FINAL REPORT

CALIBRATION OF VOLUME PREDICTION EQUATIONS FOR DIFFERENT CLONES OF RUBBER BASED ON RANDOM PARAMETER MODELS

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CONTENTS

PROJECT PROPOSAL

1. Project number	:	KFRI 464/2005
2. Title of the project	:	Calibration of volume prediction equations for different clones of rubber based on random parameter models
3. Objective	:	a) To develop tree volume prediction equations for seven different clones of rubber planted in India. b) To derive localizing functions for the volume prediction equations based on random parameter models. c) To develop yield prediction equations for different clones of rubber as a function of age, stand density and site index.
4. Expected outcome	:	a) Volume prediction equations and the corresponding volume tables for all the clones for respective sites from where the data will be gathered. b) Localizing functions based on random parameter models, which can be used to derive site-specific prediction equations using data on volume and diameter on a few trees from any site for the set of clones considered for the study. c) Equations for predicting yield of timber from different clones as a function of age, stand density and site index.
5. Date of commencement	:	September 2005
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7. Funding agency	:	Rubber Research Institute of India, Rubber Board Kottayam
8. Project team		**RRII:** J. Rajeswari Meenattoor, Scientist S3, Division of Botany, T. Gireesh, Scientist S2, Division of Botany, Ramesh B. Nair, Assistant Director (Statistics) **KFRI:** K. Jayaraman, Programme Coordinator, Division of Forest Information Management System

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ABSTRACT

Attempts were made to develop volume prediction equations for thirteen clones of rubber viz., GT 1, Java 1, PB 235, PB 260, PB 217, PB 28/59, PB 5/51, PR 107, RRII 105, RRII 118, RRIM 600, RRIM 628 and Tjir 1. The data were collected from plantations in different parts of Kerala and Tamil Nadu. The data consisted of girth at breast-height on standing trees and the corresponding volume of trees as calculated from measurements on billets taken after felling the trees. For calculation of volume, two grades of rubber wood were identified, viz., Grade A (wood > 23" girth over bark) and Grade B (wood > 27" girth over bark). Volume prediction equations were developed for each clone based on data pooled over different locations. The predictivity of the models were in general only moderate due to variation in wood volume from tree to tree caused by variation in height, taper and branch wood for any given diameter at breast-height. However, models with coefficient of determination higher than 0.7 are suggestible for field use.

Resemblance structure among the clones with respect to the intercept and slope coefficients of the volume equations, was examined using the corresponding parameter estimates obtained through least square analysis. Cluster analysis using average linkage method based on Euclidean distance indicated two broad groups of clones, one consisting of PB 217, PB 28/59 and RRIM 628 and the other group consisting of GT 1, PR 107, RRIM 600, Java 1, PB 235, PB 260, PB 5/51, RRII 105, RRII 118, and Tjir 1. The first group was characterized by high intercept and low slope coefficient probably indicating trees of higher density wood whereas the second group had a different combination of the parameters considered.

Localizing functions for tree volume equations based on random parameter models were developed for GT 1, RRIM 600 and RRII 105. The analysis was done using *MLwiN* software. Other than tree diameter, age of the stand came out as predictor in the mean function. The intercept parameter showed significant variation at location level but slope coefficient showed very little variation over the locations. The variation in intercept parameter over locations indicated the need for localizing volume equations.

All the information required for applying the best linear unbiased predictor to generate local volume equations was worked out for the two clones. The predictivity of the localizing functions was evaluated using simulated calibration. The calibration was done by excluding one location each time from the estimation data set and generating predicted values for the excluded set and repeating the process for each location. A set of five randomly selected sample trees was used for localizing the function for any location. The whole exercise was repeated thirty times, each time using a fresh set of randomly selected trees for calibration. The average R^2 (prediction) was computed using the deviations of observed values from the predicted values. Except for a few cases, the values of R^2 (prediction) were above 0.8 for the cases considered.

Yield prediction models at stand level based on age and number of trees per ha were worked out for four clones, viz. GT 1, PB 235, RRII 105 and RRIM 600. The data were obtained from temporary sample plots laid out in plantations in different locations. The data consisted of girth at breast-height on trees in plots of size varying around 20 m X 20

m. The plots were aligned on a transect running through the center of the plantations with a random start for the first plot in any transect. The functions contained volume per ha as the dependent variable and inverse of age as predictor. The R^2 values were reasonable and the functions are recommendable for predicting stand yield directly based on the predictor mentioned.

Other than illustrating the use of random parameter models for localizing volume prediction equations, the study has generated valuable information useful for predicting commercial volume of rubber both at tree and stand level and also volume and yield tables for many clones grown mainly in the state of Kerala. Both the methodology and the output are new for the species.

1. INTRODUCTION

Hevea brasiliensis (Willd. ex Adr. De Juss.) Muell. Arg. is a domesticated forest tree species, introduced to South East Asia during 18^{th} Century for exploiting its latex production. Subsequently, through genetic improvement, the average rubber production potential has been increased from 250 to 3500 kg/ha/year (Licy *et al.*, 1997). With the advances in wood science and technology, the use of rubber wood for nontraditional purposes has been on the increase. Rubber, hitherto identified purely as a latex-yielding crop, is now increasingly looked upon as a wood-yielding crop as well. Krishnankutty (1990) observed that nearly one million cubic metre of wood comes to the market from rubber estates in Kerala annually, which is about 6.8 per cent of the total annual wood supply in Kerala. Now rubber wood has become a major source of renewable industrial raw material. A host of studies on rubber wood and its related aspects have taken place like wood anatomy (Gnanaharan and Dhamodaran 1993; Gilchrist *et al*. 1997; Oguta *et al*. 2001); technical properties (Kamala and Krishna Rao 1993; Gnanaharan 1996); breeding and selection for wood (Othman *et al*. 1995) and timber yield (Viswanathan et al., 2003).

Measurement of rubber wood production from plantations has a pivotal role in ensuring steady supply of raw materials to the consuming industry. It is very difficult to determine the volume of wood in a standing tree or a plantation through direct measurements, but the problem can be simplified by the use of prediction equations based on easily measurable characteristics like girth at breast height. For commercial purposes, it is important to have volume prediction equations both at the stand and tree level. In addition, this would help the breeders in selecting latex-timber or timber-latex clones from breeding population. However, no volume prediction equations are found reported in the case of this important crop. This project was aimed at establishing tree level volume prediction equations for rubber based on easily measured characteristics like girth at breast-height.

One common feature noted with allometric equations is that the parameters of such equations exhibit variation from stand to stand. Part of this variation could be related to the stand features like density or mean diameter but rest of the variation could be random. With the advanced modelling technology, it is now possible to quantify the random variation and also predict the status of the random parameters for individual stands. The practical implication of this modelling strategy, which uses random parameter models, is the possibility of deriving locally applicable volume prediction equations. The process of localizing a generally applicable allometric relation is technically known as calibration.

Lappi (1991) introduced the concept of random parameter models to explain random variation in parameter values and to generate stand specific predictions in forestry. Introduction of such models brought in a drastic change in the methodology used for establishing prediction equations. Jayaraman and Lappi (2001) discussed the use of similar models for estimation and prediction of height-diameter curves in planted teak stands in the context of analyzing data from a stratified two-stage sample survey. Jayaraman and Zakrzewski (2001) compared the efficiency of a random parameter approach for calibrating a height-diameter model of trees in natural sugar maple *Acer saccharum* (Marsh.) stands in Ontario with that of a fixed parameter approach.

Rubber trees being grown extensively under a range of environmental conditions are likely to show variation in their allometric relations. Since it is not feasible to establish local volume tables for each and every site, attempts are to be made to develop localizing functions, which will enable creation of site-specific prediction equations.

With the increasing importance of rubber wood, it has also become necessary to work out the expected yield of different clones with respect to timber in different locations and relate the same to age, spacing or other site factors. The present project addressed the latter issue as well.

2. MATERIALS AND METHODS

Short descriptions of the *Hevea* clones considered for the study are given below.

1. **PB 260:** A hybrid clone developed by the Prang Besar Estates Ltd. in Malaysia. Parents are PB 5/51 and PB 49. Trees have tall and straight trunk with light branches balanced with strong union, canopy dense foliage pale green. Vigour before tapping is high and average after opening. Latex yield is high, mean yield over five years is 1631 kg/ha/yr. Damage due to wind is below average.

2. **RRIM 600:** A high yielding clone developed by the Rubber Research Institute of Malaysia and extensively grown in all rubber growing countries. Parents are Tjir 1and PB 86. Tree is tall straight, moderate to fairly heavy branching and with weak branch union. Crown narrow, broom shaped, foliage sparse with small yellowish green leaves. Girth at opening low, girth increment after opening high. The clone shows rising yield trend. Average annual yield per ha. in estates over 20 years is 1349 kg.

3. **GT 1:** A primary clone developed in Indonesia and introduced to India for extensive planting, which shows variable branching habit, narrow globular crown and dense dark green glossy canopy. Girth at opening is medium to high and girth increment on tapping is medium. The clone shows rising yield trend. Average annual yield over 19 years is 1420 kg/ha.

4. **RRII 105: An** indigenous hybrid clone developed by the Rubber Research Institute of India and currently enjoying maximum popularity in the country. Parents are Tjir 1 and GT 1. Trunk tall, with more than one leader branch with strong unions. Canopy dense, mostly restricted to the top. Foliage dark green, leaflets long and glossy. Yield is high, mean yield obtained over 15 years of tapping is 2210 kg/ha/yr. Wind damage is comparatively high in the absence of corrective pruning.

5. **PB 28/59: A** Malaysian primary clone, trees have fluted and crooked trunk, moderate to heavy branches with low branching tendency. Girth at opening average and girth increment on tapping low. Annual average commercial yield over 19 years is 1477 kg/ha.

6. **PB 217:** A Malaysian hybrid clone; parents are PB 5/51 and PB 6/9. Trunk tall and straight with light branches, foliage dense. Girth at opening average; girth increment on tapping high. Average estate yield over the first 15 years is 1508 kg/ha/yr. Wind damage is comparatively low.

7. **PB 235:** A Malaysian clone with PB 5/51 and PB S/78 as parents, very vigorously growing with tall and straight stem. Branches are light with spreading foliage. Girth increment on tapping is average. Mean annual yield from large estates over a period of 15 years of tapping is 1501 kg/ha.

8. **PB 5/51:** A clone evolved in Malaysia with parentage PB 56 and PB 24. Stem straight and upright, branches light, horizontal and well distributed. Crown is conical with light

sparse foliage, small yellowish–green coloured leaves. Growth is average before tapping and low after opening. Commercial yield in India is 1389 kg/ha./yr. during the first 20 years. Highly resistant to wind damage.

9. **RRII 118:** Indigenous clone developed by crossing Mil 3/2 and Hil 28. Trunk tall and stout, prominent heavy branches, secondary branches long and slightly drooping in young stage. Several braches arise almost at the same level. Canopy dense, balanced crown. Average commercial yield is 1164 kg/ha/ yr.

10. **PR 107:** This is a primary clone developed in Indonesia, trees are sturdy, wind resistant and with average vigour. Shows good girth increment on tapping. In India, average yield over 15 years of tapping is 1043 kg/ha/yr.

11. **RRIM 628 :** A hybrid clone developed in Malaysia with parentage Tjir 1 and RRIM 527. Growth before tapping is normal and girth increments after tapping is low. Average rubber yield over 10 years is 1096 kg/ha/yr.

12. **Tjir 1 :** A primary clone developed in Indonesia, trees are very vigorous with dense canopy highly susceptible to wind damage. Average rubber yield over 15 years of tapping is 987kg/ha/yr. This clone is the female parent of RRII 105 developed later, which is one of the high yielding clones.

13. **Java 1**: A primary clone selected from the seedling population.

2.1. Tree level data for volume equations

Rubber plantations are felled usually after 20 to 25 years from planting. Plantations of different clones due for felling were identified in different rubber growing regions of Kerala and Tamil Nadu. Trees for measurement in plantation were selected to cover the range of diameter available for the clone in that plantation or location. Measurement of girth at breast height was made first. Girth at different height levels on the trunk was also measured on the standing trees at 1 m intervals. The length of the terminal billet was also noted apart from the measurements on girth. The lower limit of utilizable wood in terms of girth values was fixed as follows which conformed to the Industrial Standards.

B-Grade: Wood greater than 27" girth over bark.
A-Grade: Wood greater than 23" girth over bark.

Billet volume was computed based on measurement of girth and length made on the billets using Smalian's formula (Chaturvedi and Khanna, 1982).

$$V = \frac{\left(b^2 + t^2\right)l}{8\pi} \quad (1)$$

where V is volume of the billet (m^3)
b is the girth of the log at the basal portion (m)

t is the girth at the thin end of the log (m)
l is the length of the log or height of the log (m)

The billet volume was then aggregated to the tree level.

2.2. Methods to develop tree volume equations

The aggregated billet volume at predefined girth limits was then regressed to diameter at breast-height. The following volume prediction model was fitted to the data.

$$\ln V = \alpha + \beta \ln D + e \tag{2}$$

where V is the volume of tree (m^3)
D is the diameter at breast height (cm)
α and β are parameters to be estimated
e is the error term

Several equation forms could be considered but the choice was limited to the one based on allometry for biological validity. Residual analysis was performed to see whether the residuals satisfied the assumptions of normality and homoscedasticity. This exercise was repeated for each clone in each locality. Prediction equations were developed for each clone pooling the data over different locations as well.

2.3. Methods used for deriving calibration functions

Localizing functions were derived using Best Linear Unbiased Estimator (Searle, 1971). The details of the methods are given below.

Equation (2) can have different parameters in different locations. The model for tree i in location j was so described by

$$\ln V_{ij} = \alpha_j + \beta_j \ln D_{ij} + e_{ij} \tag{3}$$

where $\alpha_j = \alpha + a_j$
$\beta_j = \beta + b_j$
a_j and b_j are deviations in intercept and slope coefficient for location j

For a particular location j, the values of both slope and intercept coefficients are subject to random deviations (location effect) which were assumed to have zero means and constant variances. The residual errors were assumed to be independent with constant variance. Symbolically,

$$\mathrm{E}(a_j) = 0,\ \mathrm{E}(b_j) = 0,\ \mathrm{Var}(a_j) = \sigma_a^2, \mathrm{Var}(b_j) = \sigma_b^2, \mathrm{Cov}(a_j, b_j) = \sigma_{ab}, \mathrm{Var}(e_{ij}) = \sigma_e^2$$

In the basic model, only the intercept parameter was allowed to be random at tree level. It was taken as a reference model. In the subsequent models, intercept and slope coefficients were allowed to be random at location level, one parameter after the other. Age and number of trees per ha were also included as systematic predictor variables in the models.

The parameters of the different prediction models were estimated by restricted iterative generalized least squares (RIGLS) method using *MLwiN* software (Goldstein *et al*., 1998) and the best model in each case was selected by comparing the –2 Log Likelihood values using likelihood ratio test. Likelihood ratio test can be employed to test simultaneously a set of parameters included in the model. Suppose that a fitted model has m_1 parameters (Model 1). A likelihood ratio test allows an assessment of whether the addition of another m_2 terms improves the adequacy of a model significantly. The null hypothesis is that Model 1, with m_1 parameters is the true model, whereas the alternative hypothesis is that Model 2 with $m_1 + m_2$ parameters is the true model. The test statistic is,

$$\chi^2 = -2\ln(\lambda_1 / \lambda_2) \qquad (4)$$

where λ_1 and λ_1 are the maximum values of the likelihood function for Model 1 and Model 2 respectively. If Model 1 is the true model, the test statistic follows a χ^2 distribution with m_2 degrees of freedom (Goldstein, 1995).

Localizing functions could be developed only for those clones for which data were available from many locations. All random effects in the model were predicted using standard linear prediction theory. According to the theory, sample tree measurements at any location can be described by,

$$\mathbf{y} = \boldsymbol{\mu} + \mathbf{Zb} + \mathbf{e} \qquad (5)$$

where $\mathbf{y}$ = vector of observed values of the dependent variable
$\boldsymbol{\mu}$ = the vector of expected values of the dependent variable which is the fixed part of the model
$\mathbf{b}$ = vector of random effects
$\mathbf{Z}$ = matrix which describes how $\mathbf{y}$ depends on $\mathbf{b}$

Then, BLUP of **b** (Searle, 1971) is given by

$$\hat{\mathbf{b}} = \left[\mathbf{Z}'\mathbf{R}^{-1}\mathbf{Z} + \mathbf{D}^{-1}\right]^{-1}\mathbf{Z}'\mathbf{R}^{-1}(\mathbf{y} - \boldsymbol{\mu}) \qquad (6)$$

where
$\mathbf{D}$ = variance-covariance matrix of $\mathbf{b}$
$\mathbf{R}$ = diagonal matrix with the diagonal elements equals to the variance of the residual error (var(e_{ij})) and non diagonal elements equals to zero.

Estimates of $\boldsymbol{\mu}$, **D** and **R** were obtained from the estimation data set. Localized or calibrated prediction equation was then obtained by using Equation (7).

$$\hat{\mathbf{y}} = \hat{\boldsymbol{\mu}} + \mathbf{Z}\hat{\mathbf{b}} \tag{7}$$

The predictivity of the localized functions was tested in a cyclical manner. The mean function was first localized for any particular location using a subsample of volume and diameter measurements for that location and the BLUP given in Equation (6). The subsample from any location consisted of not more than 5 trees selected randomly. Jayaraman and Lappi (2001) had found through simulated calibration that not more than 3 trees are needed for localizing mean functions in the case of height-diameter relations for even-aged teak stands. Moreover, 5 trees were considered as a practical limit for a sample to be used for calibration purposes. Predicted values for all the trees in that location were then generated through the localized function. Generally, half of the mean square error is added to the predicted values in logarithmic scale as a correction for bias (Baskerville, 1972). The predicted values were compared with the actual values available. The comparisons were in terms of R^2 (prediction). The computational formula for the same was as follows.

$$R^2(\text{prediction}) = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \tag{8}$$

where y_i is the observed value of *i*th unit
$\hat{y}_i$ is the predicted value of *i*th unit
$\bar{y}$ is the mean of all the observed *y* values.

In any location, the process of localizing was repeated 30 times using randomly selected sets of 5 trees every time. This procedure was repeated for all the locations one by one, i.e., localizing and computing the value of R^2(prediction) and average over all the locations and subsamples was computed.

2.4. Plot level data for yield functions

In order to develop the yield prediction models, data pertaining to different clones were gathered from sample plots from different sites. Within a planted block in each site, temporary sample plots of size varying around 20 m x 20 m were laid out along a transect running through the center of the block and measurement of girth at breast-height was made on trees in each plot. Volume of trees predicted through pooled clone level prediction functions was aggregated at the plot level and converted to unit area level. Localized functions were used for prediction of tree volume for clones for which such functions were available.

2.5. Methods to develop yield prediction models

The plot level yield figures were regressed to age and stand density. The following equations were considered for predicting yield based on age and number of trees per ha.

$$\ln V = \alpha + \beta \ln A^{-1} + \gamma \ln N + e \quad (9)$$

where V = Volume (m^3/ha)
A = Age (year)
N = Number of trees per ha

Site index could not be included in the above model since tree height was not measured during data collection time. Height of trees was not measured considering the difficulties in locating the crown tip of individual trees in closely planted stands.

2.6. Methods to estimate timber yield of clones

The estimates of yield obtained for different clones from different locations need not be comparable directly because of the differences in age and spacing. In order to achieve comparability, adjusted location means (adjusted for variation in age and stand density) have to be obtained through least square analysis using the following model.

$$\ln V = \alpha + \lambda_i + \beta \ln A^{-1} + \gamma \ln N + e \quad (10)$$

where V = Volume (m^3/ha)
A = Age (year)
N = Number of trees per ha
λ_i = Effect of location i

However, due to the lack of intra-group (within location) variation in age of the plantations, the model could not be fitted and so further analysis was abandoned in this regard and the equations for predicting yield based on age were considered good enough for the purpose. Since the variation in density over locations as measured by number of trees per unit area was less, the latter was not included as a predictor variable.

3. RESULTS AND DISCUSSION

3.1. Volume prediction equations for individual clones

The number of trees on which data were gathered for developing volume equations in each site is given in Table 1.

Table 1. The number of trees considered for gathering billet level data

Clone	Location Code															Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
GT 1		15		15	15				15	15				15	15	105
Java1							15									15
PB 217														15		15
PB 235						15				15				15	15	60
PB 260										15						15
PB 28/59												15				15
PB 5/51			15													15
PR 107		15														15
RRII 105					15					15	15			15	15	75
RRII 118	11															11
RRIM 600	15		15	15				15		15	15		15		15	120
RRIM 628												15				15
Tjir1							15									15
Total	26	30	30	30	30	15	30	15	15	75	30	30	15	60	60	491

Not all the clones were found grown in all the locations. The distribution of the sample was mainly constrained by availability of clones in different locations. The names of the locations are reported below.

Table 2. Name of locations from which data were collected

Location code	Location name
1	RRII,Central Experiment Station, Chethackal, Ranni
2	Shaliakary Estate, Punalur
3	Rehabilitation Plantation Ltd., Kulathupuzha
4	Malankara Estate, Thodupuzha
5	VK Estate, Killimangalam, Palakkad
6	Mannarcad, Palakkad
7	Vaikudum AgroTech, Kaliyal
8	NewAmbadi Estate, Kulasekharam
9	Cochin Malabar Estate, Thrissur
10	SFCK,Chitalvetti, Punalur
11	Dhoni, Palakkad
12	Greenham,Vellarada, Thiruvananthapuram
13	Emaculate,Kothamangalam
14	Muply Estate, Thrissur
15	Tropical Farm, Kozhikode

Volume equations for Grade A timber

Table 3 gives the range of girth and volume for the trees of different clones, considered for the study.

Table 3. Range of girth and volume for each clone in different locations

Location code	Clone	Diameter (cm)		Grade A volume (m^3)	
		Min	Max	Min	Max
1	RRII 118	28.0	50.3	0.300	1.691
	RRIM 600	26.7	47.1	0.273	1.201
2	GT 1	26.1	34.7	0.261	0.809
	PR 107	20.7	37.5	0.095	0.732
3	PB 5/51	25.3	39.3	0.205	0.948
	RRIM 600	23.9	45.8	0.190	1.371
4	GT 1	25.8	50.9	0.191	1.996
	RRIM 600	24.5	31.8	0.207	0.459
5	GT 1	21.9	31.8	0.092	0.322
	RRII 105	19.6	27.4	0.078	0.219
6	PB 235	20.7	32.2	0.100	0.760
7	Java 1	21.0	49.9	0.067	1.463
	Tjir 1	23.4	49.3	0.162	0.999
8	RRIM 600	19.4	38.2	0.070	0.939
9	GT 1	22.9	37.2	0.118	0.718
10	GT 1	22.9	29.9	0.115	0.320
	PB 235	22.9	34.4	0.103	0.420
	PB 260	21.8	31.5	0.113	0.369
	RRII 105	21.3	28.3	0.069	0.271
	RRIM 600	18.8	31.2	0.044	0.284
11	RRII 105	18.8	25.9	0.045	0.236
	RRIM 600	21.8	28.0	0.087	0.189
12	PB 28/59	26.7	45.2	0.327	0.959
	RRIM 628	21.0	31.2	0.106	0.307
13	RRIM 600	18.5	30.9	0.067	0.429
14	GT 1	21.0	44.5	0.146	1.020
	PB 217	24.5	40.7	0.274	0.943
	PB 235	24.2	41.4	0.314	1.257
	RRII 105	18.6	31.8	0.085	0.449
15	GT 1	18.3	23.5	0.030	0.237
	PB 235	17.8	24.8	0.052	0.315
	RRII 105	17.5	21.9	0.029	0.184
	RRIM 600	17.2	25.5	0.045	0.353

The volume equations developed for the different clones in each site are reported first.

Location 1

Clone	Equations	MSE	R^2	Number of trees
RRII 118	$\ln V = \underset{(1.570)}{-9.633} + \underset{(0.424)}{2.606} \ln d$	0.053	0.808	11
RRIM 600	$\ln V = \underset{(1.391)}{-8.482} + \underset{(0.396)}{2.270} \ln d$	0.062	0.717	15

Note : The figures in brackets are standard errors of the coefficients

Location 2

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = \underset{(2.070)}{-12.581} + \underset{(0.606)}{3.452} \ln d$	0.037	0.714	15
PR 107	$\ln V = \underset{(1.078)}{-12.135} + \underset{(0.320)}{3.300} \ln d$	0.056	0.891	15

Location 3

Clone	Equations	MSE	R^2	Number of trees
PB 5/51	$\ln V = \underset{(1.374)}{-11.371} + \underset{(0.399)}{3.054} \ln d$	0.041	0.818	15
RRIM 600	$\ln V = \underset{(0.954)}{-10.879} + \underset{(0.272)}{2.936} \ln d$	0.025	0.900	15

Location 4

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = \underset{(1.231)}{-10.897} + \underset{(0.353)}{2.939} \ln d$	0.070	0.842	15
RRIM 600	$\ln V = \underset{(1.614)}{-8.640} + \underset{(0.486)}{2.226} \ln d$	0.021	0.617	15

Location 5

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = \underset{(1.347)}{-12.383} + \underset{(0.412)}{3.277} \ln d$	0.038	0.829	15
RRII 105	$\ln V = \underset{(2.462)}{-9.644} + \underset{(0.774)}{2.436} \ln d$	0.060	0.433	15

Location 6

Clone	Equations	MSE	R^2	Number of trees
PB 235	$\ln V = \underset{(1.112)}{-12.900} + \underset{(0.341)}{3.617} \ln d$	0.039	0.897	15

Location 7

Clone	Equations	MSE	R^2	Number of trees
Java1	$\ln V = -\underset{(1.226)}{11.911} + \underset{(0.350)}{3.235}\ln d$	0.101	0.868	15
Tjir 1	$\ln V = -\underset{(1.093)}{10.305} + \underset{(0.315)}{2.728}\ln d$	0.055	0.852	15

Location 8

Clone	Equations	MSE	R^2	Number of trees
RRIM 600	$\ln V = -\underset{(1.387)}{10.837} + \underset{(0.414)}{2.987}\ln d$	0.128	0.800	15

Location 9

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(1.413)}{10.709} + \underset{(0.418)}{2.888}\ln d$	0.051	0.786	15

Location 10

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(1.858)}{10.200} + \underset{(0.571)}{2.617}\ln d$	0.038	0.617	15
PB 235	$\ln V = -\underset{(1.482)}{10.790} + \underset{(0.450)}{2.831}\ln d$	0.046	0.753	15
PB 260	$\ln V = -\underset{(1.427)}{10.980} + \underset{(0.440)}{2.8521}\ln d$	0.031	0.764	15
RRII 105	$\ln V = -\underset{(2.168)}{10.726} + \underset{(0.672)}{2.743}\ln d$	0.058	0.562	15
RRIM 600	$\ln V = -\underset{(1.579)}{9.885} + \underset{(0.491)}{2.519}\ln d$	0.071	0.669	15

Location 11

Clone	Equations	MSE	R^2	Number of trees
RRII 105	$\ln V = -\underset{(2.534)}{13.095} + \underset{(0.819)}{3.509}\ln d$	0.074	0.586	15
RRIM 600	$\ln V = -\underset{(1.333)}{7.916} + \underset{(0.421)}{1.845}\ln d$	0.017	0.597	15

Location 12

Clone	Equations	MSE	R^2	Number of trees
PB 28/59	$\ln V = -\underset{(0.953)}{7.467} + \underset{(0.278)}{1.953}\ln d$	0.020	0.792	15
RRIM 628	$\ln V = -\underset{(2.377)}{8.537} + \underset{(0.736)}{2.087}\ln d$	0.091	0.382	15

Location 13

Clone	Equations	MSE	R^2	Number of trees
RRIM 600	$\ln V = -\underset{(1.379)}{13.824} + \underset{(0.425)}{3.769} \ln d$	0.046	0.858	15

Location 14

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(1.097)}{10.716} + \underset{(0.328)}{2.927} \ln d$	0.063	0.860	15
PB 217	$\ln V = -\underset{(1.117)}{7.342} + \underset{(0.320)}{1.929} \ln d$	0.039	0.737	15
PB 235	$\ln V = -\underset{(0.681)}{8.429} + \underset{(0.197)}{2.274} \ln d$	0.017	0.911	15
RRII 105	$\ln V = -\underset{(0.967)}{9.873} + \underset{(0.300)}{2.645} \ln d$	0.028	0.857	15

Location 15

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(3.137)}{17.126} + \underset{(1.043)}{4.924} \ln d$	0.133	0.632	15
PB 235	$\ln V = -\underset{(2.719)}{18.841} + \underset{(0.911)}{5.622} \ln d$	0.094	0.746	15
RRII 105	$\ln V = -\underset{(3.214)}{19.975} + \underset{(1.082)}{5.934} \ln d$	0.077	0.698	15
RRIM 600	$\ln V = -\underset{(2.159)}{15.924} + \underset{(0.702)}{4.524} \ln d$	0.095	0.762	15

The R^2 values obtained for different locations are combined and shown in Table 4 for easy reference. Since the R^2 for many clones in individual locations is low, the data for any particular clone were combined over all available locations and the pooled R^2 was worked out for each clone. The pooled R^2 values are also shown in Table 4.

Table 4. The R^2 values of volume equations for Grade A timber for different clones in different locations

Loc. code	GT 1	Java 1	PB 217	PB 235	PB 260	PB 28/59	PB 5/51	PR 107	RRII 105	RRII 118	RRIM 600	RRIM 628	Tjir1
1										0.81	0.72		
2	0.71							0.89					
3							0.82				0.90		
4	0.84										0.62		
5	0.83								0.43				
6				0.90									
7		0.87											0.85
8											0.80		

9	0.79												
10	0.62			0.75	0.76				0.56		0.67		
11									0.59		0.600		
12						0.79						0.38	
13											0.86		
14	0.86		0.74	0.91					0.86				
15	0.63			0.75					0.70		0.76		
Pooled R^2	0.85	0.87	0.74	0.83	0.76	0.79	0.82	0.89	0.63	0.81	0.84	0.38	0.85

The pooled regression equations are given in Table 5.

Table 5. Tree volume prediction equations for Grade A timber for each clone based on data pooled over locations

Clone code	No. of locations	Number of observations	Equation	MSE	R^2
GT 1	7	105	$\ln V = \underset{(0.484)}{-12.759} + \underset{(0.146)}{3.469} \ln d$	0.088	0.845
Java 1	1	15	$\ln V = \underset{(1.226)}{-11.911} + \underset{(0.350)}{3.235} \ln d$	0.101	0.868
PB 217	1	15	$\ln V = \underset{(1.117)}{-7.342} -+ \underset{(0.320)}{1.929} \ln d$	0.039	0.737
PB 235	4	60	$\ln V = \underset{(0.602)}{-11.264} + \underset{(0.185)}{3.067} \ln d$	0.097	0.826
PB 260	1	15	$\ln V = \underset{(1.427)}{-10.980} + \underset{(0.440)}{2.8521} \ln d$	0.031	0.764
PB 28/59	1	15	$\ln V = \underset{(0.953)}{-7.467} + \underset{(0.278)}{1.953} \ln d$	0.020	0.792
PB5/51	1	15	$\ln V = \underset{(1.374)}{-11.371} + \underset{(0.399)}{3.054} \ln d$	0.041	0.818
PR 107	1	15	$\ln V = \underset{(1.078)}{-12.135} + \underset{(0.320)}{3.300} \ln d$	0.056	0.891
RRII 105	5	75	$\ln V = \underset{(0.847)}{-11.439} + \underset{(0.270)}{3.026} \ln d$	0.103	0.633
RRII 118	1	11	$\ln V = \underset{(1.570)}{-9.633} + \underset{(0.424)}{2.606} \ln d$	0.053	0.808
RRIM600	8	120	$\ln V = \underset{(0.459)}{-12.644} + \underset{(0.139)}{3.430} \ln d$	0.096	0.838
RRIM 628	1	15	$\ln V = \underset{(2.377)}{-8.537} + \underset{(0.736)}{2.087} \ln d$	0.091	0.382
Tjir 1	1	15	$\ln V = \underset{(1.093)}{-10.305} + \underset{(0.315)}{2.728} \ln d$	0.055	0.852

Volume equations for Grade B timber

Table 6 gives the range of diameter and volume for the trees of different clones, considered for the study.

Table 6. Range of diameter and volume for each clone in different locations

Location code	Clone code	Diameter (cm)		Grade B volume (m^3)	
		Min	Max	Min	Max
1	RRII 118	28.0	50.3	0.244	1.485
	RRIM 600	26.7	47.1	0.234	1.072
2	GT 1	26.1	34.7	0.198	0.616
	PR 107	20.7	37.5	0.038	0.598
3	PB 5/51	25.3	39.3	0.138	0.811
	RRIM 600	23.9	45.8	0.137	1.071
4	GT 1	25.8	50.9	0.145	1.624
	RRIM 600	24.5	31.8	0.122	0.421
5	GT 1	21.9	31.8	0.081	0.322
	RRII 105	19.6	27.4	0.034	0.219
6	PB 235	20.7	32.1	0.046	0.755
7	Java 1	23.2	49.9	0.112	1.458
	Tjir 1	23.4	49.3	0.085	0.882
8	RRIM 600	19.4	38.2	0.056	0.840
9	GT 1	22.9	37.2	0.061	0.651
10	GT 1	22.6	29.9	0.067	0.255
	PB 235	22.6	34.4	0.065	0.393
	PB 260	21.8	31.5	0.063	0.257
	RRII 105	21.4	28.3	0.041	0.271
	RRIM 600	18.8	31.2	0.014	0.257
11	RRII 105	18.8	25.9	0.014	0.151
	RRIM 600	21.5	28.0	0.040	0.162
12	PB 28/59	26.7	45.2	0.189	0.873
	RRIM 628	21.0	31.2	0.052	0.197
13	RRIM 600	18.5	30.9	0.022	0.391
14	GT 1	21.0	44.5	0.041	0.915
	PB 217	24.5	40.7	0.119	0.869
	PB 235	24.2	41.4	0.100	1.034
	RRII 105	18.6	31.8	0.025	0.285
15	GT 1	18.6	23.5	0.004	0.136
	PB 235	17.8	24.8	0.001	0.187
	RRII 105	17.8	21.9	0.007	0.077
	RRIM 600	20.0	25.5	0.012	0.256

The volume equations developed for individual locations for Grade B timber are reported below.

Location 1

Clone	Equations	MSE	R^2	Number of trees
RRII 118	$\ln V = -\underset{(1.421)}{10.939} + \underset{(0.384)}{2.911} \ln d$	0.044	0.865	11
RRIM 600	$\ln V = -\underset{(1.546)}{9.677} + \underset{(0.440)}{2.533} \ln d$	0.076	0.719	15

Location 2

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(2.049)}{11.744} + \underset{(0.599)}{3.147} \ln d$	0.036	0.679	15
PR 107	$\ln V = -\underset{(1.421)}{15.378} + \underset{(0.422)}{4.166} \ln d$	0.097	0.882	15

Location 3

Clone	Equations	MSE	R^2	Number of trees
PB 5/51	$\ln V = -\underset{(1.220)}{14.153} + \underset{(0.355)}{3.774} \ln d$	0.033	0.897	15
RRIM 600	$\ln V = -\underset{(1.211)}{12.596} + \underset{(0.345)}{3.363} \ln d$	0.040	0.880	15

Location 4

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(1.184)}{12.554} + \underset{(0.340)}{3.332} \ln d$	0.065	0.881	15
RRIM 600	$\ln V = -\underset{(1.872)}{13.736} + \underset{(0.564)}{3.659} \ln d$	0.028	0.764	15

Location 5

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(1.184)}{12.554} + \underset{(0.340)}{3.332} \ln d$	0.025	0.890	15
RRII 105	$\ln V = -\underset{(4.714)}{14.442} + \underset{(1.481)}{3.842} \ln d$	0.220	0.341	15

Location 6

Clone	Equations	MSE	R^2	Number of trees
PB 235	$\ln V = -\underset{(1.012)}{20.119} + \underset{(0.310)}{5.653} \ln d$	0.032	0.962	15

Location 7

Clone	Equations	MSE	R^2	Number of trees
Java 1	$\ln V = \underset{(1.439)}{-13.338} + \underset{(0.407)}{3.586}\ln d$	0.101	0.866	14
Tjir 1	$\ln V = \underset{(1.545)}{-11.841} + \underset{(0.446)}{3.097}\ln d$	0.110	0.788	15

Location 8

Clone	Equations	MSE	R^2	Number of trees
RRIM 600	$\ln V = \underset{(1.664)}{-14.153} + \underset{(0.497)}{3.869}\ln d$	0.184	0.823	15

Location 9

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = \underset{(1.915)}{-15.237} + \underset{(0.567)}{4.135}\ln d$	0.094	0.803	15

Location 10

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = \underset{(1.335)}{-15.626} + \underset{(0.411)}{4.166}\ln d$	0.020	0.888	15
PB 235	$\ln V = \underset{(1.646)}{-16.046} + \underset{(0.499)}{4.309}\ln d$	0.057	0.851	15
PB 260	$\ln V = \underset{(1.309)}{-13.838} + \underset{(0.404)}{3.600}\ln d$	0.026	0.860	15
RRII 105	$\ln V = \underset{(1.357)}{-19.397} + \underset{(0.421)}{5.326}\ln d$	0.023	0.925	15
RRIM 600	$\ln V = \underset{(1.917)}{-17.552} + \underset{(0.596)}{4.747}\ln d$	0.104	0.830	15

Location 11

Clone	Equations	MSE	R^2	Number of trees
RRII 105	$\ln V = \underset{(2.881)}{-20.976} + \underset{(0.931)}{5.854}\ln d$	0.096	0.753	15
RRIM 600	$\ln V = \underset{(2.992)}{-16.471} + \underset{(0.944)}{4.437}\ln d$	0.085	0.629	15

Location 12

Clone	Equations	MSE	R^2	Number of trees
PB 28/59	$\ln V = \underset{(1.403)}{-9.572} + \underset{(0.409)}{2.509}\ln d$	0.044	0.743	15
RRIM 628	$\ln V = \underset{(2.592)}{-10.782} + \underset{(0.802)}{2.623}\ln d$	0.108	0.451	15

Location 13

Clone	Equations	MSE	R^2	Number of trees
RRIM 600	$\ln V = -\underset{(1.773)}{18.943} + \underset{(0.547)}{5.263} \ln d$	0.077	0.877	15

Location 14

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(1.762)}{16.280} + \underset{(0.526)}{4.445} \ln d$	0.163	0.846	15
PB 217	$\ln V = -\underset{(1.679)}{11.392} + \underset{(0.481)}{3.013} \ln d$	0.088	0.751	15
PB 235	$\ln V = -\underset{(1.279)}{15.216} + \underset{(0.370)}{4.117} \ln d$	0.062	0.905	15
RRII 105	$\ln V = -\underset{(1.413)}{16.863} + \underset{(0.438)}{4.599} \ln d$	0.060	0.895	15

Location 15

Clone	Equations	MSE	R^2	Number of trees
GT 1	$\ln V = -\underset{(5.664)}{41.101} + \underset{(1.861)}{12.390} \ln d$	0.248	0.831	11
PB 235	$\ln V = -\underset{(8.025)}{37.977} + \underset{(2.683)}{11.457} \ln d$	0.762	0.603	14
RRII 105	$\ln V = -\underset{(4.799)}{31.415} + \underset{(1.607)}{9.316} \ln d$	0.120	0.753	13
RRIM 600	$\ln V = -\underset{(5.501)}{31.366} + \underset{(1.763)}{9.221} \ln d$	0.226	0.732	12

Table 7. The R^2 values of volume equations for Grade B timber for different clones in different locations

Loc. code	GT 1	Java 1	PB 217	PB 235	PB 260	PB 28/59	PB 5/51	PR 107	RRII 105	RRII 118	RRIM 600	RRIM 628	Tjir1
1										0.87	0.72		
2	0.68							0.88					
3							0.90				0.88		
4	0.88										0.76		
5	0.89								0.34				
6				0.96									
7		0.87											0.79
8											0.82		
9	0.80												
10	0.89			0.85	0.86				0.93		0.83		
11									0.75		0.63		
12						0.74						0.45	
13											0.88		
14	0.85		0.75	0.91					0.90				

15	0.83			0.60					0.75		0.73		
Pooled R^2	0.83	0.87	0.75	0.83	0.86	0.74	0.90	0.88	0.82	0.87	0.84	0.45	0.79

Table 8. Tree volume prediction equations for Grade B timber for each clone based on data pooled over locations

Clone code	No. of locations	Number of observations	Equation	MSE	R^2
GT 1	7	101	$\ln V = \underset{(4.894)}{-17.891} + \underset{(0.222)}{4.894} \ln d$	0.172	0.831
Java1	1	14	$\ln V = \underset{(1.439)}{-13.338} + \underset{(0.407)}{3.586} \ln d$	0.101	0.866
PB 217	1	15	$\ln V = \underset{(1.679)}{-11.392} + \underset{(0.481)}{3.013} \ln d$	0.088	0.751
PB 235	4	59	$\ln V = \underset{(1.121)}{-20.521} + \underset{(0.344)}{5.681} \ln d$	0.320	0.827
PB 260	1	15	$\ln V = \underset{(1.309)}{-13.838} + \underset{(0.404)}{3.600} \ln d$	0.026	0.860
PB 28/59	1	15	$\ln V = \underset{(1.403)}{-9.572} + \underset{(0.409)}{2.509} \ln d$	0.044	0.743
PB 5/51	1	15	$\ln V = \underset{(1.220)}{-14.153} + \underset{(0.355)}{3.774} \ln d$	0.033	0.897
PR 107	1	15	$\ln V = \underset{(1.421)}{-15.378} + \underset{(0.422)}{4.166} \ln d$	0.097	0.882
RRII 105	5	73	$\ln V = \underset{(0.974)}{-20.321} + \underset{(0.309)}{5.645} \ln d$	0.122	0.824
RRII 118	1	11	$\ln V = \underset{(1.421)}{-10.939} + \underset{(0.384)}{2.911} \ln d$	0.044	0.865
RRIM600	8	117	$\ln V = \underset{(0.591)}{-16.198} + \underset{(0.178)}{4.390} \ln d$	0.142	0.840
RRIM 628	1	15	$\ln V = \underset{(2.592)}{-10.782} + \underset{(0.802)}{2.623} \ln d$	0.108	0.451
Tjir1	1	15	$\ln V = \underset{(1.545)}{-11.841} + \underset{(0.446)}{3.097} \ln d$	0.110	0.788

The predictivity of the models in general was moderate except for a few clones. Setting a minimum standard for R^2 as 0.7, the corresponding volume equations can be suggested for field use.

One of the reasons for poor R^2 values in general was on account of the branching habit of rubber trees, which is subject to much variation from tree to tree. Except for a clear bole at the tapping region and the adjoining portion above on the trunk, usually rubber trees show profuse branching though the extent varies from clone to clone. Trees put in additional increment on the trunk to support the larger weight they have to hold as the age advances. However, the tree diameter may not be directly reflective of the wood volume in dense stands. In a dense stand, the trees standing close together lessen the effect of wind and hence diameter at breast-height need not wholly account for the variation in wood volume especially that of the branches.

Another reason for the low R^2 values is the absence of height in the prediction models. For a given diameter, variation in volume could arise due to variation in height of trees. As this variation was not accounted for, the R^2 values were naturally lower. Height was not included considering the difficulty in measuring height in planted stands. For measurement of height, tip of the crown of each tree must be clearly visible which was not the case in closely planted stands.

In allometric relations of the kind considered for this study, variation in intercept indicates the variation in volume among trees of unit diameter. Such variations are clearly traceable to the variation due to height, taper or branch wood volume. The slope coefficient on the other hand is related to the change in volume for a unit change in diameter in the logarithmic scale and is indirectly related to wood density. Thus the intercept and slope coefficient of the volume prediction equation together are indicative of the morphological and internal structure of the trees. As the estimates of these parameters obtained through least square analysis could be correlated out of mere statistical considerations, these estimates are not comparable individually across the clones. The differences in these two parameters over the clones have to be looked at simultaneously. In order to see if any similarity exists between the clones with respect to these parameters, a cluster analysis was carried out taking clones as entities and parameters estimates as characters. Clustering was done using average linkage method and Euclidian distance as distance measure. The dendrogram obtained based on intercept and slope coefficients for Grade A volume is shown below.

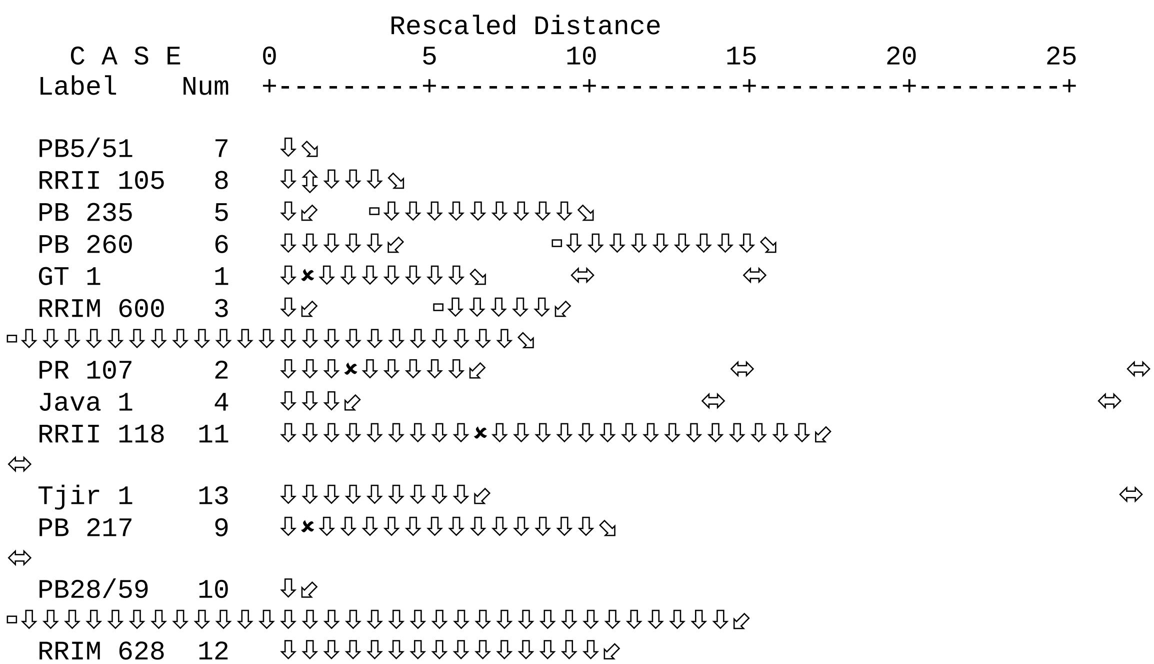

Figure 1. Dendrogram showing resemblance among clones based on Grade A timber.

At the 20-phenon level, 5 natural clusters could be identified as follows.

Cluster	Clones	Mean Intercept	Mean slope
1	GT 1, PR 107, RRIM 600, Java 1	-12.36	3.36
2	PB 235, PB 260, PB 5/51, RRII 105	-11.26	3.00
3	PB 217, PB 28/59	-7.40	1.94
4	RRII 118, Tjir 1	-9.97	2.57
5	RRIM 628	-8.54	2.09

In summary, the group consisting of PB 217, PB 28/59 and RRIM 628 show more resemblance with respect to their growing habit and internal structure than all other clones put together.

The exact scatter of the clones in the (intercept-slope) space is shown in Figure 2.

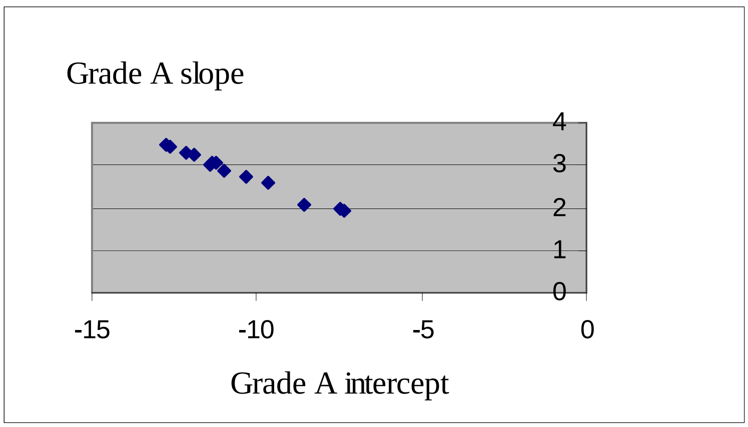

Figure 2. Scatter plot of clones in the Intercept-Slope coefficient space for Grade A volume

The negative correlation between the intercept and slope coefficient is very evident from Figure 2 indicating that the effects of these parameters are complementary on the volume.

Apart from the systematic causes described above, the low R^2 values could also arise due to random variation in parametric values over different sites. Put differently, the variation in volume not accounted by the systematic part of the model could be treated as random and can be dealt with using random parameter models, which forms the content of the next section.

For field use, volume tables constructed for the different clones are given in the Appendix. The tables in the Appendix are output of equations reported in Table 5 and Tables 8. While generating the volume tables, a correction factor equivalent to (MSE/2) was applied to the predicted values before they were transformed from the logarithmic scale to the original units (Baskerville, 1972). Since the models for Grade A and Grade B volume were fitted independently, the predicted values for Grade B volume were greater than that of Grade A in stray cases. In all such cases, the Grade B volumes were restricted to the values of Grade A volume.

3.2. Calibrating functions for volume prediction

The results pertaining to the different models tried as localizing functions are reported below. The localizing functions could be developed only for GT 1, RRIM 600 and RRII 105 for which data were available from many locations.

Models for Grade A timber

GT 1

Table 9. Estimates of parameters and standard error of estimates for the different tree volume prediction models for Grade A timber for GT 1

Parameter	Model 1 (Intercept random at plot level)	Model 2 (Model 1 + Additional term Age)	Model 3 (Model 2 + intercept random at plantation level)	Model 4 (Model 2 + Slope coefficient of *lnd* random at plantation level)
Fixed part				
Constant	-12.759 (0.484)	-11.982 (0.532)	-11.981 (0.559)	-11.983 (0.532)
ln *d*	3.469 (0.146)	3.094 (0.188)	3.093 (0.188)	3.094 (0.188)
A		0.013 (0.006)	0.018 (0.014)	0.018 (0.006)
Random				
σ_a^2			0.026 (0.016)	
σ_b^2				0.000 (0.000)
σ_{ab}				
σ_e^2	0.088 (0.012)	0.082 (0.011)	0.063 (0.009)	0.082 (0.011)
-2LL	41.248	32.278	18.060	32.278

Note : The values indicated as 0.000 in the table are to be taken as very small positive fractions. Values indicated in brackets are standard error of estimates

The chi square test on successive values of 2LL indicated that Model 3 is the best model. R^2 (prediction) for this model worked out to 0.8721 whereas R^2 (prediction) for the reference model was only 0.7924 indicating the substantial increase in predictivity due to the use of calibrated function.

RRIM 600

Table 10. Estimates of parameters and standard error of estimates for the different tree volume prediction models for Grade A timber for RRIM 600

Parameter	Model 1 (Intercept random at plot level)	Model 2 (Model 1 + Additional term Age)	Model 3 (Model 1 + intercept random at plantation level)	Model 4 (Model 3 + Slope coefficient of *lnd* random at plantation level)
Fixed part				
Constant	-12.645 (0.459)	-12.257 (0.499)	-11.295 (0.521)	-11.209 (0.795)
ln *d*	3.430 (0.139)	3.210 (0.181)	3.020 (0.156)	3.001 (0.245)
A		0.014 (0.008)		
Random				
σ_a^2			0.044 (0.024)	2.592 (2.448)
σ_b^2				0.251 (0.232)
σ_{ab}				-0.798 (0.751)
σ_e^2	0.096 (0.012)	0.094 (0.012)	0.064 (0.009)	0.059 (0.008)
-2LL	57.142	53.632	27.916	27.691

The chi square test on successive values of 2LL indicated that Model 3 is the best model. R^2 (prediction) for this model worked out to 0.8097. R^2 (prediction) for the reference model worked out to 0.7498.

RRII 105

Table 11. Estimates of parameters and standard error of estimates for the different volume prediction models for Grade A timber for RRII 105.

Parameter	Model 1 (Intercept random at plot level)	Model 2 (Model 1 + Additional term Age)	Model 3 (Model 1 + intercept random at plantation level)	Model 4 (Model 3 + Slope coefficient of *lnd* random at plantation level)
Fixed part				
Constant	-11.439 (0.847)	-11.755 (0.870)	-11.556 (0.919)	-12.026 (1.529)
ln *d*	3.026 (0.270)	3.275 (0.320)	3.063 (0.291)	3.232 (0.503)
A		-0.023		

		(0.016)		
Random				
σ_a^2			0.046 (0.032)	7.102 (7.135)
σ_b^2				0.794 (0.0.773)
σ_{ab}				-2.366 (2.346)
σ_e^2	0.103 (0.017)	0.101 (0.017)	0.066 (0.011)	0.061 (0.011)
-2LL	40.103	38.068	18.854	19.244

Note : Values indicated in brackets are standard error of estimates.

The chi square test on successive values of 2LL indicated that Model 3 is the best model. R^2 (prediction) for this model worked out to 0.8327. R^2 (prediction) for the reference model worked out to 0.6383.

Models for Grade B timber

GT 1

Table 12. Estimates of parameters and standard error of estimates for the different tree volume prediction models for Grade B timber for GT1

Parameter	Model 1 (Intercept random at plot level)	Model 2 (Model 1 + Additional term Age)	Model 3 (Model 2 + intercept random at plantation level)	Model 4 (Model 2 + Slope coefficient of *lnd* random at plantation level)
Fixed part				
Constant	-17.891 (0.738)	-16.955 (0.787)	-16.508 (0.810)	-16.802 (0.679)
ln *d*	4.8942 (0.222)	4.425 (0.271)	4.244 (0.264)	4.350 (0.232)
A		0.024 (0.009)	0.030 (0.014)	0.028 (0.008)
Random				
σ_a^2			0.031 (0.022)	
σ_b^2				0.000 (0.000)
σ_{ab}				
σ_e^2	0.172 (0.024)	0.161 (0.023)	0.139 (0.020)	0.113 (0.017)
-2LL	106.862	98.989	94.700	99.475

Chi square test indicated Model 3 as the best model. R^2 (prediction) for Model 3 came to 0.7897 in comparison to 0.6175 for the reference model.

RRIM 600

Table 13. Estimates of parameters and standard error of estimates for the different tree volume prediction models for Grade B timber for RRIM 600

Parameter	Model 1 (Intercept random at plot level)	Model 2 (Model 1 + Additional term Age)	Model 3 (Model 1 + intercept random at plantation level)	Model 4 (Model 2 + Slope coefficient of *lnd* random at plantation level)
Fixed part				
Constant	-16.197 (0.591)	-16.221 (0.618)	-15.535 (0.688)	-16.198 (0. 524)
ln *d*	4.390 (0.178)	4.406 (0.213)	4.189 (0.207)	4.390 (0.158)
A		0.001 (0.009)		
Random				
σ^2_a			0.021 (0.015)	
σ^2_b				0.000 (0.000)
σ_{ab}				
σ^2_e	0.142 (0.019)	0.143 (0.019)	0.126 (0.017)	0.112 (0.015)
-2LL	101.866	101.870	97.309	105.069

Chi square test indicated Model 3 as the best model with R^2 (prediction) of 0.5007, which is a very low value. R^2 (prediction) for model 1 was 0.4024

RRII 105

Table 14. Estimates of parameters and standard error of estimates for the different volume prediction models for Grade B timber for RRII 105.

Parameter	Model 1 (Intercept random at plot level)	Model 2 (Model 1 + Additional term Age)	Model 3 (Model 2 + intercept random at plantation level)	Model 4 (Model 2 + Slope coefficient of *lnd* random at plantation level)
Fixed part				
Constant	-20.322 (0.974)	-19.839 (0.955)	-19.839 (0.955)	-19.840 (0.955)
ln *d*	5.645 (0.309)	5.200 (0.343)	5.200 (0.343)	5.200 (0.343)
A		0.046 (0.018)	0.046 (0.018)	0.046 (0.018)
Random				

σ_a^2			0.000 (0.000)	
σ_b^2				0.000 (0.000)
σ_{ab}				
σ_e^2	0.122 (0.020)	0.113 (0.019)	0.113 (0.018)	0.113 (0.019)
-2LL	51.532	44.854	44.854	44.854

Note : The values indicated as 0.000 in the table are to be taken as very small positive fractions. Values indicated in brackets are standard error of estimates

The chi square test on successive values of 2LL indicated that Model 2 was the best model. R^2 (prediction) worked out for model 1 was 0.6481 and that for model 2 was 0.7308.

In general, the variation in intercept at plantation level was much higher compared to the corresponding variation in slope coefficient. The reason is that wood density is relatively stable over trees of the same clone and so the slope coefficient over locations or stands could be minimal whereas branching habit or height are more easily modified by local condition of the stand and are thus subject to more variation. However, a comparison strictly based on variances is not possible because of the high correlation between the deviations in slope and intercept coefficients.

The models indicated as best in Tables 9 to 14 can be utilized for generating localizing functions for the corresponding utility class of timber for the clones indicated using the BLUP given in Equation (6).

3.3. Yield prediction models

The range of age and number of trees for the data used for developing the yield prediction models is reported in Table 15.

Table 15. The range of data used for developing yield prediction models

Clone	Age (year)		Number per ha		Grade A volume (m^3/ha)		Grade B volume (m^3/ha)	
	Min	Max	Min	Max	Min	Max	Min	Max
GT 1	15	35	370	500	34.24	466.67	16.77	457.13
PB 235	15	24	413	555	48.98	273.67	14.93	257.13
RRII 105	15	24	348	500	36.40	93.05	13.56	73.32
RRIM 600	15	31	370	500	36.85	382.46	20.41	360.88

The equations developed for predicting per ha volume directly based on age of trees is reported below. In the equations given below, V_1 indicates Grade A volume/ha and V_2 indicates grade B volume/ha.

Table 16. Yield prediction models for Grade A timber for different clones

Clone	Number of plots	Fitted equation	MSE	R^2
GT 1	22	$\ln V_1 = \underset{(0.222)}{6.951} - \underset{(5.502)}{51.708}\,A^{-1}$	0.078	0.815
PB 235	10	$\ln V_1 = \underset{(0.221)}{7.949} - \underset{(4.422)}{59.504}\,A^{-1}$	0.017	0.958
RRII 105	14	$\ln V_1 = \underset{(0.199)}{5.522} - \underset{(4.118)}{27.847}\,A^{-1}$	0.016	0.792
RRIM 600	23	$\ln V_1 = \underset{(0.322)}{7.276} - \underset{(7.581)}{56.611}\,A^{-1}$	0.123	0.726

Table 17. Yield prediction models for Grade B timber for different clones

Clone	Number of plots	Fitted equation	MSE	R^2
GT1	22	$\ln V_2 = \underset{(0.264)}{7.28} - \underset{(6.546)}{67.199}\,A^{-1}$	0.111	0.841
PB 235	10	$\ln V_2 = \underset{(0.487)}{9.19} - \underset{(9.758)}{92.974}\,A^{-1}$	0.081	0.919
RRII 105	14	$\ln V_2 = \underset{(0.393)}{6.051} - \underset{(8.152)}{48.600}\,A^{-1}$	0.064	0.748
RRIM 600	23	$\ln V_2 = \underset{(0.421)}{7.559} - \underset{(9.926)}{70.286}\,A^{-1}$	0.211	0.705

The R^2 values were reasonably high for the models to be used for direct prediction of yield based on age alone. The corresponding yield tables are reported below for ready reference.

Table 18a. Expected timber yield as per age for different clones of rubber

Age (year)	Volume (m^3/ha)			
	GT 1		PB 235	
	Grade A	Grade B	Grade A	Grade B
15	34.56	17.38	54.09	20.74
16	42.87	23.00	69.30	30.56
17	51.85	29.45	86.25	43.01
18	61.40	36.68	104.77	58.28
19	71.42	44.64	124.68	76.49
20	81.83	53.28	145.81	97.69
21	92.55	62.52	168.00	121.90
22	103.51	72.31	191.10	149.07
23	114.64	82.58	214.94	179.14
24	125.90	93.27	239.41	212.00
25	137.23	104.33	264.37	247.53
26	148.60	115.69	289.71	285.60
27	159.95	127.31	*	*
28	171.28	139.15	*	*
29	182.54	151.15	*	*
30	193.72	163.29	*	*

Table 18b. Expected timber yield as per age for different clones of rubber

Age (year)	Volume (m^3/ha)			
	RRII 105		RRIM 600	
	Grade A	Grade B	Grade A	Grade B
15	39.39	17.17	35.28	19.66
16	44.24	21.02	44.67	26.35
17	49.01	25.13	55.01	34.12
18	53.67	29.46	66.18	42.94
19	58.23	33.96	78.10	52.73
20	62.66	38.59	90.64	63.45
21	66.95	43.32	103.72	75.00
22	71.11	48.13	117.25	87.33
23	75.13	52.98	131.13	100.34
24	79.02	57.86	145.29	113.97
25	82.77	62.74	159.66	128.13
26	*	*	174.19	142.76
27	*	*	188.82	157.80
28	*	*	203.50	173.17
29	*	*	218.20	188.83
30	*	*	232.87	204.72

* Values are out of range

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Appendix : Volume tables for different clones of rubber

Diameter (cm)	Volume (m^3)					
	GT 1		Java		PB 217	
	Grade A	Grade B	Grade A	Grade B	Grade A	Grade B
20	0.0980	0.0431	*	*	*	*
21	0.1161	0.0547	*	*	*	*
22	0.1364	0.0687	*	*	*	*
23	0.1591	0.0854	0.1796	0.1304	*	*
24	0.1845	0.1052	0.2061	0.1519	*	*
25	0.2125	0.1285	0.2352	0.1758	0.3285	0.1921
26	0.2435	0.1557	0.2670	0.2024	0.3543	0.2162
27	0.2776	0.1873	0.3017	0.2318	0.3810	0.2423
28	0.3149	0.2238	0.3393	0.2641	0.4087	0.2703
29	0.3556	0.2657	0.3801	0.2995	0.4374	0.3005
30	0.4000	0.3136	0.4242	0.3382	0.4669	0.3328
31	0.4482	0.3682	0.4716	0.3805	0.4974	0.3674
32	0.5004	0.4301	0.5226	0.4264	0.5288	0.4042
33	0.5568	0.5000	0.5774	0.4761	0.5612	0.4435
34	0.6175	0.5787	0.6359	0.5300	0.5944	0.4853
35	0.6828	0.6669	0.6984	0.5881	0.6286	0.5295
36	0.7529	0.7655	0.7650	0.6506	0.6637	0.5765
37	0.8280	0.8280	0.8360	0.7178	0.6997	0.6261
38	0.9083	0.9083	0.9113	0.7899	0.7367	0.6784
39	0.9939	0.9939	0.9912	0.8671	0.7745	0.7337
40	1.0852	1.0852	1.0758	0.9495	0.8133	0.7918
41	1.1822	1.1822	1.1652	1.0375	0.8530	0.8530
42	1.2853	1.2853	1.2597	1.1312	*	*
43	1.3946	1.3946	1.3593	1.2308	*	*
44	1.5104	1.5104	1.4643	1.3367	*	*
45	1.6328	1.6328	1.5747	1.4489	*	*
46	1.7622	1.7622	1.6907	1.5678	*	*
47	1.8987	1.8987	1.8125	1.6936	*	*
48	2.0425	2.0425	1.9403	1.8264	*	*
49	2.1940	2.1940	2.0741	1.9667	*	*
50	2.3533	2.3533	2.2142	2.1145	*	*

*Values out of range

Diameter (cm)	Volume (m^3)					
	PB 235		PB 260		PB 28/59	
	Grade A	Grade B	Grade A	Grade B	Grade A	Grade B
20	0.1317	0.0354	*	*	*	*
21	0.1529	0.0467	*	*	*	*
22	0.1764	0.0608	0.1166	0.0674	*	*
23	0.2021	0.0782	0.1324	0.0791	*	*
24	0.2303	0.0996	0.1495	0.0922	*	*
25	0.2610	0.1256	0.1679	0.1068	*	*
26	0.2944	0.1570	0.1878	0.1230	*	*
27	0.3305	0.1945	0.2091	0.1409	0.3605	0.2778
28	0.3695	0.2391	0.2320	0.1606	0.3870	0.3044
29	0.4115	0.2919	0.2564	0.1822	0.4145	0.3324
30	0.4566	0.3539	0.2824	0.2058	0.4429	0.3619
31	0.5049	0.4263	0.3101	0.2316	0.4722	0.3929
32	0.5565	0.5106	*	*	0.5024	0.4255
33	0.6116	0.6081	*	*	0.5335	0.4597
34	0.6702	0.6702	*	*	0.5655	0.4954
35	0.7325	0.7325	*	*	0.5985	0.5328
36	0.7986	0.7986	*	*	0.6323	0.5718
37	0.8687	0.8687	*	*	0.6671	0.6125
38	0.9427	0.9427	*	*	0.7027	0.6549
39	1.0209	1.0209	*	*	0.7393	0.6990
40	1.1033	1.1033	*	*	0.7768	0.7448
41	1.1901	1.1901	*	*	0.8151	0.7924
42	*	*	*	*	0.8544	0.8418
43	*	*	*	*	0.8946	0.8930
44	*	*	*	*	0.9357	0.9357
45	*	*	*	*	0.9777	0.9777
46	*	*	*	*	*	*
47	*	*	*	*	*	*
48	*	*	*	*	*	*
49	*	*	*	*	*	*
50	*	*	*	*	*	*

Diameter (cm)	Volume (m^3)					
	PB 5/51		PR 107		RRII 105	
	Grade A	Grade B	Grade A	Grade B	Grade A	Grade B
20	*	*	*	*	0.0980	0.0351
21	*	*	0.1274	0.0709	0.1136	0.0463
22	*	*	0.1486	0.0861	0.1308	0.0601
23	*	*	0.1721	0.1036	0.1496	0.0773
24	*	*	0.1980	0.1237	0.1702	0.0983
25	*	*	0.2266	0.1467	0.1926	0.1238
26	0.2465	0.1587	0.2579	0.1727	0.2169	0.1544
27	0.2766	0.1830	0.2921	0.2021	0.2431	0.1911
28	0.3091	0.2100	0.3293	0.2351	0.2714	0.2346
29	0.3441	0.2397	0.3698	0.2722	0.3018	0.2860
30	0.3817	0.2724	0.4135	0.3135	0.3344	0.3344
31	0.4219	0.3083	0.4608	0.3593	0.3693	0.3693
32	0.4648	0.3476	0.5117	0.4101	0.4065	0.4065
33	0.5106	0.3904	0.5664	0.4662	*	*
34	0.5593	0.4369	0.6250	0.5280	*	*
35	0.6111	0.4874	0.6877	0.5958	*	*
36	0.6660	0.5421	0.7547	0.6699	*	*
37	0.7242	0.6012	0.8262	0.7510	*	*
38	0.7856	0.6648	*	*	*	*
39	0.8505	0.7333	*	*	*	*
40	*	*	*	*	*	*
41	*	*	*	*	*	*
42	*	*	*	*	*	*
43	*	*	*	*	*	*
44	*	*	*	*	*	*
45	*	*	*	*	*	*
46	*	*	*	*	*	*
47	*	*	*	*	*	*
48	*	*	*	*	*	*
49	*	*	*	*	*	*
50	*	*	*	*	*	*

Diameter (cm)	Volume (m^3)					
	RRII 118		RRIM 600		RRIM 628	
	Grade A	Grade B	Grade A	Grade B	Grade A	Grade B
20	*	*	0.0982	0.0510	0.1179	0.0644
21	*	*	0.1161	0.0632	0.1300	0.0728
22	*	*	0.1362	0.0775	0.1426	0.0818
23	*	*	0.1586	0.0942	0.1558	0.0914
24	*	*	0.1835	0.1136	0.1697	0.1018
25	*	*	0.2111	0.1359	0.1842	0.1128
26	*	*	0.2415	0.1614	0.1993	0.1246
27	*	*	0.2749	0.1905	0.2150	0.1370
28	0.3974	0.2961	0.3114	0.2234	0.2313	0.1502
29	0.4355	0.3280	0.3513	0.2607	0.2483	0.1642
30	0.4757	0.3620	0.3946	0.3025	0.2659	0.1789
31	0.5181	0.3983	0.4416	0.3493	*	*
32	0.5628	0.4368	0.4924	0.4016	*	*
33	0.6098	0.4778	0.5472	0.4596	*	*
34	0.6591	0.5211	0.6062	0.5240	*	*
35	0.7109	0.5670	0.6695	0.5951	*	*
36	0.7650	0.6155	0.7375	0.6734	*	*
37	0.8216	0.6666	0.8101	0.7595	*	*
38	0.8808	0.7204	0.8877	0.8539	*	*
39	0.9425	0.7770	0.9705	0.9570	*	*
40	1.0067	0.8364	1.0585	1.0585	*	*
41	1.0737	0.8987	1.1521	1.1521	*	*
42	1.1432	0.9640	1.2513	1.2513	*	*
43	1.2155	1.0324	1.3565	1.3565	*	*
44	1.2906	1.1038	1.4678	1.4678	*	*
45	1.3684	1.1784	1.5854	1.5854	*	*
46	1.4491	1.2563	1.7096	1.7096	*	*
47	1.5326	1.3375	1.8404	1.8404	*	*
48	1.6191	1.4220	*	*	*	*
49	1.7084	1.5100	*	*	*	*
50	1.8008	1.6014	*	*	*	*

Diameter (cm)	Volume (m^3)	
	Tjir 1	
	Grade A	Grade B
20	*	*
21	*	*
22	*	*
23	*	*
24	0.2003	0.1432
25	0.2239	0.1625
26	0.2492	0.1835
27	0.2762	0.2062
28	0.3051	0.2308
29	0.3357	0.2573
30	0.3682	0.2858
31	0.4027	0.3163
32	0.4391	0.3490
33	0.4776	0.3839
34	0.5181	0.4211
35	0.5607	0.4607
36	0.6055	0.5027
37	0.6525	0.5472
38	0.7018	0.5943
39	0.7533	0.6441
40	0.8072	0.6966
41	0.8634	0.7520
42	0.9221	0.8102
43	0.9832	0.8715
44	1.0468	0.9358
45	1.1130	1.0032
46	1.1818	1.0739
47	1.2532	1.1479
48	1.3273	1.2252
49	1.4041	1.3060
50	*	*