Form factor and volume equations for individual trees of *Shorea robusta* in Western low land of Nepal

Formfaktor- und Volumengleichungen für den Salbaum (*Shorea robusta*) im westlichen Tiefland von Nepal

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Schlüsselbegriffe: DBH, Formfaktor, Modelle, *Shorea robusta*, Volumenvorhersage

Abstract

Precise and accurate prediction of tree volume is important to quantify growing stock and to support decision making for sustainable forest management. This study was carried out to estimate the form factor and to develop volume prediction models of *Shorea robusta*. We selected 48 sample trees from the Western low land of Nepal through purposive sampling. The diameters at 0.3 m, 0.8 m, 1.3 m and 1.8 m above the ground level were measured before felling the trees. After felling the diameters were measured at 2.8 m, 4 m, 6 m above the ground level and continue up to the tip of the tree at the interval of 2 m. We also measured the length of each section between two consecutive diameter measurement point and total height. We estimated breast height and absolute form factors, and calculated the arithmetic mean and variation of the form factors. We developed a model that can predict under bark diameter from over bark diameter and diameter at breast height (DBH) from stump diameter. Similarly, we developed models to predict stem volume using a different

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combination of predictor variables (DBH and/or height). The breast height form factor was 0.43 and absolute form factor was 0.40. The linear model fitted best to describe the under bark to over bark relation and DBH to stump diameter relation. Simple power function (R^2=0.95) best fitted to our volume data. The product of squared DBH and height (R^2=0.96) performed as the best predictor for volume prediction. Our form factor and volume model significantly differed with the previously developed form factor and models of *Shorea robusta*. Thus, we recommend developing site-specific form factors and volume models of *Shorea robusta* across the country. The models developed in this study are expected to contribute to predicting volume, biomass and carbon and thus contribute to sustainable forest management and may contribute to the calculation of the national carbon budget.

Zusammenfassung

Eine präzise und genaue Schätzung des Stammvolumens ist wichtig für die Berechnung des Bestandszuwachses, um damit die nachhaltige Waldbewirtschaftung zu unterstützen. Diese Studie wurde mit dem Ziel durchgeführt, den Formfaktor abzuschätzen und Modelle zur Berechnung des Holzvolumens von *Shorea robusta* zu entwickeln. Wir wählten 48 Probebäume aus dem westlichen Tiefland von Nepal durch gezielte Stichproben aus. Die Durchmesser in 0,3 m, 0,8 m, 1,3 m und 1,8 m Höhe über dem Boden wurden am stehenden Baum gemessen. Nach der Fällung wurden die Durchmesser in 2,8 m, 4 m, 6 m über dem Boden und ab 6 m bis zur Spitze des Baumes im Abstand von 2 m gemessen. Bei geschätzter Brusthöhe und absoluten Formfaktoren berechneten wir das arithmetische Mittel und die Variation der Formfaktoren. Wir entwickelten ein Modell, welches den Durchmesser ohne Rinde aus dem Durchmesser mit Rinde und den Brusthöhendurchmesser (DBH) aus dem Stubbendurchmesser vorhersagen kann. In ähnlicher Weise entwickelten wir Modelle zur Vorhersage des Stammvolumens unter Verwendung einer anderen Kombination von Prädiktorvariablen (DBH und/oder Höhe). Der Formfaktor in Brusthöhe betrug 0,43 und der absolute Formfaktor 0,40. Das lineare Modell passte am besten, um das Verhältnis zwischen ohne Rinde und mit Rinde sowie zwischen DBH und Stubbendurchmesser zu beschreiben. Die einfache Potenzfunktion (R^2=0,95) passte am besten zu unseren Volumendaten. Das Produkt aus dem Quadrat von DBH und Höhe (R^2=0,96) war der beste Prädiktor für die Volumenvorhersage. Unser Formfaktor- und Volumenmodell unterschied sich signifikant von den zuvor entwickelten Formfaktor- und Volumenmodellen von *Shorea robusta*. Daher empfehlen wir die Entwicklung von standortspezifischen Formfaktoren und Volumenmodellen für *Shorea robusta* im ganzen Land. Es wird erwartet, dass die in dieser Studie entwickelten Modelle zur Vorhersage von Volumen, Biomasse und Kohlenstoff beitragen und somit einen Beitrag zur nachhaltigen Waldbewirtschaftung und zur Berechnung des nationalen Kohlenstoffbudgets leisten können.

1. Introduction

Forest measurement and inventory crucially assists forest management decisions and provides the information required for current and future forest management planning. The common variables measured in forest inventories are diameter at breast height (DBH), height, crown measures and these variables are used to derive other variables such as form factor, volume, biomass, carbon, productivity, diversity and importance value index (Baral *et al.*, 2020; Bhandari *et al.*, 2021a; Bhandari *et al.*, 2021b). The form factor is an important factor as this converts the volume of the reference cylinder of a tree to the actual volume (Tenzin *et al.*, 2017). DOF (2004) has recommended a constant value of 0.5 as a form factor for all tree species and tree sizes individuals in Nepal. However, the value of form factor varies greatly with size, age, stand density, species, and management regimes of forest (Chaturvedi and Khanna, 2011; Shrestha *et al.*, 2018a; Baral *et al.*, 2020). Using a single form factor for all the species and all sized individual is likely to introduce errors in estimating tree volumes. Thus, estimating form factor for each species in each geographical region is required to estimate the accurate volume of individual trees. Furthermore, form factor also provides important information about the rate of tapering of the stem of a tree which has a fundamental role in estimating the tree volume (Chaturvedi and Khanna, 2011). Deriving volume from DBH and height requires a mathematic relationship of volume with DBH alone or DBH and height. Such mathematical relationships are generally expressed as allometric equations. The allometric equations of volume with DBH and/or height have been used as one of the appropriate means to estimate the volume of an individual tree or the stand. Such prediction of the volume provides useful information in management and silvicultural research (Ozçelik *et al.*, 2010).

Forests cover 44.7% of the total area of Nepal (DFRS, 2015). These forests provide a significant proportion of contribution in the gross domestic product (GDP) (Ranjit, 2011; MOFSC, 2017) and are an integral part of livelihood in rural communities of Nepal (Pandey et al., 2010). These forests not only provide timber, fuelwood, fodder, food and grasses but also provide other ecosystem services, habitat for a large number of wild animals and store carbon dioxide emitted in the atmosphere (DFRS, 2015; Sadaula et al., 2020). Terai region of Nepal consists of 8.4% forests with an average growing stock of 161.7 m³ha⁻¹ and has an important tropical forest that provides habitat for economically valuable tree species including Sal (*Shorea robusta*, C.F. Gaertn, family Dipterocarpaceae) (DFRS, 2015).

The Sal tree is a large-sized dominant tree species that grows in the tropical forest of Nepal (Jackson, 1994). *Shorea robusta* grows up to a height of 30 m to 50 m and DBH of 3 m to 3.5 m (Chitale and Behera, 2012). *Shorea robusta* is distributed across Nepal, India, Bangladesh and Myanmar (Stainton, 1972; Gautam and Devoe, 2006; Awasthi *et al.*, 2015; Awasthi *et al.*, 2020). In Nepal, it is distributed from 120 m to 1200 m elevation but is more common in < 800 m elevation (Sah, 2000; Jackson, 1994). *Shorea robusta* contributes 19.3% (31.8 m³ ha⁻¹) in total standing volume, an average

stem number of 65 stems per ha (dbh ≥ 10 cm) and 15.3% of the forest area in Nepal are covered by *Shorea robusta* forest (DFRS, 2015). While comparing the species wise contribution, *Shorea robusta* is in the first rank in total standing volume, density and forest type coverage. *Shorea robusta* is a multipurpose tree species and has been extensively used as timber, construction material and fuelwood (Jackson, 1994), leaves as fodder (Kibria *et al.*, 1994) and plates (Kora, 2019), resin as medicine of dysentery and gonorrhoea (Joshi, 2003).

Despite the huge importance of *Shorea robusta* forest in the country, there are limited studies that focus on the measurement and estimation of growth and yield. A few biomass prediction equations of *Shorea robusta* have been developed by Chapagain *et al.* (2014) and Bhandari and Chhetri (2020), however, these biomass prediction equations are for small-sized individuals. Sharma and Pukkala (1990) developed volume equation of *Shorea robusta* using the sample from the whole country and Subedi (2017) developed volume equation of *Shorea robusta* using the sample from only two districts (Kanchanpur and Kailali) of Sudurpashchim province of Nepal. The volume equation of Sharma and Pukkala (1990) is very old and the equation of Subedi (2017) is restricted to small geographical areas. As the variability in altitude, rainfall, management regimes and disturbance exist in the forest of *Shorea robusta* across the country, a universal equation may not be able to accurately predict the volume. This emphasized the necessity of site or region-specific volume equations. While developing the volume equation, sub-model that can predict the under bark DBH from over bark DBH facilitates the prediction of under bark volume which is commonly used to estimating the timber volume during timber trade. Sub-model that can predict DBH from the stump diameter is also an important component of total volume prediction for the special cases such as prediction of individual tree volume from the stump that has been felled and removed in the past. These sub-models play an important role in predicting total volume and economic value of trees where the illegal felling of trees occurs.

The overall aim of this study was to determine the form factor and to develop a model that can predict the total stem volume of *Shorea robusta*. To achieve this aim, we estimated two different types of form factors (breast height form factor, and absolute form factor). To select the best model that can predict the volume of individual trees of *Shorea robusta*, we fitted different forms of the models and identified the best form of the model. After identifying the best form of the model, we further optimized the model of that form, using a different combination of predictor variables. We also simplified our models to make them more applicable depending on the availability of different predictor variables. The developed models were also compared with the previously developed volume models of *Shorea robusta*.

2. Materials and Methods

2.1 Study area

The study was conducted in Shamshergunj-Mathewas block forest (Area=2578 ha) of Banke district Nepal (27°36'N to 28°29'N and 82°2'E to 82°5'E) (Figure 1). The forest coverage in the district is 50.17% (DFRS 2015) and 48.14% of the total forest area is under Divisional Forest Office, Banke while the remaining forest is under the National Park and Buffer Zone (FMOP, 2017). The altitude of the district ranges from 127 m to 1231 m above mean sea level (FMOP, 2017). The forest is a *Shorea robusta* dominated forest and consist of other species such as *Syzygium cumini*, *Terminalia chebula*, *Terminalia belerica*, *Phyllanthus emblica*, *Woodfordia fruticose* and *Aegle marmelos*. The average minimum and maximum temperature measured in the nearest weather station are 9.3 °C in January and 34.4 °C in June and average annual rainfall is 1210 mm (DHM, 2017).
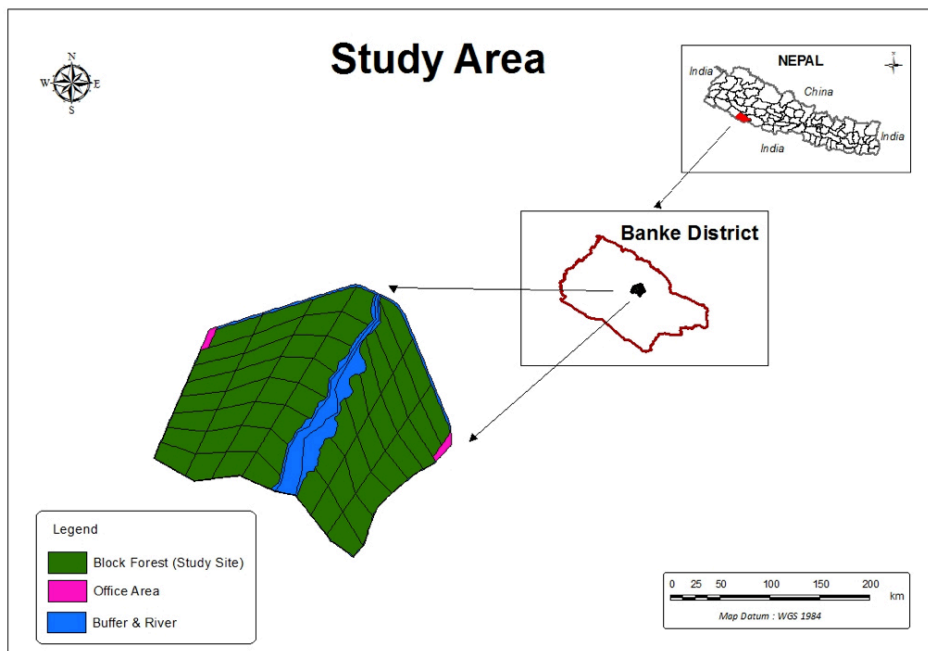

Figure 1: Map of Nepal showing location of study site.

Abbildung 1: Karte von Nepal mit Lage des Untersuchungsgebietes.

2.2 Data collection

Size variation of the individual *Shorea robusta* tree in the forest was identified from the previous measurements and documents of the forests. We selected 48 sample trees purposively from the whole forest in such a way that the selected sample trees could represent the variation in site quality, stand density, and tree size (Adinugroho and Sidiyasa, 2006; Shrestha *et al.*, 2018b). We physically inspected the potential sample trees to avoid broken top, abnormal stem, dead, dying and diseased (Shrestha *et al.*, 2018b; Bhandari and Chhetri, 2020). This is a quite common approach used in selecting the sample tree in purposive sampling to minimize the error. Since the forest consists of larger size *Shorea robusta* trees, our sample did not include trees smaller than 30 cm over bark DBH (DBHOB).

Data collection was carried out during February/March 2020. The over bark diameter at 0.3 m, 0.8 m, 1.3 m, and 1.8 m above the ground level were measured using the diameter tape before felling the trees. After felling the trees at 0.3 m above the ground level, the over bark diameter were measured at 2.8 m, 4 m, 6 m, up to the tip of the tree at the interval of 2 m. The under-bark diameter was also measured at each point where the over bark diameter was measured after removing the bark. The total height of felled trees was measured using linear tape and the height of stump was also added to obtain the total height of the sample tree. The sectional method was used for volume calculation of each tree, assuming stump as a cylinder, top portion as cone and all other middle portion as paraboloid. Therefore, we used the cylindrical formula for stump (equation 1), the Smalian formula for the middle portion (equation 2) and the conical formula for the top section (equation 3) of the tree.

$$Cylindrical\ volume = \frac{\pi\ D_1^2}{4} \times L \qquad (1)$$

$$Volume\ by\ Smalian\ formula = \left(\frac{\frac{\pi\ D_1^2}{4} + \frac{\pi\ D_2^2}{4}}{2}\right) \times L \qquad (2)$$

$$Cone\ volume = \frac{\pi\ D_1^2}{12} \times L \qquad (3)$$

In equations 1-3, for cylindrical volume D_1 is the diameter at thin end, and for Smalian and cone volume, D_1 is the diameter at the thick end, D_2 is the diameter at the thin end and L is the length of the section.

The total stem volume (over and under bark volume) of each tree was calculated by adding the volume (over and under-bark volume) of each section including the

stump and top portion of the tree. The summary of the data used in this study is presented in Table 1.

Table 1: Descriptive statistics of variables used for the form factor estimation and volume modelling.

Tabelle 1: Deskriptive Statistik der für die Formfaktorschätzung und Volumenmodellierung verwendeten Variablen.

DBHOB class (cm)	Variables	Mean±Std.(range)
30-40	Under bark DBH (cm)	29.96±2.92(26.40-34.70)
	Over bark DBH (cm)	34.77±3.27(30.20-39.40)
	Height (m)	22±3.61(14.10-27.70)
	Under bark volume (m^3)	0.76±0.20(0.47-1.16)
	Over bark volume (m^3)	1.02±0.22(0.71-1.32)
	Number	10
40-50	Under bark DBH (cm)	40.42±2.67(36-43)
	Over bark DBH (cm)	45.89±2.93(41.8-49.70)
	Height (m)	27.48±2.02(24-30.3)
	Under bark volume (m^3)	1.51±0.20(1.15-1.87)
	Over bark volume (m^3)	1.95±0.20(1.57-2.23)
	Number	10
50-60	Under bark DBH (cm)	48.62±3.14(43.7-51.8)
	Over bark DBH (cm)	55.25±3.32(50.6-59.6)
	Height (m)	29.40±1.03(27.2-30.4)
	Under bark volume (m^3)	2.16±0.27(1.69-2.44)
	Over bark volume (m^3)	2.85±0.37(2.09-3.23)
	Number	11
60-70	Under bark DBH (cm)	56.32±2.96(53.8-61.3)
	Over bark DBH (cm)	64.04±3.13(60-69.7)
	Height (m)	30.52±4.32(25-38.5)
	Under bark volume (m^3)	3.06±0.53(2.42-4.01)
	Over bark volume (m^3)	4.00±0.75(3.27-5.44)
	Number	10
>70	Under bark DBH (cm)	75.41±6.21(64.3-81.3)
	Over bark DBH (cm)	85.3±7.62(72.1-92.7)
	Height (m)	33.5±0.65(32.3-34.3)
	Under bark volume (m^3)	6.16±1.44(4.77-8.76)
	Over bark volume (m^3)	7.80±1.43(5.83-9.69)
	Number	7
Overall	Under bark DBH (cm)	47.78±14.50(26.40-81.30)
	Over bark DBH (cm)	54.50±16.19(30.20-92.70)
	Height (m)	28.13±4.57(14.10-38.50)
	Under bark volume (m^3)	2.41±1.75(0.47-8.76)
	Over bark volume (m^3)	3.12±2.18(0.71-9.69)
	Number	48

2.3 Data analysis

2.3.1 Estimation of form factors

We estimated two different types of form factor: (i) Breast height or artificial form factor, (ii) Absolute form factor. Breast height form factor was estimated as the ratio between the actual total stem volume of a tree above the ground level and the product of cross-sectional area at breast height and the total height of the trees (Equation 4) (Chaturvedi and Khanna, 2011). The absolute form factor was estimated as the ratio between the actual total stem volume of a tree and the product of cross-sectional area at any convenient height, and height of the tree above the point of measurement of cross-sectional area (Equation 5) (Chaturvedi and Khanna, 2011). We considered 0.8 m above the ground as a convenient height to calculate the absolute form factor. For both categories of form factors, over-bark and under-bark form factors were calculated.

$$Breast\ height\ FF = \frac{V}{\frac{\pi \times dbh^2}{4} \times H} \tag{4}$$

In equation (4), V is the actual stem volume of tree (m³), dbh is the diameter at breast height (m), and H is the total height of tree (m).

$$Absolute\ FF = \frac{V}{\frac{\pi \times d^2}{4} \times h} \tag{5}$$

In equation (5), V is the actual stem volume of tree (m³), d is the diameter at 0.8 m above the ground level (m), and h is the height of the tree above 0.8 m from the ground level (m).

2.3.2 Relationship of over bark diameter with under bark diameter and DBHOB with stump diameter

We fitted a linear model and a power model to predict under bark diameter from over bark diameter and DBH from stump diameter (over bark diameter at 30 cm above the ground) (Table 2). All diameter measurements along the stem were used to model the relationship between the over-bark and under-bark diameter.

Table 2: Fit statistics (R², RMSE and AIC) of model for predicting under bark diameter from over bark diameter and DBH from stump diameter (DO is over-bark diameter, DU is under-bark diameter, DBHOB is the diameter at breast height over bark, Stump DO is the stump diameter over bark).

Tabelle 2: Anpassungsstatistiken (R², RMSE und AIC) des Modells zur Vorhersage des Durchmessers ohne Rinde aus dem Durchmesser mit Rinde und des DBH aus dem Stubbendurchmesser (DO ist der Durchmesser mit Rinde, DU ist der Durchmesser ohne Rinde, DBHOB ist der Durchmesser auf Brusthöhe mit Rinde, Stubben DO ist der Stubbendurchmesser mit Rinde).

Model	Model form	Equation	R^2	RMSE	AIC
M1	Linear	$DU = -1.38 + 0.90\,DO + \varepsilon_{ij}$	0.9972	0.85	1765
M2	Power	$DU = 0.72\,DO^{1.04} + \varepsilon_{ij}$	0.9970	0.87	1797
M3	Linear	$DBHOB = 3.28 + 0.81 Stump\,DO + \varepsilon_{ij}$	0.9670	2.80	175
M4	Power	$DBHOB = 1.10\,Stump\,DO^{0.94} + \varepsilon_{ij}$	0.9669	2.81	175

2.3.3 Volume modelling

We fitted different forms of models including linear, logarithmic, inverse, quadratic, power, sigmoid and exponential (Table 3) to our data to select the best under bark volume prediction model. For volume prediction, we fitted the models with under bark volume as the dependent variable and under bark diameter as the predictor variable. The parameters and fit statistics for each model were estimated in R-platform using the lm, nls and nlsLM function in the minpack.lm package (R Core Team, 2017), and evaluated using different criteria including the significance of estimated parameters (at 5% level of significance); coefficient of determination (R^2); root mean squared error (RMSE) (Montgomery *et al.*, 2001); and Akaike Information Criterion (AIC) (Akaike, 1972). We also analysed the distribution of residuals against the predicted value in selecting the best model.

Table 3: Different forms of the estimated volume models with their respective R², RMSE and AIC. VU is under bark volume, DU is under bark breast height diameter).

Tabelle 3: Verschiedene Varianten der Volumenmodelle mit R², RMSE und AIC. VU ist Volumen ohne Rinde, DU ist der Brusthöhendurchmesser ohne Rinde.

Model	Model form	Equation	R^2	RMSE	AIC
M5	Linear	$VU = -3.07 + 0.11\,DU + \varepsilon_{ij}$	0.90	0.54	79
M6	Logarithmic	$VU = -17.47 + 5.20\,log\,DU + \varepsilon_{ij}$	0.80	0.76	111
M7	Inverse	$VU = 7.15 - \dfrac{207.30}{DU} + \varepsilon_{ij}$	0.67	0.98	134
M8	Quadratic	$VU = 0.86 - 0.05\,DU + 0.001\,DU^2 + \varepsilon_{ij}$	0.95	0.36	45
M9	Power	$VU = 0.00026\,DU^{2.32} + \varepsilon_{ij}$	0.95	0.36	43
M10	Sigmoidal	$VU = exp\left(3.56 - \dfrac{133.96}{DU}\right) + \varepsilon_{ij}$	0.93	0.44	63

Once the best form of volume equation was selected, different combinations of predictor variables were used in that form of volume equation by following the methods of Bhandari and Chhetri (2020). The different combinations of predictor variables used were DBH alone, the product of DBH and height, the product of the squared DBH and height. We developed two categories of volume models; (i) model based on DBH only and, (ii) model based on both DBH and height. For each category, we also developed the separate models to predict under bark volume from; (i) under bark DBH and, (ii) over bark DBH. We also developed a model to predict over bark volume from over bark DBH.

2.3.4 Comparison of volume models with previously developed models

The volume models developed in this study were also compared with previously developed stem volume models of *Shorea robusta* in Nepal. Sharma and Pukkala (1990) (Equation 6) and Subedi (2017) (Equation 7) had developed stem volume models for Shorea robusta in Nepal.

$$\ln(Volume) = -2.4554 + 1.9026 * \ln DBH + 0.8352 * \ln height \qquad (6)$$

$$\ln(Volume) = -8.04674 + 2.26641 * \ln DBH \qquad (7)$$

Where ln is natural logarithm and DBH is diameter at breast height (cm).

For comparison, we predicted the volume using the models of Sharma and Pukkala (1990), and Subedi (2017) and the models developed in this study. After predicting the volume from each model, we plotted the predicted volume against over bark DBH. To test whether the volume predicted by the model of this study and previously developed models differ significantly, we used paired sample t-test at a 95% confidence interval.

3. Results

3.1 Form factor

The variation in breast height form factor and the absolute form factor is presented in Figure 2. The median value of both breast height form factor and absolute form factor was higher for over bark form factor compared to under bark form factor. The over bark breast height form factor of *Shorea robusta* varied from 0.34 to 0.57 with an average value of 0.43, whereas under bark breast height form factor of *Shorea robusta* varied from 0.32 to 0.64 with an average value of 0.42. The over bark absolute form factor of *Shorea robusta* varied from 0.32 to 0.52 with an average value of 0.40, whereas under bark absolute form factor of *Shorea robusta* varied from 0.28 to 0.64 with an average value of 0.40).
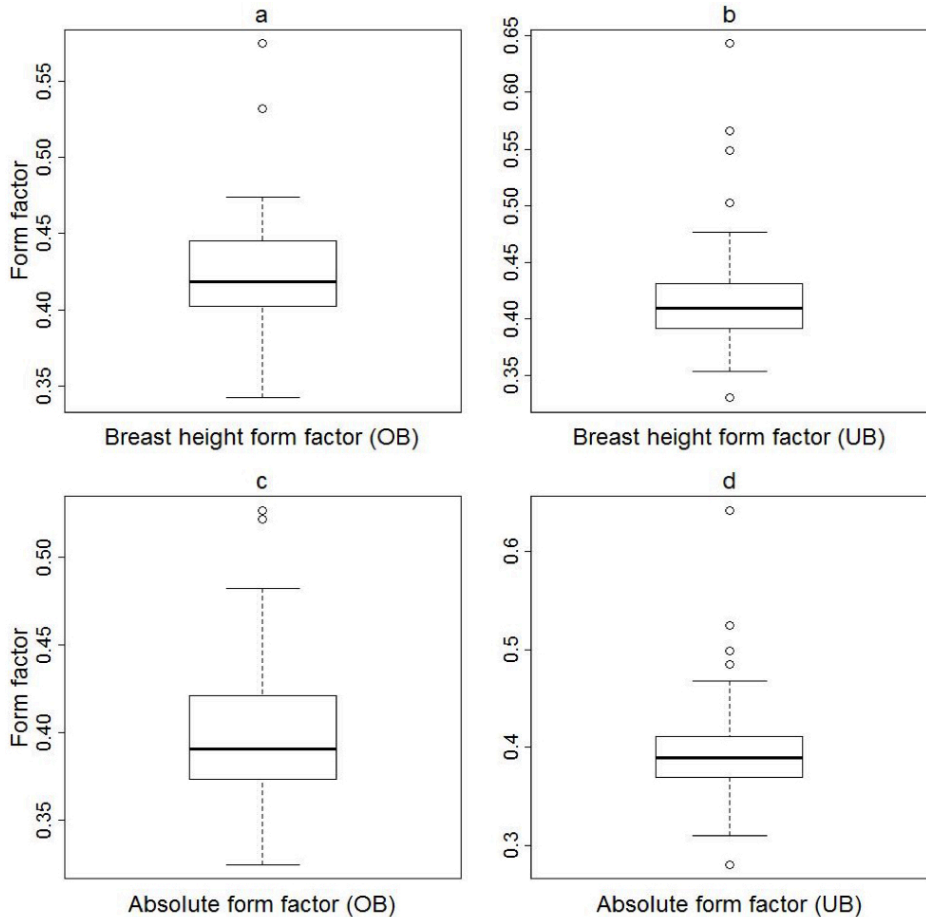
Figure 2: Variation of over bark absolute form factor and under bark absolute form factor. The box and whisker plots shows 25%, 75% quartile and median.

Abbildung 2: Variation des absoluten Formfaktors ohne Rinde und des absoluten Formfaktors mit Rinde. Die Box- und Whisker-Plots zeigen auch 25%, 75% Quartil und Median an.

3.2 Relationship of over bark diameter with under bark diameter and DBHOB with stump diameter

The linear model (M1) produced 0.02% more R^2, 2.29% less RMSE and 1.78% less AIC than the power model (M2) in predicting the under-bark diameter from the over-bark diameter. Similarly, the linear model (M3) produced 0.01% more R^2, 0.35% less RMSE and no improvement in AIC than the power model (M4) in predicting DBHOB from

over-bark stump diameter. Therefore, we selected the linear model (M1) to predict under-bark diameter from the over-bark diameter and linear model (M3) to predict the DBHOB from over bark stump diameter (Table 2).

3.3 Volume modelling

All the models, we fitted to predict volume, produced significant parameters at a 95% confidence interval. The inverse form of the model (M7) only described 67% of the variation in total stem volume with highest RMSE and AIC than other models (Table 3). The logarithmic form of the model (M6) only described 80% of the variation in total stem volume and with 0.76 RMSE and 111 AIC. The remaining four models described more than 90% variation in total stem volume. The residuals plotted against the predicted under bark volume showed that the power form of the model (M9) had minimum residuals compared to other models (Figure 4). The quadratic (M8) and power (M9) form of the model described more than 95% variation in total stem volume with a minimum residual of 0.36. The AIC of the power form of the model (43) was smaller than the AIC of the quadratic form of the model (45), therefore we selected the power form of the model for prediction of stem volume of *Shorea robusta*.
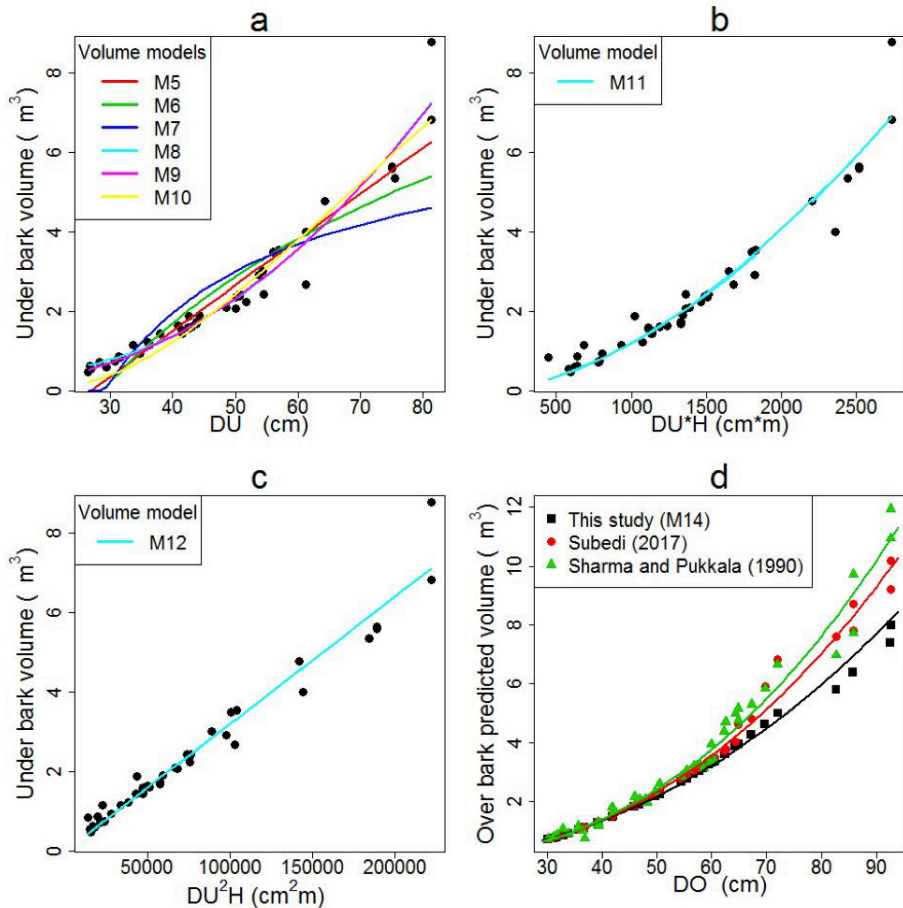
Figure 3: Different volume models and the observations (panel a); volume models based on the product of under bark diameter and height only (b); volume models based on the product of square of under bark diameter and height only (c); comparison of volume models developed in this study with the previous models (d).

Abbildung 3: Verschiedene Volumenmodelle und die Beobachtungen (Panel a); Volumenmodelle, die nur auf dem Produkt aus dem Durchmesser ohne Rinde und der Höhe basieren (b); Volumenmodelle, die nur auf dem Produkt aus dem Quadrat des Durchmessers ohne Rinde und der Höhe basieren (c); Vergleich der in dieser Studie entwickelten Volumenmodelle mit den bisherigen Modellen (d).
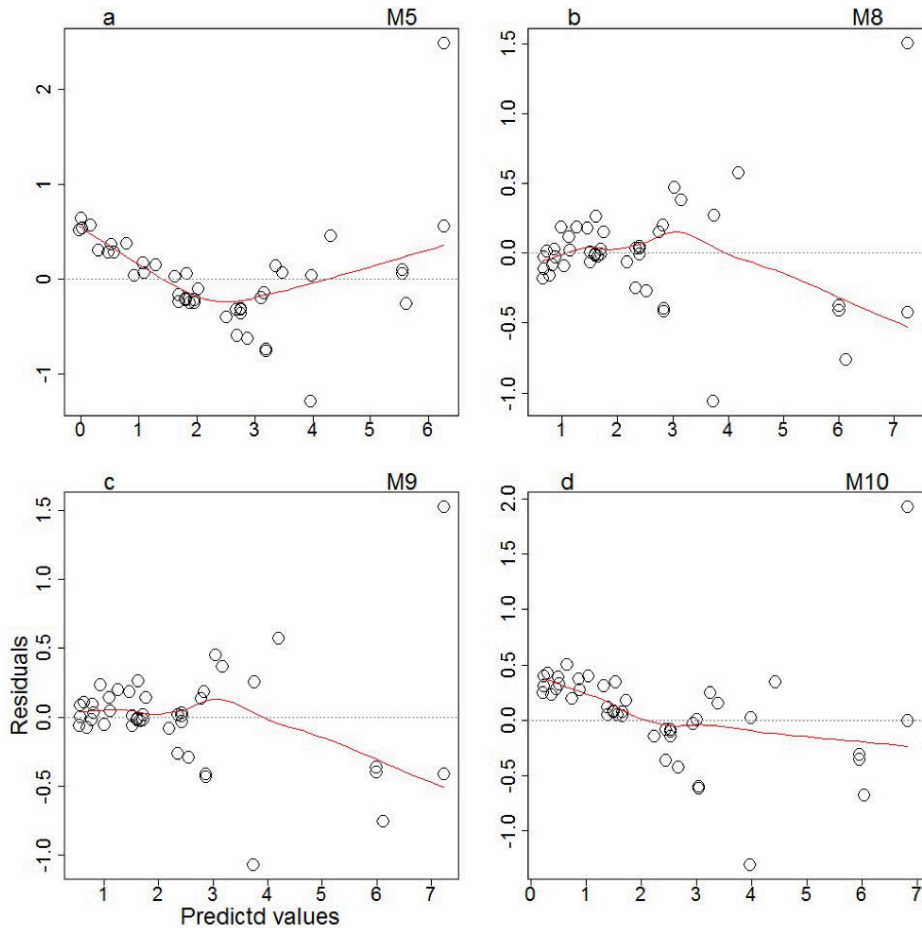
Figure 4: Distribution of residuals for four best performing volume models.

Abbildung 4: Verteilung der Restmengen für die vier leistungsstärksten Volumenmodelle.

The best-selected form of the model (power form; M9) was also further examined by including a different combination of predictor variables to optimize the predictive capacity of the model (Table 4). The estimated parameters for three different catego-ries of the power model were significant. The addition of height in the model did not improve the model, however, the addition of height with the square of under bark diameter improved the fit statistics by 1.05% in R², 9.09% in RMSE and 18.44% in AIC. The model M9 can be used to predict the volume when only DBH is available and model M12 can be used to predict volume when both DBH and height is available.

Table 4: Variables and the estimated values of the parameters used for volume prediction models of Shorea robusta in power form with their respective R², RMSE and AIC (DU is under bark DBH, H is total height).

Tabelle 4: Variablen und die geschätzten Werte der verwendeten Parameter für die Volumenvorhersagemodelle von Shorea robusta in Potenzform mit ihrem jeweiligen R², RMSE und AIC (DU der DBH ohne Rinde, H ist die Gesamthöhe).

Model	Variables	α_1	α_2	R^2	RMSE	AIC	Rank
M9	DU	0.00026	2.32	0.95	0.36	43.93	II
M11	DUH	0.0000075	1.73	0.94	0.40	54.49	III
M12	DU²H	0.000031	1.00	0.96	0.33	37.09	I

We further made our models more applicable depending on the availability of predictor variables (Table 5). Model M9 can be used to predict under bark volume using under bark DBH. Model M13 can be used to predict under bark volume using over bark DBH. Model M14 can be used to predict over bark volume using over bark DBH. Model M15 can be used to predict under bark volume using the square of under bark DBH and height. Model M16 can be used to predict under bark volume using the square of over bark DBH and height. Similarly, model M17 can be used to predict over bark volume using the square of over bark DBH and height.

Table 5: Power form of the model to predict over bark and under bark volume depending on the availability of different predictor variables of Shorea robusta.

Tabelle 5: Leistungsfähigkeit des Modells zur Schätzung des Volumens mit Rinde und ohne Rinde in Abhängigkeit von der Verfügbarkeit verschiedener Prädiktorvariablen von Shorea robusta.

Model	Model form	Equation	R^2	RMSE	AIC
M9	Power	$VU = 0.00026\,DU^{2.32}$	0.95	0.36	43.93
M13	Power	$VU = 0.00018\,DO^{2.34}$	0.95	0.35	41.06
M14	Power	$VO = 0.00033\,DO^{2.25}$	0.97	0.31	29.90
M15	Power	$VU = 0.000031\,(DU^2H)^{1.00}$	0.96	0.33	37.90
M16	Power	$VU = 0.000023\,(DO^2H)^{1.00}$	0.96	0.33	35.56
M17	Power	$VO = 0.000044\,(DO^2H)^{0.97}$	0.98	0.25	9.91

3.4 Comparison of models with previously developed volume models

The predicted volume by the model of this study (M14) was significantly different (p<0.05) with the predicted volume of each of the previous models of Subedi (2017) and Sharma and Pukkala (1990). All these three models predicted almost the equal volume for the trees with smaller DBHOB, however, the difference increased with an increase in DBHOB (Figure 3d).

4. Discussion

This study found an average value of over bark breast height form factor 0.43 which is 14% lower than the average value of 0.50 recommended by the Department of the forest, Government of Nepal, for all species across the country (DOF 2004). In a study carried out to estimate the form factor of *Shorea robusta* from the Bara district of central Terai, Nepal, Baral *et al.* (2020) reported the over bark average breast height form factor 0.33 and under bark average breast height form factor 0.27. This has prevailed that the form factor recommended by the government of Nepal overestimate the standing volume of the individual trees while the form factor recommended by Baral *et al.* (2020) underestimates the standing volume of the individual trees. Shrestha *et al.* (2018a) reported the form factor up to 10 cm top diameter of *Shorea robusta* 0.51 to 0.65, *Dalbergia sissoo* 0.50 to 0.56 and *Terminalia alata* 0.52 to 0.66. Similarly, Thakur (2006) estimated the form factor for *Shorea robusta*, *Schima wallichii*, *Castanopsis indica*, *Pinus roxburghii* in middle hill district (Parbat district) of Nepal. He found form factor of *Shorea robusta* 0.58, *Schima wallichii* 0.57, *Castanopsis indica* 0.58 and *Pinus roxburghii* 0.63. Adekunle *et al.* (2013) estimated form factor of major tree species of Katarniaghat Wildlife Sanctuary which ranged between 0.42 to 0.57. Thakur (2006) reported that the form factor at the pole stage was higher than form factor at sapling or mature stage. Baral *et al.* (2020) also reported that the form factor of *Shorea robusta* was higher for medium-sized trees compared to smaller and larger-sized trees. It also revealed another fact that form factor varied not only with species and geographical region, but also with the age of the individual trees. Stand density (number of trees ha⁻¹ or basal area ha⁻¹) plays an important role in the growth of DBH and height of individual trees (Bhandari *et al.*, 2021b). The individual tree that grows in low stand density prioritizes more for diameter growth while the individual tree that grows in high stand density prioritizes more for height growth. This results in individual trees with a shorter heights and larger diameters (low height-diameter ratio) in low-density stands, and taller heights and smaller diameters (high height-diameter ratio) in high-density stands. These varying levels of stand density effects on individual tree growth also influences the stem form of trees.

Our study showed a linear relationship between under bark and over bark diameter and between DBH and stump diameter. In a growth analysis of *Pinus roxburghii*, Gyawali *et al.* (2015) reported that the linear function performed best to describe over bark and under bark diameter relationship. In a growth modelling study of *Shorea ro-*

busta, Sapkota and Meilby (2009) found a simple power model best described the relationship between over bark and under bark diameter and between DBH and stump diameter. The relationship between over bark and under bark diameter is applicable in predicting under bark diameter, under bark basal area, under bark volume from the over bark measurement.

Results from this study revealed the simple power form of the volume models performed best in predicting the individual tree volume compared to other forms of the models. This result is in agreement with several other studies which also showed the simple power function as the best model form in predicting either volume or biomass of individual trees (Sharma *et al.*, 2017; Shrestha *et al.*, 2018b; BK *et al.*, 2019; Bhandari and Chhetri, 2020). It is a well-established fact that the volume, biomass or its growth generally follows a non-linear pattern, however, the form of the non-linear model might be different with species, geographical region and stand density (Huxley and Teissier, 1936; Chave *et al.*, 2005; Chapagain *et al.*, 2014).

Diameter at breast height and the total height of the individual trees are the commonly used predictor variables along with wood density, crown measures, stand density and some other measures of competition. However, using DBH only is one of the most common practice because the measurement of DBH is easier, accurate and cost-effective compared to height and other variables. Our study showed that DBH alone can describe more than 95% variation in stem volume of *Shorea robusta*. Addition of height together with DBH as predictor variable improved the model predictability (1.05% increase in R^2, 8.33% decrease in RMSE and 15.57% decrease in AIC) (Table 5, model M12). Models with DBH only as predictor variable can also be used with acceptable accuracy in the absence of height data. Other studies have reported DBH alone (Nurudeen *et al.*, 2014; Subedi, 2017; Shrestha *et al.*, 2018a), DBH and height (Sharma and Pukkala, 1990; Mugasha *et al.*, 2016) and DBH, height and other predictors (Nurudeen *et al.*, 2014) for predicting the individual tree volume depending on the availability of predictor variables.

We have developed different volume equations to facilitate the prediction of volume depending on the availability of predictor variables. The volume models developed in this study can be used to predict both over bark volume and under bark volume from both over bark DBH and/or under bark DBH. Volume can also be predicted if only DBH data is available or both DBH and height data are available. Our models also facilitate the prediction of under bark DBH from over bark DBH. The allometric relationship between stump diameter and DBH is applicable to predict the DBH and volume of individual trees which were already felled in the forest and the only stump is available. This model might contribute to estimating the timber volume of individual trees which might have been illegally felled and removed from the forest.

As the models developed in this study are based on data from a forest of Banke District, these models may not be able to predict the accurate volume of individual trees

of other geographical regions. We observed that the predicted volume of our model differed significantly with those of the earlier model of Sharma and Pukkala (1990) and Subedi (2017). The models of Sharma and Pukkala (1990) was developed using the data collected from across Nepal and the model of Subedi (2017) was developed using the data collected from the two districts (Kanchanpur and Kailali) of the far western part of Nepal. The number of sampled trees used in the model of Sharma and Pukkala (1990) was 895 and in the model of Subedi (2017) was 81 however the number of individual trees used in the present study was only 48. The size of the individual trees used in the models of Sharma and Pukkala (1990) ranged between 12.70 cm to 144.50 cm in DBH and that of Subedi (2017) ranged between 30.10 cm and 108.50 cm in DBH. The DBH range of individual trees used in the present study was relatively smaller (30.20 to 92.7 cm in DBH) than that of Sharma and Pukkala (1990) and Subedi (2017). Besides these, variation in the climate (rainfall and temperature), stand density (basal area and/or number of trees per unit area), management regimes and human disturbance might have played a significant role in the *Shorea robusta* forest used in these three studies. This demonstrates that the models developed from one geographical region may not be able to predict the volume accurately in another geographical region even for the same species. Therefore, the development of volume prediction models for each region or at least for each state of Nepal is recommended. Alternately, a parameter describing the regional variation in tree shape may be included in the volume equation.

The form factors and volume models developed in this study have potentials to contribute to predicting volume, biomass and carbon for the individual trees of *Shorea robusta*. As these volume models facilitate the prediction of volume/biomass/carbon from the *Shorea robusta* forests, this will contribute to the calculation of national carbon budgets of Nepal. Precise prediction and estimation of products from a forest always facilitate in making appropriate decisions in forest management. Indirectly, the model developed in this study will contribute to minimizing the climate change effect through the sustainable management of forest. The sustainable management of forest is not only associated with carbon sequestration and greenery but also associated with livelihood improvement of local people. The modelling approach used in this study might be useful for the development of volume prediction model for other species from the same region or species from other geographical regions. Model validation is one of the important steps in the formulation of the model, however, we could not validate our models because of the lack of independent data sets. Validation of these models with independent data sets is recommended in future to test whether these models can be generalized in other parts of the country.

5. Conclusion

We estimated two types of form factor (breast height form factor and absolute form factor) for *Shorea robusta* from the western low land of Nepal. The average breast height form factor was 0.43 and 0.42 for over bark and under bark respectively while

the average absolute form factor was 0.40 for both over bark and under the bark. The linear model fitted best to describe the under bark to over bark relation and DBH to stump diameter relation. Simple power function best fitted to our volume model. Product of DBH squared and height performed as the best predictor (R^2=0.96). This study showed a lower value of form factor than the form factor prescribed by the Department of Forest, Government of Nepal. The estimated form factor and developed volume models in this study are significantly different from the previous studies. Thus, we recommend estimating separate form factor and develop the different site and size-specific volume models across the country. The models developed in this study are expected to contribute to predicting volume, biomass and carbon amount and thus contribute to the calculation of national carbon budget.

Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

The concept of this study was designed by Mr. Thakur Subedi and Mr. Dipak Mahatara. Data were by collected by Mr. Thakur Subedi, Mr. Dipak Mahatara and Mr. Nabin Pandey. Mr. Shes Kanta Bhandari and Mr. Yajna Prasad Timilsina analysed the data and developed the models. Mr. Shes Kanta Bhandari prepared the draft manuscript. All authors have read thoroughly and agreed to the submitted version of the manuscript.

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