ISSN 0104-7760
v.25 n.2 2019

CERNE

Rana Bahadur B.K.[1], Ram P. Sharma[2a], Shes K. Bhandari[3+]

A GENERALIZED ABOVEGROUND BIOMASS MODEL FOR JUVENILE INDIVIDUALS OF *Rhododendron arboreum* (SM.) IN NEPAL

BAHADUR, R. B. K.; SHARMA, R. P.; , F.; BHANDARI, S. K. A generalized aboveground biomass model for juvenile individuals of *Rhododendron arboreum* (Sm.) in Nepal. **CERNE**, v. 25, n. 2, p.119-130, 2019.

HIGHLIGHTS

Keywords:
Allometric modelling
Community forest
Crown measures
Crown spread ratio
Height-to-diameter ratio

A biomass model for juvenile individuals of *Rhododendron arboreum* was developed.

A power function showed the best fit to the data (R^2_{adj}=0.9013); RMSE = 59.349 g.

Crown measures significantly contributed to fitting improvement of the model.

Slenderness coefficient also significantly contributed to fitting improvement of the model.

ABSTRACT

Historic:
Received 29/10/2018
Accepted 19/04/2019

Carbon in the juvenile plants contribute significant share to the total carbon stock in forests. A precise estimate of aboveground biomass of the juvenile stages of trees is therefore very important. We developed a generalized allometric biomass model for the prediction of aboveground biomass of the juvenile individuals of *Rhododendron arboreum* (Sm.). We used data from 66 destructively sampled juveniles of *R. arboreum* in Gorkha district- one of the mountainous districts in Nepal, for the purpose. Using eight nonlinear functions of various forms (power, exponential, fractional forms), we evaluated several individual-level characteristics, such as size (diameter, height), crown measures (crown ratio, crown width, crown spread ratio, crown index, crown fullness ratio), height-to-diameter ratio (plant bole slenderness), number of branches, wood density, and stand-level characteristics, such as altitude and slope of sites for their potential contributions to the biomass variations of the juvenile individuals. A simple power function with cross-product of the squared-diameter and height as a main predictor and crown spread ratio as a covariate predictor showed the best fit to data (R^2_{adj}=0. 90); RMSE=59.35 g) without substantial trends in the residuals. Our model is site-specific and its application should therefore be limited to those stands which were the basis of this study. Further works on recalibration, validation, and verification of our model using a larger dataset collected from a wider range of species distribution will be more interesting.

[+]Correspondence:
shesu15@yahoo.com

[1] Ministry of Industry, Tourism, Forest and Environment, Gandaki Province, Pokhara, Nepal
[2] Czech University of Life Sciences in Prague, Czech Republic - ORCID: 0000-0002-8623-6211[a]
[3] Institute of Forestry, Tribhuvan University, Nepal

DOI:
10.1590/01047760201925022610

INTRODUCTION

Global warming, heavy rainfall, drought, shift of rainy season, and change of rainfall intensity are the major consequences of climate change, which are caused by both the anthropogenic and natural phenomena (Amedie, 2013). Various options can be mobilized appropriately to minimize the impacts of climate change. Forests are natural resources of terrestrial ecosystem which play vital role to minimize the impact of climate change. Forest plants sequester carbon through the process of photosynthesis, which ultimately reduces the concentration of greenhouse gases in the atmosphere (Nogia et al., 2016). To quantify the amount of carbon stored in the forests, plant biomass is estimated using either direct or indirect methods (Vogt et al., 1998). The direct method includes the destructive felling of sampled plants and weighing their all parts. This is a traditional approach that requires a large amount of resources, but produces a higher estimation precision compared to indirect method (De Gier, 2003). Because of the higher inventory costs involved in this method, it is generally used for smaller area and sample size, and to validate the results of other non-destructive sampling methods (Clark et al., 2001; Ketterings et al., 2001). The main application of destructive method is to develop allometric biomass equations that can be applied to the species of interest in a large forest area (Navar, 2009a; Segura and Kanninen, 2005). The indirect method estimates the biomass of forest without felling individual plants (Subedi and Sharma, 2012; Sharma et al., 2017). Therefore, this method can also be applicable to the species of interest in a large forest area. Application of allometric equations is one of the potential options of the indirect method for estimation of forest biomass. The allometry of plant species establishes the quantitative relationships between easily measurable characteristics and other related attributes that are difficult to measure (Enquist, 2002).

In the past, priority was given to develop the allometric biomass equations only for larger-sized trees which could be used for timber (Navar, 2009b; Muukonen, 2007; Muukkonen and Makiapa, 2006; Zianis et al., 2005; Brown et al., 1989). However, in recent years, some studies (Chapagain et al., 2014; Chaturvedi et al., 2012a; Bhandari and Neupane, 2014a; 2014b) were carried out to develop allometric biomass equations for smaller-sized plant individuals, such as juveniles (plant $\geq$30 cm in height and $<$10 cm in circumference at 10 cm aboveground surface) (Chaturvedi et al., 2012a). It is necessary do so, because of the importance of the juvenile plants, which have a significant contributions to future forest, soil conservation, and wildlife habitat (Modrzynski et al., 2015). In general, the density of smaller plants is much higher than that of large and mature sized trees (Ranjitkar et al., 2014). Even there are a large number of juvenile individuals in the forest; these juveniles are usually excluded while carrying out inventory and estimating biomass and carbon storage mainly due to lack of allometric biomass models of juveniles. The juvenile plants may contribute about 5% biomass share to a total forest biomass (Francis, 2000). Estimation of the juvenile plant biomass is necessary for quantification of forest fuels, assessing the potential of young stands as fiber sources, assessing the stand's potential for carbon sequestration, and they are used as indicators of net primary production (Wagner and Ter-Mikaelian, 1999). The juvenile plant biomass can also be used as a response variable in studying the competition impact of the surrounding individuals (Ter-Mikaelian and Parker, 2000). The juvenile plants play a vital role in maintaining the balance of an overall forest ecosystem, and therefore cannot be overlooked while assessing the amount of forest biomass and carbon.

Biomass and carbon of a large forest area have been estimated using the general biomass equations (Houghton, 2001) which may not be precise. The most important errors in the estimation of biomass would occur during the selection of the allometric equations. Biomass of a forest is affected by several factors, such as stand age, species composition, topography, environmental heterogeneity, and other natural and anthropogenic disturbance (Neupane and Sharma, 2014). A considerable uncertainty would exist in the estimation of the spatial distribution of plant biomass (Singh et al., 2011; Fang et al., 2007). This uncertainty can be reduced by employing site-specific allometric equations. The allometric equation, which is developed through regression analysis, has the advantages that once equations are developed and validated, they can be applied to similar forest types on a wide range of sites (Satto and Madgwick, 1982).

Rhododendron arboreum Sm. (Family Ericaceae), the national flower of Nepal, state tree of Uttarakhand, state flower of Himachal Pradesh and Nagaland (India), known as Lali gurans in Nepali, is a medium sized tree of 7-14 m height (Rawat et al., 2017; Shrestha and Budhathoki, 2012). This is distributed across Nepal, India, Sri Lanka, China, Myanmar, Bhutan, Pakistan and Thailand (Rawat et al., 2017; Ranjitkar et al., 2014). In Nepal, it is distributed from 1500 m to 3300 m, but is more common above 2300 m (Jackson, 1994). The total area coverage of this species in Nepal and other countries is still unexplored, however, genus level information is available. The genus *Rhododendron* has 57.8 stems per hectare, 13.5% of trees (by number), 8.68 m^3 per ha (stem volume) in Nepalese forests (DFRS, 2015). Common associates of this species are *Myrsine semiserrata*, *Alnus nepalensis, Abies pindrow, Abies spectabilis, Betula utelis, Daphne bholua, Larix griffithiana, Betula utilis, and Tsuga Dumosa* (Ranjitkar et al., 2014; Shrestha and Budhathoki, 2012). In some area, it also forms the monospecific stands. The leaves are unpalatable to the browsing animals, and overgrazing favors the spread of the species. The wood of this species is used as fuelwood, small wooden vessels and utensils, handles of Nepali traditional knife (Ranjitkar et al., 2014). Flowers are used to prepare pickles and produce juices. The species contains several chemical constituents which can be used as medicines for several diseases (Rawat et al., 2017). The dried flowers of this species are very effective in controlling the diarrhea and dysentery (Laloo et al., 2006). The paste of flower, if applied on forehead, reduces the headache (Watt, 1892). Aesthetic value of *R. arboreum* is much promising because of its evergreen and flowering nature.

Like other species, it also has a higher stand density of small-sized individuals than larger ones (Ranjitkar et al., 2014). Despite this fact, juveniles are generally excluded from forest inventory and biomass assessment. Main reason for this exclusion is due to unavailability of allometric biomass equations for *R. arboreum* juveniles. Allometric equations to estimate the biomass of juvenile stage plants in Nepal have been developed for *Shorea robusta*, *Terminalia tomentosa*, *Acacia catechu* (Chapagain et al., 2014), *Castanopsis indica* (Bhandari and Neupane, 2014a), *Alnus nepalensis* (Bhandari and Neupane, 2014b). The existing juvenile biomass models are applicable to tropical forest (Chapagain et al., 2014) and sub-tropical forest (Bhandari and Neupane, 2014a; 2014b). To the authors' knowledge, none of the allometric biomass models for juvenile plants has been developed for *R. arboreum* so far. However, biomass prediction models for larger-sized *R. arboreum* trees were developed (Adhikari et al., 1995). Therefore, the proposed biomass model will be the first biomass model that will be applicable to the juveniles of *R. arboreum*. This allometric model will serve as a useful tool for forest managers and community forest users for better planning of the natural resources. The purposed allometric model will become a reliable reference for estimating biomass and carbon amounts using other techniques, such as remote sensing and GIS.

MATERIAL AND METHODS

Study site

This study was carried out in the Ipchena Tatha Sunanpakhaka community forest (CF) of Barpak Village Development Committee (VDC), Gorkha district (27°15'-28°15' N latitude and 84°27'-85°58' E longitude) in Western Nepal (Figure 1). The forest coverage in the district is 29.97% (DFRS, 2015) and the 27.03% forest of the district is managed by 489 CFUGs in the form of CF including 61,508 households (DFRS, 2015; DOF, 2017). The district has a high degree of variation in the altitude ranging from 330 m to 8156 m above from the mean sea level. The average minimum and maximum temperature and precipitation is 6 °C in January and 31.9 °C in June and 0 mm in January and 529.4 mm in July, respectively (DFO Gorkha, 2017). The district has five distinct types of forests that includes tropical forest, sub-tropical forest, temperate forest, sub-alpine and alpine.

The studied forest is 427.68 ha and has been managed by local CF user group (CFUG) by dividing it into five strata since 1995. The average slope of the CF is 35°, aspect is North-West and elevation is 2200 m

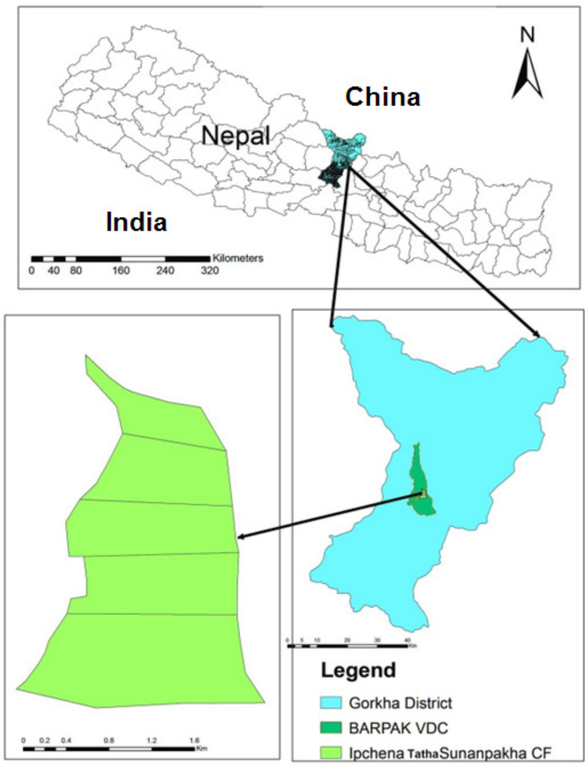


FIGURE 1 Study site [CF: community forest; VDC: village development committee – a local political administrative body according to Nepal's constitution 1993].

to 2950 m. The CFUG is implementing different forest management activities like weeding, cleaning, climber cutting, pruning, thinning and other selective cutting. The soil type varied from sandy to loam and had black brown color. The type of forest is natural and mixed in composition with dominant species of *Rhododendron arboreum*. Other common associated species are *Myrsine semiserrata*, *Alnus nepalensis, Abies pindrow.* According to operational plan, the CF has medium quality stands and crown coverage is more than 55%. The average density of the CF is 2135 ha^{-1} whereas stand density with trees >10 cm dbh is 428 ha^{-1} and trees <10 cm dbh is 1707ha^{-1}. The largest number of regenerations is of *R. arboreum* (404.1 ha^{-1}) whereas the second largest is *Alnus nepalensis* (369.1 ha^{-1}). The stand density of *R. arboreum* is the highest in the CF, and therefore Ipchena Tatha Sunanpakhaka CF was selected for the study.

Sampling and measurements

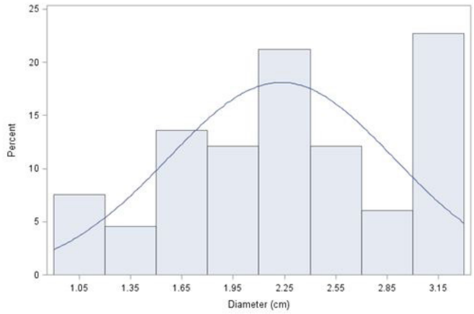
The variation in the size of the individuals of *R. arboreum* was determined from the latest forest management plan (Operational plan, 2015). According to this plan, CF has been stratified into five strata based on the stand condition, growth stage and management modality. We applied the stratified sampling strategy to select the sample juveniles. In stratified sampling, the proportional to size allocation approach (Chaturvedi and Khanna 2011) was applied to allocate the number of individuals to be felled in each stratum. The stratum with bigger size would receive larger number of individuals compared to smaller strata. Out of a total of 66 samples, 24 samples were selected from strata I, 13 from strata II, 12 from strata III, 11 from strata IV, and 6 samples from strata V. Within each stratum the samples were selected in such a way that the selected samples can represent variations in terms of plant size, site quality, stand density, stand structure, elevation, aspect and physiographic features. We measured diameter of each the juvenile individual at 10 cm aboveground and felled with a handsaw. Total height, crown length and crown width of the felled individuals were measured. Crown length was measured as the vertical distance from the position of the first branch originated from the trunk to the top of the juvenile. Crown width was measured as the average of maximum spread of the crown and perpendicular measurement to that maximum spread.

The foliage and branches were separated from the main stem for each of the individuals felled. The fresh weight of each part was recorded using the digital weighing balance (precision 0.1 g). A representative sample of each part was weighed, placed in a labeled bag, and carried to the laboratory for oven drying. The laboratory facility of the Institute of Forestry in Pokhara was used for oven dry purpose. If a part of the juvenile individual was less than 100 gm, whole part was used for drying the samples. The volume of sample of the main stem was estimated using the water displacement method (Chaturvedi and Khanna, 2011). The samples were dried on an oven at 105^0 C. The samples were dried at decreasing order of time interval. Firstly, samples were dried for 24 hours and weighed, and secondly, samples were dried for another 8 hours and weighed again. When the weight of a sample was found decreasing, it was again subjected to drying for another 4 hours, and process continued until its constant weight was observed. The wood density of stem sample was estimated using (Chave et al., 2006), where ρ (rho) is wood density in ($g{\cdot}cm^{-3}$), W_o is the oven dry weight of a sub-sample (gm); V_s is the water saturated volume of a stem sample (cm^3). Dry weight of leaf, branch and stem of each of the sampled individuals was calculated as the cross product of the fresh weight of each part and dry to fresh weight ratio of that part. The total aboveground biomass was estimated as the sum of biomass of each part of the juvenile individuals. Summary statistics of data used in this study are presented in Table 1. The distributions of diameter and height observations of the individual *R. arboretum* are shown in Figure 2, where height observations seem has more balanced distribution (normal) than diameter observations.

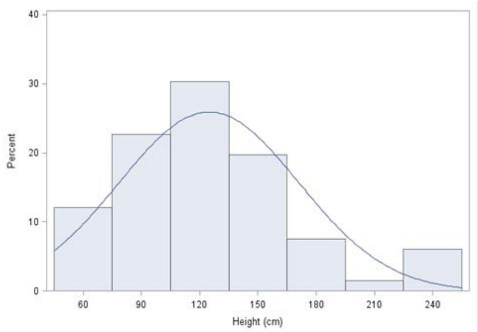
$$\rho = \frac{W_0}{V_s} \qquad [1]$$

TABLE 1 Summary statistics of data.

Variables	Mean ± sd (range)
Diameter, D (cm)	2.3 ± 0.7 (1 - 3.2)
Height, H (cm)	124.7 ± 46.2 (48 - 240)
Height-diameter ratio, HDR	57.1 ± 16.2 (30.9 - 100)
Number of branches, N	6 ±2.9 (1 - 16)
Height to crown base, HCB (cm)	80 ± 36.3 (16 - 175)
Crown width, CW (cm)	56.2 ± 20.4 (17.5 - 110)
Crown length, CL (cm)	44.7 ± 23.5 (10 - 130)
Crown ratio, CR	0.41 ± 0.22 (0.08 - 0.69)
Crown spread ratio, CSR	0.46 ± 0.12 (0.22 - 0.76)
Crown index, CI	0.89 ± 0.54 (0.11 - 3.14)
Crown fullness ratio, CFR	1.65 ± 1.42 (0.32 - 9.15)
Wood density, ρ ($g{\cdot}cm^{-3}$)	0.46 ± 0.05 (0.22 - 0.61)
Foliage biomass (g)	69.2 ± 42.6 (3 - 179.4)
Branch biomass (g)	81.3 ± 63.9 (1.4 - 249.5)
Stem biomass (g)	126.5 ± 97.6 (9.3 - 438.7)
Total biomass (g)	276.9 ± 188.9 (25.5 - 724.8)
Slope of study site, SLP (degree)	29.8 ± 10.2 (8 - 45)
Altitude of study of site, ALT (m)	2627 ± 183 (2179 - 2931)



a.



b.

FIGURE 2 Frequency distributions of diameter and height of individual rhododendron juveniles

Model construction

The plant biomass can be precisely described by various plant characteristics, such as diameter, height, crown measures (crown dimensions and any other measures derived from crown measurements), wood density, physiographic and climatic characteristics. We evaluated the juvenile plant characteristics, such as diameter, height, crown measures, wood density and measures describing the effects of physiographic features on plant biomass, such as altitude and slope, for their potential contribution to the plant biomass variations. We developed the juvenile individual biomass models using the combination of two or more variables of interest, as below:

1) Diameter of the juvenile individuals as a main predictor and each of the nine other variables as covariate predictor.

2) Cross product of squared-diameter and height as a main predictor and each of the nine other variables as covariate predictor.

Definitions of the combination of a main predictor and its associated covariate predictors used are given in Table 2. We evaluated various crown measures as covariate predictors as these measures were found describing plant biomass more effectively than other characteristics.

With the assumption of incseasing biomass nonlinearly with size of the juvenile individuals, we evulated eigth nonlinear functions of various forms (five exponential functions, one power function, and two functions of fractional form) to fit data (Table 3). Seven of them have already been applied for modelling plant biomass and they are cited in this table. We applied the parameter prediction approach (Clutter, 1983; Chapagain et al., 2014; Sharma et al., 2017; Shrestha et al., 2018) in which parameter b_1 of each formulation of the functions in Table 3 was modelled as a function of each of the nine

TABLE 2 Definition of a main predictor (x_i) and covariate predictor (z_i) used in modelling total biomass of the juvenile of *R. arboreum*.

Main predictor (x_i)	Covariate predictor (zi)
D_i = diameter at base of individual i (cm)	CI_i=crown index (crown length-to-crown width ratio) of individual i
	CW_i = crown width of individual i (cm)
	CSR_i = crown spread ratio (crown width-to-height ratio) of individual i
	ρ_i= average wood density of individual i (g·cm^{-3})
	CFR_i=crown fullness ratio, crown width-to-crown length ratio of individual i
	CR_i=live crown ratio (crown length-to-total height ratio of individual i)
	HDR_i = height-to-diameter ratio of individual i (slenderness)
	N_i=number of branches of individual i
	Inter = interaction effect of slope and altitude (degree × m)
$D^2_iH_i$=cross product of D^2 and height (H) of individual i (cm^3)	CI_i = crown index (crown length-to-crown width ratio of individual i)
	CW_i =crown width of individual i (cm)
	CSR_i = crown spread ratio (crown width-to-height ratio of individual i)
	ρ_i = wood density of individual i (g·cm^{-1})
	CFR_i = crown fullness ratio (crown width-to-crown length ratio of individual i)
	CR_i = live crown ratio (crown length-to-height ratio of individual i)
	HDR_i = height-to-diameter ratio of individual i (slenderness)
	N_i = number of branch of individual i
	Inter = interaction effect of slope and altitude (degree × m)

TABLE 3 Definition of a main predictor (x_i) and covariate predictor (z_i) used in modelling total biomass of the juvenile of *R. arboreum*.

Designation	Function	Reference
F1	$W_i = b_1 \exp(b_2 x_i) + \varepsilon_i$	Rizvi et al. (2008)
F2	$W_i = b_1 \exp(-b_2 x_i^{b_3}) + \varepsilon_i$	Sharma et al. (2017a)
F3	$W_i = b_1 [1 - \exp(-b_2 x_i)] + \varepsilon_i$	This study
F4	$W_i = b_1 \exp(-b_2 / x_i) + \varepsilon_i$	Schumacher (1939)
F5	$W_i = b_1 \exp(b_2 \sqrt{x_i}) + \varepsilon_i$	Shrestha et al. (2018)
F6	$W_i = b_1 x_i^{b_2} + \varepsilon_i$	Huxley and Teissier (1936)
F7	$W_i = x_i / (b_1 + b_2 x_i) + \varepsilon_i$	Hosoda and Iehara (2010)
F8	$W_i = [x_i / (b_1 + b_2 x_i)]^3 + \varepsilon_i$	Sharma et al. (2017a)

covariate predictors (see e.g., Equation 2 and 3). Only F6, F7 with b_1 modelled as a nonlinear function of crown spread ratio (*CSR)* best fitted to data, and therefore these were taken for further evaluation, where W_i = total biomass of individual *i* (g); x_i = main predictor of individual i and z_i = covariate predictor of individual i (see definition in Table 2); b_1, b_2, α_1, α_2 = parameters to be estimated, and ε_i=residual error, which was assumed

$$W_i = b_1 x_i^{b_2} + \varepsilon_i \qquad [2]$$

$$W_i = x_i/(b_1 + b_2 x_i) + \varepsilon_i \qquad [3]$$

$$b_1 = \alpha_1 z_i^{\alpha_2} \qquad [4]$$

to be independent and normally distributed with zero expectation and constant variance.

Model estimation and evaluation

The model parameters were estimated with nonlinear least square regression using PROC MODEL in SAS (SAS Institute Inc., 2012) applying Marquardt's method (Marquardt, 1993). We evaluated the fitting performance of the model using root mean square error (*RMSE*) analyzing the precision of the estimation, adjusted coefficient of determination (R^2_{adj}) reflecting total variability described by the model considering total number of parameters to be estimated. The expressions of *RMSE* and R^2_{adj} are found in the standard books of statistics (e.g., Montgomery et al., 2001). In addion to these numerical statistics, residual graphs and the curves produced with each model were also analyzed. The graphical analyses help better understanding whether models are attributed to the theoretical basis and biological logics (Zeide, 1993). Unless otherwise specified, we used 1% level of significance in our analysis. Validation of the models is one of the important procedures of modelling as this provides more credibility and confidence about the developed model (VANCLAY and SKOVSGAARD, 1997; KOZAK AND KOZAK, 2003). Validation is often carried out by splitting data (Ajit et al., 2011; Sharma et al., 2017). However, we did not do this either because of a small dataset. Validating model with external independent data can be the best alternative only (Sharma et al., 2019), but it was not possible for us to get additional destructive samples, because of cost limitation.

RESULTS

Among the eight functions evaluated, a simple power function (F6 or Equation 2) and fractional form (F7 or Equation 3) emerged as the first and second best, describing larger parts of the variations in the juvenile individual biomass (Table 4) than other functions. Inclusion of CSR most significantly improved the fit statistics over that of the model with the cross product of squared diameter and height of juvenile as a single predictor. Both functions described almost equal proportion of the variations in the juvenile individual biomass. All parameter estimates of two best functions (F6 and F7) and other functions, which we evaluated in our preliminary analysis (Table 3) were highly significant ($p<0.0001$) and biologically plausible. With inclusion of other covariate predictors (Table 2), all functions fitted relatively poorly (R^2_{adj} < 0.90). All functions fitted using diameter as a single predictor and each covariate of interest showed poorer fit statistics than those

TABLE 4 Fit statistics of two best fitting functions (F6 and F7 in Table 3) with use of combination of a main predictor (X_i) and each of the nine predictors (Z_i) as defined in Table 3; RMSE: root mean square error; R2adj: adjusted coefficient of determination.

Function	X_i	Z_i	RMSE (g)	R2adj
F6	Di	HDR_i	66.0380	0.8778
		CW_i	69.8994	0.8631
		N_i	81.4457	0.8142
		CR_i	87.5201	0.7854
		CFR_i	87.6178	0.7853
		CI_i	87.6179	0.7849
		CSR_i	87.6568	0.7848
		ρ_i	87.6569	0.7848
		Inter	87.6765	0.7847
	$D_i^2H_i$	CSR_i	59.3491	0.9013
		N_i	61.9088	0.8926
		CFR_i	62.0001	0.8925
		CI_i	62.0011	0.8923
		CW_i	63.4764	0.8871
		CR_i	65.3917	0.8802
		HDR_i	66.0382	0.8778
		ρ_i	67.6551	0.8718
		Inter	67.8747	0.8709
F7	Di	HDR_i	70.8175	0.8565
		CW_i	73.0019	0.8507
		N_i	83.4356	0.8050
		CSR_i	90.0001	0.7801
		CI_i	89.7102	0.7765
		CR_i	89.4543	0.7758
		CFR_i	89.7129	0.7745
		ρ_i	89.9989	0.7731
		Inter	89.9994	0.7731
	$D_i^2H_i$	CSR_i	59.4288	0.9011
		CFR_i	62.3105	0.8941
		CI_i	62.3135	0.8912
		N_i	63.4975	0.8823
		CR_i	65.0179	0.8816
		CW_i	65.7293	0.8799
		HDR_i	67.8421	0.8698
		ρ_i	68.3463	0.8678
		Inter	69.1472	0.8575

$$W_i = b_1 x_i^{b_2} \text{ with } x_i = (D_i^2 H_i)^2, b_1 = 1.329279 CSR_i^{0.370443}, b_2 = 0.857219 \quad [5]$$

$$W_i = \frac{x_i}{(b_1 + b_2 x_i)} \text{ with } x_i = (D_i^2 H_i)^2, b_1 = 1.630106 CSR_i^{-0.4271}, b_2 = 0.000377 \quad [6]$$

fitted with D^2H as a single predictor and each covariate of interest. The juvenile individual biomass models with estimated parameter values for are:

All symbols and abbreviations are the same as defined in Equation 2 and 3 and Table 2.

We also examined the residual graphs and the curves produced with each of the selected models. Serious trends in the residuals were not observed within the ranges of the measured diameter and height of the individuals (Figure 3). An approximate-overlap of the diagonal 1:1 line and regression line of the estimated biomass versus measured biomass showed the model's perfect fit to data, i.e., scattered plots of the estimated aboveground biomass versus measured biomass independently and closely distributed around the reference line having zero intercept and slope one (Figure 4). The curves produced with each of equation 5 and equation 5 clearly differentiated, indicating that height and CSR of the individuals significantly contributed to the variations in their biomasses (Figure 5). Compared to the contribution provided by height, contribution of CSR seems relatively smaller.

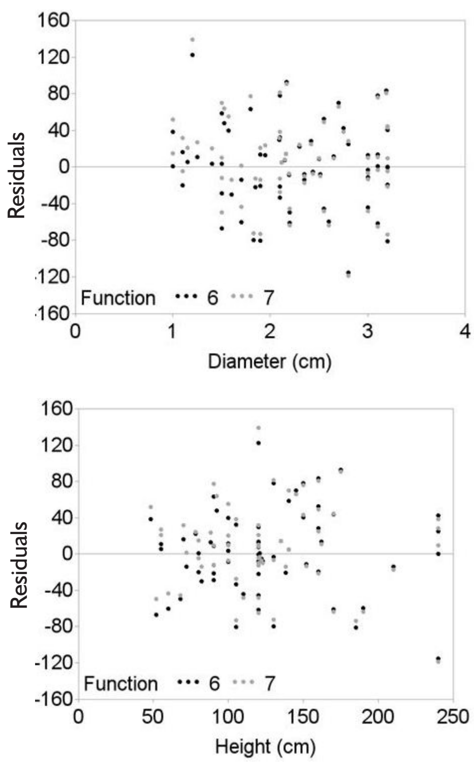


FIGURE 3 Mean residuals of the first two best models (F6 and F7) against two predictor variables: diameter and height of the juvenile rhododendron individuals. Mean residuals were calculated by diameter class with 20 mm intervals and height class with 10 cm intervals.

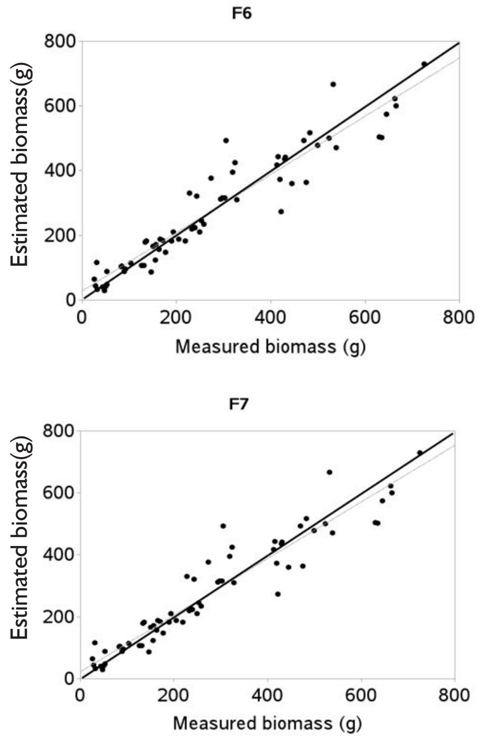


FIGURE 4 Overlay graph of diagonal 1:1 line (black line) and regression line of the estimated biomass against measured biomass (gray line), and estimated biomass over measured biomass. The first two best models (F6 and F7) were used to produce these graphs.

DISCUSSION

Data used in this study was collected through the sampling strategy involving stratification of *Rhododendron* forests into five different strata. Stratification of the population of interest would help capturing a higher level of the variability than other sampling methods. Data covers a wide range of juvenile size (Table 1), site quality, stand condition, and physiographic features. The number of juvenile individuals used in this study is fairly high and sampled by representing full ranges of the variability. Like many other studies related to modelling biomass, we used destructive sampling in this study even though it requires more resources. Number of the juvenile individuals used in this study are comparatively higher than those used in many other tree biomass studies (Ajit et al., 2011; Sharma, 2011; Chaturvedi and Raghubanshi, 2013; Subedi and Sharma, 2012; Shrestha et al., 2017) which ranged from 27 to 36 individuals. With

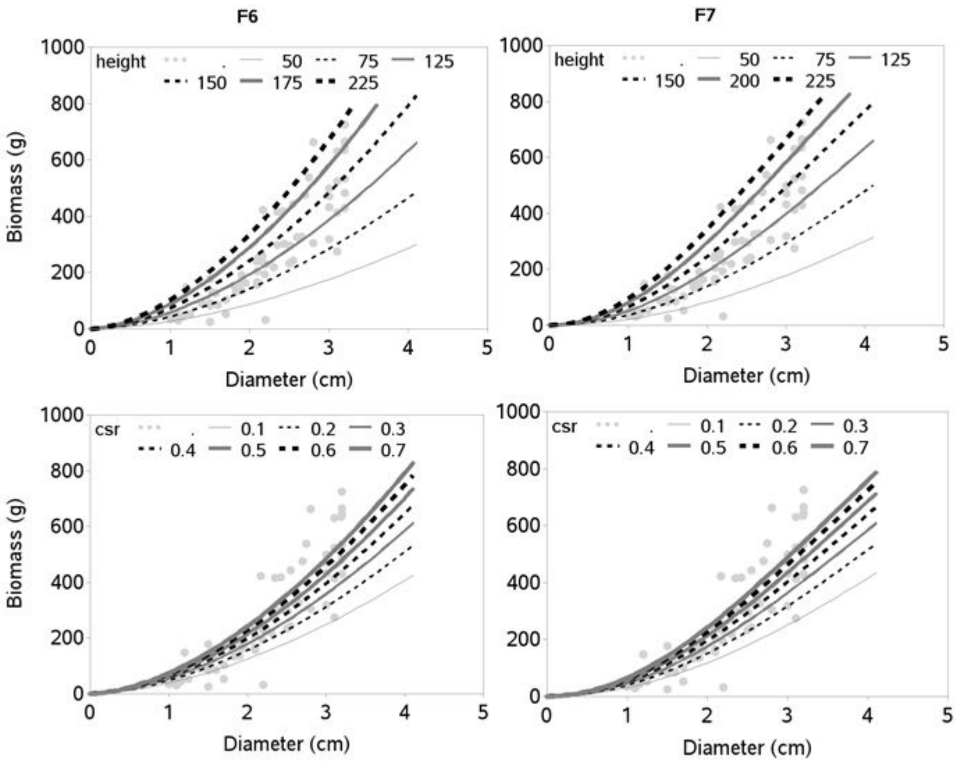


FIGURE 5 The effect of total height (height, cm) and crown spread ratio (ratio of crown width-to-total height, csr) on total biomass of the juvenile individuals. Curves were produced using parameter estimates of the first two best functions (F6, F7). Mean values of the data were used for predictor variables in the functions, except the variable of interest in the figure, which varied from approximately minimum to maximum in the data (Table 1).

few exceptions (e.g. Brown et al., 1993; Chave et al., 2005), biomass modeling studies requiring destructive sampling often use smaller sample size covering a small forest area. Data from relatively smaller number of sample trees would be sufficient for modelling biomass if they were good representative to a full range growth variabilities and environmental conditions.

The relationship between aboveground biomass of the juvenile individuals and their diameters through time would be nonlinear. Considering this, eight nonlinear functions (Table 3) were evaluated for their potential descriptions of the variations in the allometric relationships between aboveground biomass of the juvenile individuals and their diameters. Most of the functions evaluated in this study have already been used to develop biomass models in forestry. Two functions (F6, F7), which are most commonly used for modelling biomass and growth of the individual trees, fitted adequately well, depicting their identical fit statistics (Table 4) and graphical appearances (Figure 3-5). Biomass of the juvenile individuals varies with tree- and stand-level characteristics, such as individual size (diameter, height), number and size of branches, crown measures (crown length, crown ratio, crown index, crown spread ratio, crown fullness ratio, crown extension), wood density, height-to-diameter ratio (plant bole slenderness), site quality, stand density, and stand structure, species mixture, and physiographic features (slope, aspect, altitude). Considering this, modelers often develop the biomass prediction models using various characteristics, such as crown dimensions (e.g. Juker et al., 2016), wood density (e.g. Basuski et al., 2009; Albarez et al., 2012; Chapagain et al., 2014), height-to-diameter ratio (Sharma et al., 2017) as covariate predictors in addition to diameter and height of the individuals.

Even though our models (Eq. 5, 6) described large parts of the variations in the aboveground biomass, some residuals seemed larger, especially for larger juvenile individuals (Figure 3), but were distributed randomly. The absence of significant trends in the residuals within the measured data range confirms the high precision of the models. The scatter plots of the estimated biomass versus measured biomass suggests that data were independently and closely distributed around the reference line having zero intercept and slope one (Figure 4), confirming the models' high precisions. As in other studies (Ketterings et al., 2001; Subedi and Sharma, 2012; Chapagain et al., 2014; Sharma et al., 2017), the models we developed using diameter as a single predictor performed relatively poorly compared to the models that combined diameter, height and CSR, and therefore could not be applied for precise predictions of all juvenile individuals in the *Rhododendron* forests. The crown width and total height of the juvenile individuals (seedling and sapling) can be more easily measured than those of the trees, as any measuring pole may accurately measure them, and therefore inclusion of crown spread ratio and height into the model was quite relevant and reasonable. The crown measure-based biomass models and the models requiring diameter, height and crown measures are undoubtedly more accurate and precise, and have a larger scope than the models with diameter alone as the former models are composite or generalized ones. The model requiring only a few and easily measurable predictor variables is mostly preferred due to requirement of less measuring cost, and unnecessarily using many predictors into the model results in over-parameterization and biased estimation that may cause the invalidation of the hypothesis tests (Montgomery et al., 2001; Vanclay, 1994).

A wider spacing between the individual curves in figure 5 suggests that height contributes more significantly to the biomass variations of the juvenile individuals followed by their crown spread ratio. Growing height may build more biomass on the juvenile individuals than other characteristics would do. Addition of these two predictors (height and crown spread ratio) to the models significantly increased the fitting improvement. A clear differentiation of the curves within the measured data range, even for juvenile individuals with similar diameters (Figure 5), is due to larger effect of the crown spread ratio and height of the juvenile individuals on the model. Differing height and crown measures of the juvenile individuals may cause biomass differentiations, even for the juvenile individuals with identical diameters, as shown in this figure. Adequate covering of the measured data by simulated biomass curves suggests that our models are precise for most sizes of the juvenile individuals. It is known that model precision depends largely on sample size and numbers of predictors included, modelling method employed, and application of the models to growth conditions of the juvenile individuals in a population (Sharma et al., 2017). It may not be relevant to compare any biomass model developed for different species, components, and locations, as several factors may determine the accuracy of the model. However, our biomass models are closely comparable to those developed aiming at predicting aboveground biomass of the juvenile individuals of three tropical species (*Shorea robusta, Terminalia tomentosa,* and *Acacia catechu)* (Chapagain et al., 2014) and two sub-tropical species, such as *Castanopsis indica* (Bhandari and Neupane, 2014a) and *Alnus nepalensis* (Bhandari and Neupane, 2014b), and dry-tropical species (Chaturvedi et al., 2012a, b). Our models are slightly inferior to those developed by Chapagain et al. (2014) but superior to those of Bhandari and Neupane (2014a, b). Our model has higher precision than that of Chaturvedi et al. (2012a).

Generally, wood density-based biomass models (e.g., Alvarez et al., 2012; Basuki et al., 2009; Chaturvedi et al., 2012a, b; Lindner and Sattler, 2012; Návar, 2009a) are expected to better describe the aboveground biomass. However, our analyses do not indicate this, as fitting improvement achieved through inclusion of wood density (rho) into the model was lower than that of each crown measure (Table 4). Our modelling approach is therefore a novel one, as each of the crown measure included into the models show significantly more fitting improvement than wood density and any of the other predictors. The models requiring input information of wood density of the species of interest requires the additional resource to determine wood density. Like wood density, inclusion of the predictor variables describing physiographic characteristics, such as interaction of slope and altitude into the models also resulted in worse fit statistics (Table 4). It may be due to that the effects of slope and altitude on the biomass variations were described by combination of the crown measures and heights of the juvenile individuals. Height-to-diameter ratio of the juvenile individuals also does not perform better when it was used together with height.

Our model is simple and explicitly site-specific, and therefore its application should be restricted to the site and stand conditions similar to those under which our model was developed, to get the precise prediction of the aboveground biomass of the juvenile individuals of *R. arboreum*. To make the model more comprehensive, accurate, and widely applicable, the predictor variables describing site quality (e.g. site index, dominant height of individuals), stand density (e.g. competition measures), and climate characteristics (e.g. temperature, precipitation), and soil properties (soil depth, soil nutrients, etc.) need to be integrated into the biomass models. However, we did not collect these data. Even though validating model with external independent dataset is the best alternative only (Sharma et al., 2019), it might become more costly, especially for those studies which require destructive sampling, such as plant biomass modelling. Resource limitation did not allow us to acquire additional data to validate our models.

Our models can be used for the precise quantification of aboveground biomass of the juvenile individuals of *R. arboreum*. As mentioned in the introduction section of this article, this species is one of the most important tree species from economic, ecological and aesthetic perspectives for the mountain regions of Nepal. Therefore, the in-depth investigation on this species including modelling relationships of the attributes of both larger and smaller individuals would be very important. Our results (models) can be reliable basis (bench-mark) for further modelling works for small-sized plant individuals of *R. arboreum* and other species of the similar types in Nepal and other countries. The knowledge contributed by our modelling works and other studies (Jackson, 1994; Ranjitkar et al., 2014; DFRS, 2015; RAWAT et al., 2017) will be useful to the managers for the informed decision-making in natural resource management.

CONCLUSION

A generalized aboveground biomass model developed using cross-product of squared-diameter and height as a main predictor and crown spread ratio (crown width to height ratio) as covariate predictor showed the most attractive fit statistics and smallest variations of the residuals. Among the number of predictor variables evaluated for their potential contributions to the biomass variations of the juvenile individuals of *R. arboreum,* crown measures (crown ratio, crown width, crown spread ratio, crown index, crown fullness ratio) were found more promising as each of these variables showed a larger contribution to fitting improvements of the models. Further research is recommended to recalibrate, validate and verify our models using a larger dataset with variables describing a wider range of site quality, stand density, growth stage, and species distribution. Since characteristics of site quality, stand density and structure, and climate significantly influence the growth of juvenile *R. arboreum*, variables describing these characteristics need to be included into the biomass models. Modelers should take these all into account to make their models more interesting and useful.

ACKNOWLEDGEMENT

This study was granted through “Hariyo Ban Program student research grants” of WWF Nepal (Grant no. C3DA/HBP/OM/015). This publication was also supported by EVA4.0 project) in the Faculty of Forestry and Wood Sciences, Czech University of Life Sciences in Prague (No. CZ.02.1.01/0.0/0.0/16_019/0000803). We thank users of the Ipchena Tatha Sunanpakhaka CF for their support during field data collection. The constructive comments and insightful suggestions provided by two anonymous reviewers helped improve the article.

REFERENCES

ADHIKARI, B.S.; RAWAT, Y.S.; SINGH, S.P. Structure and function of high-altitude forests of Central Himalayas I. Dry matter dynamics. **Annals of Botany**, v.75, p.237-248, 1995.

AJIT DAS, D.K.; CHATURVEDI, O.P.; JABEEND, N.; DHYANI, S.K. Predictive models for dry weight estimation of above and below ground biomass components of *Populus deltoides* in India: Development and comparative diagnosis. **Biomass & Bioenergy**, v. 35, p. 1145-1152, 2011.

ALVAREZ, E.; DUQUE, A.; SALDARRIAGA. J. et al. Tree aboveground biomass allometries for carbon stocks estimation in the natural forests of Colombia. **Forest Ecology and Management**, v. 267, p.297–308, 2012.

AMEDIE, F.A. **Impacts of Climate Change on Plant Growth, Ecosystem Services, Biodiversity and Potential Adaptation Measures**. 2013. 61p. Master degree thesis. University of Gothenburg, Sweden, 2013.

BASUKI,T.M.; VAN LAAKE, P.E.; SKIDMORE, A.K.; HUSSIN, Y.A. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. **Forest Ecology and Management**, v. 257, p.1684–1694, 2009.

BHANDARI, S.K.; NEUPANE, H.L. Allometric equations for estimating the above-ground biomass of *Castanopsis indica* at juvenile stage. **Banko Jankari**, v. 24, n. 1, p.14-22, 2014a.

BHANDARI, S.K.; NEUPANE, H.L. Biomass modeling of *Alnus nepalensis* D. Don at juvenile stage. **International journal of interdisciplinary studies**, v. 2, n. 1, p.47-60, 2014b.

BROWN, S.; GILLESPIE, A.J.R.; LUGO, A.E. Biomass estimation for tropical forests with applications to forest inventory data. **Forest Science**, v. 35, n. 4, p.881–902, 1989.

BROWN, S.; IVERSON, L.R.; PRASAD, A.; LIU, D. Geographical distributions of carbon in biomass and soils of tropical Asian forests. **Geocarto International**, n. 8, p.45-59, 1993.

CHAPAGAIN, T.; SHARMA, R.P.; BHANDARI, S.K. Modelling above-ground biomass for three tropical tree species at their juvenile stage. **Forest Science and Technology**, v. 10, n. 2, p.51-60, 2014.

CHATURVEDI, R.K.; RAGHUBANSHI, A.S. Above-ground biomass estimation of small diameter woody species of tropical dry forest. **New Forests**, v. 44, n. 4, p.509–519, 2013.

CHATURVEDI, R.K.; RAGHUBANSHI, A.S.; SINGH, J.S. Biomass estimation of dry tropical woody species at juvenile stage. **The scientific world journal**, p.1-5, 2012a.

CHATURVEDI, R.K.; RAGHUBANSHI, A.S.; SINGH, J.S. Effect of grazing and harvesting on diversity, recruitment and carbon accumulation of juvenile trees in tropical dry forests. **Forest Ecology and Management**, v. 284, p.152–162, 2012b.

CHATURVEDI, A.N.; KHANNA, L.S. **Forest mensuration and biometry**.Dehradun, Khanna Bandhu. 5th Edition. 2011, 364p.

CHAVE, J.; ANDALO, C.; BROWN, S.; CAIRNS, M.A.; CHAMBERS, J.Q.; EAMUS, D.; FOLSTER, H.; FROMARD, F.; HIGUCHI, N.; KIRA, T.; LESCURE, J-P.; NELSON, B.W.; OGAWA, H.; PUIG, H.; RIERA, B.; YAMAKURA, T. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. **Oecologia**, v. 145, n. 1, p.87–99, 2005.

CHAVE; J.; MULLER-LANDAU H, C.; BAKER, T.R.; EASDALE, T.A.; TER STEEGE, H.; WEBB, C.O. Regional and phylogenetic variation of wood density across 2456 neotropical tree species. **Ecological Applications**, v. 16, n. 6, p.2356–2367, 2006.

CLARK, D.A.; BROWN, S.; KICKLIGHTER, D.W.; CHAMBERS, J.Q.; THOMLINSON, J.R.; NI, J. Measuring net primary production in forests: Concepts and field methods. **Ecological Application**s, v. 11, n. 2, p.356–370, 2001.

CLUTTER, J.L.; FORTSON, J.C.; PIENAAR, L.V.; BRISTER, G.H.; BAILEY, R.L. **Timber management: a quantitative approach**. New York:Wiley, 1983. 333p.

De GIER, A. A new approach to woody biomass assessment in woodlands and shrublands. In: ROY PS, (eds.), **Geoinfor Trop Ecosyst**. Asia Association of Remote Sensing, Dehradun, India. 2003. p.161–198.

DFO, GORKHA. Annual progress report of Gorkha district. District forest office Gorkha. 2017. 52p.

DFRS. State of Nepal's Forest. **Forest Resource Assessment (FRA) Nepal, Department of Forest Research and Survey (DFRS): Kathmandu Nepal**, 2015. 73p.

DOF. **Community forestry database**. Community forestry division, Department of Forest (DoF). Ministry of forest and soil conservation, Government of Nepal. 2017.

ENQUIST, B.J. Universal Scaling in Tree and Vascular Plant Allometry: Toward a General Quantitative Theory Linking Plant Form and Function from Cells to Ecosystems. **Tree physiology**, v. 22, p.1045–1064, 2002.

FANG, H.; MO, J.M.; PENG, S.L.; LI, Z.A.; WANG, H. Cumulative effects of nitrogen additions on litter decomposition in three tropical forests in southern China. **Plant Soil**, v. 297, p.233–242, 2007.

FRANCIS, J.K. Estimating biomass and carbon content of saplings in Puerto Rican secondary forests. **Caribbean Journal of Science**, v. 36, n. (3–4), p. 346–350, 2000

JUCKER, T.; CASPERSEN, J.; CHAVE, J.; ANTIN, C.; BARBIER, N.; BONGERS, F.; DALPONTE, M.; VAN EWIJK, K.Y.; FORRESTER, D.I.; HAENI, M.; HIGGINS, S.I.; HOLDAWAY, R.J.; IIDA, Y.; LORIMER, C.; MARSHALL, P.L.; MOMO, S.; MONCRIEFF, G.R.; PLOTON, P.; POORTER, L.; RAHMAN, K.A.; SCHLUND, M.; SONKÉ, B.; STERCK, F.J.; TRUGMAN, A.T.; USOLTSEV, V.A.; VANDERWEL, M.C.; WALDNER, P.; WEDEUX, B.M.M.; WIRTH, C.; WÖLL, H.; WOODS, M.; XIANG, W.; ZIMMERMANN, N.E.; COOMES, D.A. Allometric equations for integrating remote sensing imagery into forest monitoring programmes. **Global Change Biology**, v. 23, n. 1, p.177-190, 2017.

HOSODA, K.; IEHARA, T. Abovegroud biomass equations for individual trees of *Cryptomeria japonica*, *Chamaecyparis obtusa* and *Larix kaempferi* in Japan. **Journal of Forestry Research**, v. 15, p.299-306, 2010.

HOUGHTON, R.A.; LAWRENCE, K.T.; HACKLER, J.L.; BROWN, S. The spatial distribution of forest biomass in the Brazilian Amazon: A comparison of estimates. **Global Change Biology**, v. 7, p.731-746, 2001.

HUXLEY, J.S.; TEISSIER, G. Terminology of relative growth. **Nature**, v.137, p.780-781, 1936.

JACKSON, J.K. **Manual of afforestation in Nepal**. Kathmandu, Forest research and survey center, Ministry of forest and soil conservation, Government of Nepal, 1994, 402p.

KETTERINGS, Q.M.; COE, R.; VAN NOORDWIJK, M.; AMBAGAU, Y.; PALM, C.A. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. **Forest Ecology and Management**, v. 146, n.(1–3), p.199–209, 2001.

KOZAK, A.; KOZAK, R. Does cross validation provide additional information in the evaluation of regression models? **Canadian Journal of Forest Research**, v. 33, p. 976–987, 2003.

LALOO, R.C.; KHARLUKHI, L.; JEEVA, S.; MISHRA, B.P. Status of medicinal plants in the disturbed and undisturbed sacred forest of Meghalaya, northeast India; population structure and regeneration efficacy of some important species. **Current Science**, v.90, p. 225-232.

LINDNER, A.; SATTLER, D. Biomass estimations in forests of different disturbance history in the Atlantic Forest of Rio de Janeiro, Brazil. **New Forest**, v. 43, p. 287–301, 2012.

MARQUARDT, D.W. An algorithm for least-squares estimation of non-linear parameters. **Journal of Society of Industrial Applied Mathmatics**, v. 11, p. 431-441, 1963.

MODRZYNSKI, J.; CHMURA, D.J.; TJOELKER, M. G. Seedling growth and biomass allocation in relation to leaf habit and shade tolerance among 10 temperate tree species. **Tree Physiology**, v. 35, p. 879-893, 2015.

MONTGOMERY, D.C.; PECK, E.A.; VINING, G.G. **Introduction to linear regression analysis**. New York, Wiley, 2001. 641p.

MUUKKONEN, P. Generalized allometric volume and biomass equations for some tree species in Europe. **European Journal of Forest Research**, v. 126, n. 2, p. 157–166, 2007.

MUUKKONEN, P.; MAKIPA, R. Biomass equations for European trees: Addendum. **Silva Fennica**, v. 40, n. 4, p.763–773, 2006.

NAVAR, J. Allometric equations for tree species and carbon stocks for forests of northwestern Mexico. **Forest Ecology and Management**, v. 257, n. 2, p. 427–434, 2009a.

NAVAR, J. Biomass component equations for Latin American species and groups of species. **Annals of Forest Science**, v. 66, n. 2, 2009b.

NEUPANE, B.; SHARMA, R.P. An assessment of the effect of vegetation size and type, and altitude on aboveground plant biomass and carbon. **Journal of Agricultural and Crop Research**, v. 2, n. 3, p. 44-50, 2014.

NOGIA, P.; SIDHU, G.K.; MEHROTRA, R.; MEHROTRA, S. Capturing atmospheric carbon: biological and non-biological methods. **International Journal of Low-Carbon Technologies**, v. 11, p. 266–274, 2016.

RANJITKAR, S.; SUJAKHU, N.M.; JATI, R.; XU, J. Yield and household consumption of *Rhododendron arboreum* as a fuelwood species in Eastern Nepal. **Science and bioenergy**, v. 61, p. 245-253, 2014.

RAWAT, P.; RAI, N.; KUMAR, N.; BACHHETI, R.K. Review on Rhododendron arboreum – a magical tree. **Oriental Pharmacy and Experimental Medicine**, v.17, n. 4, p. 297-308, 2017.

RIZVI, R.H.; GUPTA, V.K.; GUPTA, A. Comparison of various linear and non-linear functions for estimating biomass and volume of *Dalbergia sissoo* grown under rainfed conditions. **Indian Journal of Agricultural Sciences**, v. 78, p. 138-141, 2008.

SAS INSTITUTE INC. **SAS/ETS1 9.1.3 User's Guide**. SAS Institute Inc., Cary, NC. 2012.

SATTO, T.; MADGWICK, H. **Forest Biomass**. Martinus Nijhoff/Dr. W. Junk. The Hague, Netherland. 1982.

SCHUMACHER, F.X. A new growth curve and its application to timber yield studies. **Journal of Forestry Research**, v.37, p.819-820, 1939.

SEGURA, M.; KANNINEN, M. Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica. **Biotropica**, v. 37, n. 1, p.2–8, 2005.

SHARMA, R.P. Allometric models for total-tree and component-tree biomass of *Alnus nepalensis* D. Don in Nepal. **Indian Forester**, v. 137, n. 12, p.1386-1390, 2011.

SHARMA, R.P.; BHANDARI, S.K.; BK, R.B. Allometric bark biomass model for *Daphne bholua* in mid-hill of Nepal. **Mountain Research and Development**, v. 37, n. 2, p. 206-215, 2017.

SHARMA, R. P.; VACEK, Z.; VACEK, S.; KUCERA, M. Modelling individual tree height-diameter relationships for multi-layered and multi-species forests in central Europe. **Trees,** v. 33, n.1, p. 103-119, 2019.

SHRESTHA, R.M.; BUDHATHOKI, N.P. The chemical compositions of *Rhododendron arboreum*,"Laligunras". **Journal of Nepal Chemical Society**, v.30, p.97-106, 2012.

SHRESTHA, D.B.; SHARMA, R.P.; BHANDARI, S.K. Individual tree aboveground biomass for *Castanopsis indica* in the mid-hills of Nepal. **Agroforestry Systems**, v.2, n.6, 2018.

SINGH, V.; TEWARI, A.; KUSHWAHA, S.P.S.; DADHWAL, V.K. Formulating allometric equations for estimating biomass and carbon stock in small diameter trees. **Forest Ecology and Management**, v.261, n.11, p.1945–1949, 2011.

SUBEDI, M.R.; SHARMA, R.P. Allometric biomass models for bark of *Cinnamomum tamala* in mid-hill of Nepal. **Biomass Bioenergy**, v.47, p.44–49, 2012.

TER-MIKAELIAN, M.T.; PARKER, W.C. Estimating biomass of white spruce seedlings with vertical photo imagery. **New Forests**, v.20, n.2, p.145–162, 2000.

VANCLAY, J.K. **Modelling forest growth and yield. Applications to mixed tropical forests**. Oxon, UK: CAB International, 1994. 312p.

VANCLAY, J.K.; SKOVSGAARD, J.P. Evaluating forest growth models. **Ecological Modelling**, v.98, n.1, p.1–12, 1997.

VOGT, K.; VOGT, D.; BLOOMFIELD, J. Analysis of some direct and indirect methods for estimating root biomass and production of forests at an ecosystem level. **Plant Soil**, v. 200, p.71–89, 1998.

WAGNER, R.G.; TER-MIKAELIAN, M.T. Comparison of biomass component equations for four species of northern coniferous tree seedlings. **Annals of Forest Sciences**, v. 56, n. 3, p. 193–199, 1999.

WATT, G.A. **Dictionary of economic product of India**. Calcutta: Superintendent Printing, Government of India, v.6, p. 492-495, 1892.

ZEIDE, B. Analysis of growth equations. **Forest Science**, v.39, p.594-616, 1993.

ZIANIS, D.; MUUKKONEN, P.; MAKIPA, R.; MENCUCCINI, M. Biomass and stem volume equations for tree species in Europe. **Silva Fennica**. Monogr, n.4 p.4:63, 2005.