VOLUME FUNCTIONS FOR COMMON TIMBER SPECIES OF NIGERIA'S TROPICAL RAIN FORESTS

A Technical Document

by

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July 2005

The preparation of this document was funded through the Freezailah Fellowship Fund of the International Tropical Timber Organisation with in-kind contributions from the University of British Columbia, Vancouver, Canada, and the Federal University of Technology, Akure, Nigeria.

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Submitted to:

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July 2005.

ABSTRACT

Volume equations were developed for common timber species in Nigeria's tropical rain forests. The data used consisted of merchantable volume, stump diameter, diameter at breast height and merchantable height for 77 timber species. The number of observations per species ranged from 5 to 142 while the diameter at breast height ranged from 20.0 cm to 230.0 cm.

The volume equations were fitted for individual species, all species combined, and groups of species. From a series of model-fitting trials, the untransformed generalised logarithmic volume function (also termed Schumacher-Hall's volume function) was found to perform better than other forms of volume functions. To stabilise the error variance, weighted least squares procedure was adopted, using the reciprocal of D^2H as the weighting factor. The coefficients from the species-specific equations were used as input variables for species grouping.

Species grouping was done by using a two-stage approach which includes cluster and discriminant analyses. The first stage involved using cluster analysis to group the more frequent species ($n \geq 30$) into five clusters, while the second stage involved using discriminant analysis to assign the less frequent species ($n < 30$) into the five clusters. The species groups obtained did not follow any particular ecological pattern as there were species of the same genus that fell into different clusters.

The results indicate that even though D^2H is a good predictor of merchantable volume for the tropical timber species, merchantable volume can also be predicted from diameter at breast alone or from stump diameter alone with reasonable level of precision. The zero-intercept quadratic volume function was the most appropriate function for such single-variable volume prediction. However, it was still necessary to weight the function by the reciprocal of the square of the independent variable ($1/D^2$ or $1/D_{st}^2$) in order to stabilise the error variance. The resulting volume functions possessed desirable statistical properties and model behaviours, and can be used to estimate timber volume in the tropical rain forest areas of Nigeria.

ACKNOWLEDGEMENTS

This study was funded by the International Tropical Timber Organisation (ITTO) through the Freezailah Fellowship Fund. The ITTO Board is gratefully acknowledged for their decision to fund the study. I also acknowledge Dr. Chisato Aoki, Coordinator of the ITTO Fellowship Programme, for effective coordination through her prompt response to my correspondences with the Institute.

My sincere gratitude goes to Dr. Peter L. Marshall (Professor and Associate Dean) and Dr. Valerie M. LeMay (Associate Professor of Forest Measurements) for accepting to be my hosts in the Department of Forest Resources Management, University of British Columbia (UBC), Vancouver, Canada where this document was prepared. These two did more than I anticipated and made my stay in Canada pleasant, exciting and educative. I thank the UBC authorities for permission to use the University libraries, computers and other facilities while preparing this report.

I acknowledge the Federal Department of Forestry, Federal Ministry of Environment, Abuja, Nigeria and Dr. Victor Adekunle of the Federal University of Technology, Akure, Nigeria, for providing me with the data used for this study. I am very grateful to my home institution, the Federal University of Technology, Akure, Nigeria, and in particular to the Vice Chancellor, Professor Peter O. Adeniyi, for approving my release from the University to enable me carry out this study.

The draft of this document was reviewed by my hosts at UBC (Drs. Peter Marshall and Valerie LeMay) and by Dr. Abdel Azim Zumrawi, Biometrician at the Research Branch, BC Ministry of Forests, Victoria, BC. Canada. I appreciate their comments and suggestions.

My deep appreciation goes to my wife, Toyin, and my two sons, Iyanu and Ayo, for their support and prayers while I was away for this study. I am also very grateful to several other people who supported me in various ways during the preparation of this document. Above all, I thank my Lord Jesus Christ for the gift of life and divine wisdom.

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1.0 INTRODUCTION

1.1 Background to the Study

The tropical rain forest is one of the major vegetation types of the globe (Richards, 1996; Whitmore, 1998). It occupies a total area of 1818.43 million hectares, representing 47% of the total land area occupied by all forest types of the world (FAO, 2003). According to Turner (2001), the tropical rain forest is the most diverse of all terrestrial ecosystems, containing more plant and animal species than any other biome. In spite of this diversity, most species are locally endemic or rare and patchily distributed (Richards, 1996). Thus, the overall timber value per unit area is generally low, thereby necessitating logging activities over large areas in order to meet the ever-increasing demand. The FAO (1999) estimated that tropical countries are losing 127,300 km^2 of forest annually. In view of the great value of the tropical rain forest and the grave consequences of losing it to unregulated logging activities and over-exploitation, it has become the focus of increasing public attention in recent years.

In Nigeria, the tropical rain forest is comprised of three vegetation types, namely mangrove forest, freshwater swamp forest and the lowland rain forest (Fig. 1.1). While the mangrove forest is found exclusively outside legally constituted forest reserves, others are found both within and outside forest reserves. Table 1.1 shows the extent of the remaining tropical rain forest in Nigeria. The data reflect only the areas actually covered by natural forests (primary and secondary), and therefore areas under other land covers such as plantations, agricultural lands, water bodies, human settlements, *etc.* are excluded. The table indicates that 974,674 hectares of tropical forests in Nigeria are within forest reserves. These are the areas under legal protection and therefore have the potential of being properly managed in a sustainable manner. This represents only 1.06% of the country's total land area of 92.377 million hectares. With a human population estimate of 120 million in 2002 (EarthTrends, 2003), it is apparent that the tropical rain forest in Nigeria is under serious pressure and would require much effort for sustainable management.

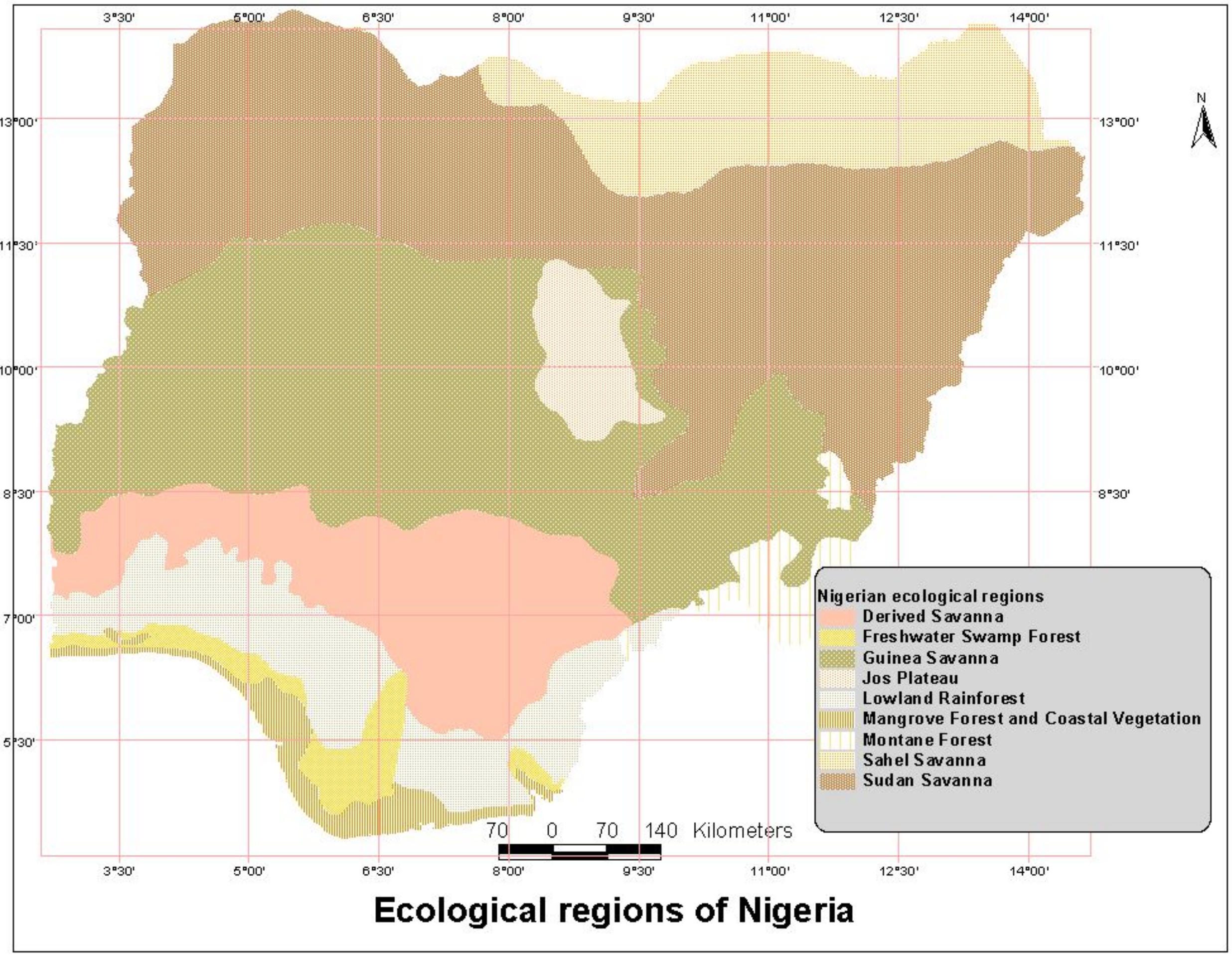

Fig. 1.1: Map of Nigeria showing the ecological regions

The most prominent wood industry in Nigeria is the sawmilling industry. In a review of the wood-based industrial sector in Nigeria, Akindele and Fuwape (1998) reported that there were 1300 sawmills in the country. With recent economic reforms and Government efforts towards poverty reduction, it is likely that this number has increased.

Table 1.1: Extent of the remaining tropical rain forest in Nigeria

Location	Forest cover type	Area (ha)
Within Forest Reserve	Freshwater Swamp Forest	186,621
	Lowland Rain Forest	788,053
	Sub-total	***974,674***
Outside Forest Reserve	Freshwater Swamp Forest	1,424,995
	Lowland Rain Forest	905,930
	Mangrove Forest	948,430
	Sub-total	***3,279,355***
Total		**4,254,029**

Source: Akindele, *et al*. (2001).

The wood industries rely mainly on the natural forests as reservoir of wood resources to meet their growing demand. Although large areas of plantations exist, natural forests are of greater attraction to timber contractors due to their wide variety of species and sizes. Furthermore, many of the well-known indigenous timber species are yet to be established as plantation species on a large scale. Consequently, there is still a heavy dependence on the natural forests as the source of such species as *Milicia excelsa, Khaya* species, *Afzelia* species, *Cordia* species, *and Entandrophragma cylindricum.*

1.2 Statement of the Problem

Sustainable forest management requires information on the growing stock. Such information guides the forest manager in timber valuation as well as in the allocation of forest areas for exploitation. For timber production, estimates of the growing stock are often expressed in terms of timber volume, which can be estimated from easily measurable dimensions of the tree. The most common procedure for volume estimation is to use volume equations, which are based on the relationship between volume and variables such as diameter, height, *etc*. The reliability of the volume estimates depends on how well the volume equation fits the data. In Nigeria, much work has been done in this regard for plantation species, most of which are exotic. The pronounced heterogeneity in species composition and structure even within small areas has precluded the development of volume functions for the natural forests. Without reliable volume equations for the indigenous hardwood species, there is no basis for planning their sustainable use. There is therefore the need to develop volume equations which can be used to obtain reliable estimates of timber volume in the natural forests. To accomplish this, financial support was sought and obtained from the International Tropical Timber Organisation (ITTO) through the Freezailah Fellowship support programme.

1.3 Objectives of the Study

The objective of this study was to develop tree volume equations for common indigenous timber species found in the tropical rain forest area of Nigeria. The specific objectives were to:

i. collate available data for the timber species,
ii. aggregate the data into species groups, and
iii. develop tree volume equations for the species groups.

It is hoped that the equations will serve as efficient tools for obtaining reliable estimates of the growing stock in the tropical rain forest ecosystem.

1.4 Scope of the Study

This study is limited to indigenous timber species that commonly grow within the lowland tropical rain forest area of Nigeria. Such species are listed in the tariff books of all the States within the ecological area. However, only those species with a minimum of five observations in the data set were included in this study. The data used were from previous inventory programmes carried out within Nigeria's lowland tropical rain forest area.

2.0 LITERATURE REVIEW

2.1 Nigeria's Tropical Forest Data

Developing volume functions for tropical timber species in Nigeria requires relevant data on the tree volume and other dimensional attributes of the trees. The appropriate functions to adopt are dictated by the limitations of available data. Data collection is generally a very tedious task, and in the Nigerian tropical rain forests, the challenges are even greater as a result of the following (Akindele, 2005):

i. High biodiversity, requiring detailed taxonomic species identification;
ii. Difficult terrain and dense undergrowth, resulting in much more time spent in plot location than in actual enumeration;
iii. Presence of dangerous animals; enumerators face high risk;
iv. Some variables (e.g. tree height and crown attributes) are difficult to measure reliably due to interlocking crowns;
v. Trees have no reliably distinct annual growth rings that can facilitate age determination from ring counts;
vi. Lack of suitable field equipment;
vii. Shortage of competent personnel to train and lead field teams;
viii. Lack of funds for forest measurement;
ix. Lack of coordination of data collection efforts; and
x. Forest ownership status (conflicts with local forest dwellers during field assessment).

The most recent nation-wide forest inventory programme in Nigeria is the national Forest Resources Study (FRS) carried out in Nigeria between 1997 and 1999 (Akindele, *et al*., 2001). During the programme, much data were collected from various forest types within and outside forest reserves across the country. The data were mainly species name and diameter at breast height of all standing trees in selected sample plots. Height to crown point (*i.e.* the base of the live crown) and diameter at base, middle and top positions along the stem height were measured only on selected trees to represent the various species encountered during enumeration. These measurements were to facilitate the computation of tree volume, using Newton-Simpson's formula (FAO, 1980). Other attributes of individual tree taper were not measured. The data were used for estimating the growing stock within plantations and natural forests in Nigeria. As is typical of tropical forest data, some tree species were under-represented due to limited number of observations. For volume equations, the common variable requirements are tree volume, diameter at breast height and tree height. Only species with these measures can be included in the development of volume equations. Other forest enumeration programmes in Nigeria are localized studies mainly in plantations of exotic species (e.g. Okojie and Nokoe, 1976; Adegbehin and Asiribo, 2002; Akindele, 1991, 2003; Onyekwelu, *et al*., 2003) with only a few in the natural forests (e.g. Okali and Ola-Adams, 1987; Adekunle *et al*., 2004).

2.2 Possible Approaches for Modeling Tropical Forest Data

Three possibilities exist for developing volume equations for the common timber species in Nigeria's tropical rain forests. These are:

1. Using the data for each species separately to develop species-specific equations.
2. Combining the data for all species and developing a single set of equations for all species combined together.
3. Classifying the species into groups and combining the data for all species within each group to developing equations for the group. The number of equations will depend on the number of groups into which the species are classified.

It is desirable for each species to have its own separate set of equations. However, existing conditions in tropical forests and the nature of data obtained from them constitute serious setbacks. Having equations for every tree species in the forest is simply impractical due to the paucity of data for many species. Where a tree species has a limited number of observations, there are serious doubts on the accuracy of equations produced for it. Hence, this option is not commonly used for tropical forest data. On the other hand, pooling the entire data set of all species for the purpose of fitting volume functions will obviously result in a large error variance and make the equations less reliable. Consequently, the common approach used for modeling forest data is to aggregate species into several groups, and develop separate equations for each group. This approach has been used by several authors including Swaine and Whitmore (1988), Vanclay (1991), Chai and LeMay (1993), Atta-Boateng and Moser (1998), Favrichon (1998), Finegan *et al*. (1999), Gourlet-Fleury and

Houllier (2000), Huth and Ditzer (2001) Phillips *et al.* (2002), Picard and Franc (2003), and Zhao *et al.* (2004). Grouping the species helps to avoid the need for specific equations for species with few data, and also facilitates a reduction in the number of functions to a more manageable number (Vanclay, 1991).

2.3 Species Grouping

Several methods have been proposed for grouping trees in mixed-species stands. According to Gitay and Noble (1997), there is no universally applicable concept for aggregating species into groups. The type of classification depends on the context of the performed aggregation (Kohler, *et al*., 2000) and the type of data available. For example, Avery and Burkhart (2002) suggested that where it is not feasible to construct separate equations for each species, those of similar taper and shape might be grouped together. Unfortunately, detailed information on tree form and taper is still lacking for most of the native tree species in the tropical rain forest. Hence, there is a need to examine other methods of grouping species. A list of the methods used by various authors is presented in Table 2.1. The common methods are:

2.3.1 Taxonomic grouping

This involves classifying tree species at the level of family or genus (e.g. Keay, 1989). Such classification is only suitable for biodiversity applications but inappropriate for growth and yield studies (Phillips, *et al*, 2002) due to variation in growth pattern and form of tree species within the same family or genus. For example, the Rubiaceae family is represented by about 85 genera in Nigeria, out of which 66 are trees, shrubs or woody climbers. Within the family, there is *Nauclea diderrichii* with clean bole and little or no buttress, which is quite different from *Corynanthe pachyceras* whose bole is often markedly fluted and crooked, branching low down (Keay, 1989). Similarly, within the Trichilia genus, *Trichilia prieuriana* is characterized by deeply fluted and twisted bole whereas the bole of *Trichilia monadelpha* is short, not fluted and without buttress. Taxonomy does not provide a good indication of growth pattern (Vanclay, 1991) and therefore cannot be used as basis for grouping species for fitting volume equations.

Table 2.1: Methods used for species grouping in some previous studies.

Method	No. of species	No. of Groups	Location	Authors
Pairwise F-tests	237	41	Rainforests of north Queensland, Austaralia	Vanclay (1991)
Ecophysiological attribute	15	2	Mixed swamp forests of Sarawak, Malaysia.	Chai and LeMay (1993)
Ecophysiological attribute	468	15	Tropical lowland rain forests in Sabah, Malaysia.	Kohler, *et al*. (2000)
Modified Pairwise F-tests	87	15	Lowland evergreen rain forests in French Guiana.	Gourlet-Fleury and Houllier (2000)
Cluster and Discriminant Analyses	64	10	Mixed tropical forest in Kalimantan (Indonesia Borneo)	Phillips, *et al*. (2002)
Minimization of Aggregation error and Cluster Analysis	27	5	Tropical rain forests in French Guiana.	Picard and Franc (2003)
Cluster Analysis	30	6	Mixed-species hardwood stands in the lower Mississippi alluvial valley, USA	Zhao, *et al*. (2004)

2.3.2 Ecophysiological Grouping

In this method, species grouping is based on ecophysiological criteria such as light demand and shade tolerance attributes of the species (Swaine and Whitmore, 1988; Whitmore, 1989; Chai and LeMay, 1993), gap requirements for regeneration (Shugart, 1997) or potential canopy layer (Richards, 1936; Poker, 1995; Condit *et al*, 1996). The major setback to the use of this method for tree species in Nigeria is that ecophysiological information on several species are not available and therefore using this method will leave such species unclassified.

2.3.3 Commercial Grouping

This involves classifying the species into commercial groups based on their utility potentials and prevailing market values. Sutter (1979) used this method to classify tree species in Nigeria's tropical rainforest into eight groups as follows:

A. Species utilized at present

1. Peelers and slicers for decorative veneers
2. Peelers and slicers for utility plywood
3. Saw wood for furniture and joinery
4. Saw wood for heavy construction
5. Saw wood for light construction
6. Wood for handicrafts and specialized uses

B. Species not utilized at present

7. Capable of reaching dimensions well over 40 cm dbh
8. Rarely reaching dimensions over 40 cm dbh.

These groups relate more to wood properties and uses than to the growth attributes of the trees. This method of classification is only appropriate for commercial analysis of a timber company's logging operation (Phillips *et al.*, 2002). Over time, uses change thereby necessitating the re-classification of some species as pointed out by FORMECU (1999).

2.3.4 Classical Grouping based on Statistical Analysis

This involves aggregating species into groups by the use of cluster analysis or any other classification procedure (Vanclay, 1991; Picard and Franc, 2003; Phillips *et al*., 2002; Zhao *et al*., 2004). Clustering is normally based on species characteristics that are used in the model (Atta-Boateng and Moser, 1998; Favrichon, 1998; Finegan *et al*., 1999; Gourlet-Fleury and Houllier, 2000; Huth and Ditzer, 2001), aggregation errors or the Euclidean distance between the species parameters (Picard and Franc, 2003). This method of species grouping may be the most adequate since it ensures that species are classified according to the functions that drive the model rather than on ecophysiological attributes for which there is only little knowledge.

2.4 Cluster Analysis

Cluster analysis is an exploratory data analysis tool which aims at sorting different objects into groups in a way that the degree of association between two objects is maximal if they belong to the same group and minimal otherwise (StatSoft, 2005). The tool encompasses a number of different algorithms and methods for grouping objects of similar kind into respective categories. The procedure performs a disjoint cluster analysis on the basis of distances computed from one or more quantitative variables. According to Dillon and Goldstein (1984), cluster analysis techniques are grouped into two broad categories, namely, hierarchical (where the resultant classification has an increasing number of nested classes) and partitioning methods (where clusters are formed by optimizing some specific clustering criterion). The methods under each category are presented in Table 2.2. The particular method to adopt in any study depends on the goal of the clustering procedure and the software available for the analysis.

In this study, the PROC FASTCLUS module in SAS for Windows 9.1 was used for the analysis. FASTCLUS uses a method that Anderberg (1973) calls *nearest centroid sorting* in which a set of points (*cluster seeds*) is selected as a first guess of the means of the clusters (SAS, 2004). Each observation is assigned to the nearest seed to form temporary clusters. The seeds are then replaced by the means of the temporary clusters, and the process is repeated until no further changes occur in the clusters. By default, the FASTCLUS procedure uses Euclidean distances, so the cluster centres are based on least-squares estimation (SAS, 2004). This kind of clustering method is often called a *k-means clustering method*, since the cluster centres are the means of the observations assigned to each cluster when the algorithm is run to complete convergence. Each iteration reduces the least-squares criterion until convergence is achieved.

Table 2.2: Cluster Analysis Methods

Hierarchical methods	Partitioning methods
1. Single Linkage or Nearest-Neighbour	1. *K*-Means Clustering
2. Complete Linkage or Furthest Neighbour	2. Trace-based methods
3. Average Linkage	
4. Ward's Error Sum of Squares	
5. Splinter-Average Distance	
6. Automatic Interaction Detection	

Source: Dillon and Goldstein (1984).

Specifically, FASTCLUS procedure operates in the following steps:

1. Observations called *cluster seeds* are selected.
2. Temporary clusters are formed by assigning each observation to the cluster with the nearest seed. Each time an observation is assigned, the cluster seed is updated as the current mean of the cluster.
3. After all observations are assigned, the cluster seeds are replaced by either the cluster means or other location estimates (cluster centres). This step can be repeated until the changes in the cluster seeds become small or zero.

4. Final clusters are formed by assigning each observation to the nearest seed. At the end, the observations would have been divided into clusters such that every observation belongs to one and only one cluster. If PROC FASTCLUS runs to complete convergence, the final cluster seeds will equal the cluster means or cluster centres.

Cluster variability is measured with respect to their means for the classifying variables. If more than one variable is used to define the clusters, the distances (dissimilarities) between clusters are measured in multi-dimensional space (i.e. Euclidean distance).

2.5 Discriminant Analysis

Discriminant analysis is a technique use to build a predictive model of group membership based on observed characteristics of each case. The technique involves deriving linear combinations of the independent variables that will discriminate between the *a priori* defined groups in such a way that the misclassification error rates are minimized (Dillon and Goldstein, 1984). Based on a set of observations for which the groups are already known, the technique constructs a set of linear functions of the predictors, known as discriminant functions, such that $L = b_1X_1 + b_2X_2 + \ldots\ldots + b_nX_n + c$, where the b's are discriminant coefficients, the X's are the input variables and c is a constant (Stockburger, 1998). The purpose is to determine the group of an observation based on a set of input variables.

The PROC DISCRIM module in SAS for Windows 9.1 is a tool that computes various discriminant functions for classifying observations into two or more groups on the basis of one or more quantitative variables (SAS, 2004). This module computes the Mahalanobis distances between a particular observation and the centroid of each cluster. This is expressed as the Generalized Squared Distance Function:

$$D_j^2(X) = (X - \overline{X}_j)'\, COV^{-1}(X - \overline{X}_j) \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

The function is then used to compute the probability of an observation being in each group. This probability is referred to as the Posterior Probability of Membership in each cluster and it is expressed as:

$$\Pr(j|X) = \frac{\exp(-0.5D_j^2(X))}{\sum_k \exp(-0.5D_k^2(X))} \qquad \ldots\ldots\ldots\ldots (2)$$

An observation is classified into a group k if setting $j = k$ produces the largest value of $Pr(j|X)$ or the smallest value of $D_j^2(X)$.

2.6 Volume Equations

Volume equations are mathematical expressions which relate tree volume to tree's measurable attributes such as diameter at breast height and/or height. They are used to estimate the average content for standing trees of various sizes and species (Avery and Burkhart, 2002). In other words, they give average volume of single trees of given dimensions (van Laar and Akca, 1997). The volume of the stem of a tree is considered a function of the independent variables, diameter, height, and form (Clutter *et al.,* 1983; Husch, *et al.,* 2003) in the expression:

$$V = f(D, H, F) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where V = volume, D = dbh, H = total, merchantable, or height to some specific limit, and F = measure of form such as the Girard form class or absolute form quotient. However, most volume equations use D (for local volume equations) and sometimes D and H (for standard volume equations) as independent variables. Tree form is not commonly used, and as pointed out by Clutter *et al.* (1983), there is no practical advantage gained from the use of form in addition to dbh and height. The reasons given for this are as follows:

1. Measurement of upper stem diameters is time-consuming and expensive.
2. Variation in tree form has a much smaller impact on tree volume or weight than does height or dbh variation.
3. With some species, form is relatively constant regardless of tree size.
4. With other species, tree form is often correlated with tree size, so that the dbh and height variables often explain much of the volume (or weight) variation actually caused by form differences.
5. In addition, the data available for this study are inadequate for computation of

reliable estimate of tree form.

The relationship between tree volume and dbh is not linear but curvilinear. However, volume is linearly related to basal area and therefore to dbh squared (D^2). When volume is expressed as a linear function of D^2, the error variance increases with tree size thereby violating the assumption of least squares regression. A common procedure to linearize the model and to eliminate heterogeneity of variance simultaneously is by carrying out logarithmic transformations. This procedure has its own limitation as it produces negatively biased estimates of tree volume (van Laar and Akca, 1997). This bias is due to the fact that the transformed regression equation passes through the arithmetic means of the logarithms of the dependent and the independent variables – which are geometrical means of the original variables (Avery and Burkhart, 2002). Geometric means are always less than arithmetic means (unless all values in a set of numbers are identical) thereby leading to under-prediction. Though methods of correcting the bias have been proposed (e.g. Baskerville, 1972; Yandle and Wiant, 1981; Lee, 1982), non-linear fit of volume equations are considered superior in volume estimation (LeMay, 1982). Moreover, the availability of suitable computer programs to handle the non-linear fit makes logarithmic transformation unnecessary. Using non-linear models directly without logarithmic transformation have the following advantages:

1. They ensure efficient use of data and can produce good estimates of the unknown parameters in the model with relatively small data sets (NIST/SEMATECH, 2005).
2. The square of actual minus predicted volumes is minimized, rather than the transformation of values (Zar, 1968).
3. The reported standard error is the standard error of the volume, thereby making re-computation unnecessary, except when there is unequal variance.

Since volume equations are normally fitted through the least squares method, it is expected that a good equation would comply with the assumptions of this technique. One of such assumptions is that the variance of the *y* values is constant for the range of values of the *x* variables. Where this assumption is violated, regression analysis will still give unbiased estimates of the regression parameters but accurate estimates of their confidence intervals cannot be obtained (LeMay and Marshall, 1990). The use of weighted least squares regression will correct this problem and allow for the correct estimation of confidence intervals. The commonly used models of volume equations are presented in Table 2.3.

In this study, the major challenges are to examine the relationships between volume and the tree growth variables, and develop suitable equations for volume prediction. Since the study is based on tropical forest data (mixed-species stands), an appropriate technique is required for classifying the species into groups in order to reduce the number of equations and also accommodate species with few observations.

Table 2.3: Common types of Volume Prediction Models and Recommended Techniques for fitting them (Clutter, *et al*., 1983).

Model Name	Original Form	Variance Assumptions	Regression Model	Parameter Estimates
Constant form factor	$V_i = b_1 D_i^2 H_i + \varepsilon_i$	$(a) \quad \sigma \propto D_i^2 H_i$ *or*	$Y_i = \beta_0$ *where* $Y_i = V_i / D_i^2 H_i$	$\hat{b}_1 = \hat{\beta}_0 = \overline{Y}$
		$(b) \quad \sigma \propto \sqrt{D_i^2 H_i}$	$Y_i = \beta_1 X_i$ *where* $Y_i = V_i \Big/ \sqrt{D_i^2 H_i}$ $X_i = \sqrt{D_i^2 H_i}$	$\hat{b}_1 = \hat{\beta}_1 = \dfrac{\sum X_i Y_i}{\sum X_i^2} = \dfrac{\sum V_i}{\sum D_i^2 H_i}$
Combined variable	$V_i = b_0 + b_1 D_i^2 H_i + \varepsilon_i$	$(a) \quad \sigma \propto D_i^2 H_i$ *or*	$Y_i = \beta_0 + \beta_1 X_i$ *where* $Y_i = V_i / D_i^2 H_i$ $X_i = 1 / D_i^2 H_i$	$\hat{b}_0 = \hat{\beta}_1$ $\hat{b}_1 = \hat{\beta}_0$
		$(b) \quad \sigma \propto \sqrt{D_i^2 H_i}$	$Y_i = \beta_1 X_{1i} + \beta_2 X_{2i}$ *where* $Y_i = V_i \Big/ \sqrt{D_i^2 H_i}$ $X_{1i} = 1 \Big/ \sqrt{D_i^2 H_i}$ $X_{2i} = \sqrt{D_i^2 H_i}$	$\hat{b}_0 = \hat{\beta}_1$ $\hat{b}_1 = \hat{\beta}_2$

Logarithmic	$V_i = e^{b_1} D_i^{b_2} H_i^{b_3} e^{\varepsilon_i}$	ε_i *has constant variance*	$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i}$ *where* $Y_i = \ln V_i$ $X_{1i} = \ln D_i$ $X_{2i} = \ln H_i$	$\hat{b}_1 = \hat{\beta}_0$ $\hat{b}_2 = \hat{\beta}_1$ $\hat{b}_3 = \hat{\beta}_2$
Generalised combined variable	$V_i = b_0 + b_1 D_i^2 + b_2 H_i + b_3 D_i^2 H_i + \varepsilon_i$	$(a) \quad \sigma \propto D_i^2 H_i$ *or*	$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i}$ *where* $Y_i = V_i \big/ D_i^2 H_i$ $X_{1i} = 1 \big/ D_i^2$ $X_{2i} = 1 \big/ H_i$ $X_{3i} = 1 \big/ D_i^2 H_i$	$\hat{b}_0 = \hat{\beta}_3$ $\hat{b}_1 = \hat{\beta}_2$ $\hat{b}_2 = \hat{\beta}_1$ $\hat{b}_3 = \hat{\beta}_0$
		$(b) \quad \sigma \propto \sqrt{D_i^2 H_i}$	$Y_i = \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i}$ *where* $Y_i = V_i \big/ \sqrt{D_i^2 H_i}$ $X_{1i} = 1 \big/ \sqrt{D_i^2 H_i}$ $X_{2i} = \sqrt{D_i^2} \big/ \sqrt{H_i}$ $X_{3i} = \sqrt{H_i} \big/ \sqrt{D_i^2}$ $X_{4i} = \sqrt{D_i^2 H_i}$	$\hat{b}_0 = \hat{\beta}_1$ $\hat{b}_1 = \hat{\beta}_2$ $\hat{b}_2 = \hat{\beta}_3$ $\hat{b}_3 = \hat{\beta}_4$

Generalised Logarithmic	$V_i = b_0 + b_1 D_i^{b_2} H_i^{b_3} + \varepsilon_i$	$(a) \quad \sigma \propto D_i^2 H_i$ *or*	$Y_i = \beta_1 X_{1i} + \beta_2 X_{2i}^{\beta_3} X_{3i}^{\beta_4}$ *where* $Y_i = V_i / D_i^2 H_i$ $X_{1i} = 1 / D_i^2 H_i$ $X_{2i} = D_i$ $X_{3i} = H_i$	$\hat{b}_0 = \hat{\beta}_1$ $\hat{b}_1 = \hat{\beta}_2$ $\hat{b}_2 = \hat{\beta}_3 + 2$ $\hat{b}_3 = \hat{\beta}_4 + 1$
		$(b) \quad \sigma \propto \sqrt{D_i^2 H_i}$	$Y_i = \beta_1 X_{1i} + \beta_2 X_{2i}^{\beta_3} X_{3i}^{\beta_4}$ *where* $Y_i = V_i / \sqrt{D_i^2 H_i}$ $X_{1i} = 1 / \sqrt{D_i^2 H_i}$ $X_{2i} = D_i$ $X_{3i} = H_i$	$\hat{b}_0 = \hat{\beta}_1$ $\hat{b}_1 = \hat{\beta}_2$ $\hat{b}_2 = \hat{\beta}_3 + 1$ $\hat{b}_3 = \hat{\beta}_4 + 0.5$

3.0 METHODOLOGY

3.1 The Data

The data used for this study were forest inventory data collected from the lowland rainforest ecosystem of Nigeria. They included the data collected by (i) Beak Consultants Limited under the Nigeria's Forest Resources Study funded by the African Development Bank and the Federal Government of Nigeria, and (ii) Dr. Victor Adekunle of the Federal University of Technology, Akure through a grant provided by the African Academy of Sciences. The data were individual tree measurements for diameter (overbark) at base, breast height, middle and top positions along the stem, and stem height to the crown point. The botanical name of each tree species was also included in the data. The minimum dbh in the data was 20 cm. Since the focus of this study was on timber species, data for species not regarded as timber species were removed from the set. A compilation of timber species from tariff books of the Forestry Department of various States in southern Nigeria served as guide for this purpose. The data were also examined to check if there were erroneous data points in the form of questionable or unrealistic values. As the field forms were not available, there was no way of correcting such errors. Such data points were therefore removed in order to avoid unnecessary noise in the data. After removal, the remaining data covered 77 species with 5 to 142 observations per species (n). In total, there were 2,391 observations. Only two species had $n \geq 100$, eleven others had n ranging from 50 to 99 and 20 others had n ranging from 30 to 49. Thus, only 33 species had $n \geq 30$. The few number of observations for many of the species is a typical phenomenon in tropical rain forests. As pointed out by Kochummen, *et al.* (1990) and Lieberman and Lieberman (1994), despite the high species diversity in tropical rain forests, most of the tree species are locally rare.

3.2 Preliminary Data Analysis

The first task was to calculate tree volume and examine its relationship with other variables. Volume may be estimated for some specific merchantable portion of the stem only or for the total stem. In this study, volume was estimated for the merchantable portion of the stem up to the crown point. Based on the data available for this study, merchantable volume was estimated using the Newton-Simpson's formula (FAO, 1980) expressed as:

$$V = \pi \frac{H}{24}\left(D_b^2 + 4D_m^2 + D_t^2\right) \qquad \text{........... (4)}$$

where V = merchantable volume, overbark (in m^3),

H = merchantable height (in m),

D_b = diameter at the base, overbark (in m),

D_m = diameter at the middle position along the stem overbark (in m),

and D_t = diameter at the top (in m).

Merchantable height is defined as the usable portion of the tree stem, that is, the part for which volume is computed or the section expected to be utilized in a commercial logging operation (Avery and Burkhart, 2002). In Nigeria, the stump (up to a height of 30 cm) and buttresses are not normally utilized in commercial logging operations. Therefore the merchantable height was obtained by reducing the stem height by 0.3 m (stump height). However, for trees whose buttresses extend beyond the stump height, stem height was reduced by the buttress height in order to obtain merchantable height. All the computations were done using the SAS for Windows Version 9.1. The Newton-Simpson's formula was chosen as it has been reported to provide the least biased and most precise estimates of individual tree volumes for tropical timber species (Fonweban, 1997) and has been widely used in Nigeria (e.g. Akinsanmi and Akindele, 1995; Onyekwelu and Akindele, 1995; Fuwape and Akindele, 1997; FORMECU, 1999; Akindele, 2003; Adekunle, *et al*., 2004).

Following the computation of tree volume, the data were summarized by computing simple descriptive statistics for each species. The statistics included number of observations, range, mean and standard error of the mean. Graphs were also plotted to examine the relationship between the variables. Only the graphs for the pooled data (all species combined) are presented in this report.

3.3 Developing the Volume Equations

3.3.1 Volume Equations for Individual Species

In developing volume equations for each of the 77 tree species in this study, the objective was to obtain coefficients which will serve as basis for grouping the species. Several model forms were considered and tried for the various species. It was clear that the best model for each species vary in form. However, the generalised logarithmic model form (Table 2.3) was the most appropriate for many of the species. The model was therefore selected for this study. In its original form, the model was the Schumacher-Hall volume model (Schumacher and Hall, 1933) expressed as:

$$V_i = b_0 + b_1 D_i^{b_2} H_i^{b_3} + \varepsilon_i \qquad \ldots\ldots\ldots(5)$$

where, V = tree volume (m^3);

D = diameter at breast height (cm);

H = merchantable height (m);

D_{st} = stump diameter (cm); and

b_0, b_1, b_2 and b_3 are the regression parameters, while ε_i is the error term.

The model indicates that tree volume increases proportional to certain powers of D and H. In some previous works (e.g. Edminster, *et al*, 1980; Abayomi, 1983; Omule *et al,* 1987) the D was fixed to the power of 2 while H was fixed to the power of 1 to give the expression

$$V = b_0 + b_1 D^2 H + \varepsilon_i \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

which Clutter *et al*. (1983) referred to as the 'combined variable' volume function.

In this study, it was considered better to compute the best estimates for b_2 and b_3 instead of fixing their values as 2 and 1 respectively. It is expected that fitting Equation (5) to the data should produce equations where b_1, b_2 and b_3 are positive. Generally, values of b_2 should approach 2 while those of b_3 should be close to 1. All the regression statistics were computed using the PROC NLIN module of SAS for Windows Version 9.1 (SAS, 2004). Fitting Equation 5 to the data produced cone-shaped residual plots, thereby indicating that one of the assumptions of least squares procedure has been violated. Evaluation of the results showed that standard deviation was proportional to D^2H $(i.e.\, \sigma \propto D_i^2 H_i)$. Consequently, weighted least squares procedure was adopted using $1/D^2H$ as the weight. The final equation fitted to the data is as follows:

$$\frac{V_i}{D_i^2 H_i} = \frac{\hat{\beta}_1}{D_i^2 H_i} + \hat{\beta}_2 D_i^{\hat{\beta}_3 + 2} H_i^{\hat{\beta}_4 + 1} \qquad \ldots\ldots\ldots\ldots (7a)$$

or simply

$$Y_i = \hat{b}_0 X_{1i} + \hat{b}_1 X_{2i}^{\hat{b}_2} X_{3i}^{\hat{b}_3} \qquad \ldots\ldots\ldots\ldots (7b)$$

where

$$Y_i = V_i / D_i^2 H_i\,,\; X_{1i} = 1/D_i^2 H_i\,,\; X_{2i} = D_i\,,\; X_{3i} = H_i\,,\; \hat{b}_0 = \hat{\beta}_1, \hat{b}_1 = \hat{\beta}_2, \hat{b}_2 = \hat{\beta}_3 + 2, \textit{ and } \hat{b}_3 = \hat{\beta}_4 + 1$$

The use of Equation 7b helped to stabilise the error variance in a way that conforms to the assumptions of least squares. This equation form was therefore used to produce the species-specific volume equations in this study.

3.3.2 Volume Equations for All Species Combined

Equation 7b was also fitted to the combined data set after aggregating all the species into one group. It was apparent that doing this would lead to large standard error because of the amount of variability present in the data. However, it was still worthwhile to embark on the process in order to have a benchmark with which to compare equations in other categories.

3.3.3 Volume Equations for Groups of Species

All the 33 species with $n \geq 30$ in this study formed the basis for species grouping. Values of the model parameters obtained by fitting Equation 7b to the individual species data served as input data for the cluster analysis. PROC FASTCLUS module in SAS was used to group the 33 species into 5 clusters. Measures of distance between cluster means were computed to evaluate the effectiveness of the clustering procedure. The clusters were also evaluated through cross-validation using the Canonical Discriminant Analysis (PROC CANDISC) procedure. The graph of canonical variables 1 and 2 were plotted in order to display the layout of the clusters.

The next task was to assign the remaining 44 species (with $n < 30$) into the 5 clusters. This was accomplished by the use of discriminant analysis technique (PROC DISCRIM module in SAS). The input variables were the coefficients obtained in Section 3.3.1 when Equation 7b was fitted to each of the species. After assigning all the species into clusters, tree volume functions were then fitted for each cluster of species. Series of volume functions were fitted and compared. None of them did as well as Equation 7b in terms of producing unbiased estimates as well as residual plots that shows conformity to the assumptions guiding the analysis.

In addition to fitting Equation 7b to the data of the species groups, volume equations were also produced based on dbh alone and stump diameter alone for each cluster. These were considered important from practical point of view. The former (using dbh alone) is appropriate in all inventory programmes where height measurement is not carried out. Height measurement under tropical forest condition is a very difficult task, and it is readily excluded in many instances where field conditions are unfavourable. The volume equation based on stump diameter alone is particularly useful in instances where there is the problem of illegal logging activities, leaving only the stump (Akindele, 1987, 2003). This equation will make it possible to obtain estimates of merchantable volume lost to such illegal activities. After several trials and comparison of different model forms, the models fitted are weighted quadratic models with no intercept. They performed best in terms of the fit statistics and randomness of the residuals over the entire range of volume prediction. Prior to weighting, the models are of the following forms:

$$V = b_1 D + b_2 D^2 \qquad \text{………(8)}$$

$$V = b_1 D_{st} + b_2 D_{st}^2 \qquad \text{………(9)}$$

where V is the merchantable volume (m^3), D is the dbh (cm), D_{st} is the stump diameter (cm); and b_1 and b_2 are the regression parameters. Equation 8 was weighted by ($1/D^2$) while Equation 9 was weighted by ($1/D_{st}^2$). The actual regression equations therefore became:

$$V/D^2 = b_1/D + b_2 \qquad \text{………(10)}$$

$$V/ D_{st}^2 = b_1/Dst + b_2 \qquad \text{………(11)}$$

The major fit statistics calculated for each volume equation is the standard error of estimate (SEE). It is the square root of the average squared error of prediction and it is used as a measure of the accuracy of prediction. SEE is expressed as:

$$SEE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n-p}} \qquad \text{………… (11)}$$

where y_i is the actual tree merchantable volume, $\hat{y}_i$ is the predicted tree merchantable volume, n is the number of observations and p is the number of parameters in the volume equation. In addition to SEE, residual analysis was carried out by plotting the residuals against the predicted volume on cluster by cluster basis.

4.0 RESULTS AND DISCUSSION

In this Chapter, the results of data analysis are presented and discussed. A separate report of other activities carried out during the period of the Fellowship is presented in Appendix 1. The Appendix also contains highlights of the in-kind contributions from the host institution which further helped to make the whole experience very worthwhile.

4.1 Data Summary

The entire data set used for this study consists of 77 common tropical timber species in Nigeria. In terms of their taxonomy, these species belong to 27 different families as indicated in Table 4.1. For ease of reference locally, the vernacular names of each species are presented in Appendix 2. For the vernacular names, the three most popular local languages in Nigeria were used. A summary of the data for the 77 species showing number of observations, means and standard error for each variable is presented in Appendix 3.

For the entire data set, the relationships between merchantable volume and each of the predictor variables (dbh, merchantable height and stump diameter) are shown in Figs. 4.1, 4.2 and 4.3, respectively. It is evident from the graphs that none of the predictor variables had linear relationship with merchantable volume. While dbh and stump diameter had curvilinear relationship with merchantable volume, merchantable height did not depict any meaningful pattern. This shows that linear regression equations are not appropriate as volume equations for common tropical timber species in Nigeria's tropical rain forest, unless with some transformations of the variables. The lack of any meaningful trend in the relationship between merchantable volume and merchantable height could be attributed to the fact that the upper limit for merchantable height measurement is the crown point which varies greatly between and within species. Crown point is usually influenced by competition, site quality, tending practices, extent of self-pruning by individual trees, *etc*. Fig. 4.4 shows that there is a very strong linear correlation between dbh and stump diameter ($r = 0.97$). This suggests that stump diameter can play a similar role to dbh as a good predictor of merchantable volume. Similar results have been reported in tropical rain forest area of Nigeria for plantation-grown *Tectona grandis* (Osho, 1983) and *Gmelina arborea*

(Akindele, 2003). An examination of the relationship between merchantable height and dbh (Fig. 4.5) indicates that very weak correlation. Thus, there is no problem of multicollinearity or redundant information in using both variables together as predictor variables for merchantable volume. Multicollinearity affects parameter estimates from the fact that the redundant information in the predictor variables reduces the precision with which their regression coefficients can be estimated, *i.e.* the standard errors of the coefficients will be large (Glantz and Slinker, 2001).

Table 4.1: Data distribution according to family

Family	No. of Species	No. of Observations
Anacardiaceae	2	36
Anisophylleaceae	1	17
Annonaceae	1	72
Apocynaceae	3	100
Bombacaceae	2	49
Boraginaceae	1	64
Burseraceae	1	12
Capparaceae	1	36
Chrysobalanaceae	1	20
Combretaceae	2	82
Dipterocarpaceae	1	20
Ebenaceae	1	29
Euphorbiaceae	1	34
Flacourtiaceae	1	23
Guttiferae	2	190
Irvingiaceae	2	27
Lecythidaceae	1	28
Leguminosae	22	615
Meliaceae	11	183
Moraceae	3	91

Myristicaceae	2	49
Olacaceae	1	113
Rubiaceae	3	53
Sapindaceae	1	20
Sapotaceae	1	62
Sterculiaceae	7	286
Ulmaceae	2	80
TOTAL	**77**	**2391**

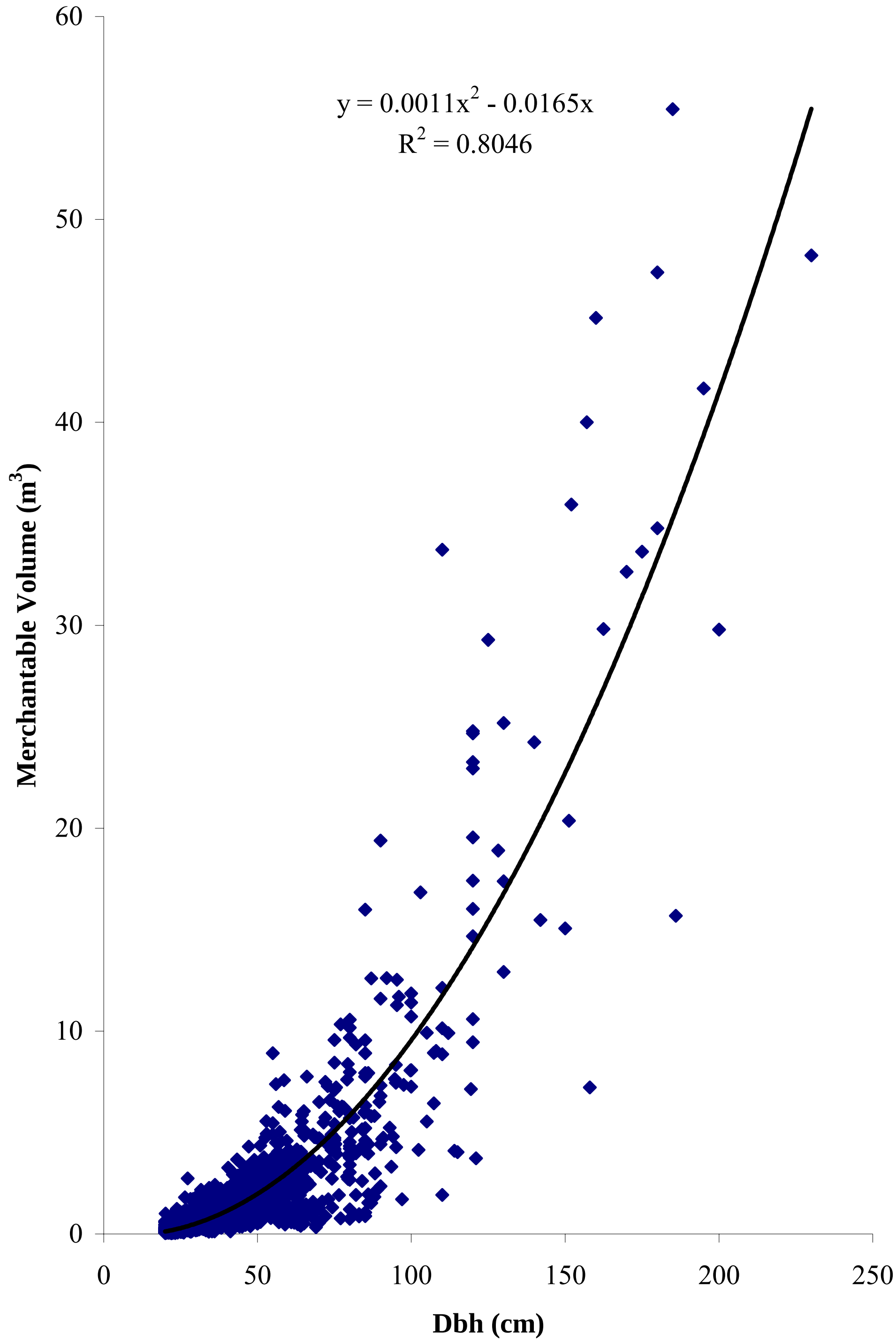

Fig. 4.1: Relationship between merchantable volume and dbh *(n = 2391)*

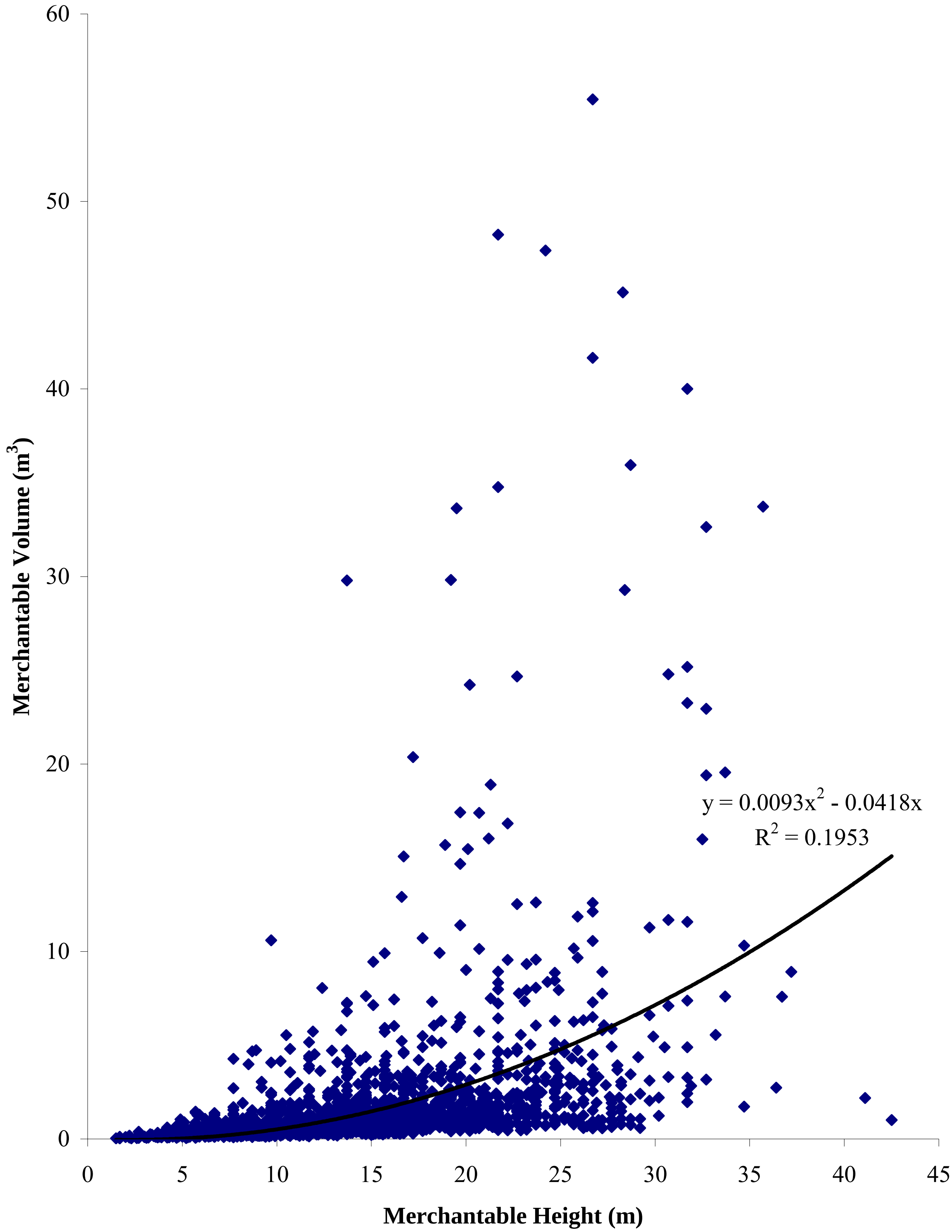

Fig. 4.2: Relationship between merchantable volume and merchantable height *(n=2391)*

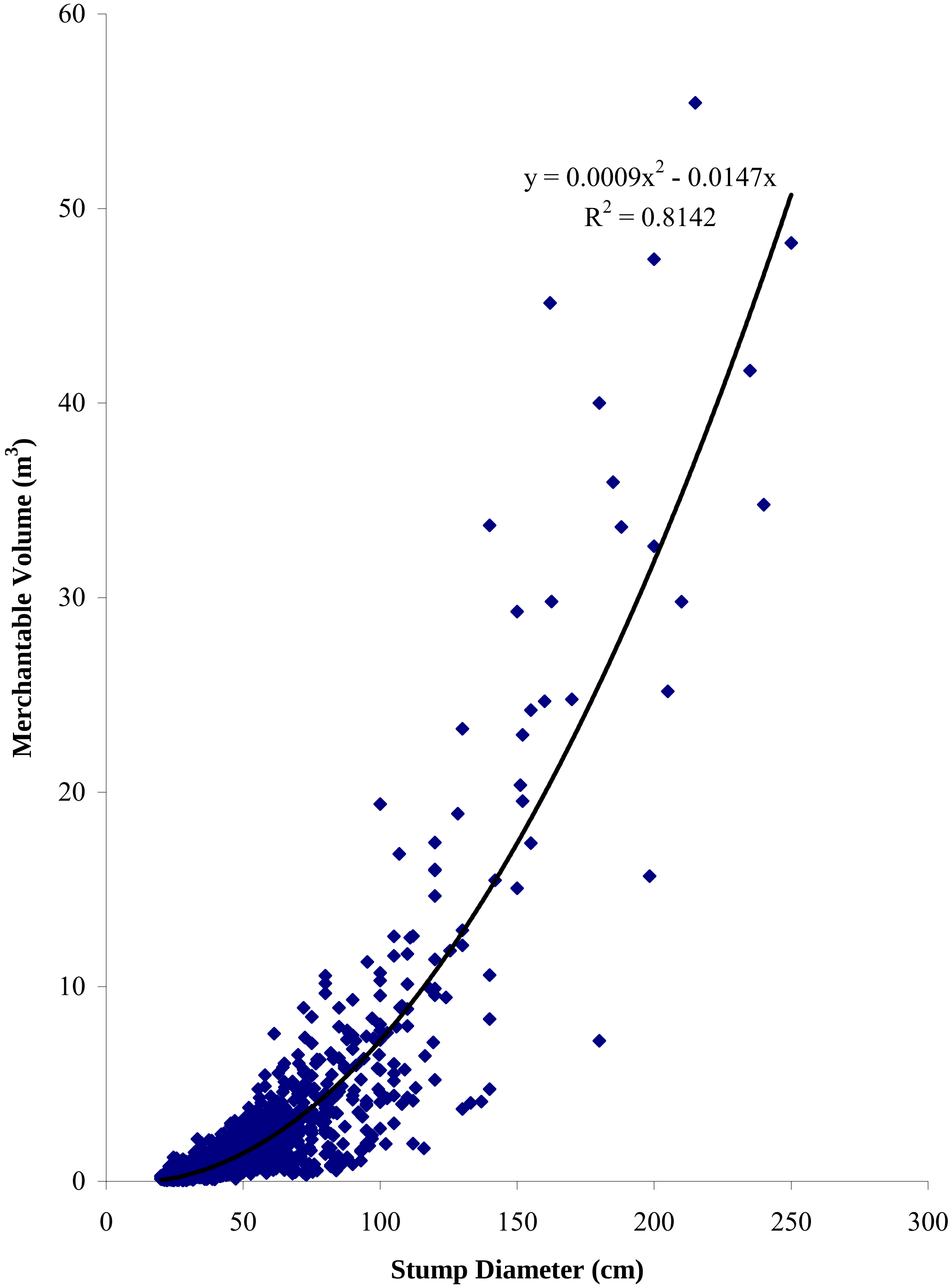

Fig. 4.3: Relationship between merchantable volume and stump diameter *(n=2391)*

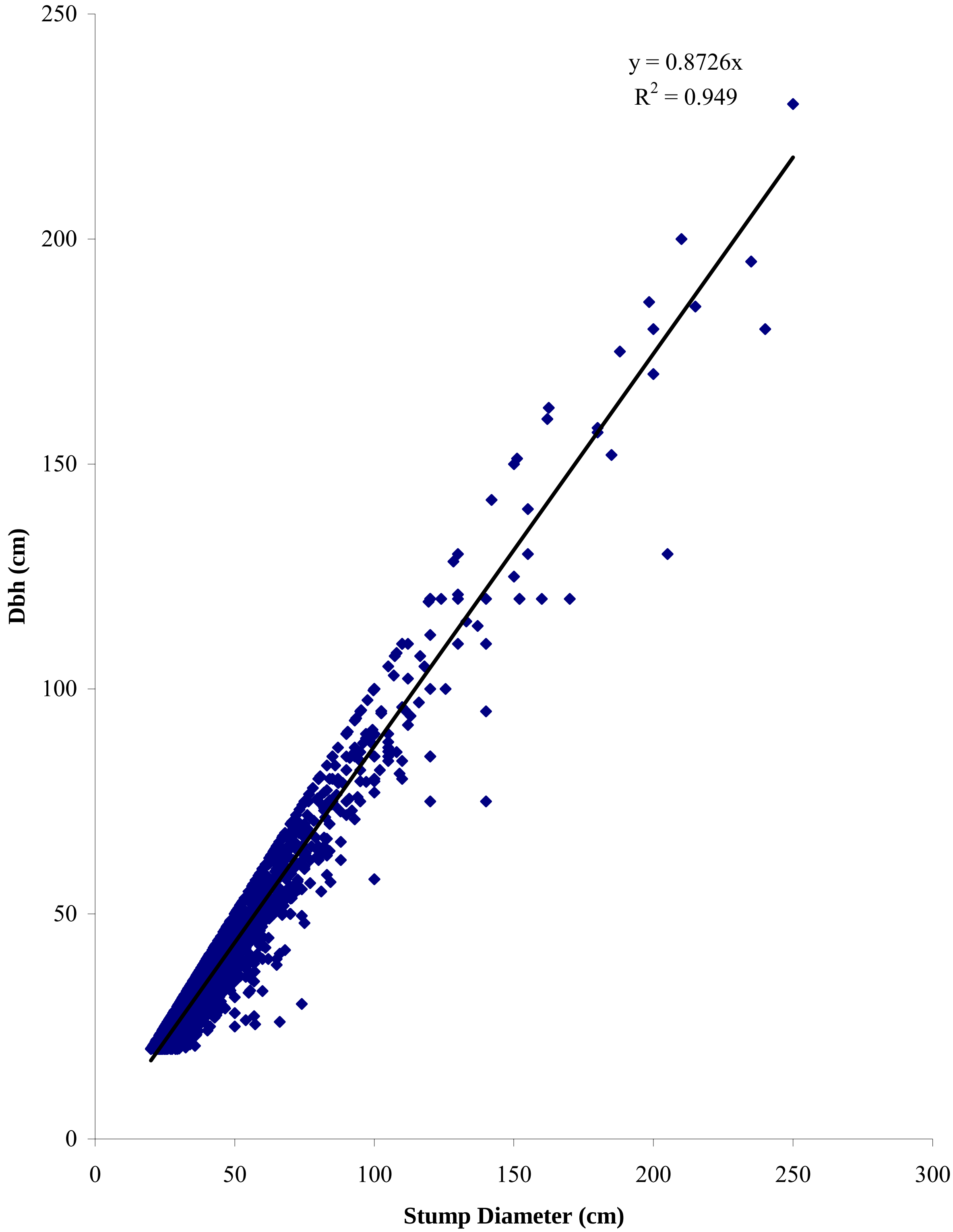

Fig. 4.4: Relationship between dbh and stump diameter *(n=2391)*

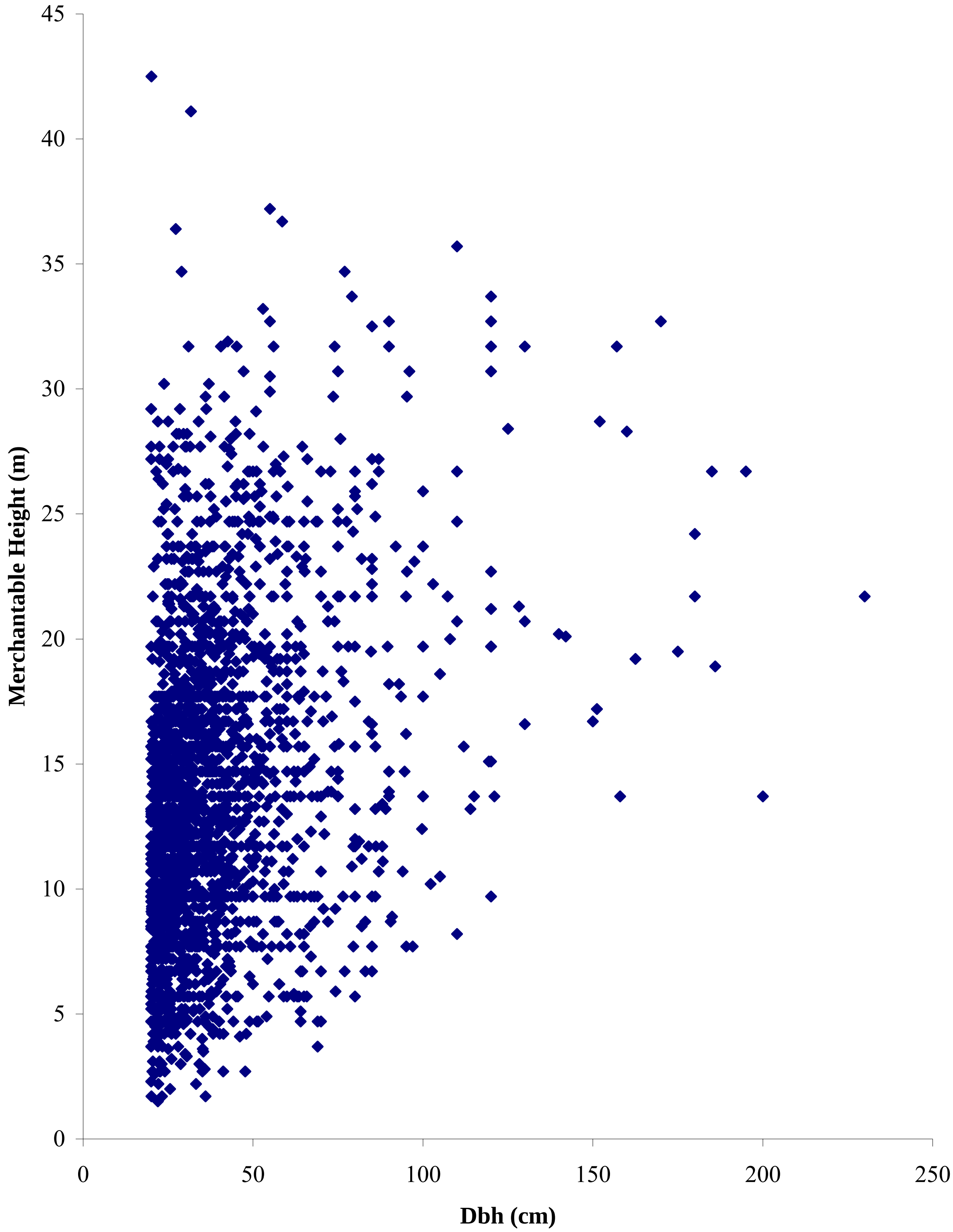

Fig. 4.5: Relationship between merchantable height and dbh *(n=2391)*

4.2 The Species Groups

The summary statistics of the cluster analysis for the initial 33 species are presented in Table 4.2. The table indicates that Cluster 3 had the highest number of species (13 species) while Cluster 2 had the least (one species). In terms of mean absolute deviation, Cluster 5 had the least value. Mean absolute deviation could not be computed for Cluster 2 since it has only one species. The presence of only one species in the cluster suggested that the species (*Guarea cedrata*) could be an outlier. Table 4.2 indicates that the cluster had the farthest distance (0.7996) to its nearest neighbour (Cluster 5). Cluster 5 appeared to be central as it was the nearest cluster to three of the other four clusters, with Cluster 3 being its closest neighbour. The spatial spread of the clusters is shown in Fig. 4.6. The entire test statistics (Wilk's Lambda, Pillai's Trace, Hotelling-Lawley Trace and Roy's Greatest Root) gave significant results ($p < 0.0001$) as presented in Table 4.3.

Table 4.2: Summary of the results of cluster analysis for the initial 33 species.

Cluster	Frequency	Mean Absolute Deviation	Maximum Distance from Cluster Seed to Observation	Nearest Cluster	Distance to the Nearest Cluster
1	6	0.0604	0.3506	5	0.7408
2	1	-	4.72E-16	5	0.7996
3	13	0.0368	0.2721	5	0.3586
4	8	0.0685	0.4641	3	0.5718
5	5	0.0460	0.2324	3	0.3586

The five clusters were well separated. They all had maximum distances from cluster seed to observation that are less than the distance between the centroid (median) of that cluster and that of its nearest neighbour (Table 4.2). Cross-validation of the results using the linear discriminant function (SAS, 2004) indicated that there was no error of classification. This suggests that cluster analysis technique was effective for grouping the 33 species. Cluster analysis has also been reported to be effective for grouping mixed species hardwood stands in the lower Mississippi alluvial valley in the United States (Zhao, *et al*., 2004) and for forest type definitions (vanHees, *et al*., 2001).

Table 4.3: Test Statistics and *F* Approximations for the FASTCLUS Procedure*

Statistic	Value	*F* Value	Num DF	Den DF	Pr > F
Wilks' Lambda	0.0074	19.18	16	77.014	<.0001
Pillai's Trace	2.2258	8.78	16	112	<.0001
Hotelling-Lawley Trace	17.0779	25.71	16	44.32	<.0001
Roy's Greatest Root**	11.5752	81.03	4	28	<.0001

**Num DF = Numerator degrees of freedom; Den DF = Denominator degrees of freedom.*
*** F Statistic for Roy's Greatest Root is an upper bound.*

In terms of assigning the remaining 44 species into the existing clusters, discriminant analysis was found to be suitable in this study. Table 4.4 provides the frequency distribution of the species among the clusters based on the two analyses. A detailed list of species in each cluster is presented in Table 4.5. The effectiveness of cluster and discriminant analyses for species grouping in this study agrees with earlier report by Phillips, *et al.* (2002) who found the methods to be appropriate for grouping mixed species stands in the Berau region of East Kalimantan (Indonesia Borneo). However, unlike in their study where some subjectivity was introduced to ensure that clustering was related to species characteristics, the species groups obtained in this study was purely by analytical methods without any subjective adjustment. The implication is that the species groups in this study did not reflect any particular taxonomic or ecophysiological trend. For instance, the two species in the Genus *Albizia* were not in the same cluster. Similarly, the four species of *Trichilia* present in the data were shared among three clusters. On the other hand, all the three species of *Brachystegia* were in Cluster 4. Other Genera whose species fell within the same cluster are *Guarea, Mitragyna* and *Terminalia*. Species grouping using analytical methods has been known to produce results that do not necessarily have ecological significance (Vanclay, 1991). To make them reflect ecological significance, subjective adjustment of the analytical results will be necessary. Such adjustment can only be done where there is sufficient information about the ecological attributes of the species. Such information is not available for most of the species considered in this study.

Table 4.4: Number of Species assigned to each Cluster from the two analyses

Cluster	Cluster Analysis	Discriminant Analysis	Total
1	6	6	**12**
2	1	12	**13**
3	13	4	**17**
4	8	14	**22**
5	5	8	**13**
Total	**33**	**44**	**77**

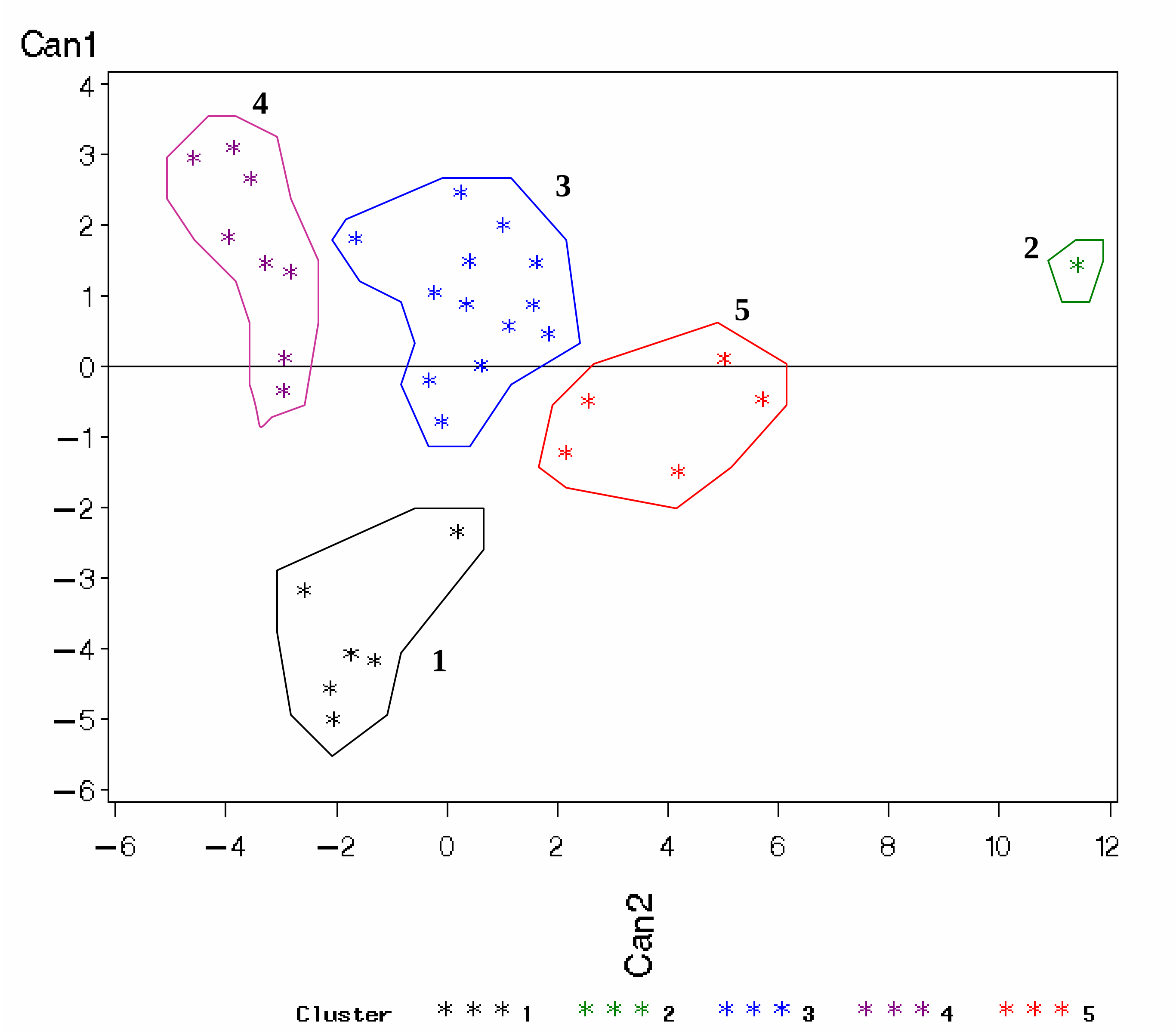

Fig. 4.6: Graphical display showing relative position in parameter space of the five clusters for the initial 33 species.

Table 4.5: Results of grouping the 77 common timber species into five clusters.

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Antrocaryon klaineanum	*Albizia ferruginea*	***Afzelia africana***	***Alstonia boonei***	***Antiaris toxicaria***
Celtis zenkeri	*Funtumia africana*	***Albizia zygia***	*Amphimas pterocarpoides*	*Blighia sapida*
Chrysobalanus icaco	*Gossweilerodendron balsamiferum*	***Ceiba pentandra***	*Bombax buonopozense*	*Entandrophragma cylindricum*
Coelocaryon preussii	***Guarea cedrata***	***Cordia millenii***	*Brachystegia eurycoma*	***Eribroma oblonga***
Copaifera mildbraedii	*Guarea thompsonii*	*Cyclicodiscus gabunensis*	*Brachystegia kennedyi*	*Hannoa klaineana*
Daniellia ogea	*Holoptelea grandis*	***Detarium senegalense***	*Brachystegia nigerica*	***Hylodendron gabunense***
Dialium guineense	*Khaya grandifoliola*	*Distemonanthus benthamianus*	*Canarium schweinfurthii*	*Lannea welwitschii*
Erythrophleum suaveolens	*Nauclea diderrichii*	***Funtumia elastica***	***Carapa procera***	*Lovoa trichilioides*
Khaya ivorensis	*Nesogordonia papaverifera*	*Lophira alata*	*Diospyros mespiliformis*	*Milicia excelsa*
Pentaclethra macrophylla	*Pterocarpus santalinoides*	***Mansonia altissima***	*Irvingia gabonensis*	***Mitragyna ledermannii***
Symphonia globulifera	*Sterculia tragacantha*	***Pterocarpus osun***	***Manilkara obovata***	*Mitragyna stipulosa*
Trilepisium madagascariense	*Trichilia monadelpha*	***Pterygota macrocarpa***	*Petersianthus macrocarpus*	***Pentadesma butyracea***
	Trichilia retusa	***Ricinodendron heudelotii***	***Piptadeniastrum africanum***	*Tetrapleura tetraptera*
		Sterculia rhinopetala	*Poga oleosa*	
		Strombosia pustulata	***Pycnanthus angolensis***	
		Trichilia prieuriana	*Scottellia coriacea*	
		Triplochiton scleroxylon	*Staudtia stipitata*	
			Stemonocoleus micranthus	
			Terminalia ivorensis	
			Terminalia superba	
			Trichilia gilgiana	
			Xylopia aethiopica	

Bold face type *indicate those with $n \geq 30$.*

4.3 The Volume Equations

4.3.1 Volume Equations for Individual Species

The volume equations developed for individual tree species are presented in Table 4.6. The table shows the number of observations (*n*) per species, the regression parameters ($\hat{b}_0, \hat{b}_1, \hat{b}_2$ and $\hat{b}_3$) and the weighted standard error of estimate (SEE). Many of the species had few observations which could have adversely affected their parameter estimates. As more data become available for these species, the equations can be re-calibrated to improve their precision. The problem of many tropical tree species having insufficient data for modelling has long been recognised by several authors including Vanclay, (1991, 1994), Atta-Boateng and Moser (1998), Clark and Clark (1999), Gourlet-Fleury and Houllier (2000), Huth and Ditzer (2001) and Phillips, *et al*. (2002). This is why species grouping is normally adopted as a way of accommodating those species with few observations.

Table 4.6: Volume Equations for individual tree species (Model Form: $V = b_0 + b_1D^{b2}H^{b3}$).

Species	*n*	$\hat{b}_0$	$\hat{b}_1$	$\hat{b}_2$	$\hat{b}_3$	Weighted SEE (m^3)
Afzelia africana	80	0.0075	0.000049	2.0910	0.8871	0.00001013
Albizia ferruginea	25	0.0983	0.000002	2.4307	1.5607	0.00001045
Albizia zygia	35	0.0010	0.000073	1.9472	0.9638	0.00001057
Alstonia boonei	39	-0.1488	0.000683	1.6360	0.5998	0.00000843
Amphimas pterocarpoides	23	-0.1372	0.000501	1.5873	0.7744	0.00000681
Antiaris toxicaria	49	0.0434	0.000031	1.9463	1.2133	0.00000970
Antrocaryon klaineanum	7	-0.0720	0.000337	1.4886	0.9625	0.00001150
Blighia sapida	20	0.0967	0.000016	2.2774	1.0182	0.00000869
Bombax buonopozense	18	-0.0339	0.000107	2.1219	0.5608	0.00000602
Brachystegia eurycoma	27	-0.0666	0.000208	1.7482	0.8732	0.00001202
Brachystegia kennedyi	11	-0.2308	0.001043	1.5817	0.5632	0.00000512
Brachystegia nigerica	21	-0.0785	0.000154	1.7479	1.0190	0.00000937
Canarium schweinfurthii	12	-0.1538	0.000487	1.5191	0.8941	0.00001150

Carapa procera	30	-0.0729	0.000189	1.9179	0.6436	0.00001256
Ceiba pentandra	31	0.0286	0.000047	1.9788	1.0475	0.00001464
Celtis zenkeri	75	0.0224	0.000078	1.6950	1.2034	0.00001117
Chrysobalanus icaco	20	-0.0020	0.001032	1.0640	1.1164	0.00001539
Coelocaryon preussii	36	-0.0380	0.000264	1.3081	1.2792	0.00000902
Copaifera mildbraedii	17	0.1092	0.000092	1.3779	1.4803	0.00000583
Cordia millenii	64	0.0189	0.000041	2.0049	1.0888	0.00001291
Cyclicodiscus gabunensis	15	0.0102	0.000166	1.7900	0.8220	0.00001072
Daniellia ogea	30	-0.0501	0.000389	1.3084	1.1840	0.00001004
Detarium senegalense	74	0.0214	0.000054	1.9785	1.1273	0.00000730
Dialium guineense	12	-0.0553	0.000560	1.3336	0.9561	0.00000941
Diospyros mespiliformis	29	-0.0779	0.000329	1.5498	0.9614	0.00001150
Distemonanthus benthamianus	26	-0.0221	0.000107	1.9082	0.8747	0.00001312
Entandrophragma cylindricum	8	0.0176	0.000008	2.2857	1.2502	0.00000936
Eribroma oblonga	54	0.0252	0.000036	1.8522	1.2872	0.00001092
Erythrophleum suaveolens	34	-0.0119	0.000428	1.3979	1.0433	0.00000656
Funtumia africana	6	0.2594	0.000000012	2.9144	2.5063	0.00000904
Funtumia elastica	55	0.0076	0.000057	1.9577	1.0165	0.00001256
Gossweilerodendron balsamiferum	9	0.2512	0.00000084	2.4695	1.7271	0.00000658
Guarea cedrata	30	0.1184	0.000002	2.4381	1.5540	0.00000928
Guarea thompsonii	12	-0.6121	0.036142	0.7003	0.4544	0.00000954
Hannoa klaineana	5	0.0850	0.000014	1.7008	1.7901	0.00001619
Holoptelea grandis	5	0.2908	0.000002	1.1882	3.0336	0.00000398
Hylodendron gabunense	47	0.0773	0.000021	1.9464	1.3307	0.00001375
Irvingia gabonensis	22	-0.0467	0.000123	1.8552	0.9061	0.00001191
Khaya grandifoliola	6	-2.0966	0.372804	0.5351	0.0824	0.00000689
Khaya ivorensis	23	-0.0391	0.000107	1.6115	1.2689	0.00001358
Lannea welwitschii	29	0.0808	0.000009	2.2765	1.2000	0.00001205
Lophira alata	20	-0.0091	0.000127	1.9816	0.7462	0.00000802
Lovoa trichilioides	24	0.0469	0.000023	1.9187	1.3645	0.00001316
Manilkara obovata	62	-0.0688	0.000218	1.6895	0.9203	0.00001172

Mansonia altissima	59	0.0212	0.000050	2.0284	0.9383	0.00001140
Milicia excelsa	9	0.0733	0.000013	2.0596	1.4004	0.00001429
Mitragyna ledermannii	31	0.0892	0.000015	2.1194	1.2398	0.00001337
Mitragyna stipulosa	9	0.1479	0.000029	1.3729	1.9167	0.00000817
Nauclea diderrichii	13	0.1678	0.000005	1.9800	1.8463	0.00000767
Nesogordonia papaverifera	5	-0.6346	0.003726	1.3977	0.4029	0.00000528
Pentaclethra macrophylla	15	-0.1424	0.001426	1.2539	0.8230	0.00001776
Pentadesma butyracea	48	0.0944	0.000013	2.0961	1.3257	0.00001002
Petersianthus macrocarpus	28	-0.1160	0.000276	1.7476	0.7508	0.00000751
Piptadeniastrum africanum	34	-0.1873	0.000908	1.5394	0.6294	0.00000933
Poga oleosa	17	-0.0577	0.000147	1.7572	0.9940	0.00001101
Pterocarpus osun	33	0.0326	0.000061	1.9204	1.0331	0.00001250
Pterocarpus santalinoides	13	0.1281	0.0000000047	1.9780	4.7225	0.00000921
Pterygota macrocarpa	32	0.0238	0.000041	2.0923	0.9443	0.00001204
Pycnanthus angolensis	31	-0.1088	0.000185	1.8474	0.8031	0.00001066
Ricinodendron heudelotii	34	0.0064	0.000099	1.9762	0.7620	0.00001034
Scottellia coriacea	23	-0.0997	0.000354	1.6600	0.7596	0.00001359
Staudtia stipitata	18	-0.0869	0.000140	1.8223	0.8974	0.00001062
Stemonocoleus micranthus	20	-0.0346	0.000349	1.6717	0.7359	0.00000845
Sterculia rhinopetala	72	0.0307	0.000037	2.0726	1.0170	0.00001154
Sterculia tragacantha	18	0.1335	0.000002	2.7221	1.0965	0.00001214
Strombosia pustulata	113	0.0031	0.000083	1.8401	1.0424	0.00001084
Symphonia globulifera	142	-0.0090	0.000205	1.4431	1.2301	0.00001108
Terminalia ivorensis	31	-0.1616	0.000242	1.7720	0.8073	0.00001028
Terminalia superba	51	-0.0768	0.000156	1.7972	0.8976	0.00001067
Tetrapleura tetraptera	14	0.1198	0.000010	2.1258	1.3961	0.00001264
Trichilia gilgiana	6	-0.0710	0.000073	2.1097	0.8126	0.00000772
Trichilia monadelpha	14	0.0281	0.000006	2.6881	1.0475	0.00001037
Trichilia prieuriana	25	0.0133	0.000141	1.7424	0.9536	0.00001610
Trichilia retusa	5	0.1884	0.00000027	2.7502	1.9723	0.00001086
Trilepisium madagascariense	33	-0.0420	0.000499	1.4052	0.9385	0.00001106

Triplochiton scleroxylon	46	0.0333	0.000092	1.8307	1.0170	0.00001307
Xylopia aethiopica	72	-0.0286	0.000239	1.6937	0.8309	0.00001007

The results of fitting volume equations for the individual species confirm the great variability among species. The weighted standard errors of estimate (SEE) ranged from 0.00000398 m^3 for *Holoptelea grandis* to 0.0001776 m^3 for *Pentaclethra macrophylla*. For those species with higher weighted SEE, it might have been possible to obtain lower values had other model forms been used. However, since the coefficients were to be used for species grouping, it was necessary to use the same model form for all species. For many of the species, the value of $\hat{b}_2$ is close to 2 while that of $\hat{b}_3$ is close to 1.

4.3.2 Volume Equations for All Species combined

The volume equation for all species combined is presented in Tables 4.7a and 4.7b. Considering the relationship between merchantable volume and diameter at breast height for all species combined together as shown in Fig. 4.1, this equation is somewhat reliable on a general basis. Apparently, the large number of observations helped to suppress the variability among the different species. The equation can therefore be used in situations where the objective to obtain rough estimates of tree merchantable volumes for common timber species in the tropical rain forest area of Nigeria. Its major weakness is the implicit assumption that trees of various species have the same form. This is certainly not true in the tropical rain forest area. Consequently, a great deal of caution is required in using the equation.

Table 4.7a: Volume Equation for all tree species combined (weighted)

Model Form	*n*	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	Weighted SEE (m^3)
$\hat{Y}_i = \hat{\beta}_1 X_{1i} + \hat{\beta}_2 X_{2i}^{\hat{\beta}_3} X_{3i}^{\hat{\beta}_4}$	2391	0.006307	0.000081	-0.1351	0.0113	0.00001236

where $Y_i = V_i / D_i^2 H_i$, $X_{1i} = 1 / D_i^2 H_i$, $X_{2i} = D_i$, $X_{3i} = H_i$

Table 4.7b: Volume Equation for all tree species combined (de-transformed)

Model Form	$\hat{b}_0$	$\hat{b}_1$	$\hat{b}_2$	$\hat{b}_3$
$\hat{V}_i = \hat{b}_0 + \hat{b}_1 D_i^{\hat{b}_2} H_i^{\hat{b}_3}$	0.006307	0.000081	1.8649	1.0113

$$where\ \hat{b}_0 = \hat{\beta}_1, \quad \hat{b}_1 = \hat{\beta}_2, \quad \hat{b}_2 = \hat{\beta}_3 + 2, \quad \hat{b}_3 = \hat{\beta}_4 + 1$$

4.3.3 Volume Equations for the Species Groups

The coefficients for the volume equations for the species groups are presented in Tables 4.8a and 4.8b. The two tables are related in the sense that one is derived from the other. Table 4.8a shows the values of the coefficients obtained through weighted nonlinear regression. In this study, weighted least squares with D^2H as weighting factor was found to be appropriate in reducing heteroscedasticity. Similar remarks have been made by several authors including Cunia (1964), Snowdon (1985) and Philip (1994). Table 4.8b shows the coefficients of the actual model that will be used directly in practical applications of the volume functions.

Table 4.8a: Regression statistics for the volume equation for each cluster (weighted)

$$\hat{Y}_i = \hat{\beta}_1 X_{1i} + \hat{\beta}_2 X_{2i}^{\hat{\beta}_3} X_{3i}^{\hat{\beta}_4}$$

CLUSTER	n	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	Weighted SEE(m^3)
1	444	0.0153	0.000187	-0.5277	0.1963	0.00001194
2	161	0.0555	0.000027	-0.0201	0.2369	0.00001097
3	814	0.0021	0.000076	-0.0355	-0.0826	0.00001214
4	625	-0.0363	0.000130	-0.1517	-0.1187	0.00001054
5	347	0.0582	0.000025	-0.0149	0.2455	0.00001152

$$where \quad Y_i = V_i / D_i^2 H_i, \quad X_{1i} = 1 / D_i^2 H_i, \quad X_{2i} = D_i, \quad X_{3i} = H_i$$

The parameter estimates in Table 4.8b compare well with what has been reported elsewhere outside the tropical rain forest (*e.g.* Newnham, 1967). These results show that $\hat{b}_2$ is close to 2 (except for Cluster 1) while $\hat{b}_3$ is close to 1. The residual plots for these equations are presented in Appendices 4a to 4e. The plots indicate good fits and confirmed the effectiveness of weighted least squares in stabilising error variance.

Table 4.8b: Regression statistics for the volume equation for each cluster (de-transformed)

$$\hat{V}_i = \hat{b}_0 + \hat{b}_1 D_i^{\hat{b}_2} H_i^{\hat{b}_3}$$

CLUSTER	$\hat{b}_0$	$\hat{b}_1$	$\hat{b}_2$	$\hat{b}_3$
1	0.007561	0.000231	1.4558	1.1461
2	-0.040435	0.000156	1.8016	0.8772
3	0.007638	0.000075	1.9246	0.9607
4	0.032543	0.000043	1.8592	1.2323
5	-0.001736	0.000071	1.9811	0.9160

where $\hat{b}_0 = \hat{\beta}_1, \quad \hat{b}_1 = \hat{\beta}_2, \quad \hat{b}_2 = \hat{\beta}_3 + 2, \quad \hat{b}_3 = \hat{\beta}_4 + 1$

The results of the single-variable volume equations, using dbh or stump diameter only as predictor variable, are presented in Tables 4.9 and 4.10. From a series of model-fitting trials, the quadratic function performed best within the limit of data used for each species group. In an earlier study on plantation-grown *Tectona grandis* (Akindele, 1987), the quadratic function was also found to perform better than other models for computing tree volumes from stump diameter. In the present study, the function was conditioned to have zero intercept since there will be no merchantable volume when either dbh or stump diameter is zero. With the exception of Cluster 1, the value of $\hat{b}_1$ is negative in both tables. However, $\hat{b}_2$ has a positive value for each cluster in both tables. The standard errors are reasonably low and their residual plots shown in Appendices 5a to 5e and 6a to 6e indicate that the errors did not form any definite pattern. The use of weighted least squares procedure helped to stabilise the error variance. For each function the weight was the reciprocal of the diameter (dbh or stump diameter, respectively). These results indicate that the zero-intercept quadratic function is suitable for estimating merchantable volume from either dbh alone or stump diameter alone. It should however be emphasized that quadratic function could result in large error of prediction at the upper extremes of the predictor variable. To avoid this, the volume equations should not be used for trees whose diameter values exceed the maximum diameters reported in this study.

Table 4.9: Volume Equations based on Dbh alone.

$$V = b_1D + b_2D^2$$

CLUSTER	*n*	$\hat{b}_1$	$\hat{b}_2$	Weighted SEE (m^3)
1	444	0.00212	0.00055	0.00034
2	161	-0.0060	0.00085	0.00035
3	814	-0.0069	0.00096	0.00038
4	625	-0.0085	0.00101	0.00031
5	347	-0.0121	0.00114	0.00035

Table 4.10: Volume Equations based on Stump Diameter (D_{st}) alone

$$V = b_1D_{st} + b_2D_{st}^2$$

CLUSTER	*n*	$\hat{b}_1$	$\hat{b}_2$	Weighted SEE (m^3)
1	444	0.00163	0.00044	0.00027
2	161	-0.0045	0.00064	0.00027
3	814	-0.0059	0.00071	0.00029
4	625	-0.0077	0.00078	0.00024
5	347	-0.0117	0.00092	0.00028

5.0 CONCLUSION

The paucity of data for many tropical timber species impairs the development of reliable species-specific volume equations for them. The results of this study show that this problem can be mitigated by aggregating the species into groups and then developing appropriate equations for each species group. Species grouping was done using a two-stage approach involving cluster analysis for more frequent species ($n \geq 30$) to form the groups, and discriminant analysis for assigning the less frequent species ($n < 30$) into the groups. This two-stage approach was found suitable for grouping the tropical timber species Nigeria's lowland rain forest area.

In this study, many species in the same genus fell into different clusters, indicating that grouping of the species did not follow taxonomic or ecological pattern. Any attempt to impose specific ecological pattern into the clustering process will involve some subjectivity. The clusters generated in this study are adequate in the context of the data available, although further work is required to incorporate measures of tree form into the clustering process. Consequently, the grouping in this study should not be considered as final. There would be the need to repeat the analysis as more data become available, until the resulting groupings show some stability.

The generalised logarithmic volume function (also termed Schumacher's volume function) performed better than other forms of volume functions. To stabilised the error variance, the reciprocal of D^2H was found to be the appropriate weighting factor for the two-variable volume function. This results obtained in this study also indicate that single-variable volume functions based on either dbh or stump diameter alone could be used to obtain reliable estimates of tree volume. The zero-intercept quadratic function was the most appropriate function for this purpose.

The same model form was used in this study for the species-specific equations in order to have a common basis for aggregating them into groups. Where there is a particular interest on species-specific volume equations, the testing of other model forms should be considered in order to see if there will be any improvement on the equations presented in this study. In addition, as more data becomes available, there would be the need to re-calibrate the volume equations of those species with few observations.

The tree volume equations for the species groups appear to be more robust due to relatively large number of observations and should therefore be used instead of the species-specific equations for which sample size was small. In areas prone to illegal logging activities, the volume equations based on stump diameter alone are adequate to provide estimates of tree volume illegally removed.

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APPENDICES

Appendix 1

FELLOWSHIP REPORT

1. Background

The International Tropical Timber Organisation (ITTO) is an intergovernmental organization promoting the conservation and sustainable management, use and trade of tropical forest resources. Its 59 members represent about 80% of the world's tropical forests and 90% of the global tropical timber trade. The organization was established under the auspices of the United Nations in 1986 amidst increasing worldwide concern for the fate of tropical forests. While almost everyone was alarmed at the rate of deforestation occurring in many tropical countries, there was also considerable agreement that the tropical timber trade was one of the keys to economic development in those same countries. The reconciliation of these two seemingly disparate phenomena is ITTO's story. Further information about ITTO can be obtained from their website: http://www.itto.or.jp/live/index.jsp.

ITTO offers fellowships through the Freezailah Fellowship Fund to promote human resource development and to strengthen professional expertise in member countries in tropical forestry and related disciplines. The goal is to promote the sustainable management of tropical forests, the efficient use and processing of tropical timber, and better economic information about the international trade in tropical timber. As of December 2003, the Programme, which began in 1989, has enabled more than 750 young and mid-career people from over 30 countries working for government, research institutions, civil society and the private sector to pursue their professional development and improve their career prospects. In 2004, 29 applications were approved (out of a total of 158) during the 36th session of the International Tropical Timber Council (ITTO, 2004a, 2004b)[1]. The fellowship application for this study was one of them (the first to a Nigerian). Through the Fellowship, the recipient

[1] ITTO (2004a). ITTO Fellowship Selection Panel Report. 4 pp. http://www.itto.or.jp/live/Live_Server/634/E-C36-17.doc

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was able to visit Canada (also a member nation of ITTO) for six months to prepare a technical document entitled: "*Volume functions for common timber species of Nigeria's tropical rain forests*".

2. Host Institution for the Study

The study was carried out at the University of British Columbia (UBC), Vancouver, Canada. Canada is also a member of the ITTO. UBC has a world-class Faculty of Forestry (http://www.forestry.ubc.ca) with state-of-the-art facilities for teaching and research. The Faculty is endowed with many professionals who are eminent scholars in various areas of specialization. Following initial contacts made with Dr. Peter Marshall (Professor and Associate Dean) and Dr. Valerie LeMay (Associate Professor of Forest Measurements) in the Department of Forest Resources Management of the Faculty, arrangements were made to provide logistic support for me to enable carry out the study at UBC. Drs. Marshall and LeMay were my hosts at the institution. The facilities provided include:

- Office Space;
- Desktop Computer;
- Access to Biometrics laboratory; and
- Access to all Library facilities.

In addition to the in-kind contributions provided by my hosts to support me on the fellowship, sponsorship was provided to enable me attend the following meetings:

1. Global Change Symposium organized by BC Forum on Forest Economics and Policy and Forest Products Association of Canada held at Vancouver, BC on January 27, 2005. (*Theme:* Besieged by Global Change: Defining the future of BC's forest sector).
2. Training Workshop on Prognosis^{BC} Growth and Yield Model organized by the Research Branch, BC Ministry of Forests, held at Kamloops, BC on February 9 & 10, 2005.
3. 57th ABCPF Forestry Conference and Annual General Meeting organized by the Association of BC Professional Foresters, held at Prince George, BC between February 23 & 25, 2005. (*Theme:* Perspectives: What's your passion?).

4. Timber Supply Database Workshop organized by the Pacific Forestry Centre, held at Victoria, BC on March 14, 2005. (*Theme:* How can the BC Natural Disturbance Database inform Timber Supply Analysis?).
5. 2005 Western Mensurationists Conference at Hilo, Hawaii, USA from July 3 – 7, 2005. There I presented the results of this work to enable me have input from professional colleagues from different parts of the world. The paper presented was titled: *Volume Equations for Native Tropical Species in Nigeria.* (see Fig. A1).

Fig. A1: The author presenting a paper during the 2005 Western Mensurationists Conference at Hilo, Hawaii, USA.

3. Fellowship Activities and Benefits

In the course of this fellowship at UBC, the following activities were carried out:

1. Compilation and review of existing literature on the development of tree volume functions. Carrying out the study at UBC gave me access to relevant modeling literature and current methodologies in developing volume functions.
2. Interaction with colleagues in the areas of forest mensuration, biometrics, timber trade and sustainable forest management. I presented a seminar titled: *Forestry Practice in Nigeria: an Overview* (http://www.forestry.ubc.ca/biometrics/Documents/Akindele2.ppt). This gave me the opportunity to share information and knowledge on tropical timber resources in Nigeria with colleagues in a timber consumer nation.
3. Collation and screening of existing data on mensurational characteristics of tree species in the tropical rain forest area of Nigeria.
4. Analysis of data to estimate tree volume, and development of tree volume functions for individual timber species;
5. Carrying out of cluster and discriminant analyses to group the timber species into homogenous equation groups, and preparing new sets of volume functions for the timber species group. The volume functions produced will become useful tools in the regular inventory of tropical forests in Nigeria.
6. Presentation of seminars for review of the work, and interacting with colleagues both within and outside UBC to foster further collaboration aimed at promoting sustainable tropical forest management and supporting activities to secure Nigeria's tropical forest resources.
7. Preparation and production of the technical document. Overall, the Fellowship has provided me with the opportunity to contribute to national and international knowledge-base on tropical timber species in Nigeria. It has also provided opportunity for human resources development and enhancement of my professional expertise.

4. List of key people met during the Fellowship Programme

S/No.	Name	Affiliation
1.	Ciesweski, Chris	Professor, Warnell School of Forest Resources, University of Georgia, Athens, GA., USA.
2.	Flewelling, Jim.	Biometrics Consultant, Seattle, WA., USA.
3.	Furnival, George	Professor Emeritus, The Yale School of Forestry & Environmental Studies, New Haven, CT., USA.
4.	Garcia, Oscar	Professor, University of Northern British Columbia, Prince George, BC., Canada.
5.	Iles, Kim.	Forest Inventory Consultant, Kim Iles & Associates, Nanaimo, BC., Canada.
6.	Kozak, Antal	Professor Emeritus, Dept. of Forest Resources Management, UBC, Vancouver, BC., Canada.
7.	LeMay, Valerie	Associate Professor, Dept. of Forest Resources Management, UBC, Vancouver, BC., Canada.
8.	Marshall, Peter	Professor & Associate Dean, Faculty of Forestry, UBC, Vancouver, BC., Canada.
9.	Mason, Euan	Associate Professor, School of Forestry, University of Canterbury, Christchurch, New Zealand.
10.	Omule, Stephen	Biometrician, Pacific Forestry Centre, Canadian Forest Service, Victoria, BC., Canada.
11.	Turnblom, Eric	Associate Professor, College of Forest Resources, University of Washington, Seattle, WA., USA.
12.	Zumrawi, Abdel Azim	Biometrician, BC Ministry of Forests, Victoria, Canada.

Appendix 2: List of common tropical timber species included in this study.

S/No.	Species	Family/Sub-family	Yoruba	Igbo	Hausa
1	*Afzelia africana*	Leguminosae/Ceasalpinioideae	Apa	Akpaluta	Kawo
2	*Albizia ferruginea*	Leguminosae/Mimosoideae	Ayinre ogo	Ngu	Tsintsiyar kurmi
3	*Albizia zygia*	Leguminosae/Mimosoideae	Ayinreta	Nyie avu	N/A
4	*Alstonia boonei*	Apocynaceae	Awun	Egbu	N/A
5	*Amphimas pterocarpoides*	Leguminosae/Papilionoideae	Ogiya	Awo	N/A
6	*Antiaris toxicaria*	Moraceae	Oro	Ojianwu	Farin loko
7	*Antrocaryon klaineanum*	Anacardiaceae	Ifa okete	N/A	N/A
8	*Blighia sapida*	Sapindaceae	Isin	Okpu	Gwanja kusa
9	*Bombax buonopozense*	Bombacaceae	Ponpola	Akpu	Gujiya
10	*Brachystegia eurycoma*	Leguminosae/Ceasalpinioideae	Akolodu	Achi	N/A
11	*Brachystegia kennedyi*	Leguminosae/Ceasalpinioideae	N/A	N/A	N/A
12	*Brachystegia nigerica*	Leguminosae/Ceasalpinioideae	N/A	N/A	N/A
13	*Canarium schweinfurthii*	Burseraceae	Agbabubu origbo	N/A	Atile
14	*Carapa procera*	Meliaceae	Irere	Nkpaku	N/A
15	*Ceiba pentandra*	Bombacaceae	Araba	Akpu	N/A
16	*Celtis zenkeri*	Ulmaceae	Ita-gidi	N/A	Dunki
17	*Chrysobalanus icaco*	Chrysobalanaceae	Awonrinwon	N/A	N/A
18	*Coelocaryon preussii*	Capparaceae	Egberin	Aiwanili	N/A
19	*Copaifera mildbraedii*	Leguminosae/Ceasalpinioideae	N/A	N/A	N/A

S/No.	Species	Family/Sub-family	Yoruba	Igbo	Hausa
20	*Cordia millenii*	Boraginaceae	Omo	N/A	N/A
21	*Cyclicodiscus gabunensis*	Leguminosae/Mimosoideae	Olosan	Uzi	N/A
22	*Daniellia ogea*	Leguminosae/Ceasalpinioideae	Ojia	Abwa	N/A
23	*Detarium senegalense*	Leguminosae/Ceasalpinioideae	Ogbogbo	N/A	Taurar kurmi
24	*Dialium guineense*	Leguminosae/Ceasalpinioideae	Awin	Icheku	Tsamiyar kurmi
25	*Diospyros mespiliformis*	Ebenaceae	Kanya	Igidudu	N/A
26	*Distemonanthus benthamianus*	Leguminosae/Ceasalpinioideae	Ayan	Ochasi	N/A
27	*Entandrophragma cylindricum*	Meliaceae	Ijebu	Owura	N/A
28	*Eribroma oblonga*	Sterculiaceae	Oroforofo	Ebenebe	N/A
29	*Erythrophleum suaveolens*	Leguminosae/Ceasalpinioideae	Erun-obo	Inyi	Gwaska
30	*Funtumia africana*	Apocynaceae	Ako-ire	Mba miri	N/A
31	*Funtumia elastica*	Apocynaceae	Ire	Mba	N/A
32	*Gossweilerodendron balsamiferum*	Leguminosae/Ceasalpinioideae	Losin erin	Achi aro	N/A
33	*Guarea cedrata*	Meliaceae	Olofun	N/A	N/A
34	*Guarea thompsonii*	Meliaceae	Ofe-Olofun	Ugbokpo	N/A
35	*Hannoa klaineana*	Irvingiaceae	Igbo	Oghulu	N/A
36	*Holoptelea grandis*	Ulmaceae	Inajoko	N/A	N/A
37	*Hylodendron gabunense*	Leguminosae/Ceasalpinioideae	Arasa-ganigan	N/A	N/A
38	*Irvingia gabonensis*	Irvingiaceae	Oro	Ogbono	Goron biri
39	*Khaya grandifoliola*	Meliaceae	Oganwo	Ono	Male
40	*Khaya ivorensis*	Meliaceae	Oganwo	Ono	N/A

S/No.	Species	Family/Sub-family	Yoruba	Igbo	Hausa
41	*Lannea welwitschii*	Anacardiaceae	Ekika	N/A	N/A
42	*Lophira alata*	Dipterocarpaceae	Ekki	Akufo	Mijin kadanya
43	*Lovoa trichilioides*	Meliaceae	Sida, Akoko igbo	N/A	N/A
44	*Manilkara obovata*	Sapotaceae	Emido	Ukpi	Kadanyar rafi
45	*Mansonia altissima*	Sterculiaceae	Ofun	N/A	N/A
46	*Milicia excelsa*	Moraceae	Iroko	Oji	Loko
47	*Mitragyna ledermannii*	Rubiaceae	Abura	Uburu	N/A
48	*Mitragyna stipulosa*	Rubiaceae	Abura	Uburu	Ganyen gori
49	*Nauclea diderrichii*	Rubiaceae	Opepe	Uburu	N/A
50	*Nesogordonia papaverifera*	Sterculiaceae	Otutu	Otalo	N/A
51	*Pentaclethra macrophylla*	Leguminosae/Mimosoideae	Apara	Ugba	N/A
52	*Pentadesma butyracea*	Guttiferae	Orogbo erin	Oze	N/A
53	*Petersianthus macrocarpus*	Lecythidaceae	Akasun	Anwushi	N/A
54	*Piptadeniastrum africanum*	Leguminosae/Mimosoideae	Agboin	Ufi	Kiriyar kurmi
55	*Poga oleosa*	Anisophylleaceae	N/A	Imono	N/A
56	*Pterocarpus osun*	Leguminosae/Papilionoideae	Osun	Ubie	N/A
57	*Pterocarpus santalinoides*	Leguminosae/Papilionoideae	Gbengbe	Nturukpa	Gunduru
58	*Pterygota macrocarpa*	Sterculiaceae	Oporoporo	N/A	N/A
59	*Pycnanthus angolensis*	Myristicaceae	Akomu	Akwa-mili	N/A
60	*Ricinodendron heudelotii*	Euphorbiaceae	Erinmado	Okwe	Wawanputu kurmi
61	*Scottellia coriacea*	Flacourtiaceae	Odoko	Akporo	N/A

S/No.	Species	Family/Sub-family	Yoruba	Igbo	Hausa
62	*Staudtia stipitata*	Myristicaceae	Oropa	Ichala	N/A
63	*Stemonocoleus micranthus*	Leguminosae/Ceasalpinioideae	N/A	Nre	N/A
64	*Sterculia rhinopetala*	Sterculiaceae	Aye	N/A	N/A
65	*Sterculia tragacantha*	Sterculiaceae	Alawefun	Oloko	Kukukin rafi
66	*Strombosia pustulata*	Olacaceae	Itako	N/A	N/A
67	*Symphonia globulifera*	Guttiferae	Agben	N/A	N/A
68	*Terminalia ivorensis*	Combretaceae	Idigbo	N/A	Baushe
69	*Terminalia superba*	Combretaceae	Afara	Edo	Baushe
70	*Tetrapleura tetraptera*	Leguminosae/Mimosoideae	Aridan	Oshosho	N/A
71	*Trichilia gilgiana*	Meliaceae	N/A	N/A	N/A
72	*Trichilia monadelpha*	Meliaceae	Akika	N/A	N/A
73	*Trichilia prieuriana*	Meliaceae	Awe	N/A	N/A
74	*Trichilia retusa*	Meliaceae	N/A	N/A	N/A
75	*Trilepisium madagascariense*	Moraceae	Gangaran	Oze	N/A
76	*Triplochiton scleroxylon*	Sterculiaceae	Arere	Okpobo	N/A
77	*Xylopia aethiopica*	Annonaceae	Erunji	Uda	Kimba

N/A = Not Available.

Appendix 3: Summary of Data for the 77 timber species

Species	n	Stump Diameter (cm)		Dbh (cm)		Merch. Height (m)		Merch. Vol. (m^3)	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Afzelia africana	80	25.5	210.0	21.2	200.0	2.7	32.7	0.10	33.63
Albizia ferruginea	25	24.4	75.0	20.5	60.5	4.7	24.7	0.13	2.61
Albizia zygia	35	21.2	100.0	20.0	80.0	5.7	33.2	0.24	5.93
Alstonia boonei	39	22.0	95.0	20.0	79.5	7.2	28.7	0.20	3.90
Amphimas pterocarpoides	23	21.7	80.6	20.4	80.6	6.2	31.9	0.25	5.02
Antiaris toxicaria	49	22.7	108.0	20.0	108.0	4.7	34.7	0.15	10.32
Antrocaryon klaineanum	7	24.5	42.2	21.5	37.4	4.7	19.5	0.07	1.33
Blighia sapida	20	24.0	66.2	20.0	62.5	6.8	21.2	0.23	4.11
Bombax buonopozense	18	23.0	120.0	20.0	120.0	9.3	28.2	0.21	16.02
Brachystegia eurycoma	27	29.0	102.5	23.8	94.6	7.8	36.7	0.29	7.63
Brachystegia kennedyi	11	23.3	97.5	20.2	97.5	5.7	23.1	0.20	7.35
Brachystegia nigerica	21	20.2	170.0	20.2	142.0	4.2	30.7	0.11	24.78
Canarium schweinfurthii	12	27.6	86.0	25.0	74.0	5.7	31.7	0.12	6.50
Carapa procera	30	20.1	52.0	20.0	45.0	2.7	17.7	0.06	1.49
Ceiba pentandra	31	22.0	200.0	20.0	186.0	6.4	31.7	0.13	47.39
Celtis zenkeri	75	20.0	105.0	20.0	87.0	2.6	27.2	0.06	12.59
Chrysobalanus icaco	20	25.0	133.0	21.0	115.0	1.7	13.7	0.04	4.03
Coelocaryon preussii	36	24.0	65.4	22.0	55.0	8.1	24.9	0.14	3.77

Species	n	Stump Diameter (cm)		Dbh (cm)		Merch. Height (m)		Merch. Vol. (m^3)	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Copaifera mildbraedii	17	34.1	95.0	31.8	86.0	3.7	16.7	0.27	2.62
Cordia millenii	64	23.5	215.0	20.0	185.0	2.7	36.4	0.13	55.44
Cyclicodiscus gabunensis	15	25.1	151.2	22.0	151.2	5.7	17.7	0.18	20.37
Daniellia ogea	30	20.0	59.0	20.0	54.0	5.3	23.7	0.09	2.44
Detarium senegalense	74	21.5	65.0	20.4	58.5	2.7	16.2	0.09	2.58
Dialium guineense	12	26.0	180.0	20.0	158.0	3.2	19.7	0.08	7.22
Diospyros mespiliformis	29	24.2	70.2	20.5	68.0	4.2	22.4	0.10	3.61
Distemonanthus benthamianus	26	20.0	65.0	20.0	51.0	2.3	28.2	0.04	3.67
Entandrophragma cylindricum	8	22.0	55.5	20.0	48.1	7.2	23.2	0.09	2.33
Eribroma oblonga	54	20.0	100.0	20.0	100.0	3.7	26.7	0.09	9.66
Erythrophleum suaveolens	34	21.3	61.5	20.0	56.5	1.7	13.7	0.04	1.74
Funtumia africana	6	26.0	50.0	23.0	44.0	8.3	24.7	0.28	2.59
Funtumia elastica	55	23.9	80.0	20.0	64.0	4.7	25.7	0.10	4.30
Gossweilerodendron balsamiferum	9	34.0	77.5	30.8	65.0	7.7	31.7	0.52	3.27
Guarea cedrata	30	21.9	63.5	20.4	56.3	5.2	20.2	0.16	1.95
Guarea thompsonii	12	21.6	44.0	20.0	42.4	4.4	22.7	0.23	1.15
Hannoa klaineana	5	25.5	43.3	23.0	43.3	5.8	19.9	0.14	1.93
Holoptelea grandis	5	28.5	57.0	25.0	46.0	5.7	22.7	0.30	2.45
Hylodendron gabunense	47	22.0	120.0	20.0	120.0	3.7	42.5	0.12	17.41
Irvingia gabonensis	22	22.2	107.0	20.5	103.0	5.7	31.7	0.13	16.83

Species	n	Stump Diameter (cm)		Dbh (cm)		Merch. Height (m)		Merch. Vol. (m^3)	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Khaya grandifoliola	6	24.9	53.5	20.5	50.1	9.7	22.3	0.20	1.52
Khaya ivorensis	23	22.6	88.7	20.1	79.1	7.7	37.2	0.16	8.92
Lannea welwitschii	29	23.0	80.0	20.5	80.0	3.0	31.7	0.13	10.56
Lophira alata	20	23.5	155.0	21.0	140.0	6.4	41.1	0.20	24.23
Lovoa trichilioides	24	22.5	120.0	20.5	95.3	10.7	26.7	0.20	12.52
Manilkara obovata	62	22.0	124.0	20.0	120.0	3.1	24.7	0.06	9.45
Mansonia altissima	59	22.0	105.0	20.0	85.0	7.2	27.7	0.11	6.03
Milicia excelsa	9	24.6	120.0	20.5	85.0	4.2	32.5	0.11	15.98
Mitragyna ledermannii	31	23.0	140.0	20.0	120.0	5.4	35.7	0.17	33.72
Mitragyna stipulosa	9	26.6	46.8	24.0	39.5	9.7	19.5	0.33	1.61
Nauclea diderrichii	13	25.7	91.0	23.7	75.6	5.7	25.2	0.35	7.23
Nesogordonia papaverifera	5	31.8	79.0	31.8	67.0	12.7	20.7	0.87	3.41
Pentaclethra macrophylla	15	24.0	102.5	22.1	95.1	4.3	13.2	0.09	4.27
Pentadesma butyracea	48	21.7	58.0	20.3	48.0	1.7	21.6	0.12	2.73
Petersianthus macrocarpus	28	23.3	99.6	22.4	89.6	5.9	24.7	0.19	6.50
Piptadeniastrum africanum	34	21.6	110.0	20.4	110.0	4.7	28.7	0.11	10.13
Poga oleosa	17	22.9	128.3	21.6	128.3	5.7	26.7	0.14	18.90
Pterocarpus osun	33	22.0	70.0	21.1	70.0	2.7	24.7	0.12	2.80
Pterocarpus santalinoides	13	22.0	48.0	20.0	45.0	4.7	12.2	0.11	0.74
Pterygota macrocarpa	32	22.3	120.0	20.0	112.0	8.2	31.7	0.18	11.40

Species	n	Stump Diameter (cm)		Dbh (cm)		Merch. Height (m)		Merch. Vol. (m^3)	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Pycnanthus angolensis	31	21.5	185.0	20.0	152.0	9.7	29.2	0.17	35.94
Ricinodendron heudelotii	34	26.0	76.4	23.3	75.0	2.2	24.7	0.17	4.90
Scottellia coriacea	23	22.2	97.0	20.2	89.0	5.1	17.7	0.16	2.18
Staudtia stipitata	18	21.8	62.5	20.0	62.5	7.9	22.2	0.13	2.94
Stemonocoleus micranthus	20	21.2	46.6	20.3	42.7	4.7	22.8	0.14	2.00
Sterculia rhinopetala	72	22.2	109.0	20.0	81.2	6.7	27.6	0.17	8.45
Sterculia tragacantha	18	24.9	56.0	21.7	51.2	4.9	24.2	0.17	2.15
Strombosia pustulata	113	22.0	82.0	20.0	73.6	4.2	30.7	0.09	6.60
Symphonia globulifera	142	21.0	102.0	20.0	90.0	3.7	23.7	0.08	2.63
Terminalia ivorensis	31	22.0	240.0	21.5	180.0	9.7	34.7	0.21	34.78
Terminalia superba	51	22.7	250.0	20.0	230.0	5.2	32.7	0.20	48.23
Tetrapleura tetraptera	14	26.3	53.5	20.6	53.5	4.8	16.6	0.18	2.03
Trichilia gilgiana	6	26.2	38.5	23.3	30.0	3.6	13.7	0.11	0.55
Trichilia monadelpha	14	21.2	38.0	20.3	32.5	3.0	21.4	0.10	1.49
Trichilia prieuriana	25	24.4	112.0	20.3	102.3	2.0	13.7	0.09	4.14
Trichilia retusa	5	31.3	47.0	28.0	39.7	7.2	10.2	0.31	0.86
Trilepisium madagascariense	33	20.5	87.0	20.0	87.0	2.7	28.2	0.07	5.80
Triplochiton scleroxylon	46	20.8	205.0	20.0	157.0	7.2	33.7	0.23	40.00
Xylopia aethiopica	72	23.0	65.5	20.0	63.2	1.5	21.2	0.03	2.39

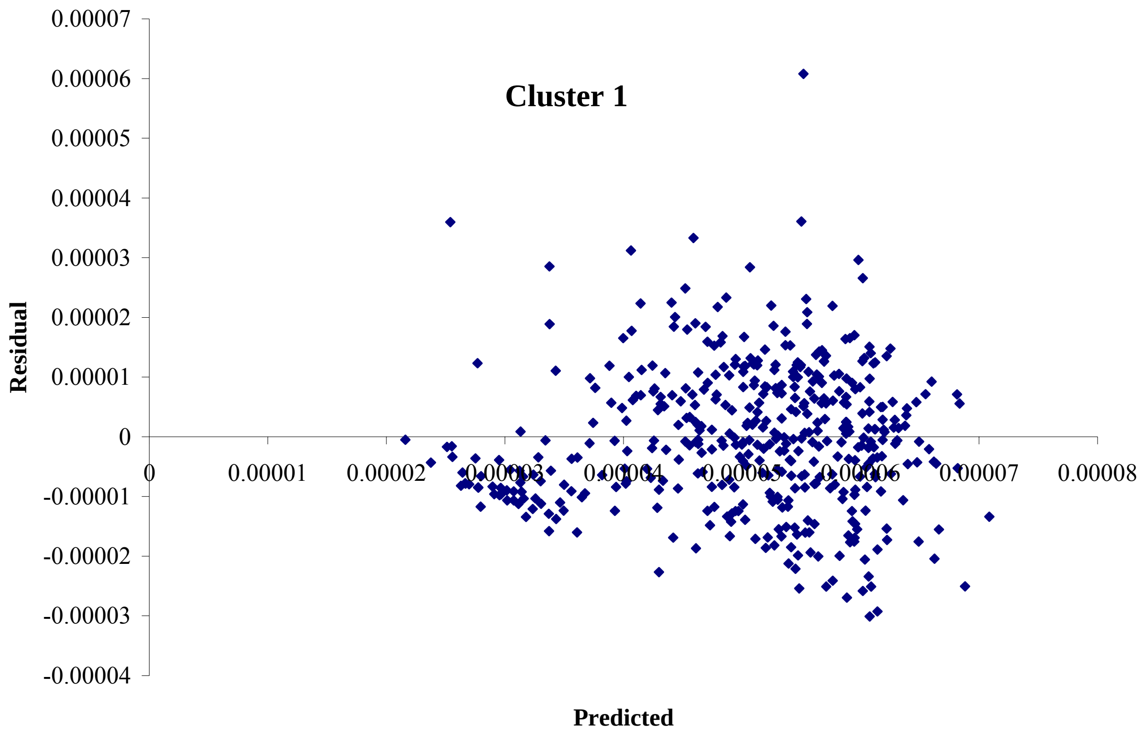
Species	Stump Diameter (cm)		Dbh (cm)		Merch. Height (m)		Merch. Vol. (m^3)	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Afzelia africana	67.75	4.27	59.73	3.84	12.79	0.88	4.15	0.76
Albizia ferruginea	39.79	2.69	34.87	2.19	11.82	0.93	0.83	0.13
Albizia zygia	39.03	3.25	34.18	2.69	13.67	1.05	1.13	0.25
Alstonia boonei	39.56	2.75	32.11	2.25	15.36	0.84	0.99	0.15
Amphimas pterocarpoides	43.26	3.18	40.77	3.18	15.68	1.37	1.51	0.25
Antiaris toxicaria	43.42	2.93	38.22	2.72	16.44	0.86	1.73	0.34
Antrocaryon klaineanum	32.59	2.54	28.57	2.21	13.13	1.93	0.57	0.16
Blighia sapida	35.84	2.97	32.15	2.83	13.25	0.90	0.96	0.23
Bombax buonopozense	51.34	6.72	45.29	6.46	17.32	1.27	2.65	0.95
Brachystegia eurycoma	54.63	4.20	49.78	4.17	14.74	1.21	2.36	0.45
Brachystegia kennedyi	41.41	6.53	37.43	6.98	13.55	1.66	1.48	0.65
Brachystegia nigerica	53.28	9.17	45.99	7.86	14.72	1.60	3.26	1.33
Canarium schweinfurthii	45.33	5.43	38.18	5.06	15.83	2.47	1.80	0.65
Carapa procera	29.10	1.29	25.39	1.02	8.86	0.64	0.33	0.05
Ceiba pentandra	79.19	9.76	72.08	9.27	16.33	1.21	8.22	2.30
Celtis zenkeri	38.24	1.85	35.85	1.78	15.63	0.61	1.30	0.21
Chrysobalanus icaco	56.37	6.93	48.42	6.53	7.74	0.62	0.70	0.19
Coelocaryon preussii	36.11	1.66	31.46	1.38	13.49	0.66	0.72	0.11
Copaifera mildbraedii	72.56	4.40	65.26	3.79	9.62	0.69	1.02	0.15

Species	Stump Diameter (cm)		Dbh (cm)		Merch. Height (m)		Merch. Vol. (m^3)	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Cordia millenii	56.54	3.83	47.35	3.30	16.73	0.88	2.83	0.87
Cyclicodiscus gabunensis	45.46	8.81	42.78	9.10	13.22	0.87	2.14	1.32
Daniellia ogea	37.37	1.85	32.36	1.75	12.13	0.83	0.74	0.11
Detarium senegalense	42.10	1.37	37.30	1.20	9.21	0.31	0.99	0.07
Dialium guineense	79.08	13.99	70.73	12.09	8.83	1.38	1.58	0.60
Diospyros mespiliformis	39.26	2.04	33.91	1.98	11.88	0.87	0.85	0.14
Distemonanthus benthamianus	34.47	2.20	30.29	1.83	13.59	1.54	0.76	0.16
Entandrophragma cylindricum	33.76	4.67	29.79	3.83	12.33	2.08	0.74	0.34
Eribroma oblonga	40.18	2.42	37.33	2.48	15.70	0.84	1.48	0.26
Erythrophleum suaveolens	27.69	1.22	24.41	1.12	5.97	0.38	0.26	0.05
Funtumia africana	36.17	3.47	32.00	3.38	15.65	2.65	0.88	0.36
Funtumia elastica	41.13	1.68	34.88	1.48	14.19	0.70	1.04	0.12
Gossweilerodendron balsamiferum	47.29	4.27	40.61	3.70	19.09	2.81	1.64	0.37
Guarea cedrata	31.86	1.56	28.51	1.39	11.50	0.68	0.55	0.08
Guarea thompsonii	34.93	1.94	30.73	1.82	9.94	1.39	0.48	0.08
Hannoa klaineana	32.86	3.66	30.14	4.13	11.50	2.33	0.63	0.33
Holoptelea grandis	38.36	5.12	33.46	3.67	14.06	3.03	0.96	0.40
Hylodendron gabunense	40.15	2.85	35.85	2.94	14.66	1.00	1.50	0.44
Irvingia gabonensis	44.74	4.02	40.30	4.01	15.35	1.51	1.86	0.73
Khaya grandifoliola	37.97	4.74	32.83	4.67	16.05	2.01	0.88	0.24

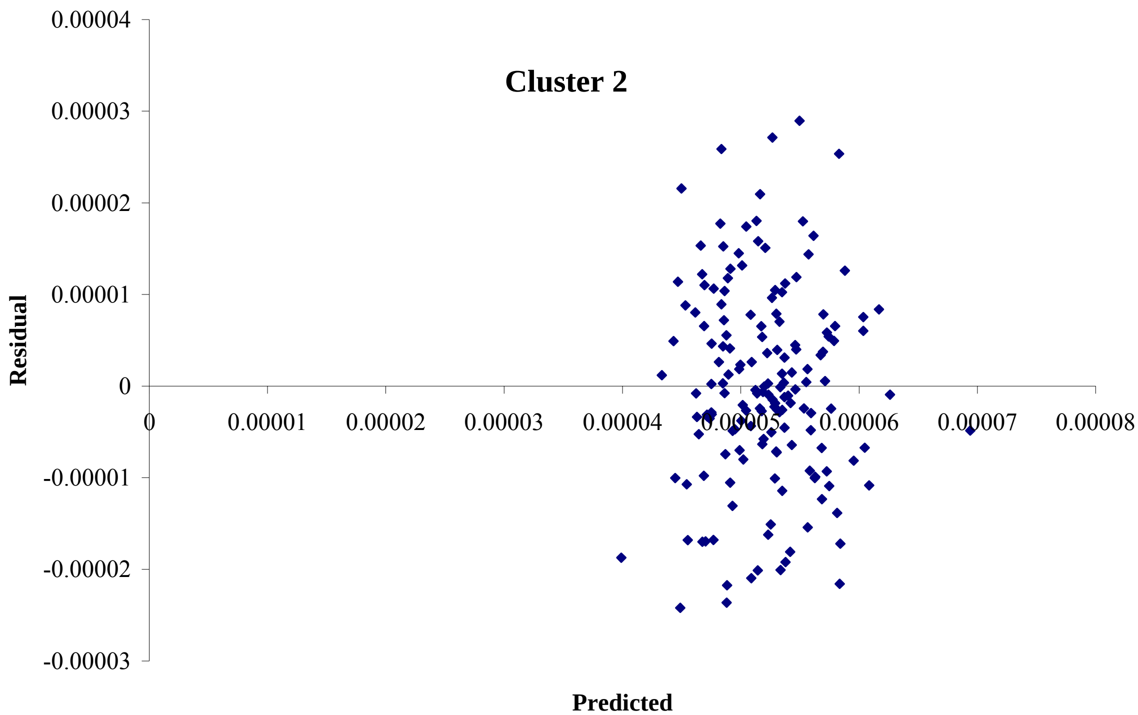
Species	Stump Diameter (cm)		Dbh (cm)		Merch. Height (m)		Merch. Vol. (m^3)	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Khaya ivorensis	44.59	3.89	37.22	3.33	15.35	1.68	1.61	0.49
Lannea welwitschii	42.08	2.63	37.97	2.37	14.65	1.43	1.55	0.43
Lophira alata	53.23	6.07	46.38	5.44	18.93	1.75	3.03	1.14
Lovoa trichilioides	50.46	6.11	42.00	4.89	15.81	0.97	2.08	0.60
Manilkara obovata	44.54	2.96	38.84	2.70	11.68	0.52	1.25	0.21
Mansonia altissima	40.61	2.19	34.35	1.91	14.42	0.59	1.08	0.16
Milicia excelsa	52.07	10.46	43.12	7.65	18.74	2.98	3.55	1.71
Mitragyna ledermannii	47.29	5.35	40.08	4.54	13.78	1.06	2.23	1.10
Mitragyna stipulosa	33.88	2.18	29.84	1.82	15.07	0.99	0.76	0.12
Nauclea diderrichii	46.42	5.61	40.99	4.50	15.07	1.66	1.49	0.50
Nesogordonia papaverifera	49.14	8.66	46.70	6.68	15.98	1.51	1.84	0.49
Pentaclethra macrophylla	46.60	5.87	42.94	5.53	9.27	0.67	0.93	0.26
Pentadesma butyracea	36.75	1.27	32.20	1.15	14.15	0.53	0.80	0.08
Petersianthus macrocarpus	43.74	3.19	38.57	2.80	14.26	0.92	1.26	0.24
Piptadeniastrum africanum	44.02	3.63	41.26	3.64	13.56	0.88	1.48	0.32
Poga oleosa	43.02	6.43	40.35	6.62	11.80	1.45	2.15	1.11
Pterocarpus osun	38.75	2.08	35.67	2.19	11.26	1.10	0.83	0.12
Pterocarpus santalinoides	30.92	2.51	27.86	2.41	8.00	0.73	0.28	0.06
Pterygota macrocarpa	54.06	4.99	49.54	4.83	15.58	0.93	2.58	0.51
Pycnanthus angolensis	46.74	6.06	40.31	5.05	17.18	1.03	2.74	1.17

Species	Stump Diameter (cm)		Dbh (cm)		Merch. Height (m)		Merch. Vol. (m^3)	
	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Ricinodendron heudelotii	46.15	2.39	39.24	2.35	11.00	0.78	1.05	0.21
Scottellia coriacea	39.49	3.44	35.31	3.04	10.53	0.65	0.73	0.12
Staudtia stipitata	29.13	2.21	25.79	2.33	14.72	1.07	0.58	0.16
Stemonocoleus micranthus	30.26	1.84	27.96	1.72	12.65	0.83	0.61	0.10
Sterculia rhinopetala	45.39	2.10	36.14	1.73	14.69	0.57	1.24	0.16
Sterculia tragacantha	36.71	2.17	32.31	2.10	13.41	1.20	0.79	0.15
Strombosia pustulata	36.66	1.04	30.91	0.89	16.30	0.60	1.01	0.10
Symphonia globulifera	38.49	1.45	33.74	1.24	13.12	0.35	0.76	0.04
Terminalia ivorensis	56.98	7.41	48.99	5.96	19.75	1.00	3.70	1.28
Terminalia superba	60.95	7.10	50.90	6.15	18.47	0.87	4.34	1.36
Tetrapleura tetraptera	37.81	2.33	34.50	2.87	10.14	0.92	0.74	0.16
Trichilia gilgiana	30.28	1.93	25.78	0.99	6.40	1.52	0.25	0.07
Trichilia monadelpha	27.73	1.30	24.51	1.03	8.75	1.41	0.37	0.10
Trichilia prieuriana	43.31	3.56	36.80	3.44	6.28	0.63	0.59	0.17
Trichilia retusa	38.62	3.35	33.40	2.30	8.50	0.49	0.50	0.10
Trilepisium madagascariense	34.65	2.41	31.00	2.28	10.85	1.08	0.69	0.19
Triplochiton scleroxylon	61.65	5.72	51.01	4.41	20.20	1.05	4.18	1.06
Xylopia aethiopica	35.63	1.02	31.75	0.97	14.40	0.49	0.80	0.06

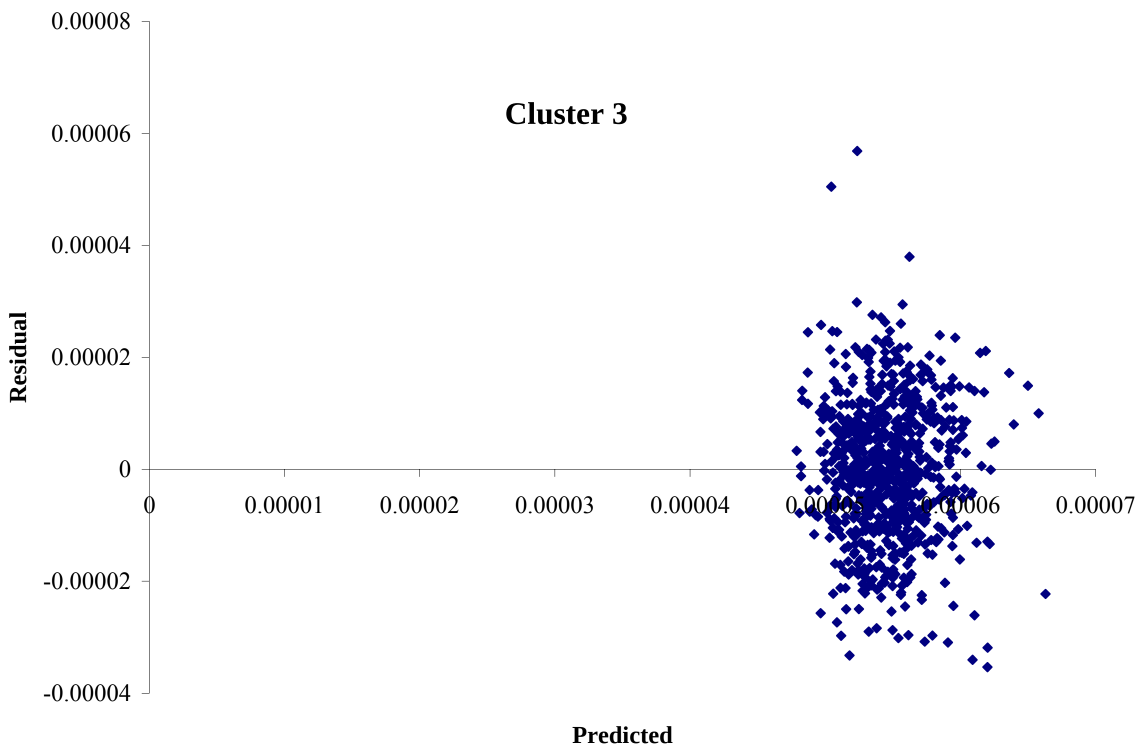
Appendix 4a: Residual Plot for Cluster 1 using the weighted Schumacher-Hall volume function



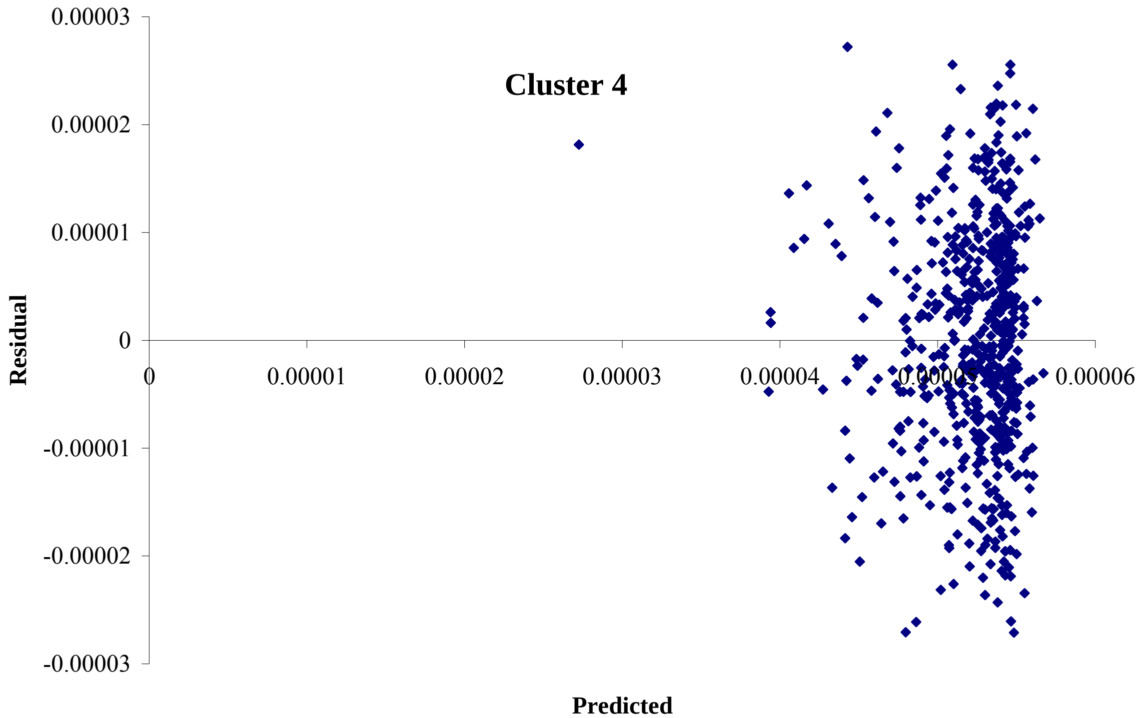
Appendix 4b: Residual Plot for Cluster 2 using the weighted Schumacher-Hall volume function



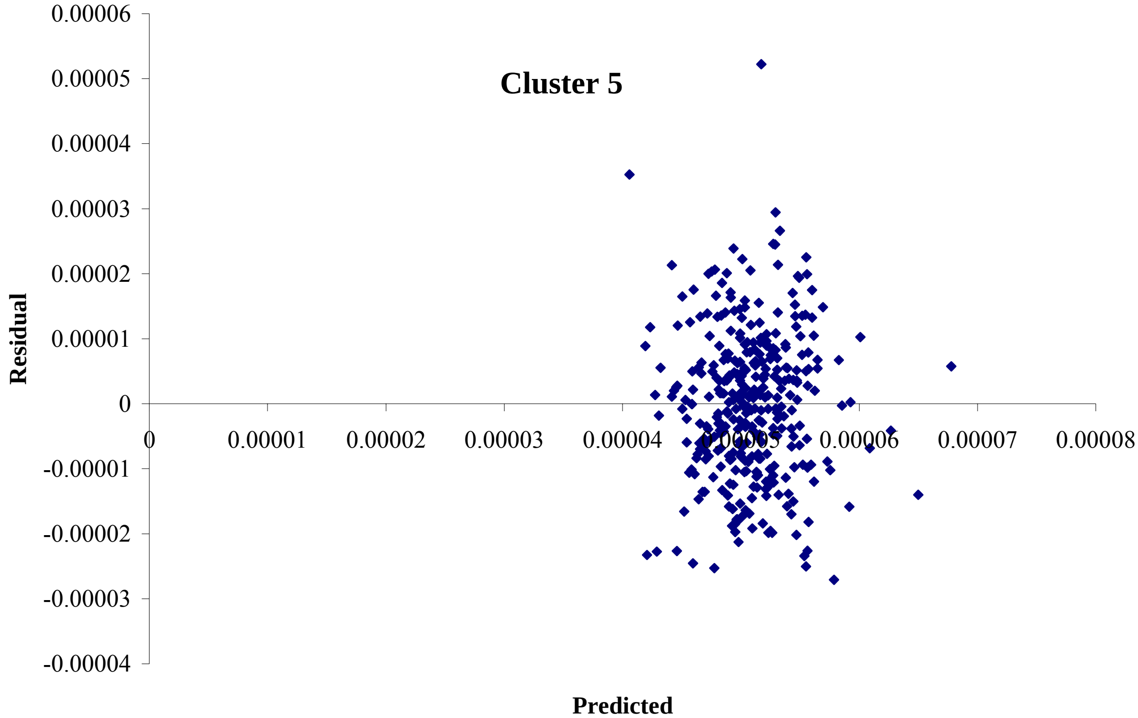
Appendix 4c: Residual Plot for Cluster 3 using the weighted Schumacher-Hall volume function



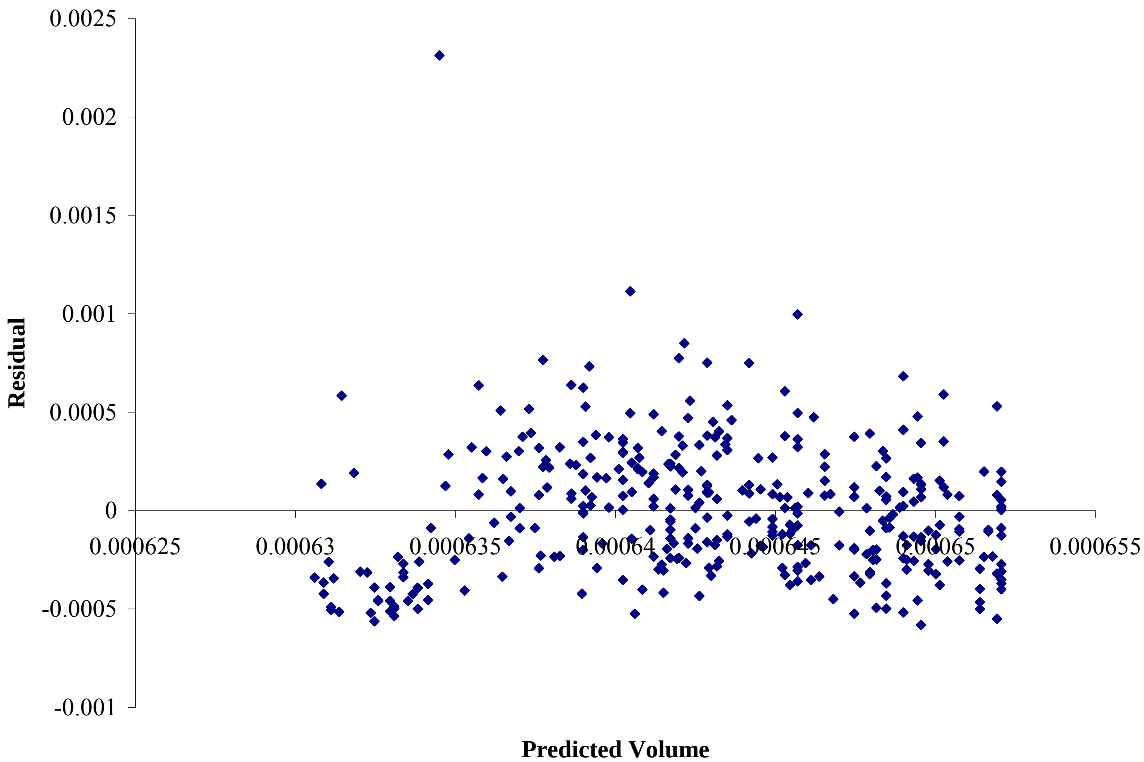
Appendix 4d: Residual Plot for Cluster 4 using the weighted Schumacher-Hall volume function



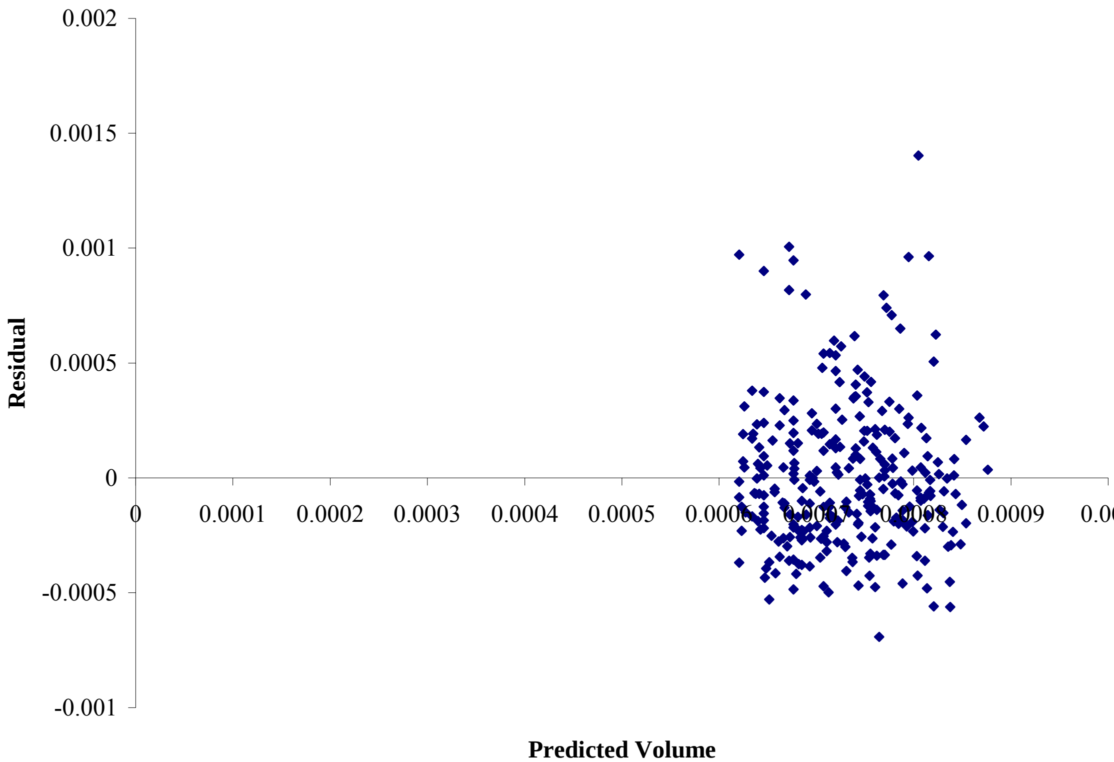
Appendix 4e: Residual Plot for Cluster 5 using the weighted Schumacher-Hall volume function



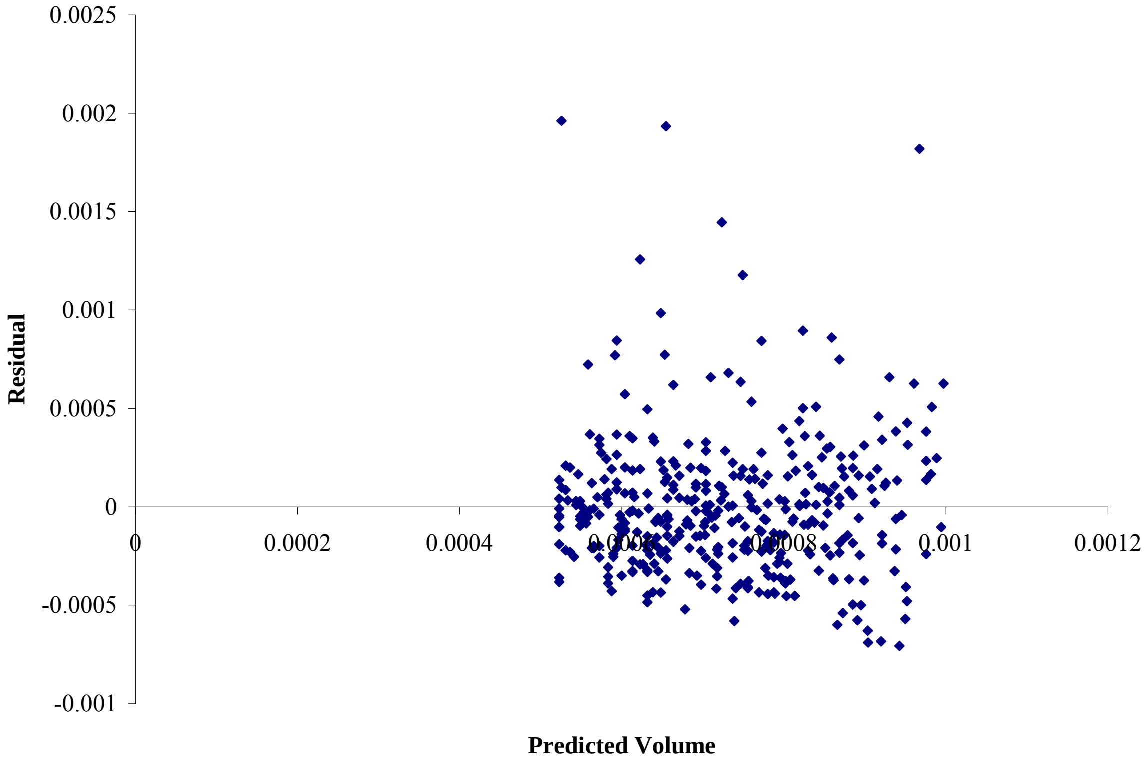
Appendix 5a: Residual Plot for Cluster 1 species using the weighted quadratic volume function based on dbh alone



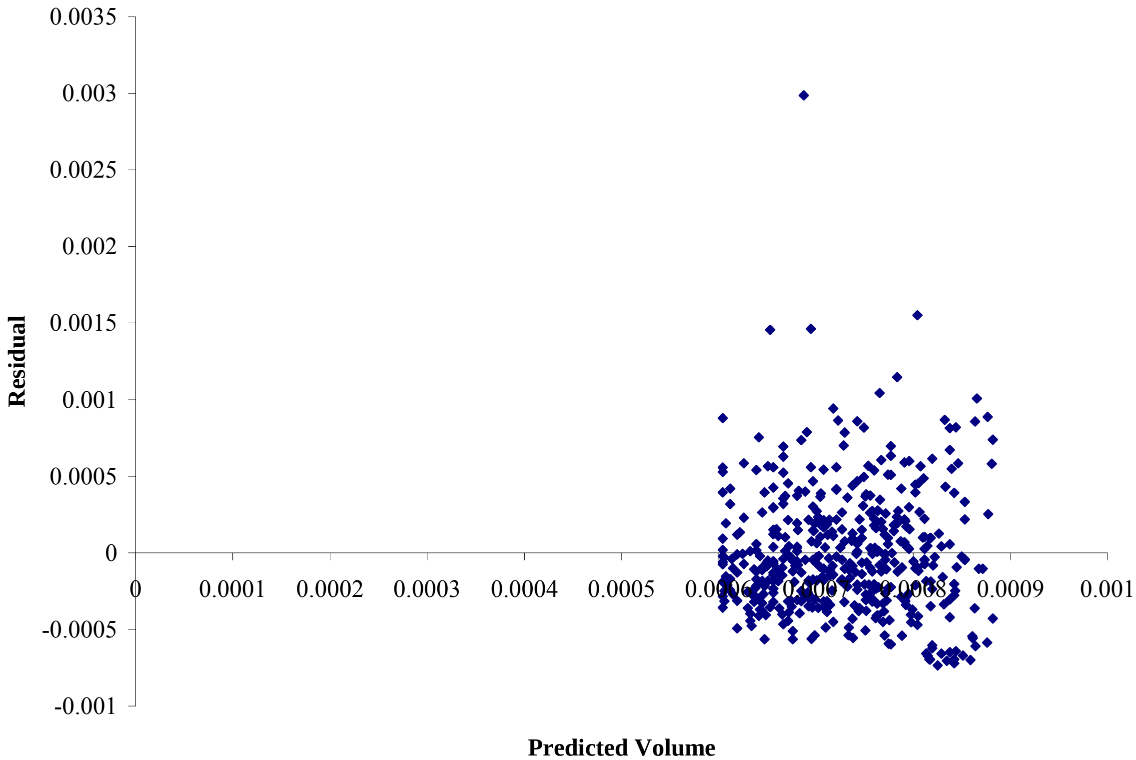
Appendix 5b: Residual Plot for Cluster 2 species using the weighted quadratic volume function based on dbh alone



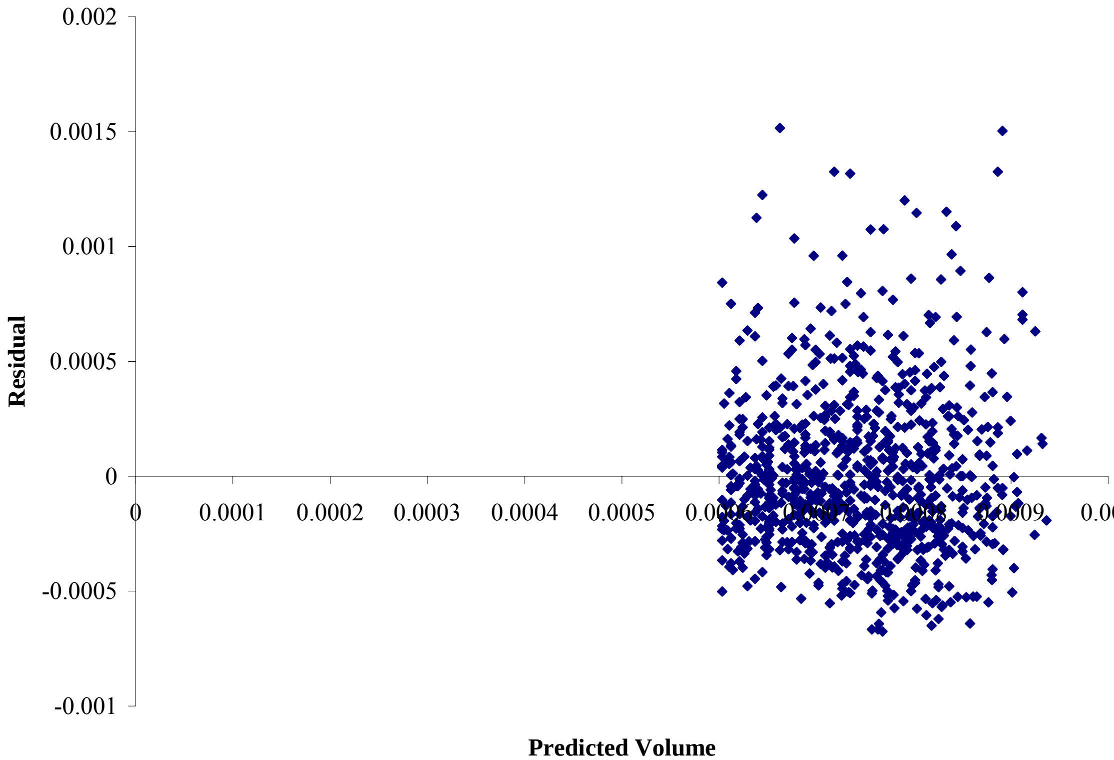
Appendix 5c: Residual Plot for Cluster 3 species using the weighted quadratic volume function based on dbh alone



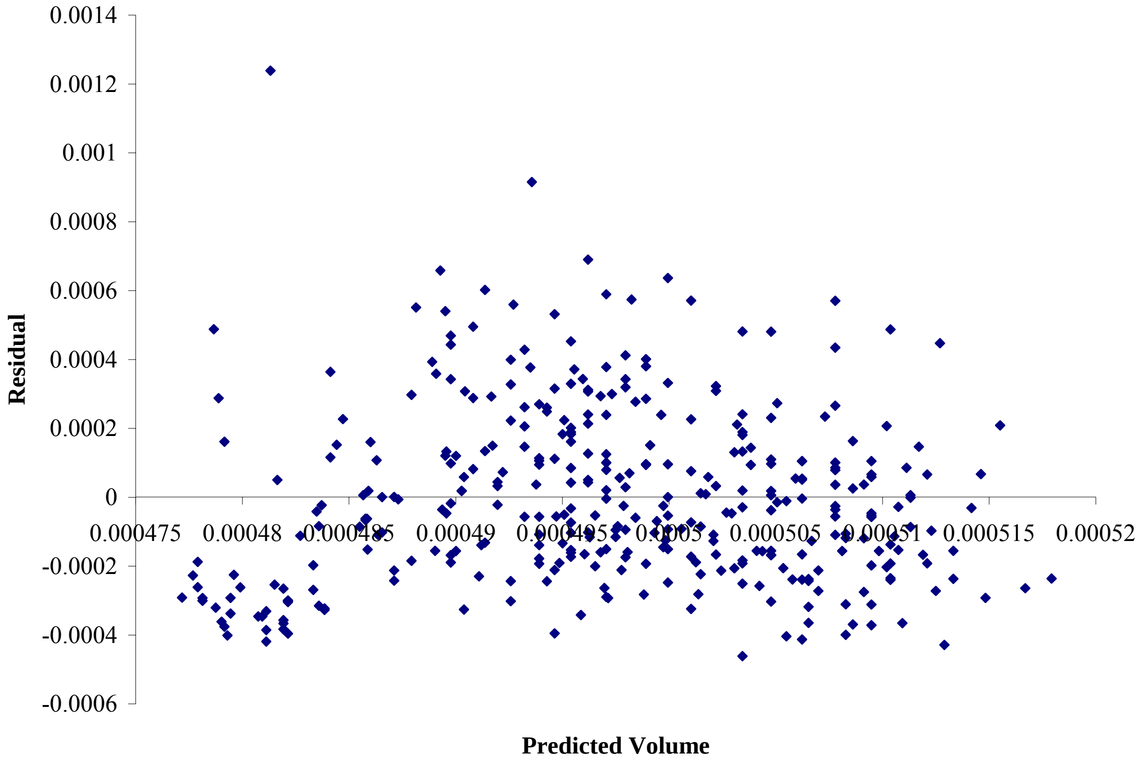
Appendix 5d: Residual Plot for Cluster 4 species using the weighted quadratic volume function based on dbh alone



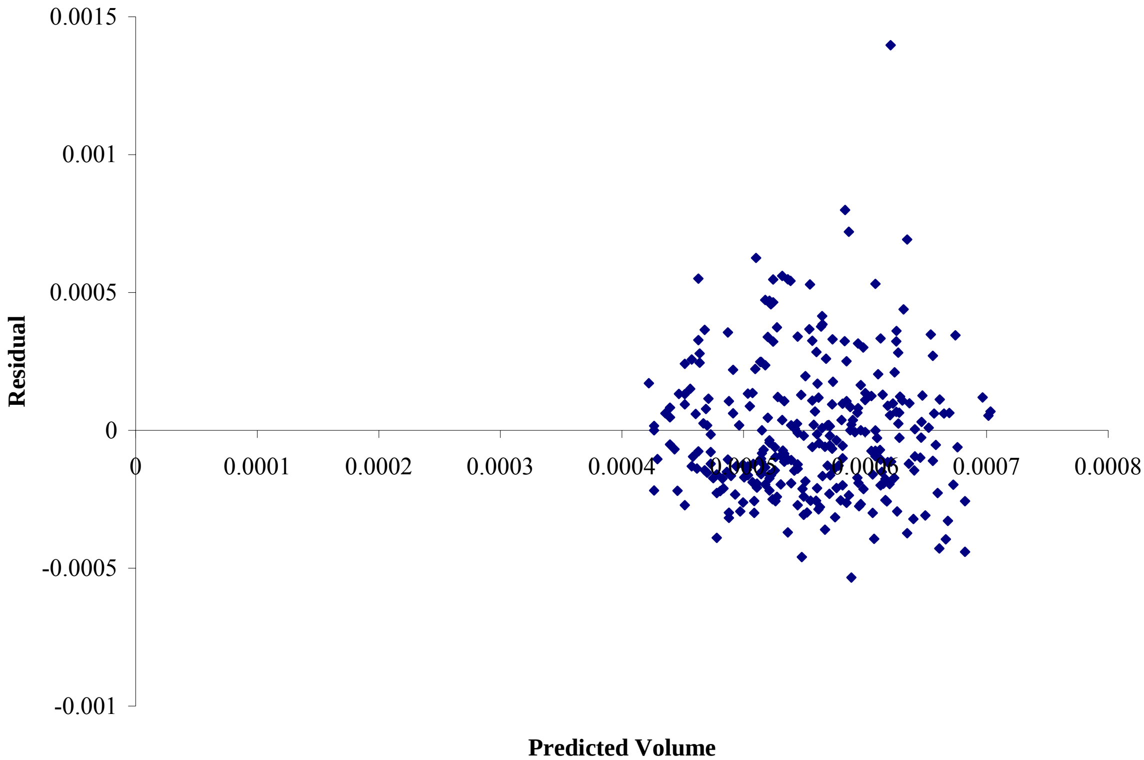
Appendix 5e: Residual Plot for Cluster 5 species using the weighted quadratic volume function based on dbh alone



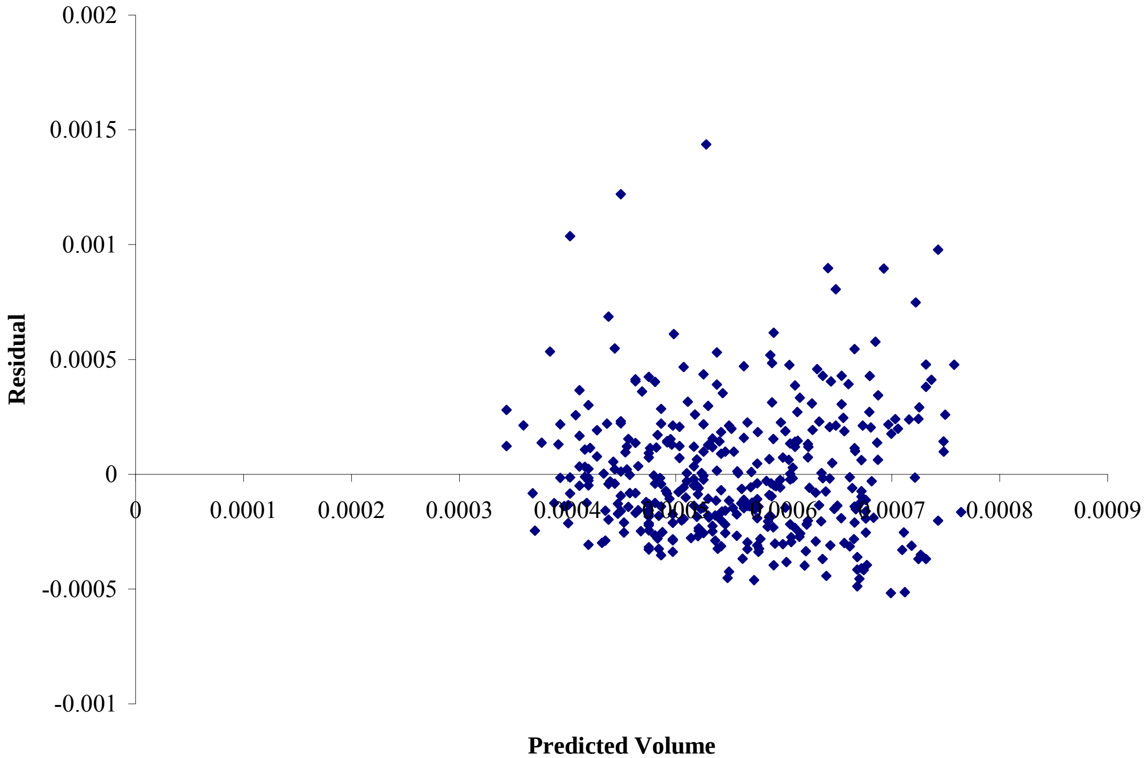
Appendix 6a: Residual Plot for Cluster 1 species using the weighted quadratic volume function based on stump diameter alone



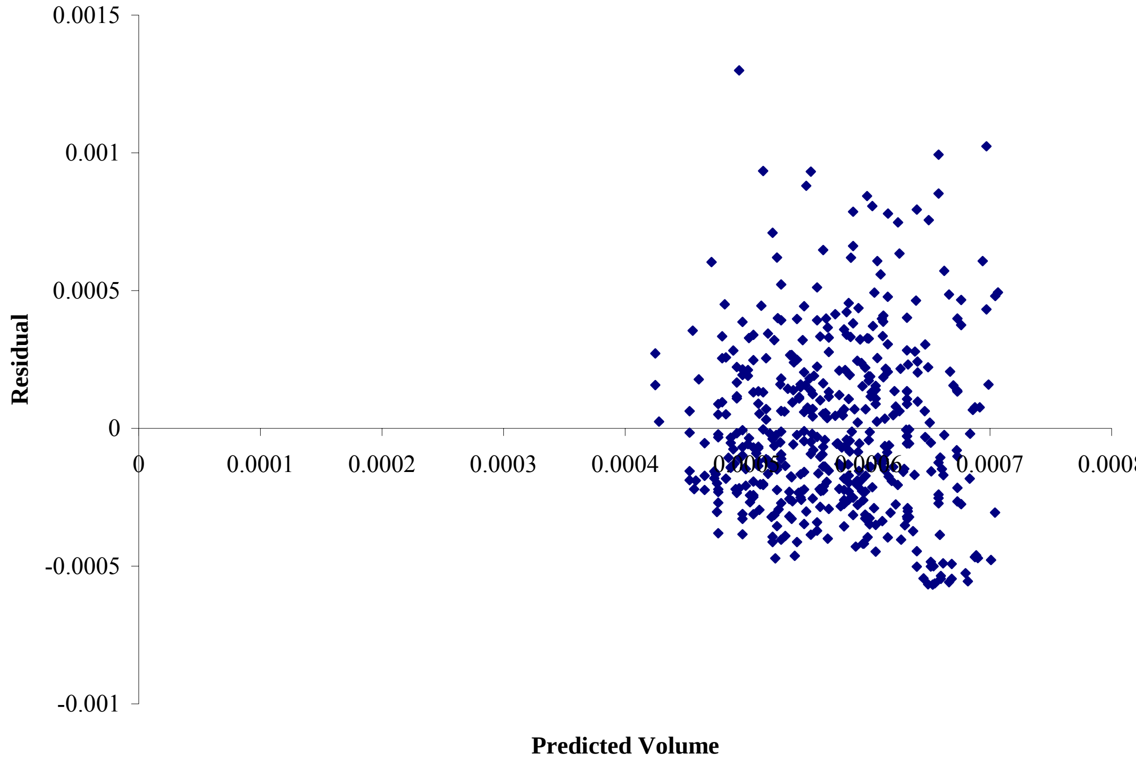
Appendix 6b: Residual Plot for Cluster 2 species using the weighted quadratic volume function based on stump diameter alone



Appendix 6c: Residual Plot for Cluster 3 species using the weighted quadratic volume function based on stump diameter alone



Appendix 6d: Residual Plot for Cluster 4 species using the weighted quadratic volume function based on stump diameter alone



Appendix 6e: Residual Plot for Cluster 5 species using the weighted quadratic volume function based on stump diameter alone