Agroforest Syst (2024) 98:3129–3144
https://doi.org/10.1007/s10457-024-01078-4

Biomass tables and allometric equations for predicting the fodder and fuelwood production of prominent tree resources in agricultural landscapes of the mid-hills of the North-Western Himalayas

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Received: 21 June 2024 / Accepted: 23 September 2024 / Published online: 27 September 2024

Abstract Fodder trees in the North-Western Himalayas are crucial for sustaining livestock, energy and timber needs, biodiversity conservation, nutrient cycling, and environmental regulation. Methods for quantifying their annual leaf and fuelwood biomass harvest must be developed using species and site-specific biomass tables and allometric equations. The present study deals with estimating fodder and fuelwood biomass by developing biomass tables and allometric models for prominent scattered tree species in the mid-hill regions of North-Western Himalayan ecosystems. To achieve this goal, branches, and leaves from tree of all diameter class were harvested, dried, weighed, and recorded as dry weight (DW). Among the fodder species dry leaf production was maximum in *Celtis australis* (10.71 kg ha^{-1} yr^{-1}), closely followed by *Quercus leucotrichophora* (8.80 kg ha^{-1} yr^{-1}) and *Grewia optiva* (7.71 kg ha^{-1} yr^{-1}). A similar trend was observed for productivity of dry branch and crown biomass (leaf plus branch). The allometric equations developed to estimate leaf, branch, and leaf + branch biomass production from measurable morphometric variables. Using simple linear regression equations, DBH and tree height were the most influential variables for predicting leaf, branch, and crown (leaf + branch) biomass productivity in tree species. Crown area and width contributed significantly to the predictive power for dry leaf biomass. Multiple linear regression equations were more appropriate for prediction than linear and complex equations. The developed equations and biomass tables are important for researchers, dairy farmers, and environmentalists to estimate production, support sustainable practices and estimate carbon credits.

Keywords Crown biomass · Carbon stock · Morphometric variables · Agroecosystem · Fodder and fuelwood

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10457-024-01078-4.

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Introduction

Trees on farmland and/or agroecosystems in the North-Western Himalayas play a central role in supporting the livelihoods (Kumar 2012; Sharma et al. 2018; Sarath et al. 2023) of rural communities, especially indigenous people, and contribute significantly to achieve many sustainable development goals (SDGs) (Mbow et al. 2014). Trees provide crucial cattle fodder and fuelwood along with helping to regulate the environment by absorbing carbon dioxide and locking carbon, which assists the country in meeting its nationally determined contributions (NDCs). Globally, 43% of all agroecosystems have at least 10% tree cover, emphasizing the significance of trees in rural sustenance (Dhayani 2014). As per global estimates, over 900 million people are actively engaged in agroforestry (AF), covering approximately 1 billion hectares of land (Zomer et al. 2016). In India, agroforestry encompasses approximately 28.43 million hectares, accounting 8.65% of the country's total geographical area (Arunachalam et al. 2022). The northern hill states cover 4.10 million hectares, or 12.41% of India's agroforestry area, serving as a vital source of commodities such as timber, fruits, fuelwood, fodder, and fibre both during lean periods and throughout the year (Sharma et al. 2007; Kala 2010).

Farmers in mid-hill regions use scattered trees on their farms and rangeland from many generations for diverse purposes. This practice not only provides multiple benefits but also helps mitigating the negative impact of human activities on natural forests (Mbow et al. 2014; Chavan et al. 2022). Native trees and/or woody vegetation is more readily available for indigenous people than introduced or "improved" species (Salem and Smith 2008), which require more attention for management (Roothaert and Franzel 2001). The most preferred and prevalent species in this area are *Bauhinia variegata* (L.) Benth, *Celtis australis* L., *Grewia optiva* J.R. Drumm. Ex Burett, *Leucaena leucocephala* (Lam.) de Wit and *Quercus leucotrichophora* A.Camus. These species are highly valued for their crucial role in meeting farmer's need (Table 1).

While extensive investigations have been carried out on the nutritional value of these critical fodder resources (Bhardwaj et al. 2019; Navale et al. 2022), estimating biomass production or browsing biomass presents challenges due to methodological complexities (Balehgen et al. 2012) owing to lopping, a fundamental silvicultural practice, prevalent in the study area being anticipated to substantially impacting tree in structural attributes. However, the documentation of the influence of lopping on leaf biomass modelling remains incomplete (Sèwadé et al. 2017).

Table 1 Local uses, management practices and ecological features of tree species

Species	Common name	Use	Management	Ecological features
Bauhinia variegata (L.) Benth	Karali	Fodder, food	Loping + pollarding	Deciduous, common in sub-tropical Himalayan tracts up to 1500 m amsl
Celtis australis L	Khirak	Fodder, fuelwood, timber	Lopping	Deciduous, common on terrace bunds and occasional occurrence in forest up to 2000 m amsl
Grewia optiva J.R. Drumm. Ex Burett	Bihul	Fodder, fibre, fuelwood	Lopping + pollarding	Deciduous, common in upland farms, rare in forests, found up to 1500 m amsl
Leucaena leucocephala (Lam.) de Wit	Rasuniya	Fodder, fuelwood	Pollarding + Cutting	Evergreen, common in sub-tropical, dry, and rugged sub-Himalayan tracts up to 1200 m amsl
Quercus leucotrichophora A.Camus	Ban	Fodder, fuelwood	Lopping	Evergreen and common in sub-temperate to temperate hillsides up to 2500 m amsl

The four methods for determining aboveground biomass are destructive method, biomass table, remote sensing techniques (Asner 2009; Chabi et al. 2016), and allometric equations (Youkhana and Idol 2011; Kuyah et al. 2016). As the destructive method is cumbersome (Afas et al. 2008), while the remote sensing method is limited by variable cloud cover, fly over frequency, technical feasibility, and economic viability (Xie et al. 2008) whereas biomass table limited by one value based on diameter class and/ other value providing an average estimate. Therefore, most convenient and viable method is to establish growth functions using a regression equation between tree biomass and easily measurable attributes such as DBH, Height (H) and some crown attributes (Dawoe et al. 2016; del Rio et al. 2019; Numbisi et al. 2021; Bazrgar et al. 2024).

Generalized equations can lead to biased estimates for specific species (Pilli et al. 2006), making it essential to establish species-specific allometric models and biomass tables. Therefore, this study aimed to prepare biomass table and species specific equation to predict the leaf, fuelwood, and leaf plus branch biomass per tree for five most prevalent tree species (Table 1) in agroecosystems in the North-Western Himalayas. To achieve this goal, we conducted destructive sampling of individual tree branches covering the entire tree diameter range to predict fodder and fuel production (Navale et al. 2022). The purpose of the sampling was to develop species specific branch, leaf and crown biomass equations (ii) to test the accuracy of the best-fit biomass models using different test statics.

Materials and methods

Site descriptions

The study site is at an altitude of 1250 m above mean sea level (amsl) in the mid-hill region of the Himalayas (falling under subtropical climatic conditions). The soil is a well-drained silty loam, and topography is hilly and undulating, with depressions and elevations (Verma et al. 2023). The average annual temperature in the area is 19.8 °C, with a minimum temperature of 1 °C in winter and a maximum temperature of 36 °C in summer. The warmest months are May and June, while December and January are the coldest months. The area receives an annual rainfall of 1110–1250 mm, with the highest concentration occurring in July and August (Panda et al. 2021).

Among studied species, *A. lebbeck* stands out an important fodder tree due to its thigh nutritional attributes for sheep and goats. *G. optiva* is particularly valuable in the winter months as it is extensively used for the fodder and agricultural practices. *C. australis* serves multiple purposes, including smallwood, fodder and fuelwood. Meanwhile, *Q.* leucotrichophora is used for fuelwood and coal owing to its high calorific values along with fodder supplies. All these species are widely distributed up to 2000 m amsl except *Q. leucotrichophora* which extends even above this elevation.

The present investigations aimed to estimate the leaf and branch biomass yield table and allometric equation by measuring various stem and crown parameters of scattered trees of these species located on and around the main campus of Dr. Y.S. Parmar University of Horticulture and Forestry, Solan, India. Since these species are extensively lopped in the region, therefore, to accomplish this objective, we classified the available trees of each species into diameter classes with 5 cm intervals (5–10, 10–20 and so on) and made efforts to encompass the full spectrum of diameter classes for each species leading to minimized error from structural differences. To estimate the biomass, we began by cutting the branches of the sample tree and separating them into branches and leaves. We then used a spring balance to weigh the separated leaves and branches. To estimate the dry weight of the branches, we selected a representative branch, dried it in an oven at 105 °C according to Chidumaya's formula (Chidumaya 1990) and expressed the weight in kilograms per tree. Similarly, to estimate leaf biomass, we removed representative leaves from the sampled branches, weighed them, and then oven-dried them separately at 80 ± 5 °C until a constant weight was achieved, which was expressed as the weight in kg per tree (Chidumaya 1990). The crown biomass was calculated by adding the leaf and branch biomass and expressed this in kilograms per tree. Using the collected data, we subsequently established the relationships between tree parameters and leaf, branch, and crown or foliage (leaf + branch) biomass.

To develop allometric equations and biomass tables, we need to measure various tree variables. A tree calliper was used to measure the diameter at breast height (DBH) of the trees, which is 1.37 m above the ground. The tree's total height (H) is measured using a Ravi Multimeter and expressed in meters. The height of the tree's crown (CH), which was the point where the crown starts from the ground, is also measured using a Ravi Multimeter and is expressed in meters. The foliage and crown width of the trees were measured using a measuring tape in the north−south and east−west directions. The calculation of crown width was in accordance with the formula proposed by Assmann (1970) and Chaturvedi and Khanna (1982). Crown depth (CD), expressed in metres, is calculated using a formula suggested by Balehegn et al. (2012). The area of the crown (CA) is assumed to be a circle, and it is calculated using the formula proposed by Chaturvedi and Khanna (2002), which expresses it in square meters. The crown volume (CV) was calculated using the formula proposed by Balehegn et al. (2012). We applied different linear models (lm) and multiple linear models (mln) to develop allometric equations for estimating leaf, branch, and leaf + branch biomass in trees using DBH, H, CD, CA, CV, and CH as predictor variables.

Statistical analysis

The statistical analysis for developing allometric equations was conducted using IBM SPSS Statistics version 29.0.2.0 (IBM Corp 2023) and RStudio (Posit team 2024). Different linear and nonlinear models (cubic, compound, exponential, growth, inverse, logarithmic, power, quadratic, and S) were evaluated through regression analysis. As most of the nonlinear models were unfit compared with the linear models (in terms of Adj R^2 and other test statics) thus we developed most models using the lm function for ensuring their easy and wider applicability. Furthermore, in some of the equations, we resorted to natural logs, leading to improved goodness-of-fit statistics. The plots of observed vs. predicted variables were made through the ggplot2 package in RStudio.

Criteria for the selection of appropriate functions

The appropriateness of the function was determined by checking whether the sign and magnitude of the estimated parameters align with the theoretical expectations.

The adjusted R^2 values were calculated using the linear model (lm) function in RStudio (Posit Team 2024). The adjusted R^2 is a valuable tool for determining the fundamental form of a function. Generally, a function with a higher Adj. R^2 value is preferred e.g., if Adj. R^2 is 0.80, means 80 percent of the variance in dependent variable (biomass) is explained by the model and rest 20 percent is due to random factors.

A function with higher explained variance corresponds to the best fit equation.

Various regression equations, including linear, quadratic, and logarithmic functions were developed for branch and leaf biomass based on their adjusted (Adj.) R^2 values. Multilinear regression equations were developed by considering variables such as DBH, H, CD, CD, CA, and CV. Biomass equations were validated statistically using Akaike information criteria (AIC), Akaike information criteria corrected (AICc), Bayesian information criterion (BIC), root mean square error (RMSE) and a paired *t*-test (to compare observed and predicted values), assuming no difference (Kaushal et al. 2024). As the selection of the most parsimonious equations requires the utmost care, we resorted to multiple criteria selection. Among all the tested combinations of variables, we presented the three most parsimonious equations for each dependent variable (dry branch biomass, dry leaf biomass, and branch + leaf biomass). The AIC and AICc were used as criteria for selection between allometric equations corresponding to their ability to trade off goodness of fit and model complexity. The model with lower values of AIC, AICc, BIC and RMSE were selected. However, the models were validated using the adjusted coefficient of multiple determination (adj. R^2), t test statistics (observed vs predicted) and RMSE.

Results

Volume and biomass

Tables 2, 3, 4, 5 and 6 present information on the developmental characteristics of five common AF tree species used for fodder and fuel purposes in the North-Western Himalayan agroecosystem of the mid-Hills. The data are categorized in 5 cm DBH intervals. The tables revealed that *B. variegata* and *L.*

leucocephala were presented in four diameter classes (5–10, 10–15, 15–20 and 20–25 cm), followed by *G. optiva* and *Q. leucotrichophora* in five diameter classes each (5–10 to 25–30 cm) and *C. australis* in twelve diameter classes (5–10 to 60–65 cm).

The data in Table 2 indicated that the parameters of the *B. variegata* trees were not significantly different, but their biomass components varied significantly. D_4 had the widest crown width, while D_3 had the maximum tree height, crown depth, and volume. D_4 also had the highest crown height and area values and branch, leaf, and crown biomass values, which were 11.96 kg tree^{-1}, 7.92 kg tree^{-1}, and 19.88 kg tree^{-1}, respectively. In *C. australis*, all parameters related to growth and biomass (Table 3) showed significant variation. Generally, all tree parameters and biomass increased linearly along diameter class. The maximum dry branch, leaf, and crown biomass values occurred at D_{12} (60–65 cm), at 81.04 kg tree^{-1}, 29.63 kg tree^{-1}, and 110.66 kg tree^{-1}, respectively. For *G. optiva*, D_3 (15–20 cm) had the highest values for tree height, crown height, and crown volume, while the maximum crown width and area were in the 20–25 cm diameter range (Table 4). The dry branch, leaf, and crown biomass were greatest in D_3, at 13.67 kg tree^{-1}, 9.20 kg tree^{-1}, and 21.67 kg tree^{-1}, respectively.

The growth parameters and biomass components of *L. leucocephala* trees varied significantly across the diameter classes, as shown in Table 5, except for crown height and depth. The largest crown width (6.90 m), area (36.66 m^2), and volume (859.44 m^3) were observed in D_4. Additionally, the highest dry branch biomass (14.52 kg tree^{-1}), dry leaf biomass (7.06 kg tree^{-1}), and total biomass (21.58 kg tree^{-1}) were recorded in the D_4 diameter class. Table 6 shows that the *Q. leucotrichophora* trees had five diameter classes, and significant variations were observed in the tree growth parameters and biomass components across these classes. D_2 (10–15 cm) exhibited the greatest height, crown width, depth, area, and volume values. D_4 had the highest dry branch biomass (28.97 kg tree^{-1}), while D_5 had the highest leaf biomass (10.83 kg tree^{-1}) and total biomass (39.80 kg tree^{-1}). Table 7 shows the variability in the growth characteristics of different fodder-yielding tree species. The dominant species based on size (D.B.H.) were *C. australis*, followed by *G. optiva, Q. leucotrichophora, B. variegata,* and *L.*

Table 2 Variation in different tree growth parameters and biomass in *Bauhinia variegate*

Dia class (cm)	DBH (cm)	Tree height (m)	Crown height (m)	Crown width (m)	Crown depth (m)	Crown area (m^2)	Crown volume (m^3)	Branch biomass (kg tree^{-1})	Leaf biomass (kg tree^{-1})	Total biomass (L+B) kg tree^{-1}
D_1 (5–10)	7.82	4.94	1.91	1.90	3.03	3.73	83.21	4.34^a	1.43^a	5.77^a
D_2 (10–15)	13.00	5.00	2.46	2.44	2.54	5.43	76.39	4.86^a	2.51^{ab}	7.37^a
D_3 (15–20)	16.85	8.90	2.86	2.47	6.04	4.95	577.36	8.85^{ab}	4.99^{bc}	13.84^{ab}
D_4 (20–25)	21.90	7.80	2.90	2.70	4.90	6.10	281.27	11.96^b	7.92^c	19.88^b
SE		1.88	0.57	0.59	1.70	2.20	305.96	2.70	1.42	3.82
$CD_{0.05}$		NS	NS	NS	NS	NS	NS	5.73	3.01	8.10

Different superscript letters denote the mean statistical grouping by DMRT at $P < 0.05$ for each parameter separately

Table 3 Variation in different tree growth parameters and biomass in *Celtis australis*

Dia class (cm)	DBH (cm)	Tree height (m)	Crown Height (m)	Crown width (m)	Crown depth (m)	Crown area (m^2)	Crown volume (m^3)	Branch biomass (kg $tree^{-1)}$	Leaf biomass (kg $tree^{-1}$)	Total biomass (L + B) (kg $tree^{-1}$)
D_1 (5–10)	7.50	3.83^{a}	2.90^{a}	2.27^{a}	0.93^{a}	4.03^{a}	17.64^{a}	2.76^{a}	1.52^{a}	4.29^{a}
D_2 (10–15)	13.23	8.33^{b}	3.83^{c}	2.33^{a}	4.50^{b}	5.10^{a}	243.55^{ab}	8.58^{ab}	2.62^{ab}	11.21^{ab}
D_3 (15–20)	17.53	10.00^{bc}	4.33^{c}	3.33^{ab}	5.67^{bc}	9.26^{a}	514.29^{ab}	14.72^{bc}	6.49^{ab}	21.20^{abc}
D_4 (20–25)	23.93	11.17^{bc}	4.83^{bc}	2.25^{a}	6.33^{bcd}	5.84^{a}	415.61^{ab}	14.44^{b}	5.18^{ab}	19.62^{abc}
D_5 (25–30)	27.93	11.33^{bcd}	3.67^{abc}	3.58^{ab}	7.67^{bcd}	11.40^{ab}	1048.96^{ab}	18.41^{bc}	8.52^{ab}	26.93^{bc}
D_6 (30–35)	32.60	12.33^{cd}	3.67^{bc}	2.25^{a}	8.67^{cde}	4.40^{a}	699.27^{ab}	20.15^{bc}	8.60^{ab}	28.74^{bc}
D_7 (35–40)	34.00	12.50^{cd}	3.00^{ab}	3.50^{ab}	9.50^{de}	9.75^{a}	1163.18^{b}	16.43^{bc}	4.69^{ab}	21.12^{abc}
D_8 (40–45)	43.93	14.40^{de}	3.33^{ab}	4.90^{bc}	11.07^{e}	18.92^{b}	2143.57^{c}	21.20^{c}	5.81^{ab}	27.02^{bc}
D_9 (45–50)	47.00	16.00^{ef}	4.67^{abc}	6.00^{cd}	11.33^{e}	28.39^{c}	2744.75^{c}	26.33^{c}	9.96^{b}	36.29^{c}
D_{10} (50–55)	52.57	18.67^{fg}	4.17^{abc}	7.47^{de}	14.50^{f}	43.87^{d}	5562.33^{d}	50.45^{d}	20.11^{c}	70.56^{d}
D_{11} (55–60)	58.03	20.33^{g}	5.00^{bc}	8.50^{ef}	15.33^{f}	56.85^{e}	7110.95^{e}	72.89^{e}	25.35^{cd}	98.24^{e}
D_{12} (60–65)	62.00	20.67^{g}	5.33^{bc}	9.17^{f}	15.33^{f}	66.01^{f}	7714.34^{e}	81.04^{e}	29.63^{d}	110.66^{e}
SE		1.41	0.75	0.77	1.45	4.11	471.78	5.33	3.11	8.02
$CD_{0.05}$		2.92	1.54	1.59	2.99	8.47	973.76	10.99	6.42	16.55

Different superscript letters denote the mean statistical grouping by DMRT at $P < 0.05$ for each parameter separately

Table 4 Variation in different tree growth parameters and biomass in *Grewia optiva*

Dia class (cm)	DBH (cm)	Tree height (m)	Crown height (m)	Crown width (m)	Crown depth (m)	Crown area (m^2)	Crown volume (m^3)	Branch biomass (kg $tree^{-1}$)	Leaf biomass (kg $tree^{-1}$)	Total biomass (L + B) (kg $tree^{-1}$)
D_1 (5–10)	7.18	4.84^c	1.90^{ab}	1.70^a	2.94^b	2.34^a	58.79^a	4.04^a	2.52^a	6.56^a
D_2 (10–15)	12.66	5.20^c	2.10^{ab}	2.46^{ab}	3.10^b	5.02^{ab}	97.31^a	10.47^c	6.95^b	17.41^{bc}
D_3 (15–20)	16.84	7.60^d	2.64^b	2.40^{ab}	4.96^c	4.95^{ab}	210.23^b	13.67^d	9.20^b	21.67^c
D_4 (20–25)	22.80	3.54^{ab}	1.86^{ab}	3.14^c	1.68^a	7.90^b	62.32^a	5.96^{ab}	4.28^a	10.24^a
D_5 (25–30)	27.40	3.26^a	1.00^a	2.34^{ab}	2.26^{ab}	4.73^{ab}	57.01^a	8.64^{bc}	7.15^b	15.79^b
SE		0.69	0.52	0.41	0.52	1.65	24.50	1.45	1.22	2.22
$CD_{0.05}$		1.43	1.08	0.86	1.09	3.44	51.11	3.02	2.55	4.64

Different superscript letters denote the mean statistical grouping by DMRT at $P < 0.05$ for each parameter separately

Table 5 Variation in different tree growth parameters and biomass in *Leucaena leucocephala*

Dia class (cm)	DBH (cm)	Tree height (m)	Crown height (m)	Crown width (m)	Crown depth (m)	Crown area (m^2)	Crown volume (m^3)	Branch biomass ($kgtree^{-1}$)	Leaf biomass ($kgtree^{-1}$)	Total biomass (L + B) ($kgtree^{-1}$)
D_1 (5–10)	7.04	6.40^a	3.00	2.56^a	3.40	6.17^a	141.88^a	3.16^a	1.69^a	4.85^a
D_2 (10–15)	11.26	7.08^{ab}	3.86	2.95^a	3.22	7.72^a	191.44^a	5.85^{ab}	2.58^{ab}	8.44^{ab}
D_3 (15–20)	17.86	9.70^b	2.88	3.95^a	6.28	12.49^a	667.39^{ab}	9.68^{bc}	5.45^{bc}	15.13^{bc}
D_4 (20–25)	23.22	7.50^{ab}	3.50	6.90^b	4.60	36.66^b	859.44^b	14.52^c	7.06^c	21.58^c
SE		1.33	0.72	0.63	1.37	3.82	247.06	2.29	1.36	3.64
$CD_{0.05}$		2.81	NS	1.34	NS	8.10	523.77	4.85	2.89	7.71

Different superscript letters denote the mean statistical grouping by DMRT at $P < 0.05$ for each parameter separately

Table 6 Variation in different tree growth parameters and biomass in *Quercus leucotrichophora*

Dia class (cm)	DBH (cm)	Tree height (m)	Crown height (m)	Crown width (m)	Crown depth (m)	Crown area (m^2)	Crown volume (m^3)	Branch biomass ($kgtree^{-1}$)	Leaf biomass ($kgtree^{-1}$)	Total biomass (L + B) ($kgtree^{-1}$)
D_1 (5–10)	7.86	8.30^{ab}	1.20^{a}	2.20^{a}	7.10^{ab}	4.00^{a}	431.96^{a}	5.60^{a}	2.35^{a}	7.95^{a}
D_2 (10–15)	12.28	10.98^{b}	1.44^{ab}	5.05^{c}	9.54^{b}	20.97^{b}	1940.54^{b}	27.79^{b}	12.06^{b}	39.85^{b}
D_3 (15–20)	17.84	8.00^{a}	2.70^{bc}	2.55^{ab}	5.30^{a}	5.58^{a}	342.31^{a}	15.07^{ab}	9.20^{b}	24.27^{ab}
D_4 (20–25)	21.48	10.80^{ab}	3.30^{cd}	3.80^{bc}	7.50^{ab}	12.17^{ab}	863.82^{ab}	29.07^{b}	9.56^{b}	38.63^{b}
D_5 (25–30)	27.42	10.40^{ab}	4.38^{d}	3.40^{ab}	6.02^{a}	10.54^{a}	496.20^{a}	28.97^{b}	10.83^{b}	39.80^{b}
SE		1.28	0.63	0.71	1.33	4.38	560.80	6.93	2.18	8.61
$CD_{0.05}$		2.67	1.32	1.48	2.77	9.14	1169.83	14.46	4.54	17.96

Different superscript letters denote the mean statistical grouping by DMRT at $P < 0.05$ for each parameter separately

Table 7 Species-wise variability analysis and growth characteristics of fodder species

Tree characteristics	*B. variegata*			*C. australis*			*G. optiva*			*L. leucocephala*			*Q. leucotrichophora*		
	Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)
Diameter (cm)	14.89	5.51	37.01	35.02	17.37	49.60	17.78	8.12	45.68	14.85	6.45	43.48	17.38	7.11	40.93
Height (m)	6.66	3.26	48.89	13.30	5.07	38.15	5.51	2.34	42.46	7.67	2.31	30.06	9.70	2.26	23.31
Crown height (m)	2.53	0.93	36.64	4.06	1.08	26.57	2.01	0.84	41.67	3.31	1.12	33.90	2.60	1.51	58.08
Crown width (m)	2.38	0.91	38.22	4.63	2.60	56.18	2.06	0.97	47.30	4.09	1.97	48.17	3.40	1.45	42.56
Crown depth (m)	4.13	2.86	69.23	9.24	4.63	50.16	3.50	1.74	49.67	4.38	2.35	53.60	7.09	2.42	34.12
Crown area (m^2)	5.05	3.31	65.54	21.98	21.68	98.64	4.01	3.43	85.50	15.76	13.77	87.38	10.65	8.79	82.51
Crown volume (m^3)	254.56	490.68	192.8	2448.2	2735.9	111.75	110.1	153.68	139.51	465.04	476.86	102.54	814.97	1008.9	123.80
Dry branch biomass (kg)	7.50	5.06	67.41	28.95	25.14	86.83	9.30	8.83	94.91	8.30	5.50	66.25	21.30	13.90	65.26
Dry leaf biomass (kg)	4.21	3.29	78.06	10.71	9.46	88.40	6.80	5.96	87.66	4.20	2.97	70.82	8.80	4.66	53.00
Crown biomass (kg)	11.71	7.99	68.17	39.66	34.39	86.72	16.10	14.63	90.83	12.50	8.43	67.49	30.10	17.84	59.28

leucocephala. The average productivity of dry leaf production of the tree species was as follows: C. australis (10.71 kg ha^{-1} yr^{-1}), *Q. leucotrichophora* (8.80 kg ha^{-1} yr^{-1}), *G. optiva* (6.80 kg ha−1 yr^{-1}), *B. variegata* (4.21 kg ha^{-1} yr^{-1}), and *L. leucocephala* (4.20 kg ha^{-1} yr^{-1}). A similar trend was observed for dry branches and crown biomass productivity (leaf + branch).

Allometric equations

Dry branch biomass (kg)

Table 8 shows the best-fit models, adjusted R^2, AIC, AICc, BIC, RMSE, *P* value (F static), and t-table values for all the dependent variables corresponding to the five species. The best fit allometric equations for the dry branch biomass (kg) of *Q. leucotrichophora* were obtained using D and crown volume (CV) as independent variables (Adj. $R^2 = 0.97$; AIC = 78.23; RMSE = 2.51). This was followed by the equation using DBH and H under a quadratic function (Adj. $R^2 = 0.94$; AIC = 89.33; RMSE = 3.64) and the equation using height as a single independent variable, representing 87% of the explained variance (Adj. $R^2 = 0.87$; AIC = 99.36; RMSE = 5.08). In *C. australis*, the three most parsimonious equations included crown volume in a quadratic function (Adj. $R^2 = 0.86$; AIC = 371.31; RMSE = 9.15), followed by a multilinear equation of D, CV, CW (Adj. $R^2 = 0.84$; AIC = 376.67; RMSE = 9.46), and D, CW, CA (Adj. $R^2 = 0.84$; AIC = 377.74; RMSE = 9.56) as independent or explanatory variables.

For *L. leucocephala*, the most parsimonious equations included diameter based quadratic function (Adj. $R^2 = 0.76$; AIC = 119.96; RMSE = 1.99), followed by multilinear equation using crown height and diameter as predictor variable (Adj. $R^2 = 0.76$; AIC = 122.02; RMSE = 1.93), a Gompertz function of diameter (Adj. $R^2 = 0.74$; AIC = 121.90; RMSE = 1.99). In *G. optiva*, the best fit corresponded to a multilinear function based on crown height and crown volume (Adj. $R^2 = 0.70$; AIC = 241.25; RMSE = 3.56), H, crown width, and crown volume (Adj. $R^2 = 0.70$; AIC = 242.11; RMSE = 3.51), followed by crown volume, diameter, and crown height (Adj. $R^2 = 0.63$; AIC = 249.90; RMSE = 3.93). Finally, in *B. variegata*, the most parsimonious multilinear equations were based on height, diameter, and crown area (Adj. $R^2 = 0.74$; AIC = 128.04; RMSE = 2.23); height and crown width (Adj. $R^2 = 0.71$; AIC = 130.56; RMSE = 2.34), and height, diameter, and crown volume (Adj. $R^2 = 0.71$; AIC = 131.37; RMSE = 2.37).

Dry leaf biomass (kg)

The best fit regression equations for estimating dry leaf biomass (kg) included the variables DBH, CW, CH, or a combination thereof. For *Q. leucotrichophora*, the equations for DBH, CW, and CH (Adj. $R^2 = 0.86$; AIC = 66.47; RMSE = 1.48) was found to be the best-fit model, followed by two other equations with the same parameters but in different combinations (adj. R^2 0.85 and 0.82). In *C. australis*, Adj. R^2 of the best-fit equations ranged from 0.70 to 0.76, as validated by different test statistics. In *L. leucocephala*, for dry leaf biomass prediction, the best results were obtained with a multilinear equation based on CH and DBH (Adj. $R_2 = 0.66$; AIC = 95.04; RMSE = 1.26), a quadratic function based on DBH (Adj. $R^2 = 0.65$; AIC = 96.41; RMSE = 1.29), and a multilinear equation based on H, CW, and DBH (Adj. $R^2 = 0.61$; AIC = 98.78; RMSE = 1.35). In *G. optiva*, the best-fit equation (Adj. $R^2 = 0.52$–0.59) confirmed a strong relation between CV and dry leaf biomass, with CV being a predictor in all best fit equations. For *B. variegata*, the coefficient of multiple determination indicated that the fitted models explained 38–41% of the variance in dry leaf biomass, as further validated by test statistics.

Crown biomass (kg)

Based on the parametric estimates and goodness-of-fit statistics of cross-validation (Adj. R^2, AIC, BIC, and RMSE), the equation systems fitted for species showed that crown biomass were best predicted for *Q. leucotrichophora* (Adj R^2 ranging from 81 to 95%) and least for *B. variegata* (Adj $R^2 = 59$–63%). The fitted models explained 59–95% of the variance among studied species. In *C. australis*, a regression run on a combination of DBH, CV, CA, and CW fit well (Adj. $R^2 = 0.82$–0.83). In *L. leucocephala*, D and H were the main predictor variables, which provided the most parsimonious equations (Adj. $R^2 = 0.70$–0.71). In *G. optiva*, the CV was the primary predictor variable in combination with CA (Adj. $R_2 = 0.65$); CH, CW (Adj. $R^2 = 0.63$ and 0.60). In *B. variegata*, among

Table 8 Best-fit Eq. (3) for estimating dry branch, leaf, and total biomass of fodder species in the North-Western region of the Himalayas

Fodder tree species	No	Relation	Equation type	Equation	Adj. R^2	AIC, AICc	BIC	RMSE	*P*-value	Paired *t*-test Predicted versus oserved
Dry branch biomass										
Q leucotrichophora	[1]	D, CV	Multi-linear	$-5.905+0.9295$ D $+0.11$ CV	0.97	78.23, 82.23	81.06	2.51	3.34e−10	− 7.3e−15
	[2]	D, H	Quadratic	$-12.55+0.51$ D $+0.26$ H^2	0.94	89.33, 93.44	92.17	3.64	2.38e−08	− 3.89e−15
	[3]	H	Quadratic	-1.216–0.318 H $+0.2699$ H^2	0.87	99.36	102.19	5.08	1.56 e−06	−3.822
C. australis	[1]	CV	Quadratic	0.11 + 4.624 e−03 CV + 5.12 e−07 CV^2	0.86	371.31, 372.20	378.96	9.15	< 2.2e−16	− 1.87e−15
	[2]	D, CV, CW	Multi-linear	9.74 + 0.11D + 0.01CV-1.47 CW	0.84	376.67	386.23	9.46	< 2.2e−16	− 2.99e−15
	[3]	D, CW, CA	Multi-linear	12.49 + 0.46 D-7.74 CW + 1.63 CA	0.84	377.74	387.30	9.56	< 2.2e−16	− 3.69e−15
L. leucocephala	[1]	D	Quadratic	1.90 + 0.0215 D^2	0.76	119.96, 121.00	123.84	1.99	2.02e−09	− 1.68e−16
	[2]	D, CH	Multi-linear	2.15 + 0.14 D-1.21 CH + 0.14 D*CH	0.76	122.02	128.49	1.93	7.57e−09	6.53e−16
	[3]	D	Gompertz	551.70 (exp(− 6.052*exp(− 0.02 D)	0.74	121.90	127.08	1.99	4.162e−16	− 1.07e−2
G. optiva	[1]	CH, CV	Multi-linear	8.21–0.02 CV-1.25 CH + 0.02 CV*CH	0.70	241.25	250.05	3.56	7.89e−11	− 1.91e−15
	[2]	H, CW, CV	Multi-linear	9.00–5.46CW-1.02 H-9.84 e−06 CV^2 + 1.43 CW*H	0.70	242.11	252.68	3.51	3.066e−10	1.21e−14
	[3]	CV, D,CH	Multi-linear	3.93 + 3.12e−03 CV*D-1.48 e−05 CV^2 + 9.39e-02 CH^2	0.63	249.90	258.71	3.93	3.825e−09	3.14e−16
B. variegata	[1]	H, D, CA	Multi-linear	0.23 + 0.05 H*D + 0.41 CA	0.74	128.04	133.22	2.23	3.63e−08	− 6.21e−16
	[2]	H, CW	Multi-linear	− 2.95 + 1.06 H + 1.41 CW	0.71	130.56	135.74	2.34	1.12e−07	− 9.31e−16
	[3]	H, D, CV	Multi-linear	− 3.29 + 0.001 H*D^2 + 1.87 log CV	0.71	131.37	136.55	2.37	1.59e−07	− 4.27e−16
Dry leaf biomass (kg)										
Q leucotrichophora	[1]	D, CW, CH	Multi-linear	− 21.54 + 7.50 log D + 5.71 CW-1.82 CW*CH	0.86	66.47, 76.97	70.72	1.48	6.20e−05	− 7.34e−15
	[2]	D, H, CV, CW,CA	Multi-linear	1.86 + 0.44D-1.96H + 0.10CV + 4.96CW-0.04CA^2	0.85	68.01, 84.01	72.97	1.46	0.0002	2.69e−15
	[3]	D, CW, CH	Multi-linear	− 17.96 + 9.86 log D + 0.43 CW^2-0.04 D*CH*CW	0.82	69.71	73.25	1.77	6.54e−05	− 6.32e−13
C. australis	[1]	D, CV	Multi-linear	5.12 + 8.28 e−07 D^2CV	0.76	301.48	307.22	4.64	< 2.2e−16	1.13e−15
	[2]	CW, CH, CA	Multi-linear	14.64–3.72 CW-1.41 CH + 0.84 CA	0.71	311.69	321.25	4.94	2.86e−13	6.60e−15
	[3]	CW	Quadratic	8.90–3.27CW + 0.59 CW^2	0.70	313.42	321.10	5.13	1.78e−13	1.90e − 16
L. leucocephala	[1]	CH, D	Multi-linear	1.05 + 0.002 CH*D^2	0.66	95.04	98.92	1.26	1.37e−08	1.93e − 15
	[2]	D	Quadratic	0.93 + 0.01 D^2	0.65	96.41	100.30	1.29	2.61e−07	1.04e − 15
	[3]	H, CW, D	Multi-linear	1.55 + 0.20 e−03 D^2* H*CW	0.61	98.78	102.66	1.35	7.97e−07	1.43e − 15
G. optiva	[1]	CV, CA, D	Multi-linear	1.73 + 0.01 CV*CA + 0.02 CV*log D-0.05 CV	0.59	226.14	234.37	2.84	1.23e−08	− 6.92e − 15
	[2]	CV, CA	Multi-linear	3.36–2.44 e−05 + 0.02 CV + 1.71 e−3 CA*CV	0.54	228.06	236.87	3.05	2.83e−07	− 6.57e − 16
	[3]	CW, CH, CD, CV	Multi-linear	2.74 + 0.15CW*CH + 0.06CV-0.35 CD-0.005CV*CD	0.52	230.31	240.88	3.06	1.46e−06	− 2.62e − 15

Table 8 (continued)

Fodder tree species	No	Relation	Equation type	Equation	Adj. R^2	AIC, AICc	BIC	RMSE	*P*-value	Paired *t*-test Predicted versus oserved
B. variegata	[1]	D, CH	Multi-linear	$0.97+0.03\ CH+0.01\ D^2$	0.41	114.72	119.90	1.75	6.00e−03	−2.49e−15
	[2]	D, CW, H	Multi-linear	$-1.65+0.31\ D+0.25\ CW+0.03\ H$	0.38	117.05	123.53	1.76	2.97e−03	−2.86e−15
	[3]	D, H, CA	Multi-linear	$-1.45+0.32D+0.04\ CA+0.04\ H$	0.38	117.23	123.71	1.76	2.97e−03	−1.43e−15
Crown biomass or dry branch + dry leaf biomass (kg)										
Q leucotrichophora	[1]	D, CA	Multilinear	$-13.99+1.61\ D+3.71\ CA-0.12\ D*CA$	0.95	91.88	95.42	3.71	3.34e−08	6.21e−15
	[2]	D, CV, CH	Multi-linear	$-3.61+1.31\ D+0.01\ CV-1.17\ CH$	0.93	96.97	100.51	4.39	2.15e−07	−8.82e−16
	[3]	H	Quadratic	$4.16–0.89\ H+0.35\ H^2$	0.81	115.07	115.07	3.70	1.75e−05	6.21e−15
C. australis	[1]	CD, CV	Multi-linear	$0.15+7.46e{-}04\ CD*CV$	0.83	410.35	416.06	13.79	< 2.22e−16	< 2.22e−15
	[2]	CV	Quadratic	$15.22+5.99\ e{-}03\ CV+7.30\ e{-}07\ CV^2$	0.83	411.28	412.17	13.65	< 2.2e−16	6.05e−15
	[3]	D, CW, CA	Multi-linear	$19.10+0.62D-11.23\ CW+2.31\ CA$	0.82	417.27	426.83	14.20	< 2.2E−16	3.91e−15
L. leucocephala	[1]	D	Gompertz	$162.16\ (\exp(-4.59*\exp(-0.03\ D)$	0.71	147.80	149.61	3.22	1.93e−08	−1.25e−15
	[2]	D	Linear	$-2.86+0.95\ D$	0.71	147.52	151.41	3.33	1.94e−08	−1.26e−15
	[3]	D, H, CW	Multi-linear	$-2.77+0.75\ D+0.83\ CW-0.04\ H$	0.70	149.84	156.33	3.22	4.61e−07	−3.43e−15
G. optiva	[1]	CV, CA	Multi-linear	$7.68+0.05\ CV-5.76e{-}5\ CV^2+4.66\ e{-}03\ CA*CV$	0.65	291.51	300.32	6.38	1.26e−09	3.43e−15
	[2]	CH, CV, CW	Multi-linear	$4.95–0.07\ CV-5.12\ e{-}05\ CV^2+0.32\ CW^2*CH$	0.63	293.99	302.79	6.58	3.82e−09	3.87e−15
	[3]	CV, CH, CW	Multi-linear	$0.95+0.08\ CV-101.40\ CV^2+2.09\ CH*\log CW$	0.60	296.59	305.41	6.38	1.26e−09	3.43e−15
B. variegata	[1]	D, CW, H	Multi-linear	$-5.97+0.48\ D+0.98\ H+1.52\ CW$	0.63	157.46	163.95	3.71	9.47e−06	−4.46e−16
	[2]	CA, D, H	Multi-linear	$0.55+1.20\ H+0.002\ CA*D^2$	0.62	156.90	162.09	3.81	3.12e−06	−3.12e−06
	[3]	D, H	Multi-linear	$5.37+0.003\ D^2H$	0.59	158.43	162.33	4.07	1.88e−06	−1.21e−15

D, diameter at breast height (DBH.); **CW**, crown width; **H**, tree height; **CA**, crown area; **CV**, crown volume; **CD**, crown depth or crown length; **CH**, crown height all multiple regressions tested, only models that included DBH as predictor variable performed well. By including other variables, the models improved slightly, where DBH with CW, H (Adj. $R^2 = 0.63$; AIC = 157.46; RMSE = 3.71); DBH, CA, H (Adj. $R^2 = 0.62$; AIC = 156.90; RMSE = 3.81) and DBH, H (Adj. $R^2 = 0.59$; AIC = 158.43; RMSE = 4.07) were most parsimonious. Overall, our models achieved good predictions. However, there was more data dispersion for leaf biomass, especially in *G. optiva*, *B. variegata*, and *L. leucocephala,* due to heavy manipulation of their crowns due to lopping practices for fuelwood and fodder.

Discussion

It is important to note that the presence of scattered trees is crucial in the agroecosystem of the North-Western Himalayas. To effectively quantify their contribution, it is essential to accurately estimate leaf and branch biomass productivity, thereby reducing uncertainty in their output (Bapfakurera et al. 2024). Allometric equations are necessary for predicting tree biomass and ecosystem dynamics (Abich et al. 2024). Accurate leaf and branch biomass estimation varies with tree architecture, growth dynamics, and environmental factors (Sevel et al. 2012; Huber et al. 2017). To address this, the study tested the validity of various equations and variables.

The biomass of trees can be estimated through a biomass table and by generating allometric equations. A volume or biomass table is created to estimate the volume of the standing tree using predictor variables. The data presented in Tables 2, 3, 4, 5 and 6 revealed that tree characteristics and biomass productivity (leaf, branch, leaf + branch) varied significantly ($p < 0.05$) with the variation in the DBH classes and tree species under investigation. Variations in growth, canopy traits, leaf and biomass productivity among the selected tree species can be attributed to their life span, genetic makeup, and canopy architecture. *C. australis,* a long-leaved tree species can live up to 1000 years, is present in 12 diameter classes in the study site. Given the rapid decline of large trees in India subcontinent, it is crucial to prioritize the sustainable use and conservation of this species (Brandt et al. 2024). The crown shape of *G. optiva* and *B. variegata* somewhat spreads, while it is rounded in *L. leucocephala* and *Q. leucotrichophora* (Luna 1996). The shape of the *C. australis* crown varies from round to umbel to low dome (Magni and Caudullo 2016).

The variables DBH, H, CD, and CH are crucial for predicting species-specific branch biomass using empirical tree growth models and allometric equations. These models consider tree growth behaviour and crown characteristics, which improves upon previous findings that relied solely on age-growth criteria (Smiley and Kroschel 2008; Tewari et al. 2014). This study revealed species-specific responses to observed patterns across studied tree species. While earlier research has indicated that adding height does not enhance the prediction of aerial biomass, but DBH is significantly correlated with biomass production (Onyekwelu 2004; Peichl and Arain 2007; Tumbewaze et al. 2013), some authors have reported that both H and DBH improve model predictability (Cienciala et al. 2005; Tumbewaze et al. 2013). Nevertheless, no studies have used H as the only independent variable to explain variation in aboveground biomass.

Among the tested models, multiple regression equations were found to be the best method for estimating the biomass of leaves and branches of tree species. These equations used DBH, H, and crown parameters (CA, CD, CH, CV, and CW) as predictor variable. The t test revealed that the biomass prediction made by these equations were not significantly different from the observed values (Jana et al 2009; Singh et al. 2011; Adam and Jusoh 2018), confirming the validity of our models.

Previous research has shown significant differences in the prediction equations for various tree species (Conti et al. 2013; Paul et al. 2018; Xiang et al. 2018). Our study further revealed that the allometric functions can also vary significantly among tree species within the same area. This difference arise from diverse development patterns of tree species in terms of morphometric traits, wood specific gravity and the allocation of biomass to different components. Additionally, heavily lopped and manipulated resources such as *G. optiva, B. variegata, and L. lecocephala* exhibit a diffuse pattern and low predictability indices (Shahabedini et al. 2017). *G. optiva*, known for its good fodder (Laurie 1939), is heavily lopped for this purpose (Troup 1921), with green leaves constituting approximately 70% of the total green weight of its branches (Chandra and Sharma 1977). These findings suggest that using crown area and volume as variables can accurately estimate the biomass of heavily lopped trees (Conti et al. 2013; Paul et al. 2018). During the lopping process to provide leaves for fodder, the branches of these trees are cut, resulting in a significant reduction in crown height and area. Although the crown partially regenerates over time due to resprouting, the branches are repeatedly harvested, leading to an imbalance in the development of the tree crown compared to other sections. Under these conditions, estimating leaf biomass becomes less accurate than estimating other components (Kenzo et al. 2009; Sawadogo et al. 2010), resulting in less precise biomass predictions.

Previous studies (Ali et al. 2015) have produced species-specific equations that vary, even for the same species, due to several factors. These include the following: (a) the different independent variables used, for example, diameter (D) or cross-sectional area (CA) and density in the work of Ali et al. (2015) and DBH in the work of Lin et al. (2012); (b) the distinction in regression models, as seen in the works of Ali et al. (2015) and Zeng (2010); and (c) the variation in growth forms of species influenced by ecological factors, such as in the study of Zhang et al. (2021), which was conducted at 1400 m amsl. Our study on regularly lopped trees resulted in the underestimation of biomass due to heavy manipulation of their crown. However, our study has effectively contributed to the development of scattered fodder tree species-specific models in the North-Western Himalayas (Gower et al. 1999; Miah et al. 2020). Therefore, there has been a shift towards the use of species- and site-specific approaches for biomass estimation (Kim et al. 2010). Furthermore, foliage and/or crown based allometric models are essential for studying the long-term physiological response, output, and growth of scattered fodder trees.

Conclusions

The study provided method to measure biomass of selected tree species based on biomass tables and volume equations under diverse conditions. The biomass table revealed productivity of dry leaf production was ranked in descending order as follows: *C. australis*, *Q. leucotrichophora, G. optiva, B. variegata* and *L. leucocephala*. A similar trend was observed for dry branch and branch + leaf productivity. Based on diameter classes distribution and biomass production, *C. australis* is the most prominent fodder tree species in the mid-hills of the North-Western Himalayan ecosystem. The study revealed DBH and H as the most predicting independent variables for leaf, branch, and crown biomass estimation in most of the examined tree species when simple linear regression equations were used. Different parameters significantly impacted the evaluation statistics in multiple regression equations for branch, and crown biomass, however crown area and width significantly contributed to the predictive power of dry leaf biomass. Further, the research focussed more on multilinear regression equations because of their relative accuracy under reasonable measurements over linear and complex equations. By following a complex selection criterion, the present study has developed easy to apply biomass and predictive models that can be utilized to establish the supply of fuel and fodder from farms and the biomass and carbon sink capacity of farms located in the hills' ecosystem of the Himalayas or similar regions elsewhere.

Acknowledgements The authors are highly thankful to Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan (HP) for providing all the facilities required to carry out the study along with various department of government of HP and farmers for providing the potential help and support.

Author contributions Conceptualization: D.R. B., M.R.N Formal analysis: D.R. B., M.R.N., and P.S. Methodology: M.R.N., D.R. B. Visualization: D.R. B., R.D., T.V., P.S. Software: R.D., and P.S. Writing-original draft: T.V., P.S., D.R. B., R.D. Writing, review, and editing: R.D., T.V., A. K.

Declarations

Conflict of interest The authors declare no competing interests.

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