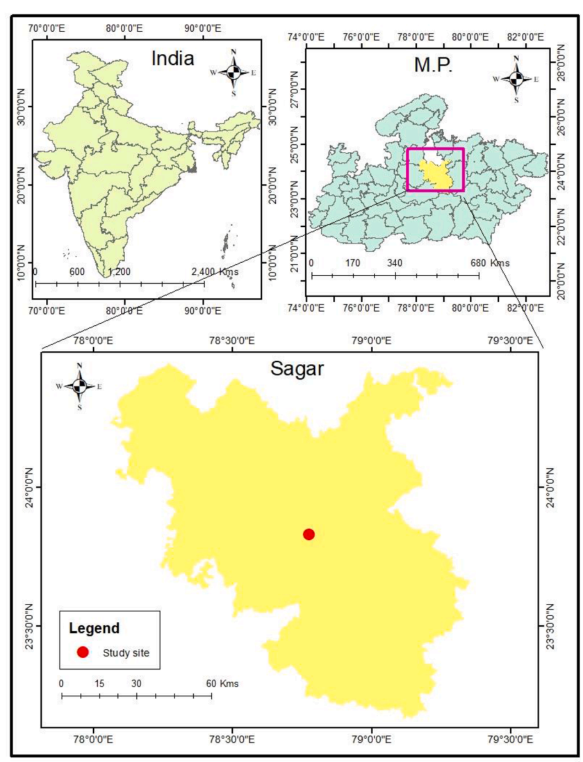

Fig. 1. Study site map.

seedlings) of each of the 23 woody species in the forest (Table 2). In all, 589 individuals were harvested from the field for study purpose. Seedlings were defined as plants with a height of less than 50 cm. Saplings were defined as plants with a height of 50–150 cm and neck-line circumference (ground diameter) in the range between 1 cm and 10 cm (Verma et al., 2017). Individuals having a height between ≥ 10 cm and < 1.3 m and diameter from 1 cm to 10 cm were harvested. Selection of individuals of different diameters was considered to generalize the distribution of predictor variables which may have an impact on AGB variability. Each individual was uprooted, the bole was marked and the above ground and below ground parts were separated. Height was measured using a measuring tape and diameter of the main branch was measured at height within 0.1 cm to 5 cm from ground away from irregularities using a digital vernier caliper. Each component (i.e. leaves, branches and bole) was separated and the branches and bole were cut into small pieces. 3 cm long wood samples were collected from the bole portion from each individual where the diameter was measured. The samples and other plant parts were sealed in polythene bags to minimize water loss and taken to the laboratory.

2.3. Wood specific gravity and biomass estimation

For basic WSG estimation, the volume of each wood sample was measured by water displacement method and thereafter the samples were kept in oven at 103±2°C until constant weight was obtained, basic WSG was estimated following USDA (1952) as under:

$$\mathrm{WSG} = \frac{\text{Weight of oven dry sample}}{\text{Volume of fresh sample}}$$

For the estimation of dry above ground biomass, branches and bole of the individual plant was dried at 103±2° and leaves at 80±2° till attainment of constant weight. Below ground part of each individual was screened and excluded if some portion was damaged or lost during excavation. They were cleaned under tap water carefully and kept in oven at 103±2°C until constant weight was obtained.

2.4. Model development and statistical analysis

The data for each species were summarized separately on excel data sheets after the completion of the field and laboratory measurements. Allometric equations for trees are usually in the form of power relationship $Y = aX^b$ or logarithmically transformed power equations as $\ln(Y) = \ln(a) + b\ln(X)$.

Where, 'Y' is the dependent variable, usually dry biomass, 'X' is the independent variable, usually diameter or height or WSG or in different combinations, 'a' is constant/intercept and 'b' is the slope.

Data were transformed using natural logarithms for linear regression fitting methods. The logarithmically transformed independent variable or predictor variable (i.e. diameter, height and WSG) of each species was used alone or in combination against the dependent variable (logarithmically transformed biomass) for species specific biomass regression models and variables of all the individuals of all species were used against logarithmically transformed biomass for the formulation of general biomass regression models. Root to shoot ratio (RSR) was used as an important factor for BGB estimation from AGB (Kenzo et al., 2020). BGB model was developed for nine species using AGB in combination with RSR as an independent variable and BGB as dependent variable. The equation takes the form of $Y = X \times RSR$.

Where Y is belowground biomass, X is aboveground biomass and RSR is the root to shoot ratio.

Best biomass regression model selection and evaluation were tested based on statistical performance including R^2 value, adjusted R^2 value, residual standard error (RSE) and p-value. The models were validated and compared by root mean square error (RMSE) and mean prediction error (MPE). RMSE indicates the spread around the line of best fit.

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} (\mathrm{Pi} - \mathrm{Oi})^2 / n}$$

Where P_i is the predicted value for the i^{th} observation, O_i is the observed value for i^{th} observation and n is the sample size.

$$\mathrm{MPE} = t_\alpha \times (\mathrm{SEE} / \bar{y}) / \sqrt{n} \times 100$$

Where t_α is the t value at confidence level α with n – p degrees of freedom, $\bar{y}$ is the mean value of samples, n is the number of samples and SEE is the standard error of estimate.

Data management and statistical analyses were performed using MS Excel 2007, IBM SPSS Statistics 20 and ORIGIN PRO 2021.

3. Results

Field measurement data (diameter, height) and WSG are presented in Table 1. Most individuals in the lower diameter class had less WSG than those in the higher diameter class of the same species. Best species specific equations and general biomass equations are shown in Table 2. Comparing the methods, most of the species specific equations explained more than 80% variability in AGB. General equations comprising of diameter only and diameter with height explained more than 80% variability in AGB (Fig. 2). Considering diameter only as predictor variable explained more than 60% of the variability in most of the AGB models. Height with diameter together further explained more than 80% of AGB variability. In most instances, application of WSG together with

Table 1
Range of wood specific gravity (ρ), diameter (D), height (H) and aboveground biomass (AGB) of the seedling and saplings harvested from the study site.

S. no.	Species name	D (mm)	H (m)	ρ	AGB (g)
1	*Azadirachta indica*	1.22 – 8.54	0.11 – 0.89	0.34 – 0.48	0.83 – 32.63
2	*Bauhinia racemosa*	1.22 – 9.23	0.21 – 1.20	0.34 – 0.55	0.68 – 38.66
3	*Bridelia retusa*	2.44 – 12.81	0.18 –0.56	0.34 – 0.57	1.87 – 61.44
4	*Butea monosperma*	1.71 – 12.33	0.13 – 0.81	0.07 – 0.47	1.53 – 175.32
5	*Cassia fistula*	2.03 – 12.38	0.19 – 1.32	0.46 – 0.67	1.4 – 208.8
6	*Cassia siemia*	2.03 – 7.73	0.11 –0.86	0.38 – 0.54	0.98 – 32.56
7	*Dalbergia paniculata*	1.89 – 12.24	0.13 – 1.16	0.32 – 0.51	1.56 – 39.61
8	*Dalbergia sissoo*	2.01 – 10.46	0.15 – 1.16	0.05 – 0.53	2.02 – 76.12
9	*Delonix regia*	2.49 – 10.22	0.19 – 0.94	0.17 – 0.50	1.86 – 65.38
10	*Diospyros melanoxylon*	2.82 – 12.68	0.15 – 1.08	0.35 – 0.55	1.69 –125.33
11	*Ehretia laevis*	2.94 – 12.35	0.15 –0.89	0.26 – 0.46	4.23 – 63.29
12	*Flacourtia indica*	2.68 – 12.64	0.20 – 0.932	0.34 – 0.63	1.34 – 31.51
13	*Gliricidia sepium*	3.01 – 13.26	0.19 –0.99	0.20 – 0.66	2.23 – 81.46
14	*Grewia asiatica*	2.20 – 12.69	0.12 –1.02	0.41 – 0.56	1.41 – 79.49
15	*Holarrhena antidysentrica*	2.98 –12.39	0.21 –0.99	0.05 – 0.42	3.45 – 51.36
16	*Leucaena leucocephala*	1.27 – 8.62	0.10 – 1.35	0.07 – 0.50	0.23 – 41.87
17	*Melia azadirech*	1.63 – 13.47	0.17 – 1.50	0.11 – 0.55	0.73 –130.34
18	*Mitragyna parvifolia*	2.24 –12.59	0.11 – 0.91	0.31 – 0.49	2.17 – 36.24
19	*Pongamia pinnata*	2.24 – 11.17	0.09 –0.81	0.34 – 0.46	1.20 – 38.63
20	*Santalum album*	1.98 – 12.86	0.16 –1.48	0.41 – 0.60	1.06 –156.42
21	*Tectona grandis*	2.84 – 17.37	0.13 – 1.04	0.32 – 0.52	2.35 –155.39
22	*Wrightia tinctoria*	1.66 – 12.59	0.11 –0.64	0.28 – 0.42	1.69 – 65.28
23	*Ziziphus jujuba*	2.26 – 11.23	0.15 –1.33	0.37 – 0.58	1.85 –118.69

Table 2
Regression models for predicting AGB in tropical dry deciduous forest.

Species name	N	Allometric equations	Model No.	Model performance statistics R^2	R^2 adjusted	RSE	p value	RMSE	MPE (%)
Azadirachta indica	26	ln AGB = 0.810 (ln (D^2 × H)) + 0.487	1	0.883	0.878	0.452	< 0.001	0.434	8.56
		ln AGB=1.229+1.29(lnD)+ 1.103(ln H)	2	0.885	0.874	0.467	< 0.001	0.430	8.47
		ln AGB = 0.789 (ln (D^2 × *H* × ρ)) + 1.276	3	0.876	0.871	0.465	< 0.001	0.447	9.02
		ln AGB = 1.172 (ln (D^2 × ρ)) – 0.202	4	0.831	0.824	0.543	< 0.001	0.522	10.28
Bauhinia racemosa	25	ln AGB = 0.675 (ln (D^2 × H)) + 0.252	5	0.875	0.869	0.397	< 0.001	0.381	8.10
		ln AGB =1.689+0.704(ln D) +1.392(ln H)	6	0.883	0.873	0.392	< 0.001	0.367	7.82
		ln AGB = 0.632 (ln (D^2 × *H* × ρ)) + 0.863	7	0.867	0.861	0.409	< 0.001	0.392	8.54
		ln AGB = 0.962 (ln (D^2)) – 1.052	8	0.851	0.845	0.432	< 0.001	0.415	8.63
Bridelia retusa	25	ln AGB = 0.816 (ln (D^2 × *H* × ρ)) + 1.187	9	0.918	0.914	0.285	< 0.001	0.273	3.91
		ln AGB = 1.962+1.298(ln D) +1.241(ln H) + 0.431(ln ρ)	10	0.927	0.916	0.281	< 0.001	0.257	3.68
		ln AGB=1.743+1.247(lnD)+1.287(ln H)	11	0.923	0.916	0.280	< 0.001	0.263	3.68
		ln AGB = 0.81 (ln (D^2 × H)) + 0.513	12	0.913	0.909	0.292	< 0.001	0.286	3.92
		ln AGB = 1.085 (ln (D^2 × ρ)) – 0.506	13	0.859	0.853	0.373	< 0.001	0.357	5.00
Butea monosperma	26	lnAGB= −0.083+2.067(ln D)+ 0.289(ln H)−0.059(ln ρ)	14	0.939	0.930	0.287	< 0.001	0.323	3.58
		ln AGB= 0.150 + 1.989(ln D) + 0.304(ln H)	15	0.939	0.933	0.282	< 0.001	0.265	2.87
		ln AGB= −0.928+2.342(ln D)−0.109(ln ρ)	16	0.931	0.925	0.298	< 0.001	0.280	3.03
		ln AGB = 1.108 (ln (D^2)) – 0.557	17	0.930	0.927	0.295	< 0.001	0.283	3.00
		ln AGB = 1.132 (ln (D^2 × H)) + 2.478	18	0.863	0.858	0.412	< 0.001	0.396	4.28
		ln AGB = 0.694 (ln (D^2 × *H* × ρ)) + 3.771	19	0.855	0.848	0.425	< 0.001	0.409	4.53
Cassia fistula	25	ln AGB = 0.863 (ln (D^2 × H)) + 0.517	20	0.947	0.945	0.299	< 0.001	0.287	3.74
		ln AGB=0.336+2.041(lnD)+0.612(lnH)−0.255ln ρ)	21	0.951	0.944	0.301	< 0.001	0.276	3.69
		ln AGB=−0.336+2.041(ln D) + 0.612(ln H) – 0.255(ln ρ)	22	0.950	0.946	0.295	< 0.001	0.277	3.61
		ln AGB = 0.854 (ln (D^2 × *H* × ρ)) + 0.995	23	0.940	0.937	0.318	< 0.001	0.305	4.08
		ln AGB = 1.356 (ln (D^2)) – 1.794	24	0.932	0.929	0.338	< 0.001	0.325	4.14
Cassia siemia	26	ln AGB = 1.261 (ln (D^2 × ρ)) – 0.379	25	0.845	0.839	0.382	< 0.001	0.367	6.73
		ln AGB = 1.423 (ln (D^2)) – 1.814	26	0.843	0.837	0.384	< 0.001	0.369	6.62
		ln AGB=0.975+2.664(ln D) + 0.749 (ln ρ)	27	0.847	0.834	0.387	< 0.001	0.364	6.68
		ln AGB = 0.702 (ln (D^2 × *H* × ρ)) + 1.468	28	0.707	0.694	0.526	< 0.001	0.505	9.48
Dalbergia paniculata	25	ln AGB = 0.501 (ln (D^2 × *H* × ρ)) + 1.405	29	0.964	0.962	0.172	< 0.001	0.165	2.83
		ln AGB = 0.524 (ln (D^2 × H)) + 0.934	30	0.963	0.961	0.174	< 0.001	0.167	2.79
		ln AGB =1.245+1.026(ln D)+ 0.500(ln H) +0.354(ln ρ)	31	0.964	0.959	0.180	< 0.001	0.165	2.82
		ln AGB= 0.903+1.063(ln D)+ 0.514(ln H)	32	0.963	0.960	0.178	< 0.001	0.167	2.79
		ln AGB = 0.764 (ln (D^2 × ρ)) + 0.327	33	0.948	0.946	0.207	< 0.001	0.199	3.32
Dalbergia sissoo	25	ln AGB= 1.082+ 1.182(ln D) + 1.066(ln H)- 0.293(ln ρ)	34	0.969	0.964	0.196	< 0.001	0.179	2.98
		ln AGB = 0.688 (ln (D^2 × H)) + 0.848	35	0.959	0.957	0.215	< 0.001	0.206	3.35
		ln AGB= 1.183+1.211(ln D)+ 0.817(ln H)	36	0.959	0.956	0.219	< 0.001	0.205	3.33
		ln AGB = 1.113 (ln (D^2)) – 0.891	37	0.940	0.937	0.260	< 0.001	0.249	3.95
		ln AGB= −1.122+2.315(ln D)- 0.092(ln ρ)	38	0.941	0.936	0.263	< 0.001	0.247	4.01
		ln AGB = 0.502 (ln (D^2 × *H* × ρ)) + 1.804	39	0.896	0.892	0.343	< 0.001	0.329	5.46
Delonix regia	25	ln AGB = 1.245 (ln (D^2)) – 1.758	40	0.839	0.832	0.411	< 0.001	0.394	5.42
		ln AGB = 0.777 (ln (D^2 × H)) + 0.535	41	0.832	0.824	0.421	< 0.001	0.403	5.68
		ln AGB= −0.972+2.176(ln D)+ 0.277(ln H)	42	0.842	0.828	0.416	< 0.001	0.390	5.49
		ln AGB=−1.916+2.525(ln D)−0.111(ln ρ)	43	0.840	0.825	0.419	< 0.001	0.399	4.62
		ln AGB = 0.703 (ln (D^2 × *H* × ρ)) +1.357	44	0.822	0.814	0.433	< 0.001	0.415	5.99
Diospyros malanoxylon	25	ln AGB = 0.727 (ln (D^2 × H)) + 0.972	45	0.788	0.779	0.506	< 0.001	0.485	6.29
		ln AGB =0.897+1.483(ln D)+0.703(ln H)	46	0.789	0.769	0.517	< 0.001	0.485	6.29
		ln AGB = 0.726 (ln (D^2 × *H* × ρ)) + 1.541	47	0.773	0.763	0.524	< 0.001	0.502	6.67
		ln AGB = 1.111 (ln (D^2 × ρ)) – 0.280	48	0.739	0.727	0.562	< 0.001	0.539	6.99
Ehretia laevis	25	ln AGB = 0.608 (ln (D^2 × H)) + 0.927	49	0.754	0.743	0.391	< 0.001	0.375	5.13
		ln AGB = 0.573 (ln (D^2 × *H* × ρ)) + 1.597	50	0.751	0.740	0.393	< 0.001	0.377	5.29
		ln AGB=2.094+0.857(ln D)+0.938(ln H)+0.170(ln ρ)	51	0.758	0.724	0.405	< 0.001	0.372	5.21
		ln AGB= 1.904+0.873(ln D)+0.949(ln H)	52	0.758	0.736	0.397	< 0.001	0.372	5.09
		ln AGB = 0.891 (ln (D^2)) – 0.729	53	0.728	0.716	0.411	< 0.001	0.394	5.27
Flacourtia indica	25	ln AGB=−0.248+1.384(ln D)+0.724(ln H)−0.808(ln ρ)	54	0.935	0.926	0.221	< 0.001	0.203	3.81
		ln AGB = 0.667 (ln (D^2 × H)) + 0.332	55	0.920	0.916	0.235	< 0.001	0.226	4.14
		ln AGB=0.082+1.438(ln D)+ 0.568(ln H)	56	0.920	0.913	0.239	< 0.001	0.224	4.12
		ln AGB = 0.980 (ln (D^2)) – 1.241	57	0.894	0.890	0.270	< 0.001	0.259	4.65
		ln AGB= −1.551+2.0(ln D)−0.360(ln ρ)	58	0.898	0.888	0.272	< 0.001	0.255	4.68
		ln AGB = 0.624 (ln (D^2 × *H* × ρ)) + 0.860	59	0.886	0.281	0.281	< 0.001	0.269	5.07
Gliricidia sepium	30	ln AGB = 1.188 (ln (D^2)) – 1.725	60	0.923	0.920	0.252	< 0.001	0.243	3.26
		ln AGB=−1.756+2.431(ln D)−0.043(ln H)+0.093(ln ρ)	61	0.923	0.915	0.260	< 0.001	0.242	3.37
		ln AGB= −1.884+2.438(ln D)−0.06(ln H)	62	0.923	0.917	0.256	< 0.001	0.243	3.32
		ln AGB=−1.640+2.387(ln D)+0.096(ln ρ)	63	0.923	0.918	0.255	< 0.001	0.242	3.31
		ln AGB = 0.768 (ln (D^2 × H)) + 0.375	64	0.907	0.903	0.277	< 0.001	0.267	3.65
		ln AGB = 0.771 (ln (D^2 × *H* × ρ)) + 1.210	65	0.879	0.874	0.316	< 0.001	0.305	4.25
Grewia asiatica	25	ln AGB = 0.741 (ln (D^2 × H)) + 0.422	66	0.865	0.859	0.441	< 0.001	0.423	6.69
		ln AGB = 0.752 (ln (D^2 × *H* × ρ)) + 0.950	67	0.860	0.854	0.449	< 0.001	0.430	6.98
		ln AGB=0.565+1.343(lnD)+0.866(lnH)−0.271(ln ρ)	68	0.866	0.847	0.460	< 0.001	0.421	6.83
		ln AGB=0.685+1.380(lnD)+0.845(ln H)	69	0.865	0.853	0.450	< 0.001	0.422	6.68
		ln AGB = 1.087 (ln (D^2)) – 1.387	70	0.844	0.837	0.474	< 0.001	0.455	7.04
Holarrhena antidysentrica	25	lnAGB=0.304+1.604(lnD)+0.214(lnH)+0.146(ln ρ)	71	0.949	0.942	0.185	< 0.001	0.170	2.28
		ln AGB = 0.917 (ln (D^2)) – 0.533	72	0.938	0.936	0.195	< 0.001	0.187	2.40
		ln AGB=0.014+1.623(lnD)+0.226(ln H)	73	0.942	0.937	0.193	< 0.001	0.181	2.38

(*continued on next page*)

Table 2 (*continued*)

Species name	N	Allometric equations	Model No.	Model performance statistics R^2	R^2 adjusted	RSE	p value	RMSE	MPE (%)
		$\ln AGB=-0.208+1.804(\ln D)+0.150(\ln \rho)$	74	0.946	0.941	0.187	< 0.001	0.175	2.30
		$\ln AGB = 0.612 (\ln (D^2 \times H)) + 1.013$	75	0.931	0.928	0.207	< 0.001	0.198	2.61
		$\ln AGB = 0.528 (\ln (D^2 \times H \times \rho)) + 2.208$	76	0.884	0.879	0.269	< 0.001	0.258	3.47
Leucaena leucocephala	30	$\ln AGB = 0.804 (\ln (D^2 \times H)) - 0.110$	77	0.969	0.968	0.301	< 0.001	0.291	11.27
		$\ln AGB = 0.651 (\ln (D^2 \times H \times \rho)) + 0.931$	78	0.959	0.957	0.348	< 0.001	0.336	13.29
		$\ln AGB = 1.350 (\ln (D^2)) - 2.210$	79	0.957	0.956	0.355	< 0.001	0.343	13.05
		$\ln AGB=-1.916+2.6(\ln D)+0.137(\ln \rho)$	80	0.958	0.955	0.357	< 0.001	0.339	13.14
Melia azadirech	27	$\ln AGB = 0.766 (\ln (D^2 \times H)) + 0.183$	81	0.934	0.931	0.352	< 0.001	0.339	5.80
		$\ln AGB=0.303+1.465(\ln D)+0.861(\ln H)-0.07(\ln \rho)$	82	0.934	0.925	0.366	< 0.001	0.337	5.88
		$\ln AGB=0.406+1.448(\ln D)+0.859(\ln H)$	83	0.934	0.928	0.359	< 0.001	0.338	5.8
		$\ln AGB = 1.103 (\ln (D^2)) - 1.616$	84	0.921	0.918	0.383	< 0.001	0.369	6.91
		$\ln AGB=-1.714+2.222(\ln D)- 0.062(\ln \rho)$	85	0.921	0.915	0.390	< 0.001	0.368	6.31
		$\ln AGB = 0.677 (\ln (D^2 \times H \times \rho)) + 1.158$	86	0.898	0.894	0.437	< 0.001	0.420	7.36
Mitragyna parvifolia	25	$\ln AGB = 0.487 (\ln (D^2 \times H)) + 1.268$	87	0.782	0.773	0.338	< 0.001	0.325	4.64
		$\ln AGB=1.867+0.736(\ln D)+0.650(\ln H)$	88	0.792	0.773	0.338	< 0.001	0.317	4.53
		$\ln AGB = 0.501 (\ln (D^2 \times H \times \rho)) + 1.721$	89	0.771	0.761	0.347	< 0.001	0.333	4.87
		$\ln AGB=1.772+0.725(\ln D)+0.647(\ln H)-0.115(\ln \rho)$	90	0.792	0.763	0.346	< 0.001	0.317	4.64
Pongamia pinnata	25	$\ln AGB=1.187+1.107(\ln D)+0.980(\ln H)$	91	0.956	0.952	0.236	< 0.001	0.222	3.99
		$\ln AGB=0.591+1.135(\ln D)+0.965(\ln H)-0.603(\ln \rho)$	92	0.958	0.952	0.236	< 0.001	0.216	3.99
		$\ln AGB = 0.736 (\ln (D^2 \times H)) + 0.266$	93	0.952	0.950	0.240	< 0.001	0.23	4.15
		$\ln AGB = 0.730 (\ln (D^2 \times H \times \rho)) + 0.919$	94	0.943	0.941	0.262	< 0.001	0.251	4.63
		$\ln AGB = 1.230 (\ln (D^2)) - 2.308$	95	0.900	0.895	0.349	< 0.001	0.335	5.89
Santalum album	25	$\ln AGB=2.257+1.223(\ln D)+1.199(\ln H)+1.78(\ln \rho)$	96	0.931	0.921	0.381	< 0.001	0.349	4.66
		$\ln AGB = 0.882 (\ln (D^2 \times H \times \rho)) + 0.590$	97	0.923	0.920	0.384	< 0.001	0.369	4.92
		$\ln AGB=0.843+1.386(\ln D)+1.299(\ln H)$	98	0.917	0.910	0.407	< 0.001	0.382	4.97
		$\ln AGB = 0.922 (\ln (D^2 \times H)) - 0.113$	99	0.913	0.909	0.409	< 0.001	0.392	5.11
		$\ln AGB = 1.330 (\ln (D^2 \times \rho)) - 1.043$	100	0.883	0.878	0.474	< 0.001	0.455	5.92
Tectona grandis	25	$\ln AGB=2.225+1.012(\ln D)+1.038(\ln H)$	101	0.932	0.925	0.310	< 0.001	0.29	3.43
		$\ln AGB=1.868+0.825(\ln D)+1.281(\ln H)-1.217(\ln \rho)$	102	0.944	0.936	0.286	< 0.001	0.262	3.17
		$\ln AGB = 0.714 (\ln (D^2 \times H)) + 0.958$	103	0.925	0.922	0.318	< 0.001	0.305	3.60
		$\ln AGB = 0.685 (\ln (D^2 \times H \times \rho)) + 1.631$	104	0.911	0.907	0.346	< 0.001	1.062	12.85
		$\ln AGB = 1.114 (\ln (D^2)) - 1.591$	105	0.864	0.858	0.427	< 0.001	0.410	4.73
Wrightia tinctoria	25	$\ln AGB=-2.441+1.723(\ln D)+0.474(\ln H)-2.098(\ln \rho)$	106	0.896	0.881	0.383	< 0.001	0.351	5.28
		$\ln AGB=0.791+1.396(\ln D)+0.764(\ln H)$	107	0.870	0.859	0.419	< 0.001	0.393	5.76
		$\ln AGB=-4.067+2.129(\ln D)-2.423(\ln \rho)$	108	0.890	0.880	0.386	< 0.001	0.362	5.31
		$\ln AGB = 0.718 (\ln (D^2 \times H)) + 0.666$	109	0.870	0.865	0.409	< 0.001	0.393	5.76
		$\ln AGB = 1.013 (\ln (D^2)) - 1.212$	110	0.852	0.845	0.438	< 0.001	0.420	6.02
		$\ln AGB = 0.700 (\ln (D^2 \times H \times \rho)) + 1.484$	111	0.849	0.843	0.441	< 0.001	0.423	6.36
Ziziphus jujuba	25	$\ln AGB=0.243+1.46(\ln D)+0.988(\ln H)-1.045(\ln \rho)$	112	0.933	0.924	0.320	< 0.001	0.293	3.66
		$\ln AGB = 0.813 (\ln (D^2 \times H)) + 0.692$	113	0.926	0.923	0.322	< 0.001	0.309	3.76
		$\ln AGB=0.799+1.585(\ln D)+0.876(\ln H)$	114	0.926	0.920	0.329	< 0.001	0.309	3.76
		$\ln AGB = 0.819 (\ln (D^2 \times H \times \rho)) + 1.325$	115	0.911	0.907	0.354	< 0.001	0.340	4.24
		$\ln AGB = 1.028 (\ln (D^2)) - 0.482$	116	0.872	0.886	0.425	< 0.001	0.407	4.85
General equation	589	$\ln AGB=-0.103+1.766(\ln D)+0.508(\ln H)$	117	0.843	0.843	0.479	< 0.001	0.477	1.40
		$\ln AGB=-0.147+1.771(\ln D) + 0.513(\ln H) -0.041(\ln \rho)$	118	0.843	0.842	0.479	< 0.001	0.477	1.40
		$\ln AGB = 0.755 (\ln (D^2 \times H)) + 0.548$	119	0.837	0.836	0.488	< 0.001	0.487	1.43
		$\ln AGB = 1.093 (\ln (D^2)) - 1.273$	120	0.817	0.817	0.516	< 0.001	0.516	1.51
		$\ln AGB=-1.253+2.184(\ln D)+0.015(\ln \rho)$	121	0.817	0.817	0.517	< 0.001	0.516	1.51
		$\ln AGB = 0.660 (\ln (D^2 \times H \times \rho)) + 1.410$	122	0.784	0.784	0.561	< 0.001	0.560	1.64
		$\ln AGB = 0.886 (\ln (D^2 \times \rho)) + 0.266$	123	0.733	0.732	0.625	< 0.001	0.624	1.83

N: Number of individuals, RSE: Relative standard error, MPE: Mean prediction error, RMSE: Root mean square error.

height and diameter in species specific AGB models has lowered R^2 value. However, in case of the general model, the use of WSG along with diameter and height shows nearly a similar value as the model consisting of diameter and height only. Amongst all general AGB models, model 117 was found as the best model for AGB estimation of the saplings and seedlings (Table 2). Present study indicates that all the dendrometric (diameter, height and WSG) variables show a positive relationship with the AGB. The aboveground biomass estimated using general allometric equation (Diameter and height as variable) was compared with the aboveground biomass obtained by harvest method for a number of dominant species and we found that the general equation predicts AGB well and can be used for biomass estimation (Fig. 3).

Average RSR values of those 9 species varied from 0.142 ± 0.039 to 0.855 ± 0.218. RSR was highest in *Pongamia pinnata*, while it was lowest in *Santalum album* (Table 3). Comparison of observed BGB, predicted BGB estimated from AGB and root to shoot ratio indicates minimal variance. However, predicted BGB calculated by generally used approach (IPCC, 2003) indicates higher variance (Fig. 4).

In the present study, we compared the AGB values obtained by the harvest method with those estimated using the best fit general model-117 (Fig. 5a), pan-tropical models (Fig. 5b–d) and regional models (Fig. 5d and e) (Table 4). We found that the best-fit general model-117 was able to predict biomass precisely with least variation (Fig. 5a). However, the widely used allometric models for mature individuals (Chave et al., 2005, 2014 and Brown, 1997) and regional models for juvenile individuals (Chaturvedi and Raghubanshi, 2013; Chaturvedi et al. 2012) failed to predict the aboveground biomass correctly for small diameter individuals (Fig. 5 (b–f)). Further, best fit general model of the present study (model 117) showed the lowest MPE (4.83%) and RMSE (0.477) compared to the frequently used pan-tropical models (Chave et al., 2005, 2014; Brown et al. 1997) and regional models for juvenile individuals (Chaturvedi and Raghubanshi, 2013; Chaturvedi et al., 2012) (Table 4).

4. Discussion

The observed species specific WSG values for seedlings and saplings in the present study are lower than the reported WSG values for saplings

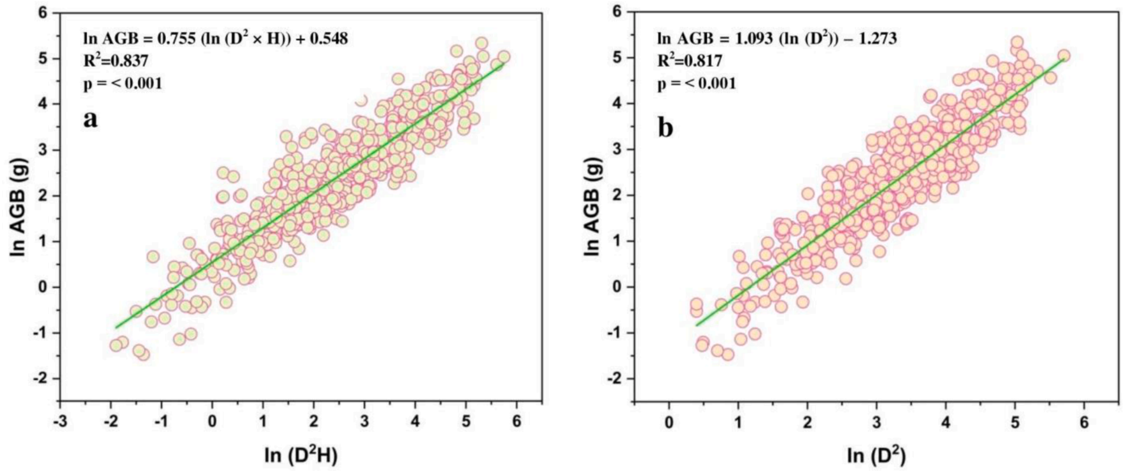

Fig. 2. Relationship between the biomass observed by harvest method with ln ($D^2H\rho$) (a) and ln (D^2) (b) in general allometric models (model 119 and 120 respectively).

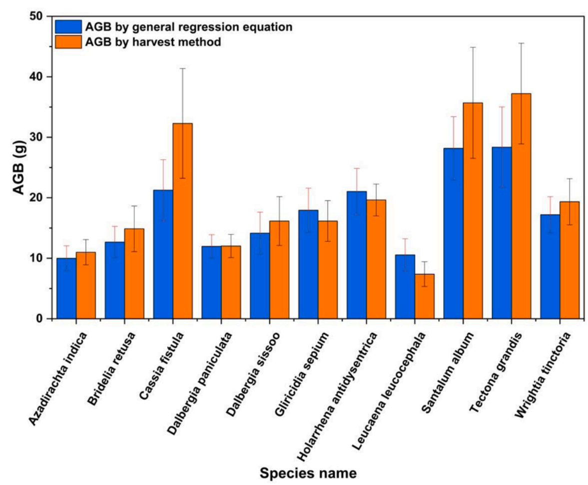

Fig. 3. Comparison of above ground biomass obtained by harvest method and general allometric equation method for dominant seedling and sapling species.

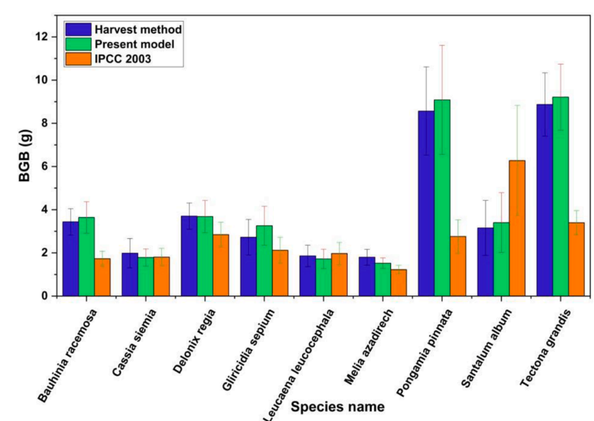

Fig. 4. Comparison of BGB obtained from harvest method, present equation and IPCC (2003) method.

Table 3
Root to shoot ratio for predicting BGB of a few species in tropical dry deciduous forest.

S. No.	Species name	N	RSR ± SD
1	*Bauhinia racemosa*	16	0.546 ± 0.133
2	*Cassia siemia*	19	0.257 ± 0.110
3	*Delonix regia*	17	0.336 ± 0.115
4	*Gliricidia sepium*	26	0.399 ± 0.181
5	*Leucaena leucocephala*	30	0. 227 ± 0.106
6	*Melia azadirech*	19	0.324 ± 0.183
7	*Pongamia pinnata*	16	0.855 ± 0.218
8	*Santalum album*	17	0.142 ± 0.039
9	*Tectona grandis*	16	0.705 ± 0.128

RSR: Root to shoot ratio., N: Number of individuals

(Chaturvedi et al., 2012; Chaturvedi and Raghubanshi, 2013). This might be due to the fact that WSG values are potentially influenced by climate, location, and management practices (Ketterings et al., 2001). It may also vary with the age of a tree, stand and other habitat factors (Slik et al., 2013). Other factors like precipitation, temperature, geographic range, forest successional stage, forest type, plot sampling, inter site variation, edaphic factors, annual rainfall, geographical location, low soil fertility, low disturbance rates and high diversity do have an impact on WSG variation (Mani and Parthasarathy, 2007; Woodcock, 2000; Keduolhouvonuo and Kumar, 2017; Muller-Landau, 2004). Results show that WSG values for a number of individuals increase with an increase in diameter. Similar relationship was also reported by other researchers (Chaturvedi et al., 2012; Chaturvedi and Raghubanshi, 2013).

Linear and logarithmic equations were found to be the best fit models for estimating biomass using simple measurements like diameter and height (Chaturvedi and Raghubanshi, 2013; Morataya et al., 1999; Parez and Kanninen, 2002, 2003). We have also found similar trends. In the present study, for most of the species, using only the diameter as an independent variable explained more than 60% of variability. Previous study had also reported that when D is applied as an estimator in the allometric equations for estimating branch biomass, improved results are obtained (Shinozaki et al., 1964). Attiwill (1962) also found a relationship between branch biomass and girth. In most of the species specific equations along with general equations, the use of height combined with diameter have increased the R^2 value. Previous studies have reported that the inclusion of height with diameter has increased the efficiency of model selection parameters during selecting the best fit model for all the components of trees (Mahmood et al., 2021; Rutishauser et al., 2013; Kusmana et al., 2018). In the present study, the use of height with diameter provides better result than using WSG with diameter for general models. Further, our results showed that the use of WSG in species specific models decreased the R^2 value. However, in case of general equation, model consisting of diameter, height and WSG

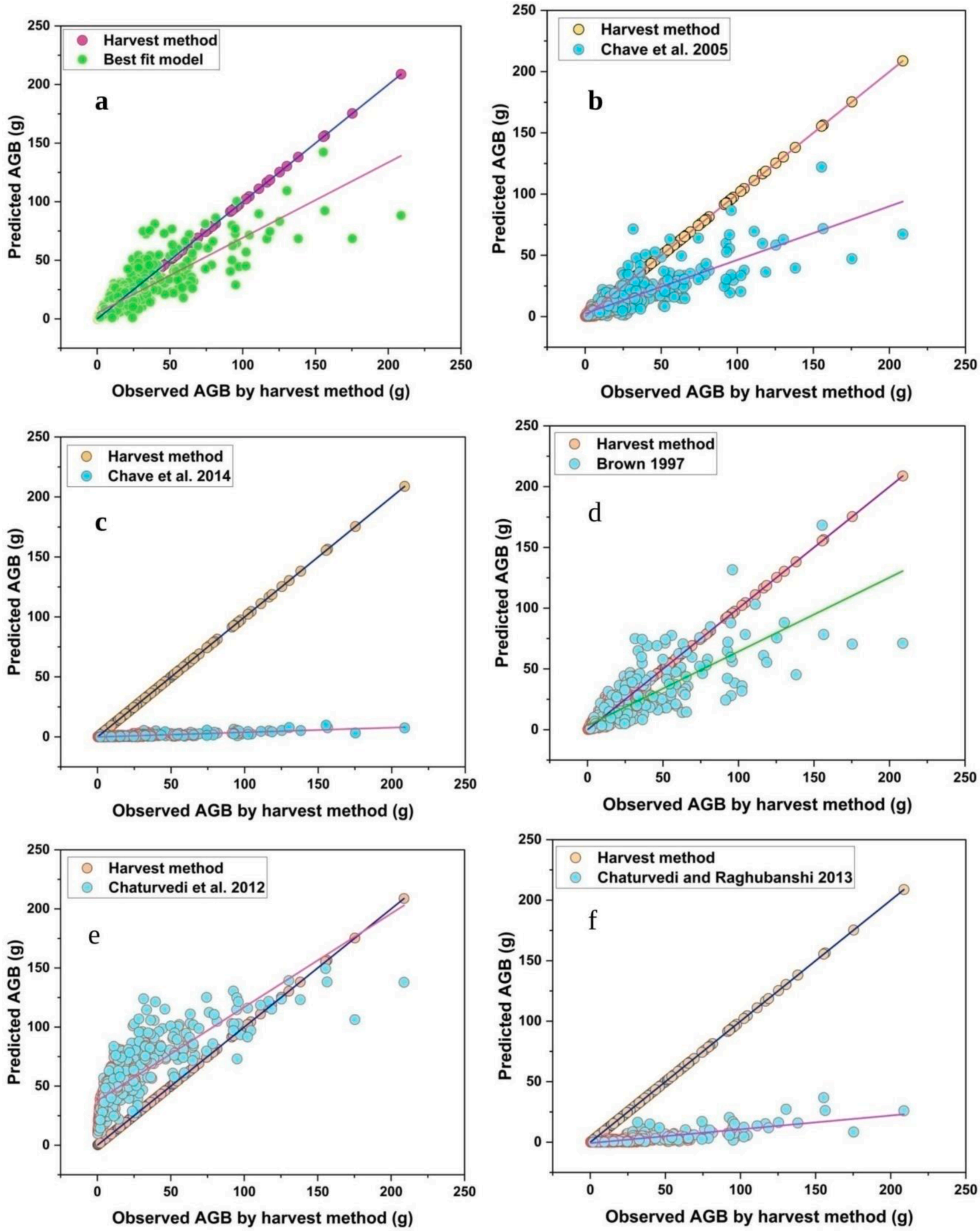

Fig. 5. Comparison of best-fit aboveground biomass model (model 117) (a) with pan-tropical models (commonly used for mature individuals) (**b**–**d**) and regional models (used for lower diameter individuals) (**e** and **f**).

(model 118) shows nearly similar R^2 value as found in the model with diameter and height (model 117). This may be attributed to the fact that WSG of different species is quite different; therefore, they play a crucial role in a general model by minimizing the variability. According to Chaturvedi and Raghubanshi (2013), incorporating WSG in a general model is required for precise AGB prediction for juvenile trees. This could be further supported by the findings of Chave et al. (2005), who found that wood density was a key predictor variable in several regression models developed for estimating AGB in tropical forests and it is included as a predictor variable along with diameter and height to capture the variability of different tree species in a common allometric model.

Determination of WSG for seedlings and saplings requires the destruction of whole individual. Further, in our previous study, we found that juvenility has a greater impact on WSG variation than climatic variation (Pati et al., 2022) indicating the inadequacy of adopting WSG values determined from mature class individuals for juvenile class individuals. Moreover, the use of reported WSG in biomass estimation may cause variation (Ramananantoandro et al., 2015). Furthermore, use of diameter and height only predicts simillar results. Therefore, WSG may be avoided in the biomass equation when estimating biomass to retain the regeneration. Present study provides an indirect method for

Table 4
Comparison of best fit AGB general model (model no. 117) with the various pantropical model and regional model.

Source	Equation	Used for growth stage type	RMSE	MPE (%)
Best fit general model (model no. 117)	ln AGB = -0.103+1.766 (ln D)+0.508(ln H)	Juvenile classes	0.477	4.83
Chave et al. (2005)	AGB = ρ × exp (–0.667 + 1.784 ln (D) + 0.207 (ln (D)) ^{2} – 0.0281 (ln (D))^3)	Mature classes	18.5977	6.43
Chave et al. (2014)	AGB = exp (- 2.6986 + 0.976 × ln ($D^2 \times H \times \rho$)	Mature classes	31.34321	10.86
Brown (1997)	AGB = exp (−2.134 + 2.5430 × ln (D))	Mature classes	15.64992	5.41
Chaturvedi and Raghubanshi (2013)	ln AGB = −3.206 + 1.337 ln ($D^2 \times H \times \rho$)	Juvenile classes	29.38275	10.35
Chaturvedi et al. (2012)	ln AGB = 3.428 + 0.310 ln ($D^2 \times H \times \rho$)	Juvenile classes	37.13899	12.87

MPE: Mean prediction error, RMSE: Root mean square error.

biomass estimation and helps in maintaining biodiversity by protecting a number of young individuals to fight against present-day crisis of climate change. Further, it will help to measure the biomass and carbon sequestration of younger individuals in newly formed forests and secondary forests.

Estimating tree biomass using regional or pantropical allometric biomass models is still common (Chave et al., 2014; Mahmood et al., 2021). However, use of these models for biomass estimation show large variation in biomass estimates compared to species specific allometric equations (Ketterings et al., 2001; Ngomanda et al., 2014). The best-fit general model has showed less variation in AGB estimates compared to the frequently used pan-tropical models and regional models. Similar results were reported by previous studies (Daba and Soromessa, 2019b; Pothong et al., 2021; Kenzo et al., 2009). This may be due to the fact that these pan-tropical biomass models were developed using data from individuals with larger diameters and from different geographic locations. This could be further supported by the findings of Fonseca et al. (2012), who found that the error in biomass estimation can also occur if the equations are applied for diameter ranges outside the one used for their formulation. Furthermore, models that focus on larger trees may overestimate the biomass of smaller trees (van Breugel et al., 2011). However, allometric models developed for juvenile species from other tropical dry forests (Chaturvedi and Raghubanshi, 2013; Chaturvedi et al., 2012) were also not able to predict the biomass precisely (Fig. 5 (e and f)). Similar results are obtained from previous studies (Pothong et al., 2021; Kenzo et al., 2009). This might be due to the change in climatic, edaphic and other habitat factors. BGB models formulated in the present study are quite efficient in predicting BGB (Fig. 4). However, it shows higher variance compared to a well used approach (IPCC, 2003), indicating the importance of habitat-species- specific model for BGB estimation in small diameter woody species. These findings show that use of site-specific allometric equation is prerequisite to minimize error in AGB as well as BGB estimation. The present study shows that to avoid destructive approach and subsequent reduction in regenerating phases, biomass of small diameter individuals can be precisely estimated using diameter and height through species specific allometric equations.

5. Conclusion

In comparison to commonly used regional or pan-tropical biomass models, the developed allometric equations in the present study are capable of estimating biomass with better accuracy for the present study site in tropical dry deciduous forest. Our results showed that the use of WSG in the general equation with combination of diameter and height (model 118) shows a nearly similar R^2 value as the model with diameter with height (model 117). However, incorporating WSG into a species-specific allometric equation reduces efficiency for lower diameter individuals. Further, WSG cannot be determined without the destruction of small diameter trees and it is not extensively documented in the literature for smaller diameter individuals. The use of reported WSG may cause variation in AGB estimation (Ramananantoandro et al., 2015). Species-specific equations, on the other hand, would predict biomass more precisely in most instances than a general model with just two easily measurable parameters (diameter and height). Therefore, we suggest use of species specific model as a better option for biomass estimation. Further, general models consisting of height and diameter may be used for biomass estimation in case of unavailability of species specific equations without destroying the regeneration. General model incorporating WSG as a covariate may be used for the estimation of biomass for different climatic conditions to overcome the impact of climate on biomass equation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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