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Local Volume Equations and Tables for two Forest Management Units in Bhutan: An Attempt to Provide FMU Specific Estimate of Timber Volume for Sustainable Forest Management

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Abstract

This study developed tree species specific local volume equations and tables for Lingmethang and Rongmanchu Forest Management Units. The field work was conducted between December, 2019 and January 2020. Data was collected for five species (*Schima* sp., *Ltihocarpus* sp., *Acrocarpus fraxinifolius, Pinus roxburghii* and *Castanopsis tribuloides*) for Lingmethang FMU and six species (*Beilschmedia* sp., *Persea* sp., *Quercus* sp., *Alnus nepalensis, Schima wallichii* and *Cinnamomum* sp.) of trees for Rongmanchu FMU. The height and diameter over bark were measured for every sample trees. Using the height and diameter, volumes for each sample tree was calculated and then the models generated were fitted with a minimum of 32 trees per species, which were destructively felled for the purpose. The models were run in R version 3.4.4. A total of 16 models were fitted and tested for each species. The selected models performed well with small deviation for individual trees.

Keywords: Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), forest management, model performance, local volume equations and tables

Introduction

Precise estimation of tree volume is the bedrock of sustainable forest management (Phuntsho *et al.*, 2019). Volumes of trees are estimated using allometric volume equations since it is practically impossible to cut down all trees and measure their volumes. For ease of use by the field staff, the volume tables are developed using the volume equations. While this makes it easier and convenient for the field staff and management to estimate volume, it is important to note that there is some deviation on the precision of the volume estimated using the volume tables. The volume tables that are currently being used in Bhutan are developed based on the volume equations developed using data collected during pre-investment survey (Laumans, 1994).

Therefore, in this study, effort was made to develop local volume tables for Lingmethang and Rongmanchu Forest Management Units (FMUs), based on local volume equations that have been developed in this study. Data were collected for five and six species of trees for

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Lingmethang and Rongmanchu FMU respectively through destructive sampling. The height and diameter over bark (DOB) were measured. Using the heights and DOB, volume for each sample tree was calculated using Smalian's formula for each section of log. Then, using the volume as a response variable, the models were fitted against explanatory variables such as diameter at breast height (DBH), basal area (BA), squared DBH x height (DBH^2H) and basal area x height (BAH). While foliage and branch volume constitute a sizeable amount of total volume of a tree, these volumes have been excluded and only volume of the main trunk up to 2 cm top DOB has been considered in calculating the total volume for modeling in this study. The focus was on estimating the timber volume rather than the total volume or biomass of a tree.

Hence, the volume estimated by volume equations and tables developed in this study will estimate the total volume of trees without branch and foliage volume, as the core interest of this study was to develop local volume equations and local volume tables to estimate timber volume up to 2 cm top DOB in the two FMUs.

Method and Materials

Study area

The data was collected from two FMUs – Lingmethang Forest Management Unit (LFMU) and Rongmanchu Forest Management Unit (RFMU) which are located in Mongar and Lhuntse Dzongkhags respectively. While the altitude of LFMU ranges from 640 m to 3321 m above mean sea level (amsl), the altitude for RFMU ranges from 965 m to 3865 m amsl. The main forest types of the FMUs are chirpine and warm broadleaved forests in lower elevation and drier areas; and cool broadleaved, blue pine, mixed conifer and fir forests in the higher elevation and moist areas.

Data collection

We felled 32 sample trees per species and collected data on heights and DOB. The sample trees included trees from different social classes, meaning some were suppressed, while others were dominant and co-dominant trees. This social class consideration was made to ensure that sample trees represent actual field conditions and provide unbiased estimate. Further, locations of sample trees were also carefully chosen to ensure that all possible locations – productive vs unproductive and disturbed vs pristine are covered well by the sampled trees. We first measured the diameter at zero height or at ground level and breast height. Following this measurements, the sample trees were felled at 0.3 m above the ground. Then the diameter was measured at 0.7 m from the base of the log or stump height. Subsequently, at every meter section we measured and recorded the DOB up to 2 cm top diameter.

Volume calculation

Although sections rarely form true circles, they are assumed so for the purpose of calculating cross sectional area in meter square, which is;

$$\text{Cross sectional area (A)} = A = \pi r^2 = \frac{\pi D^2}{4*10000} \quad (1)$$

Where r is the radius in meters and D is the diameter at breast height in centimeters.

The most commonly used formulae for calculating volume are the Huber, Newton and Smalian's formulae (Goulding, 1979; Sadiq, 2006). Of the three commonly used volume calculation approaches or formulae, the Smalian's formula was used to calculate the volume (in m^3) for this study, which is;

$$\text{Section volume } (V_s) = \frac{A+a}{2} * L \quad (2)$$

Where A = Cross sectional area in m^2 at large end of the section, a = Cross sectional area in m^2 at small end of the section, L = Length of the section in meter

Smalian's formula is the easiest and least expensive to apply as it involves measuring the diameter of logs at two ends (Brickell, 1984) and therefore we applied it to get the volume for each section of the sampled trees, while Newtwon's and Huber formulae require mid diameter measurement of logs which are practically difficult and involves measurement errors. Volumes of all sections for each tree were then summed to obtain the total volume for all sampled trees, which is;

$$\text{Volume of tree (V)} = \sum_{s=1}^{n} V_s \quad (3)$$

Here, only the main trunk volume is considered since the interest is to account for estimating the timber volume and not the total volume.

Fitting models

We fitted the models in R version 3.4.4. The data was prepared in Excel and imported into R environment for modeling. After loading the Excel file in R, basal area in square meter (BA.m2), basal area in meter times height in meter (BAH.m3) and squared DBH in meter times height in meter (DBH^2H.m3) were calculated. Other variables include the height in meter (Height.m) and diameter at breast height in centimeter (DBH.cm), which were measured in the field.

Descriptive summaries which provided mean, median and range of response and explanatory variables before fitting the models and data were checked. Then we plotted scatter graphs to obtain a visual sense of relationship between the response (volume) and explanatory variables (namely DBH.cm, BA.m2, DBH^2H.m3 and BAH.m3). The scatter plots showed curvilinear relationship between response and explanatory variables. They also revealed the presence of phenomenon, referred in statistical parlance, as heteroscedasticity, which is the increase in variation in response variable with increase in value of the explanatory variables, as was observed by Phuntsho *et al*. (2019).

The models were fitted using the gls ( ) function of the nlme package of R, which has the robustness to model heteroscedasticity. The response variables were not transformed, as it makes it difficult to directly interpret the relationship between response and explanatory variables; and secondly to compare the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values among different models, the response variables need to be identical and thirdly, the transformation attempts to normalize the data (Steson and Sally, 2015), which is not the case in forestry. The models were fitted with volume as a function of four variables; DBH.cm, BA.m2, DBH^2H.m3 and BAH.m3.

For each of the variable, one simple gls ( ) function was fitted for all species, which takes the form;

$$Y = \beta_0+\beta_1X + \varepsilon, \quad (4)$$

Where Y = Volume (V) and X = explanatory variable

And then we fitted 3 models with restricted natural cubic spline functions. The restricted natural cubic spline function enables better tracking of curvilinear relationship between response and explanatory variables (Umunay *et al*., 2017) without transforming the variable. These models introduce an additional predictor variable as part of a 3 knot-cubic spline. They take the following forms;

$$Y = \beta_0+\beta_1X_1 + \beta_2X_2 +\varepsilon, \quad (5)$$

Where Y = Response variable, volume (V),
X_1 = Explanatory variable,
$X_2 = g(X_1)$,
and $g(X_1)$ is the spline transformation of X_1 explanatory variable.

Model selection

We fitted a total of 16 models for each species. For all species except *Cinnamomum* sp., the model 7, fitted without height and model 15 fitted with height as explanatory variable came out to be the best fit model. The model 8 and 16 fitted with and without height as explanatory variables were best fit model for *Cinnamomum* sp. We selected the best fit models based on AIC and BIC values of the fitted models. The BIC value was mainly relied upon as it is more consistent and imposes a stronger

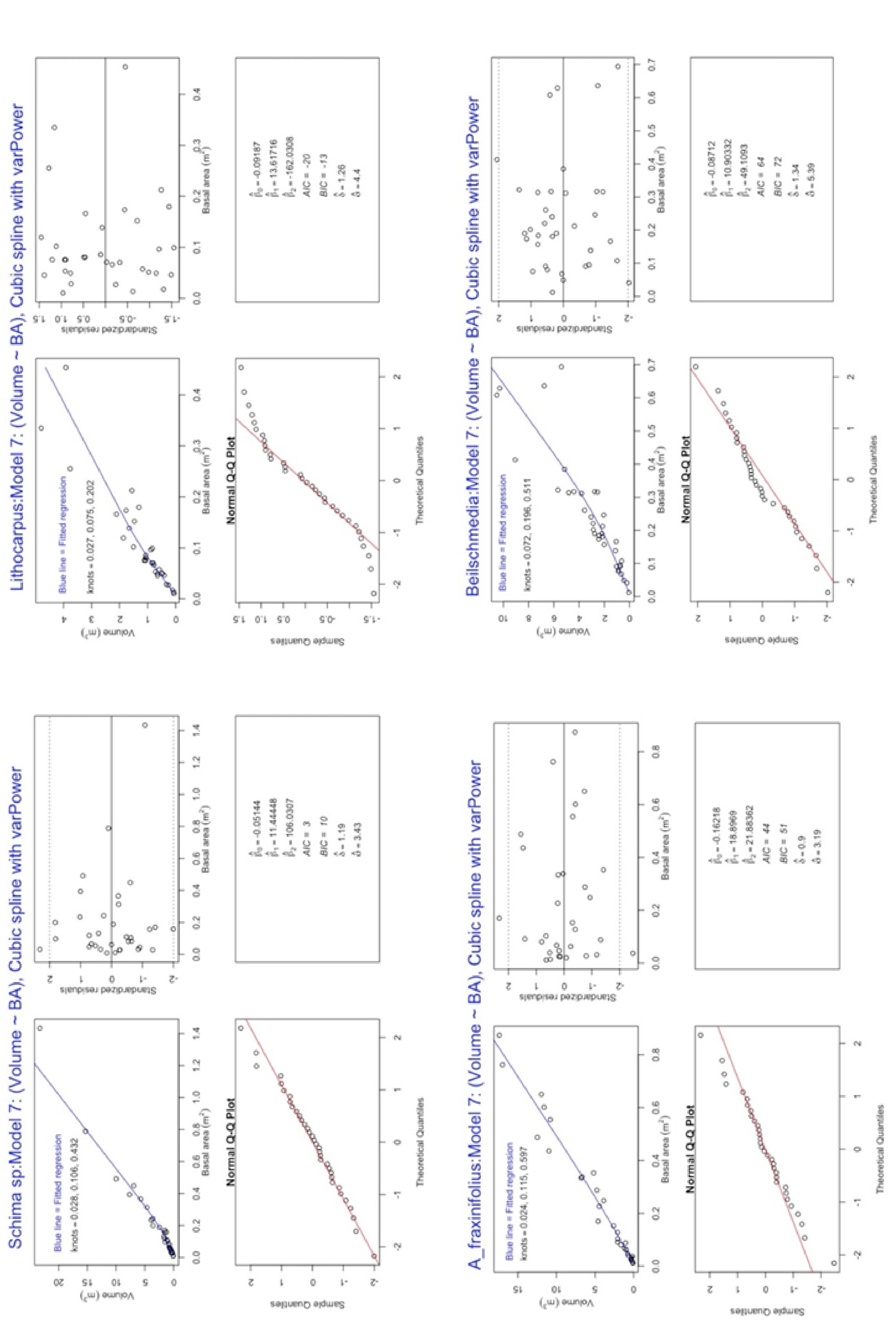


Figure 1: Plots of the selected models without height as explanatory variable

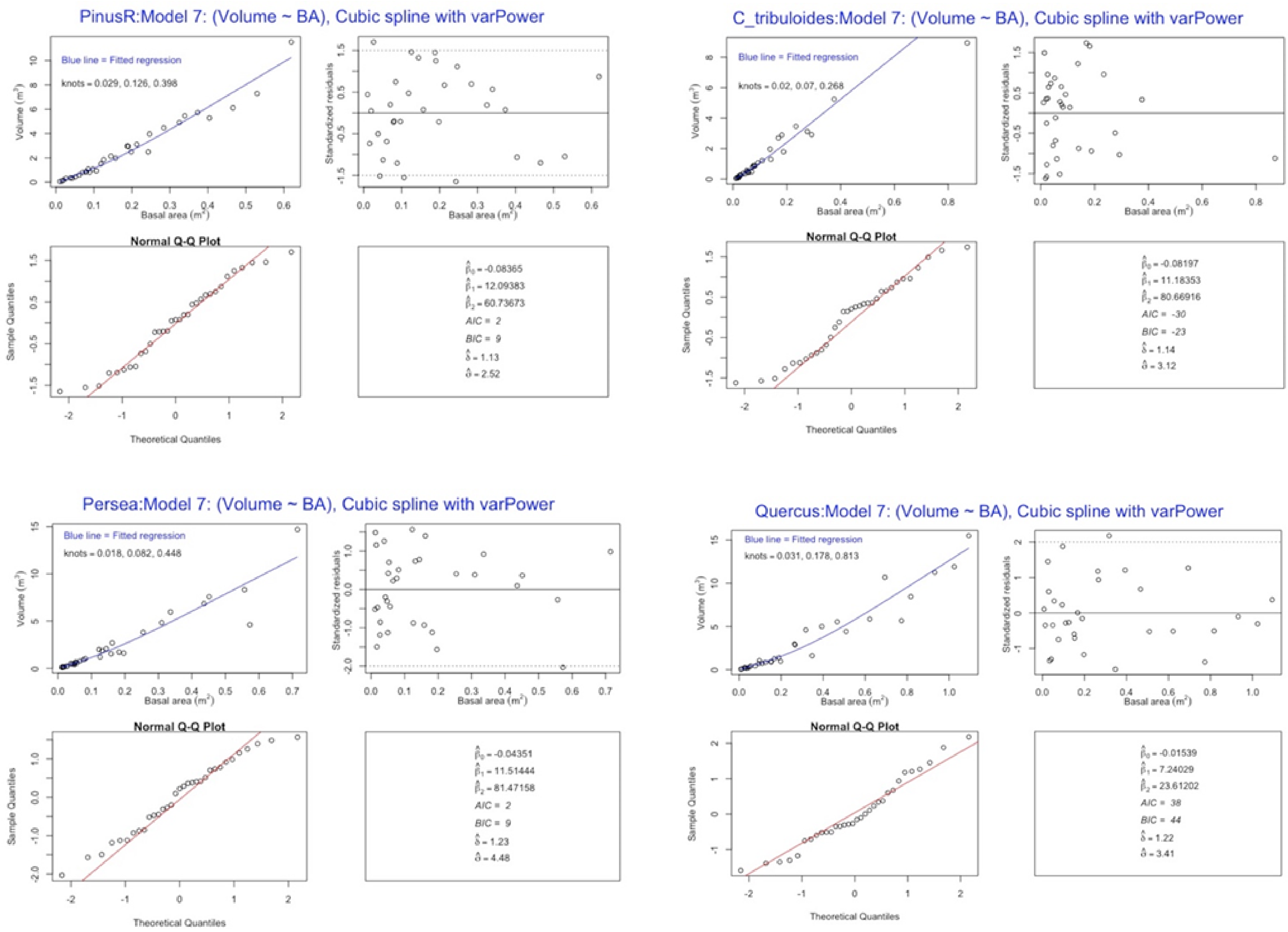
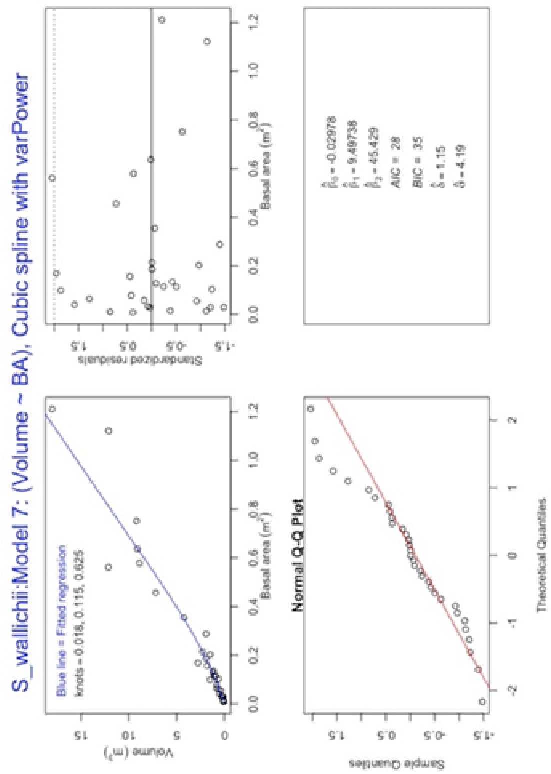


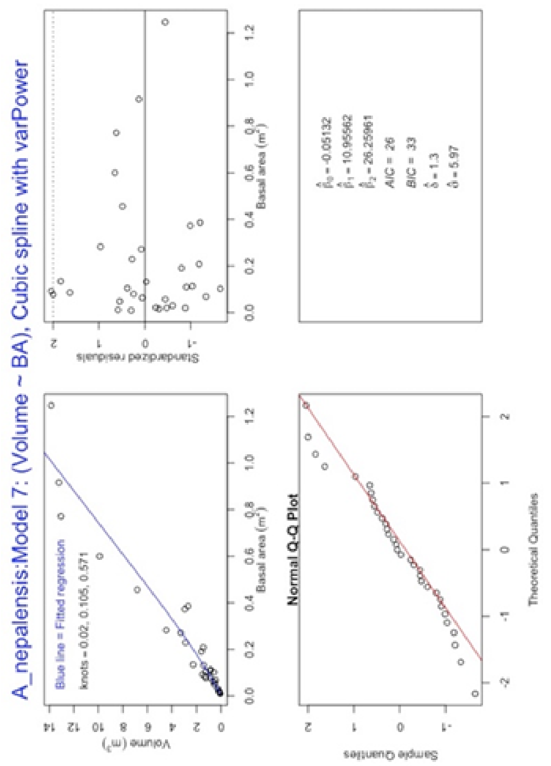
Figure 1: Plots of the selected models without height as explanatory variable *continued*…

penalty for the number of parameters in the model that need to be estimated (Acquah and Carlo, 2010). Smaller the values of AIC and BIC, better the fit of the model.

Two models were selected for each species, one without height (X_1= BA.m2) and the other with the height (X_1 = BAH.m3) as explanatory variables. Both the models were fitted with natural (restricted) cubic spline function within a linear model framework. However, for developing the volume tables in this study, the model fitted without height was selected as the best fitted model for each species, given the reasons cited in the recommendations and conclusion section. The plots of selected models used for developing local volume tables for the two FMUs are shown in the subsequent sections.

Although, nonlinear models are more flexible, they are more complicated mathematically and the complications involved in fitting nonlinear models often fail to justify the improvements it brings forth in the models (Phuntsho *et al*., 2019). Moreover, the models fitted with natural (restricted) cubic spline functions outperform and track the curvilinearity better.





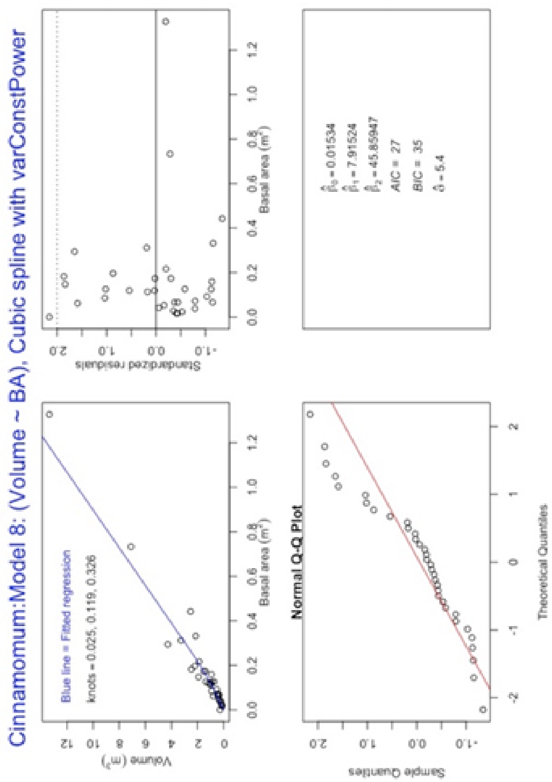


Figure 1: Plots of the selected models without height as explanatory variable *continued…*

Table 1: Selected Models

Species (Model)	AIC	BIC	β_0	β_1	β_2	t_1	t_2	t_3
Schima sp.	3	10	-0.05144	11.44448	106.0307	0.028	0.106	0.432
Lithocarpus sp.	-20	-13	-0.09187	13.61716	-162.0308	0.027	0.075	0.202
Acrocarpus fraxinifolius	44	51	-16218	18.8969	21.88362	0.024	0.115	0.597
Pinus roxburghii	2	9	-0.08365	12.09383	60.73673	0.029	0.126	0.398
Castanopsis tribuloides	-30	-23	-0.08197	11.18353	80.66916	0.02	0.07	0.268
Beilschmedia sp.	64	72	-0.08712	10.90332	49.1093	0.072	0.196	0.511
Persea sp.	2	9	-0.04351	11.51444	81.47158	0.018	0.082	0.448
Quercus sp.	38	44	-0.01538	7.24029	23.61202	0.031	0.178	0.813
Alnus nepalensis	26	33	-0.05132	10.95562	26.25961	0.02	0.105	0.571
Cinnamomum sp.	27	35	0.01534	7.91524	45.85947	0.025	0.119	0.326
Schima wallichii	28	35	0.02978	9.49738	45.429	0.018	0.115	0.625

The selected models with their AIC, BIC, β_0, β_1, β_2, t_1, t_2 and t_3 values are presented in the Table 1.

Demonstration of use of the selected best fit model

Using a *Pinus roxburghii* tree with diameter of 50.2 cm, the use of selected model was tested as hereunder. In general, the natural spline predictor with knots represented by t_1, t_2 and t_3 takes the following form;

$$Y = \beta_0 + \beta_1 X + \beta_2 X_s + \varepsilon \quad (6)$$

Where X_S corresponds to value in X as follows:

$$Xs = g(X) = (X - t1)^3_+ - (X - t2)^3_+ \frac{(t3-t1)}{(t3-t2)} + (X - t3)^3_+ \frac{(t2-t1)}{(t3-t2)} \quad (7)$$

and the value of the positive part functions depend on the values of the knots as follows;

$$(X - t1)^3_+ = (X - t1)^3_+ ,$$

if X > t1 and $(X - t1)^3_+$ =0, if X<t1 (8)

$$(X - t2)^3_+ = (X - t2)^3_+ ,$$

if X> t2, and $(X - t2)^3_+$ = 0, if X < t2 (9)

$$(X - t3)^3_+ = (X - t3)^3_+ ,$$

if X > t3, and $(X - t3)^3_+$ =0, if X<t3 (10)

Where t_1, t_2 and t_3 for the above models are 10th, 50th and 90th percentiles and are called knots. The values of knots differ from species and models.

To demonstrate use of the selected models for *Pinus roxburghii* – model 7, the knots t_1, t_2 and t_3 are 0.029, 0.126 and 0.398 as generated by the model. The model 7 was fitted with volume as function of basal area in meter square (BA.m2) i.e.;

$$BA = \pi r^2 \quad (11)$$

where in;

$$r^2 = \left[\frac{dbh}{2*100}\right]^2 \quad (12)$$

Where *r* is radius in meters and dbh is diameter at breast height in centimeters.

Therefore, *Pinus roxburghii* with diameter of 50.2 cm gave the basal area of 0.19792348 m^2, which volume can be estimated using the equation (model 7) as below. But first the value of basal area in meter (BA.m2) has to be calculated, which is;

$$BA = \pi r^2 = \frac{\pi * 50^2}{200^2} = 0.19792348 \text{ m}^2$$

$$g(X) = (X - t1)^3_+ - (X - t2)^3_+ \frac{(t3-t1)}{(t3-t2)} + (X - t3)^3_+ \frac{(t2-t1)}{(t3-t2)}$$

$$g(BA) = (BA - t1)^3_+ - (BA - t2)^3_+ \frac{(t3-t1)}{(t3-t2)} + (BA - t3)^3_+ \frac{(t2-t1)}{(t3-t2)}$$

$$g(BA) = (0.19792348 - 0.029)^3_+ - (0.19792348 - 0.126)^3_+ \frac{(0.398-0.029)}{(0.398-0.126)} + 0$$

$$g(BA) = (0.16892348)^3_+ - (0.0.07192348)^3_+ \frac{(0.369)}{(0.272)} + 0$$

$$g(BA) = 0.00482026 - 0.00037206 * 1.35661765 + 0$$

$$g(BA) = 0.00482026 - 0.00050474$$

$$= 0.00431552$$

Hence, the volume predicted for this tree by the selected model (model 7) is

$$V = \beta_0 + \beta_1.BA + \beta_2 BA.m_2 + \varepsilon$$

= -0.08365+ 12.09383* 0.19792348 + 60.73673*0.00431552

= -0.08365+2.3936529 +0.26211057

= 2.5721135 m^3

However, the field measured volume for this tree with DBH of 50.2 cm was 2.48665678 m^3, thus resulting in a difference of 0.0854567 m^3, which was a slight overprediction by the model. This overestimation seems acceptable.

Spline functions are piecewise polynomials used in curve fitting. In other words, rather than trying to find a single transformation and fitting a single relationship between response (Y) and explanatory (X) variables, we divided the range of explanatory variable (X) values into intervals, within each interval fit relationship between X and Y variables and joined the fitted values together at their ends. These joints or the meeting points of polynomials which are called knots.

Model performance

Equally, if not more, important is to assess the performance of the models after developing them. The selected models were assessed for their performance by comparing the volumes predicted by the selected models with the actual volumes as measured and calculated using the field data using Smalian's formula. The results presented in Table 2 below shows the selected model number in bracket for each species, the number of trees sampled for each species, the total actual field measured and total predicted volume of all sampled trees, and the difference between actual and predicted volume. Visual representations of the model performance for each tree are shown graphically in the Figure 2.

Table 2: Model Performance - Comparison between actual and predicted (by selected models) volume of sampled trees

Species (Selected model number)	No of sample trees	Actual volume (m^3) of sampled trees as measured	Volume (m^3) of sampled trees as predicted by the selected model	Difference in volume (m^3) which is actual – predicted volume.
Schima sp. (7)	34	104.69	108.37	-3.68
Lithocarpus sp. (7)	34	41.13	40.82	0.31
Acrocarpus fraxinifolius (7)	32	145.27	145.16	0.11
Pinus roxburghii (7)	33	84.71	84.75	-0.04
Castanopsis tribuloides (7)	33	44.65	46.78	-2.13
Beilschmedia sp. (7)	36	110.23	111.85	-1.62
Persea sp. (7)	33	78.67	78.66	0.01
Quercus sp. (7)	32	107.18	107.72	-0.54
Alnus nepalensis (7)	33	91.37	91.36	0.01
Schima wallichii (7)	33	103.73	106.83	-3.1
Cinnamomum sp. (8)	34	56.86	60.29	-3.43

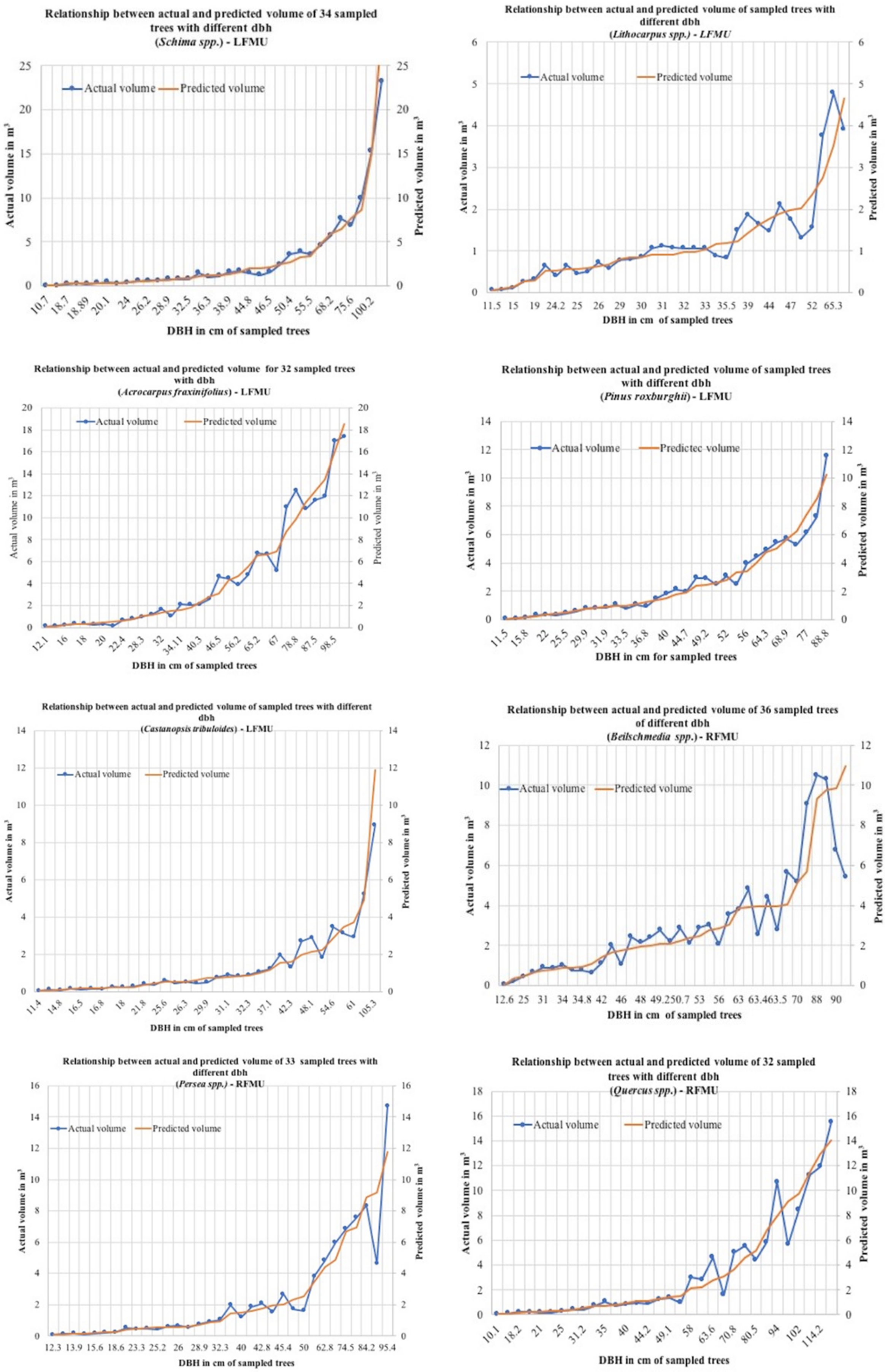
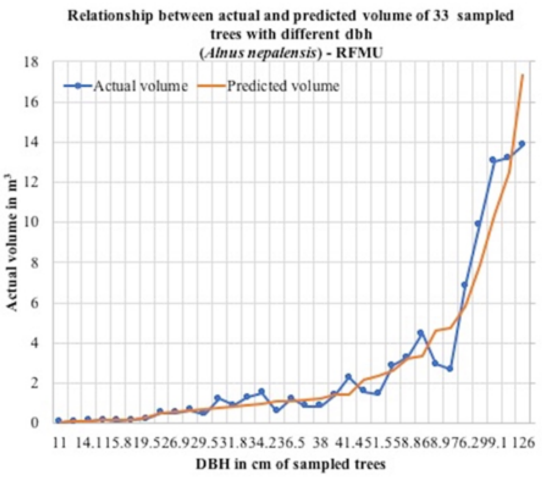
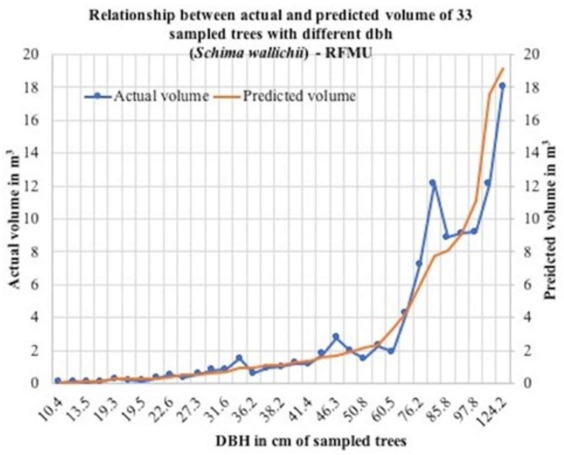


Figure 2: Graphical representation of relationship between actual & predicted volume of all sampled trees





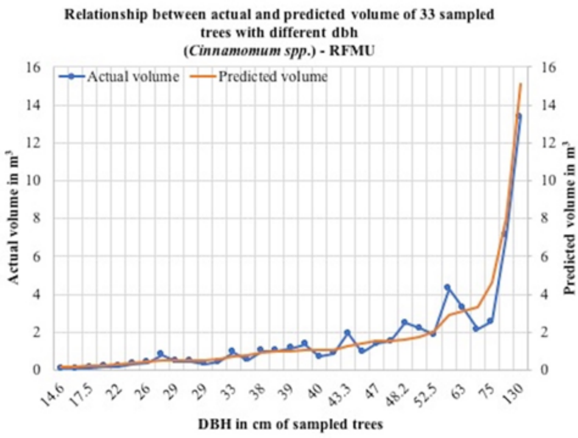


Figure 2: Graphical representation of relationship between actual & predicted volume of all sampled trees *continued* ….

Local volume tables

For ease of use by the field and frontline forestry staff, the local volume tables were developed using the local volume equations, so that these volume tables can be used to estimate volume of a tree with ease. While the local volume table makes it convenient and easier for the users to estimate the volume, there is a compromise in terms of accuracy of the estimate vis-à-vis the volume estimated by the equation.

For instance, two trees falling in the same diameter range (10 -15 cm diameter range), one with dbh of 10 cm and other with dbh of 15 cm, will have estimated as having equal volume if the local volume table is used, while in reality the volumes differ and can be estimated using the local volume equation for each of these two trees.

Using the 11 local volume equations for 11 species, developed in this study for the two FMUs, the local volume tables (Table 3 and Table 4) were generated in R version 3.4.4.

While the volume tables developed in this study are based on volume equations developed, which are useful for two FMUs, there are few caveats to be considered while using the local volume tables developed in this study. These caveats are: 1) these local volume tables are developed for and recommended to be used only for the two FMUs mentioned, 2) the volume estimated by the volume tables in this study will estimate over bark and not the under-bark volume, 3) the volumes estimated by the equations and tables in this study will estimate volume of the tree without its branch and foliage volume, 4) the volume tables developed in this study were based on models without the height as the explanatory variable because; a) the diameter is accurately, easily and conveniently measurable parameter of the tree, while height is sometimes difficult to measure accurately in the field and b) the difference between the volume estimated by two models (one with and other without height) are insignificant, albeit in some species the model with height was performing slightly better. For instance, the model without height underestimated the total volume for 33 *Castanopsis tribuloides* trees by 2.13 m^3 while the model with height underestimated the volume

Table 3: Local Volume Table for LFMU

Diameter Class	Species (Volume in m^3)				
	Schima sp.	***Lithocarpus sp.***	***Acrocarpus fraxinifolius***	***Pinus roxburghii***	***Castanopsis tribuloides***
			5 cm diameter range		
10 - 15	0.07994263	0.064454997	0.054756412	0.055187168	0.046416924
15 - 20	0.21018081	0.219418189	0.269803519	0.192814954	0.173685496
20 - 25	0.38524068	0.427134207	0.558631921	0.377695203	0.344684757
25 - 30	0.60897614	0.685192791	0.924155853	0.612604752	0.562517333
30 - 35	0.88701466	0.979396132	1.364683659	0.899680614	0.830899816
35 - 40	1.23618523	1.295952259	1.885833373	1.249169761	1.162856497
40 - 45	1.67709758	1.627711491	2.491991065	1.675243985	1.577450591
45 - 50	2.22514345	1.975601283	3.188135257	2.193104451	2.095679027
50 - 55	2.89029067	2.348051828	3.976917436	2.810180189	2.73034746
55 - 60	3.68113071	2.756299285	4.862664629	3.531854446	3.492892134
60 - 65	4.59923713	3.20153633	5.84627837	4.357159069	4.389146003
65 - 70	5.64365953	3.684718631	6.931640421	5.28294023	5.423939986
70 - 75	6.80227779	4.205083469	8.117783599	6.296331968	6.593127965
75 - 80	8.0577346	4.763012203	9.404953301	7.385711519	7.894729111
80 - 85	9.39863826	5.358504834	10.79088957	8.54844685	9.335749948
85 - 90	10.8232679	5.991180001	12.27045533	9.783783331	10.92531851
90 - 95	12.3324822	6.661419065	13.83953599	11.09246559	12.67510466
95 +	13.2740774	7.079579597	14.81849701	11.90894928	13.79804657
			10 cm diameter range		
10 - 20	0.14506172	0.141936593	0.162279965	0.124001061	0.11005121
20 - 30	0.49710841	0.556163499	0.741393887	0.495149978	0.453601045
30 - 40	1.06159995	1.137674195	1.625258516	1.074425187	0.996878157
40 - 50	1.95112052	1.801656387	2.840063161	1.934174218	1.836564809
50 - 60	3.28571069	2.552175556	4.419791032	3.171017318	3.111619797
60 - 70	5.12144833	3.44312748	6.388959395	4.82004965	4.906542994
70 - 80	7.4300062	4.484047836	8.76136845	6.841021744	7.243928538
80 - 90	10.1109531	5.674842418	11.53067245	9.16611509	10.13053423
90 +	12.4894148	6.731112487	14.00269616	11.2285462	12.86226164

by 1.12 m^3. Likewise, for *Lithocarpus* sp., the model without height underestimated total volume of 34 trees by 0.3111 m^3, whereas the model with height underestimated volume by 0.04 m^3. Conversely, for species such as *Acrocarpus* sp.*, Pinus roxburghii, Alnus nepalensis* and *Persea* sp., the model without height outperformed the model with height. For instance, volume predicted or estimated by model 7 for 33 *Pinus roxburghii* trees overestimated or over predicted by 0.045 m^3 while the model with height under estimated the volume by 0.055 m^3. Hence, for reasons cited above in (a) and also the observations cited in (b), the models without height were used to generate local volume tables for 11 species of trees for the two FMUs.

Conclusions

The local volume equations and tables are generated for the two FMUs and are not useful for other FMUs. Since the number of sample trees

Table 4: Local Volume Table for RFMU

Diameter Class	Species (Volume in m³)					
	***Beilschmedia* sp.**	***Persea* sp.**	***Quercus* sp.**	***Alnus nepalensis***	***Schima wallichii***	***Cinnamomum* sp.**
5 cm diameter range						
10 - 15	0.038050114	0.0886758	0.06773853	0.07445052	0.13880992	0.106206955
15 - 20	0.162129895	0.2197369	0.15013303	0.19912952	0.24690504	0.196282747
20 - 25	0.328732625	0.3964342	0.26078549	0.36671834	0.39244694	0.317374723
25 - 30	0.539166701	0.623227	0.40100666	0.57945587	0.57829136	0.471718804
30 - 35	0.791565197	0.9050494	0.57109783	0.83756313	0.80664345	0.661410233
35 - 40	1.089537605	1.2544907	0.77526892	1.14652785	1.08605199	0.894344723
40 - 45	1.440601405	1.6805075	1.01901111	1.51149511	1.42732817	1.181100812
45 - 50	1.859588466	2.1909424	1.31162446	1.93708143	1.84080452	1.530716897
50 - 55	2.368318499	2.7917074	1.66466813	2.42643856	2.33381374	1.946282694
55 - 60	2.987653894	3.4886057	2.08796458	2.98358367	2.91428547	2.428570651
60 - 65	3.724639611	4.2827371	2.58772194	3.6100633	3.5872123	2.972515423
65 - 70	4.583673164	5.174917	3.17125707	4.30886625	4.35854705	3.570369193
70 - 75	5.560911015	6.1586764	3.84288169	5.07930657	5.22950246	4.214843476
75 - 80	6.647750334	7.2247196	4.60680747	5.9207462	6.20034336	4.90584082
80 - 85	7.827151337	8.3640351	5.464946	6.8300481	7.26734782	5.643361226
85 - 90	9.082896764	9.5744902	6.41630727	7.80132882	8.42198132	6.426932377
90 - 95	10.41320205	10.856814	7.4582547	8.8308882	9.65323142	7.257026589
95 +	11.2431763	11.656852	8.12039037	9.47322784	10.4217385	7.774920361
10 cm diameter range						
10 - 20	0.100090004	0.1542063	0.10893578	0.13679002	0.19285748	0.151244851
20 - 30	0.433949663	0.5098306	0.33089608	0.47308711	0.48536915	0.394546764
30 - 40	0.940551401	1.0797701	0.67318337	0.99204549	0.94634772	0.777877478
40 - 50	1.650094936	1.9357249	1.16531778	1.72428827	1.63406635	1.355908855
50 - 60	2.677986196	3.1401566	1.87631635	2.70501111	2.62404961	2.187426672
60 - 70	4.154156388	4.7288271	2.87948951	3.95946478	3.97287967	3.271442308
70 - 80	6.104330674	6.691698	4.22484458	5.50002638	5.71492291	4.560342148
80 - 90	8.45502405	8.9692627	5.94062663	7.31568846	7.84466457	6.035146801
90 +	10.55153109	10.990154	7.56861064	8.93794481	9.78131594	7.343342218

felled and data collected for development of local volume equations in this study were limited to 32 – 36 trees, hence, the models and the tables can be further improved by increasing the number of sample trees in future. The sample trees felled, mainly included trees from lower diameter classes and there were relatively fewer trees sampled from the higher diameter classes. Therefore, volume estimated using the local volume equations and local volume tables generated in this study are likely to be either under or overestimate the volume for higher diameter classes. It is therefore recommended to use the volume tables with caution using the professional judgement of the users.

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