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ALLOMETRIC MODEL COMPARISON AND COMPONENTS BIOMASS EVALUATION OF *ALNUS NEPALENSIS, RHODODENDRON ARBOREUM* AND *TECTONA GRANDIS*

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The study focuses on evaluation of different component biomass of *Alnus nepalensis*, *Rhododendron arboreum* and *Tectona grandis* using pre-existing multiple species-specific equations developed by various authors. The study aimed to compare component biomass estimation obtained using these different equations keeping values of diameter, wood density and height constant for three plant species. A total of 80 equations were computed. A wide variation in component biomass estimation were observed within tree species. Biomass for all the three tree species was also evaluated and compared using two mixed standard equations which can be used across a range of conditions in India. It was observed that there was a significant difference in biomass estimation in the studied tree species. Aboveground biomass for *Tectona grandis* ranged from 551–1869 kg tree^{-1}. Leaf Biomass for *Rhododendron arboreum* ranged from -1.29 to -5.29 as negative numerals. Similar intriguing observations were reported for tree bio-volume estimation.

Keywords: Allometric models, biomass, non-destructive approach, logarithmic equations, diameter

INTRODUCTION

The estimation of tree biomass through harvested methods has turned out to be a daunting task with the present scenario of climate change and environment. At this juncture, allometric equations or regression models remain as a unilateral way to study the biomass or carbon stored in trees. Based on harvested/direct methods which involves the clear cutting and felling of trees, and indirect methods in which biomass is evaluated using biomass estimation equations, many models are developed for single tree species with varying level of uncertainties (Nelson et al. 1999, Hashimotio et al. 2000, Lodhiyal & Lodhiyal 2003, Chung-Wang & Ceulemans 2004, Ravindranath & Ostwald 2008, Devi & Yadava 2009, Garcia et al. 2015, Brahma et al. 2021). Numerous efforts have been made to develop more adaptable equations that are applicable to a wide range of species or specific ecosystems in order to reduce the ambiguity caused due to lack of biomass estimation equations. These equations could be adequate for estimating biomass at specific developmental stages of trees/forest and at regional scale, but they might not accurately represent the tree's biomass in different localities and at different developmental stages. Despite their significance, existing equations are frequently dispersed between libraries, logging corporations, forest administrations and research centres (FOA 2013). The information on biomass estimation equations for Indian tree species is highly dappled, patchy and sporadic and a very few multiple species-specific equations are available for woody Indian trees (Salunkhe et al. 2018, Brahma et al. 2021). The study focused on variability of biomass estimation equations for three tree species, i.e., *Alnus nepalensis*, *Rhododendron arboreum* and *Tectona grandis* and was restricted to Indian context only as the equation under consideration were based on Indian ecosystems. The goal of this synthesis was to identify the uncertainties brought on biomass component estimation by the use of existing different equations on a single tree. Attempts were made to explain the suffering of models/equations from problems such as negative estimation of the biomass, constant estimation of biomass and the illogical estimation of biomass. It also aimed to determine the best species-specific biomass estimation equation among the existing equations.

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MATERIALS AND METHODOLOGY

The study aimed to estimate the tree's biomass by computing different allometric and volume equations. It was hypothesised that similar biomass components estimated with different allometric equations with similar diameter, wood density and height of a specific tree species will result into the similar or nearly similar biomass, keeping constant values of diameter. Specific allometric equations and volume equations for three tree species were pooled from systematic reviews and Forest Survey of India reports (Salunkhe et al. 2018, Brahma et al. 2021, FSI 2021). Table 2 summarises allometric equations for biomass components of *A. nepalensis*, *R. arboreum* and *T. grandis* along with biomass component, unit of measurement, age class, number of trees on which these equations were developed, r^2, error of estimation or correction factor, coordinates of the study site and references. For these trees, more than one allometric equations were available for estimating different components of biomass and thus provided sufficiency for equation comparison for biomass estimation.

Sample and data collection

The study was conducted at Wood Anatomy Discipline of the Forest Research Institute (FRI), Dehradun, India. Three tree species, i.e., *A. nepalensis, R. arboreum* and *T. grandis* were selected on the basis of availability of multiple allometric equations for estimation of a single biomass component. Samples for the study were availed from Xylarium (DDw), FRI, Dehradun. The details of the samples studied are given in Table 1. These samples were collected at a standard DBH of 1.37 m from the ecotonal zone of the tree and are therefore, representation of an entire tree. The diameter of tree species was estimated through accessing growth ring widths of authentic wood samples of specific tree species under a light microscope. Observations were recorded in micrometres (μm) and then converted into millimetres (mm). A total number of 15 rings for *A. nepalensis*, 57 rings for *R. arboreum* and 58 rings for *T. grandis* were used for diameter estimation. Annual increment (as an average growth) for each tree species was evaluated. The values obtained as annual increment were multiplied with an age factor

Table 1 Three tree species along with their accession number, locality and number of rings evaluated for diameter estimation

Tree species	Accession no.	Locality	No. of rings used to estimate the diameter
Alnus nepalensis	DDw5767	Uttarakhand	15
	DDw8271	West Bengal	
	DDw83	Himachal Pradesh	
	DDw6646	Burma	
Rhododendron arboreum	DDw371	Himachal Pradesh	57
	DDw2388	West Bengal	
	DDw383	West Bengal	
	DDw3881	Tamil Nadu	
	DDw6092	Uttar Pradesh	
	DDw73	Himachal Pradesh	
Tectona grandis	DDw4444	Uttar Pradesh	58
	DDw7454	Assam	
	DDw7961	Orissa	
	DDw7254	West Bengal	
	DDw7216	Maharashtra	
	DDw5170	Tamil Nadu	
	DDw753	Karnataka	
	Total = 17		

Table 2 Details of plant species and related information

Tree species	Component	Units	Equation	R^2	CF or SE	Age (yr)	Sample size (used to develop the equation)	State	Coordinates	Reference
Alnus nepalensis	ln BLB	G	1.532 + 2.461 ln D	0.997	1.016s	7–46	17	West Bengal	27° 7' N and 88° 35' E	Sharma & Ambasht 1991
	ln BLB	Kg tree^{-1}	-8.762 + 0.209 ln Age	0.943	0.015	-	-	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh &Yadava 1994
	ln BLB	G	-13.776 + 2.117 ln D	0.974	2.137	-	-	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh &Yadava 1994
	ln BB	G	1.455 + 2.216 ln DBH	0.993	1.021	7–46	17	West Bengal	27° 7' N and 88° 35' E	Sharma & Ambasht 1991
	ln BB	Kg tree^{-1}	-4.396 + 0.711 ln Age	0.987	0.058		47	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh &Yadava 1994
	ln BB	Kg tree^{-1}	-6.941 + 1.214 ln D	0.965	0.408	7–33	47	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh &Yadava 1994
	ln LB	Kg tree^{-1}	-4.955 + 0.626 ln Age	0.967	0.160	7–33	47	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh & Yadava 1994
	ln LB	Kg tree^{-1}	-6.165+ 1.085 ln D	0.978	0.101	7–33	47	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh & Yadava 1994
	BGB	G	0.916 + 0.720 ln D	0.992	1.018	7–46	17	West Bengal	27° 7' N and 88° 35' E	Sharma & Ambasht 1991
Rhododendron arboreum	ln AGB	Kg tree^{-1}	1.176 + 0.855 ln GBH	0.712	0.0186	-	8	Uttarakhand	29° 24' N, 70° 28' E	Rawat & Singh 1988
	BLB	Kg tree^{-1}	1.120 + 0.704 ln GBH	-	-	-	-	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh & Yadava 1994
	BLB	Kg tree^{-1}	-5.689 + 1.084 ln Age	0.947	10.176	-	-			Singh & Yadava 1994
	BLB	Kg tree^{-1}	-21.265+ 2.495 ln D	0.938	13.992	-	-			Singh & Yadava 1994

continued

Table 2 Continued

Tree species	Component	Units	Equation	R^2	CF or SE	Age (yr)	Sample size (used to develop the equation)	State	Coordinates	Reference
Rhododendron arboreum	BB	Kg $tree^{-1}$	-3.780 + 0.752 ln Age	0.974	0.577	-	-	-	23° 13' N Latitude and 94° 25' E Longitude	Singh & Yadava 1994
	BB	Kg $tree^{-1}$	-13.226 + 1.687 ln D (Not significant)	5.853	5.853	-	-	-	23° 13' N Latitude and 94° 25' E Longitude	Singh & Yadava 1994
	BB	Kg $tree^{-1}$	1.113 + 0.609 ln GBH	-	-	-	-	-	23° 13' N Latitude and 94° 25' E Longitude	Singh & Yadava 1994
	ln LB	Kg $tree^{-1}$	-2.850 + 0.397 ln Age	0.971	0.44	7–33	47	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh & Yadava 1994
	ln LB	Kg $tree^{-1}$	-7.860+ 0.892 ln D	0.892	0.431	7–33	47	Manipur	23° 13' N Latitude and 94° 25' E Longitude	Singh & Yadava 1994
	LB	Kg $tree^{-1}$	1.19 + 0.17 ln GBH	-	-	-	8	Uttarakhand	29° 24' N, 70° 28' E	Rawat & Singh 1988
	SRB	Kg $tree^{-1}$	-0.12 + 0.87 ln GBH	-	-	-	8	Uttarakhand	29° 24' N, 70° 28' E	Rawat & Singh 1988
	LRB	Kg $tree^{-1}$	-1.75 + 0.98 ln GBH	-	-	-	8	Uttarakhand	29° 24' N, 70° 28' E	Rawat & Singh 1988
	FRB	Kg $tree^{-1}$	-0.01 + 0.41 ln GBH	-	-	-	8	Uttarakhand	29° 24' N, 70° 28' E	Rawat & Singh 1988
	ln BGB	Kg $tree^{-1}$	0.942 + 0.506 ln GBH	-	-	-	8	Uttarakhand	29° 24' N, 70° 28' E	Rawat & Singh 1988
Tectona grandis	AGB	Kg $tree^{-1}$	$0.0758 \times D^{2.6135}$	0.9847	-	-	-	Uttar Pradesh	Terai region	Negi et al. 1995
	ln AGB	Kg	$8.902 + 7.873\ (1+(\ln pD^2 H/14.05)^{-6.780}$	0.998	0.082	-	100	Uttar Pradesh	21° 29'–25° 11' N and 78° 15'– 84° 15' E	Chaturvedi & Raghuvanshi 2015
	AGB	Kg $tree^{-1}$	$0.06\ p(\prod D^2/4)H$	-	-	5–40	70	Kerala	-	Sandeep et al. 2015

continued

Table 2 Continued

Tree species	Component	Units	Equation	R^2	CF or SE	Age (yr)	Sample size (used to develop the equation)	State	Coordinates	Reference
Tectona grandis	AGB	Kg ha^{-1}	$0.4989D^2 - 0.202D - 21.971$	0.9476	-	1–30	33	Uttarakhand	29°3' to 29°12'N latitude and 79°20' to 79°23''E longitude	Jha 2015
	AGB	Kg $tree^{-1}$	$0.26 + 730.55D^2 H$ (D = m, H = m)	0.999	-	15–20	12	Kerala	11°17'-11°23'N and 76°16'-76°18'E	Chandrashekara 1996
	BKB	Kg $tree^{-1}$	$2.45896e^{0.0984D}$	0.8915	-	-	-	Uttar Pradesh	-Terai region-	Negi et al. 1995
	BLB	Kg $tree^{-1}$	$0.03343 \times D^{2.73532}$	0.98095	-	-	-	Uttar Pradesh	-Terai region-	Negi et al. 1995
	BLB	Kg $tree^{-1}$	$0.025D^{2.817}$	0.922	0.192	20–47	-	Tamil Nadu	Southern Zone	Buvaneswaran et al. 2006
	BLB	Kg $tree^{-1}$	$0.0581D^{2.523}$	0.943	0.168	20–47	-	Tamil Nadu	Western Zone	Buvaneswaran et al. 2006
	BLB	Kg $tree^{-1}$	$-2.85+2.655 \ln CBH$	0.98	0.075	-	15	Madhya Pradesh	-	Kale. 2004
	ln BLB	Kg $tree^{-1}$	$8.512 + 10.49/1 + (\ln pD^2 H/15.36)^{-5.252}$	0.996	0.104	-	100	Uttar Pradesh	21°29'–25°11' N and 78°15'– 84°15' E	Chaturvedi & Raghuvanshi 2015
	BLB	Kg $tree^{-1}$	$0.3699D^2 - 0.1537D - 17.8$	0.9294	-	1–30	33	Uttarakhand	29°3' to 29°12'N latitude and 79°20' to 79°23''E longitude	Jha 2015
	BLB	Kg	$0.942 + 512.69D^2 H$ (D = m, H = m)	0.999	-	15–20	12	Kerala	11°17'-11°23'N and 76°16'-76°18'E	Chandrashekara 1996
	BB	Kg $tree^{-1}$	$0.570279e^{0.1823D}$	0.9717	-	-	-	Uttar Pradesh	-Terai region-	Negi et al. 1995
	BB	Kg $tree^{-1}$	$0.0718D^{2.058}$	0.542	0.453	20–47	-	Tamil Nadu	Sothern Zone	Buvaneswaran et al. 2006
	BB	Kg $tree^{-1}$	$0.0122D^{2.523}$	0.801	0.355	20–47	-	Tamil Nadu	Western Zone	Buvaneswaran et al. 2006
	BWB	Kg $tree^{-1}$	$0.001D^{3.063}$	0.465	0.788	-	-	Tamil Nadu	Sothern Zone	Buvaneswaran et al. 2006

continued

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Table 2 Continued

Tree species	Component	Units	Equation	R^2	CF or SE	Age (yr)	Sample size (used to develop the equation)	State	Coordinates	Reference
Tectona grandis	BWB	Kg tree^{-1}	$0.001D^{3.0634}$	0.465	0.948	-	-	Tamil Nadu	Western Zone	Buvaneswaran et al. 2006
	ln BB	Kg	$6.726 + 6.000/1 + (\ln pD^2 H/12.89)^{-13.27}$	0.994	0.154		100	Uttar Pradesh	21°29'–25°11' N and 78°15'– 84°15' E	Chaturvedi & Raghuvanshi 2015
	BB	Kg ha^{-1}	$0.0678D^2 - 0.7045D + 1.5725$	0.5919	-	1–30	33	Uttarakhand	29°3' to 29°12'N latitude and 79°20' to 79°23''E longitude	Jha 2015
	BB	Kg	$0.156 + 144.89D^2 H$ (D = m, H = m)	0.977	-	15–20	12	Kerala	11°17'-11°23'N and 76°16'-76°18'E	Chandrashekara 1996
	Twig B	Kg tree^{-1}	$1.592118e^{0.0965D}$	0.8526	-	-	-	Uttar Pradesh	-Terai region-	Negi et al. 1995
	LB	Kg tree^{-1}	$-12.49108 + 1.253875 \times D$	0.9002	-	-	-	Uttar Pradesh	-Terai region-	Negi et al. 1995
	LB	Kg tree^{-1}	$0.0037D^{2.459}$	0.689	0.393	20–47	-	Tamil Nadu	Sothern Zone	Buvaneswaran et al. 2006
	LB	Kg tree^{-1}	$0.0116D^{2.1524}$	0.710	0.332	20–47	-	Tamil Nadu	Western Zone	Buvaneswaran et al. 2006
	ln LB	Kg	$2.985 + 1.029\ln D^2$	0.950	0.295	-	100	Uttar Pradesh	21°29'–25°11' N and 78°15'– 84°15' E	Chaturvedi & Raghuvanshi 2015
	ln LB	Kg	$6.356 + 7.280/1 + (\ln D^2 /6.682) - 4.706$	0.984	0.179	-	100	Uttar Pradesh	21°29'–25°11' N and 78°15'– 84°15' E	Chaturvedi & Raghuvanshi 2015
	LB	Kg ha^{-1}	$-0.0025D^2 + 0.4833D - 2.3174$	0.4565	-	1–30	33	Uttarakhand	29°3' to 29°12'N latitude and 79°20' to 79°23''E longitude	Jha 2015
	LB	Kg	$74.0D^2 H^{-2.72}$ (D = m, H = m)	0.994	-	15–20	12	Kerala	11° 17'-11° 23'N and 76° 16'-76° 18'E	Chandrashekara 1996
	RB	Kg tree^{-1}	$0.0241 \times D^{2.45322}$	0.9803	-	-	-	Uttar Pradesh	-Terai region-	Negi et al. 1995

continued

Table 2 Continued

Tree species	Component	Units	Equation	R^2	CF or SE	Age (yr)	Sample size (used to develop the equation)	State	Coordinates	Reference
Tectona grandis	SRB	Kg ha^{-1}	$0.0674D^2 - 0.8079D + 3.7722$	0.7297	-	1–30	33	Uttarakhand	29° 3' to 29° 12'N latitude and 79° 20' to 79° 23''E longitude	Jha 2015
	LRB	Kg ha^{-1}	$0.0583D^2 -1.0494D + 5.4397$	0.8406	-	1-30	33	Uttarakhand	29° 3' to 29° 12'N latitude and 79° 20' to 79° 23''E longitude	Jha 2015
	TRB	Kg $tree^{-1}$	$0.097D^{2.023}$	0.830	0.217	20–47	-	Tamil Nadu	Sothern Zone	Buvaneswaran et al. 2006
	TRB	Kg $tree^{-1}$	$0.185D^2 - 3.747D + 51.498$	0.918	9.748	20–47	-	Tamil Nadu	Western Zone	Buvaneswaran et al. 2006
	BGB	Kg ha^{-1}	$0.1257D^2 -1.8573D + 9.2119$	0.8469	-	1–30	33	Uttarakhand	29° 3' to 29° 12'N latitude and 79° 20' to 79° 23''E longitude	Jha 2015
	TB	Kg $tree^{-1}$	$0.0982 \times D^{2.5873}$	0.9862	-	-	-	Uttar Pradesh	Terai region	Negi et al. 1995
	ln TB	Kg $tree^{-1}$	$\ln (8.165) + (8.165) \ln D^2 H$	0.988	-	-	418	Madhya Pradesh	21°17'–26°52'N Latitude and 74°08'–82°49'E Longitude	Deb et al. 2016
	TB	Kg $tree^{-1}$	$0.142D^{2.469}$	0.943	0.143	20–47	-	Tamil Nadu	Sothern Zone	Buvaneswaran et al. 2006
	TB	Kg $tree^{-1}$	$0.202D^{2.353}$	0.970	0.130	20–47	-	Tamil Nadu	Western Zone	Buvaneswaran et al. 2006
	TB	Kg ha^{-1}	$0.6246D^2 - 2.0593D -12.759$	0.9523		1–30	33	Uttarakhand	29° 3' to 29° 12'N latitude and 79° 20' to 79° 23''E longitude	Jha 2015

BLB = bole biomass, BB = branch biomass, LB = leaf biomass, AGB = aboveground biomass, BGB = belowground biomass, FRB = fine root biomass, LRB = lateral root biomass, SRB = stump root biomass, BWB = branch wood biomass, TB = total biomass, GBH = girth at breast height, D = diameter, DH = diameter, height, CF = correction factor, DBH = diameter at breast height, TRB = total root biomass, BKB = bark biomass, Rho (p) = wood density

Table 3 Details of diameter, height and wood specific gravity of three tree species used to evaluate biomass components

Tree species	Mean ring width (mm)	Age	Diameter (cm) D*	Height (m)	Mean specific gravity
Alnus nepalensis	4.7	50	47	27	0.43
Rhododendron arboretum	1.78	50	17.8	7.5	0.56
Tectona grandis	3.41	50	34.10	22	0.62

Table 4 Volume equations and specific gravity (g cm^{-3}) used for computing biomass of different tree species (based on FSI 2021)

Tree species	State of India	Volume equation	Mean specific gravity
Alnus species	Sikkim	V = (0.0741 - 1.3603*D + 10.9229*D^2)	0.43
Rhododendron arboreum	Himachal Pradesh	V = (0.306492 + 4.31536*D - 1.749908*? D)	0.56
	Uttarakhand	V = (0.306492 + 4.31536*D - 1.749908*? D)	
Tectona grandis	Assam	V = (0.405890 + 1.98158*D + 0.987373*? D)	0.62
	Gujarat	V = (0.032011 - 0.995414*D + 9.91129*D^2)	
	Karnataka	V = (-0.40589 + 1.98158*D + 0.987373*? D)	
	Kerala	V = (-0.40589 + 1.98158*D + 0.987373*? D)	
	Madhya Pradesh	V = (-0.003673-0.379175*D + 6.368282*D^2)	
	Maharashtra	V = (-0.106720 + 2.562418*D)	
	Mizoram	V = (0.19112-3.25372*D + 17.9194*D^2 - 1.66117*D^3)	
	Rajasthan	V = (0.062108-0.927983*D + 6.613031*D^2)	
	Tamil Nadu	V = (0.405890 + 1.98158*D + 0.987373*?D)	
	Telangana	V = (0.023613-0.531006*D + 6.731036*D^2)	
	Tripura	V = (0.19112 - 3.25372*D + 17.9194*D^2 - 1.66117*D^3)	
	Uttar Pradesh	V = (0.08847 - 1.46936*D + 11.98979*D^2 + 1.970560*D^3)	
	West Bengal	V = (0.19112-3.25372*D + 17.9194*D^2 -1.66117*D^3)	
	Dadar & Nagar Haveli and Daman & Diu	?V = (-0.40589 + 1.98158*D + 0.987373*?D)	

of 50 and thus, assuming a constant age for all three species. Therefore, the estimated diameter and biomass components is of 50 years for all three tree species. Wood specific gravity/wood density of the same samples were evaluated as the ratio between oven dry weight of the wood to the weight of an equal volume of water-soaked wood. Data for the height was procured from the grey literature or collector registers, which gave the exact height of trees from which the samples were collected.

RESULTS

A total of 63 allometric equations and 17 volume equations (Table 5) were evaluated and biomass was estimated for different components. Maximum equations, i.e., 54 were available for *T. grandis* followed by 16 equations for *R. arboreum* and 10 equations for *A. nepalensis*. Of these, 62% of equations made use of diameter at breast height (DBH) as an explanatory variable, 14% girth at breast height (GBH), 9% each of age and diameter & height together, and 5% of equations were based on wood density, diameter and height as biomass estimation factors. None of the equations used height and wood density individually as biomass predictor (Figure 1). The study classified all the 63 equations according to their equation type (Figure 2). Accordingly, 27 equations were log transformed, 17 equations were power models, 9 polynomial, 4 linear, 3 logistic models and 3 equations were exponential regressions.

Alnus nepalensis

For every single component such as bole biomass or branch biomass or leaf biomass, no two equations resulted in the same biomass estimation. Though the equations possessed different signs (+, -) and had different statistical significance, yet two equations with same signs for same component did not result into similar values of biomass.

Tectona grandis

Among the 5 equations for aboveground biomass (AGB) estimation, 7 for bole biomass (BLB), 6 for branch biomass (BB), 7 for leaf biomass (LB) and 5 equations for total biomass (TB)

Table 5 Number of equations for each tree species and the components evaluated

Tree species	Component	No. of allometric equations	No. of volume equations
Alnus nepalensis	BLB	3	1
	BB	3	
	LB	2	
	BGB	1	
Rhododendron arboreum	AGB	1	2
	BLB	3	
	BB	3	
	LB	3	
	SRB	1	
	LRB	1	
	FRB	1	
	BGB	1	
Tectona grandis	AGB	5	14
	BLB	7	
	BB	6	
	Twig B	1	
	BWB	2	
	LB	7	
	SRB	1	
	LRB	1	
	TRB	2	
	RB	1	
	BGB	2	
	TB	5	

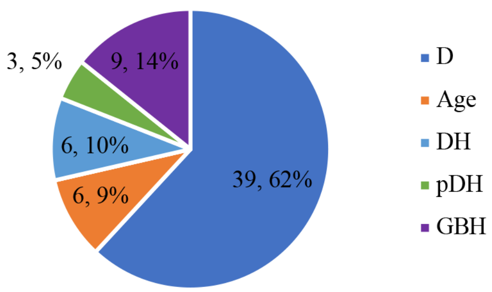

Figure 1 Number and percentage of explanatory variable used to predict the dependent variable

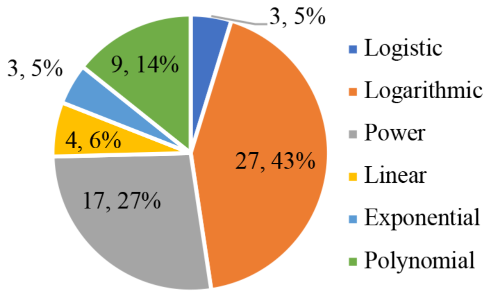

Figure 2 Number and percentage of allometric equations according to equation type

estimation, a wide range of variation was found in the estimated biomass for each component. The AGB had a range of 551–1869 kg, BLB has a range of 9–1312 kg, 56–370 kg for BB, 11–66 kg and 643–907 kg for LB and TB respectively.

There are 14 equations developed for volume estimation by the Forest Survey of India (FSI 2021) specific for state distribution. Biomass was estimated as volume multiplied with specific gravity, keeping values of diameter and specific gravity same and yet obtained a wide range of biomass of 57057–4583 kg in positive numerals. In negative numerals, the value was similar, i.e., -27988 for three states (Mizoram, Tripura and West Bengal) as the equation of estimation is the same for these states.

Rhododendron arboreum

Three equations for each component i.e., BLB, BB and LB were compared. For BLB, positive numerals had an estimation of 3.94 kg and negative numerals had a difference of -12.63. For BB, 3.55 as positive values and a range of -0.84 to -8.37 as negative values, and a range of -1.29 to -5.29 as negative numerals, and 1.87 as positive numerals for LB was resulted.

DISCUSSION

A specific tree's biomass production is influenced by a number of variables including its locality, the types and mix of its flora, developmental stages, wood specific gravity/wood density, growth rates, height, slopes, nutritional status, soil factors, anthropogenic pressure and management strategies and actions (Sharma et al. 2011, Luo et al. 2014, Powell et al. 2014, Li et al. 2015, Brahma et al. 2021). And the regression models developed for a specific tree's biomass estimation is majorly influenced by the number of samples. Model accuracy is substantially impacted by the required minimal dataset for equation development. A minimum of forty samples are recommended to assure model accuracy for biomass estimation of woody tree species (Sileshi 2014). The usage of species-specific models for mixed forest's biomass estimation could result in vague information though the vice versa may result in encouraging biomass predictions. Harvested or direct method, though the most accurate method, is not practical in all the scenarios for biomass estimation (Montes et al. 2000). Indirect methods, i.e., non-destructive and remote sensing & geographical information system needs validation of data from fields. In terms of application, the tree allometric equations seem more precise when choosing trees from the same species and growing in the same climate and soil environment (Clark & Clark 2000). Both regression models (linear and non-linear) may suffer from imprecise prediction. In this study, twelve allometric models and three volume equations resulted in negative values of biomass estimation, termed as 'negative estimation of tree size', which is common with linear regressions (Ajit et al. 2008). Negative values of biomass are not possible in practical scenarios. A range of -2.27 to 9.99 in branch biomass was estimated from three equations for *A. nepalensis* (Table 6). Six equations for *R. arboreum* (Table 6) also resulted in negative estimation of biomass. Negative values of biomass were also obtained for *T. grandis* of Mizoram, Tripura and West Bengal using volume equations (Table 7). Power function models are preferred over linear models. In biological systems, sigmoid and logistic equations are more fitted due to its lag, log and stationary compartmentalisation which is exactly the case in biological system. Allometric equations give an estimation of a dependent variable on the basis of explanatory variable, however values may vary from the exact estimation. A difference of 64% for foliage, 41% for branch and 18% for stem biomass estimation between biomass estimated from allometric equations and destructive method resulted for *Quercus* species (Han & Park 2020). There is a need for refining and developing more equations so that reliability of these equations could be compared and improved. Therefore, special care should be taken when applying allometry.

The study also evaluated the aboveground biomass in these trees using equations ln AGB = 0.349 + 1.316 ln GBH and AGB = (0.18 D ^ 2.16) × 1.32. These two equations can effectively be used to predict the tree biomass of any wood species across a range of conditions in India (Brahma et al. 2021). Interestingly, a difference of 42.13 for *A. nepalensis*, 163.209 for *R. arboreum* and 178.75 for *T. grandis* was resulted (Table 8 & Figure 3). Also, biomass estimated from these equations was significantly different from those obtained with equations listed in Table 2 for each species (Table 6). The deviation in biomass estimation in this study must be due to several reasons. The equations summarised in Table 2 are regional

Table 6 Biomass estimation of different components of tree species based on allometric equations

SN	Component estimated	Equations used D = cm, H = m except where mentioned	Estimated biomass	Units
		Alnus nepalensis		
1	ln BLB	1.532 + 2.461 ln D	11.01	G
2	ln BLB	−8.762 + 0.209 ln Age	-7.94	Kg tree^{-1}
3	ln BLB	−13.776 + 2.117 ln D	-5.63	G
4	ln BB	1.455 + 2.216 ln D	9.99	G
5	ln BB	−4.396 + 0.711 ln Age	-1.61	Kg tree^{-1}
6	ln BB	−6.941 + 1.214 ln D	-2.27	Kg tree^{-1}
7	ln LB	−4.955 + 0.626 ln Age	-2.51	Kg tree^{-1}
8	ln LB	−6.165+ 1.085 ln D	-1.99	Kg tree^{-1}
9	BGB	0.916 + 0.720 ln D	3.69	G
		Tectona grandis		
1	AGB	$0.0758\ D^{2.6135}$	768.29	Kg tree^{-1}
2	ln AGB	$8.902 + 7.873/(1+(\ln pD^2\ H/14.05)$^-6.780	16.77	Kg tree^{-1}
3	AGB	$0.06\ p(\prod D^2\ /4)H$	747.04	Kg tree^{-1}
4	AGB	$0.4989D^2 - 0.202D - 21.971$	551.27	Kg ha^{-1}
5	AGB	$0.26 + 730.55D^2\ H$ (D = m, H = m)	1869.14	Kg tree^{-1}
6	BLB	$0.03343D^{2.73532}$	520.85	Kg tree^{-1}
7	BLB	$0.025D^{\ 2.817}$	519.65	Kg tree^{-1}
8	BLB	$0.0581D^{\ 2.523}$	427.87	Kg tree^{-1}
9	BLB	-2.85 + 2.655 ln CBH	9.56	Kg tree^{-1}
10	ln BLB	$8.512 + 10.49/1 + (\ln pD2\ H/15.36)^{-5.252}$	19.00	Kg tree^{-1}
11	BLB	$0.3699D^2 - 0.1537D - 17.8$	407.08	Kg tree^{-1}
12	BLB	$0.942 + 512.69D^2\ H$ [D = m, H = m]	1312.50	Kg tree^{-1}
13	BB	$0.570279e^{0.1823D}$	285.65	Kg tree^{-1}
14	BaB	$2.45896e^{0.0984D}$	70.47	Kg tree^{-1}
15	Tw B	$1.592118e^{0.0965D}$	42.77	Kg tree^{-1}
16	BB	$0.0718D^{2.058}$	102.45	Kg tree^{-1}
17	BB	$0.0122D^{2.523}$	89.85	Kg tree^{-1}
18	ln BB	$6.726 + 6.000/1 + (\ln pD^2\ H/12.89)^{-13.27}$	57.96	Kg tree^{-1}
19	BB	$0.0678D^2 - 0.7045D + 1.5725$	56.39	Kg ha^{-1}
20	BB	$0.156 + 144.89D^2\ H$ [D = m, H = m]	370.81	Kg tree^{-1}
21	BWB	$0.001D^{3.063}$	49.53	Kg tree^{-1}
22	BWB	$0.001D^{3.0634}$	49.60	Kg tree^{-1}
23	LB	$-12.49108 + 1.253875 \times D$	30.27	Kg tree^{-1}
24	LB	$0.0037D^{2.459}$	21.74	Kg tree^{-1}
25	LB	$0.0116D^{2.1524}$	23.10	Kg tree^{-1}
26	ln LB	$2.985 + 1.029\ln D^2$	28226.00	Kg tree^{-1}
27	ln LB	$6.356 + 7.280/1 + (\ln D^2/6.682)^{-4.706}$	164847.99	Kg tree^{-1}
28	LB	$-0.0025D^2 + 0.4833D - 2.3174$	11.26	Kg ha^{-1}
29	LB	$74.0D^2\ H^{-2.72}$ [D = m, H = m]	66.65	Kg tree^{-1}
30	SRB	$0.0674D^2 - 0.8079D + 3.7722$	54.60	Kg ha^{-1}
31	LRB	$0.0583D^2 - 1.0494D + 5.4397$	37.46	Kg ha^{-1}
32	TRB	$0.185D^2 - 3.747D + 51.498$	138.85	Kg tree^{-1}

continued

Table 6 Continued

SN	Component estimated	Equations used D = cm, H = m except where mentioned	Estimated biomass	Units
33	RB	$0.0241D^{2.45322}$	138.74	Kg $tree^{-1}$
34	TRB	$0.097D^{2.023}$	122.33	Kg $tree^{-1}$
35	BGB	$0.1257D^2 - 1.8573D + 9.2119$	92.04	Kg $tree^{-1}$
36	ln TB	$\ln(8.165) + (8.165)\ \ln D^2 H$	1270.04	Kg $tree^{-1}$
37	TB	$0.142D^{2.469}$	864.29	Kg $tree^{-1}$
38	TB	$0.202D^{2.353}$	816.44	Kg $tree^{-1}$
39	TB	$0.6246D^2 - 2.0593D -12.759$	643.31	Kg $tree^{-1}$
40	TB	$0.0982D^{2.5873}$	907.42	Kg $tree^{-1}$
		Rhododendron arboreum		
1	ln AGB	1.176 + 0.855 ln GBH	4.601	Kg $tree^{-1}$
2	BLB	1.120 + 0.704 ln GBH	3.94	Kg $tree^{-1}$
3	BLB	-5.689 + 1.084 ln Age	-1.45	Kg $tree^{-1}$
4	BLB	-21.265 + 2.495 ln D	-14.08	Kg $tree^{-1}$
5	BB	-3.780 + 0.752 ln Age	-0.84	Kg $tree^{-1}$
6	BB	-13.226 + 1.687 ln D	-8.37	Kg $tree^{-1}$
7	BB	1.113 + 0.609 ln GBH	3.55	Kg $tree^{-1}$
8	ln LF	-2.850 + 0.397 ln Age	-1.29	Kg $tree^{-1}$
9	ln LF	-7.860 + 0.892 ln D	-5.29	Kg $tree^{-1}$
10	LB	1.19 + 0.17 ln GBH	1.87	Kg $tree^{-1}$
11	SRB	-0.12 + 0.87 ln GBH	3.37	Kg $tree^{-1}$
12	LRB	-1.75 + 0.98 ln GBH	2.18	Kg $tree^{-1}$
13	FRB	-0.01 + 0.41 ln GBH	1.63	Kg $tree^{-1}$
14	ln BGB	0.942 + 0.506 ln GBH	2.96	Kg $tree^{-1}$

Table 7 Aboveground biomass estimation as product of volume equations (Table 4) and specific gravity

Tree species	State of India	AGB (Kg $tree^{-1}$) = (Volume*specific gravity)	Specific gravity
Alnus species	Sikkim	10348	0.43
Rhododendron arboreum	Himachal Pradesh	1183	0.56
	Uttarakhand	1183	
Tectona grandis	Assam	6406	0.62
	Gujarat	7124	
	Karnataka	6304	
	Kerala	6304	
	Madhya Pradesh	4583	
	Maharashtra	4722	
	Mizoram	-27988	
	Rajasthan	4748	
	Tamil Nadu	6406	
	Telangana	4841	
	Tripura	-27988	
	Uttar Pradesh	57057	
	West Bengal	-27988	
	Dadar & Nagar Haveli and Daman & Diu	6304	

Table 8 Difference in aboveground biomass estimation in three tree species using two standard equations

Plant Species	Equation1 Ln AGB= 0.349 + 1.316lnGBH	Equation 2 AGB = (0.18D^2.16) *1.32	Difference
Alnus nepalensis	1013.932332	971.8020468	42.13028552
Rhododendron arboreum	282.5406332	119.3310993	163.2095339
Tectona grandis	664.7111347	485.954821	178.7563138

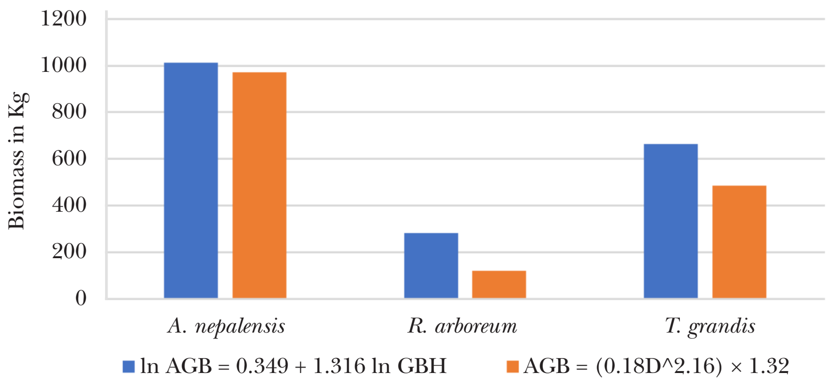

Figure 3 Difference in aboveground biomass estimation in three tree species using two standard equations

and resultant of specific age and sample size. Diameter class and growth factors are two other causal factors for biomass estimation ambiguity. These intriguing observations question the precision and accuracy of allometry.

CONCLUSIONS

The study concluded that no two or more equations could result similar and exact biomass values. The usage of allometric equations for biomass estimation of trees tends to underestimate or overestimate the biomass compared to biomass estimated using harvesting equations. This synthesis provides a clear picture of equations that must be overlooked for biomass estimation. Further studies should be carried out to enlighten accuracy of allometry used for biomass estimation so that a single equation could be obtained for biomass estimation. Diameter has remained as the most used explanatory variable for biomass estimation of trees followed by GBH, which is also a function of diameter. Major proportion of the allometry is constituted by logarithmic equations and logistic, and exponential equations are less explored. Logistic equations have more potential to foresee vegetation biomass. There is variability in biomass estimation when including height along with diameter. Thus, there is a need to develop robust equations for biomass estimation of trees. Further application of existing equations should be explored and database on such equations should be studied.

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