# Taper and volume equations for Sal (*Shorea robusta* Gaertn. f.) in the Western Terai, Nepal

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A thesis Submitted in Partial Fulfillment of the Requirement for the Degree of Master of Science in Forestry

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# Taper and volume equations for Sal (*Shorea robusta* Gaertn. f.) in the Western Terai, Nepal

A Dissertation Submitted for Partial Fulfillment of the Requirement for the Degree of Master of Science in Forestry


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# Declaration

I, Ramesh Silwal, hereby declare that this research report entitled "Taper and volume equations for Sal (*Shorea robusta*) in the Western Terai, Nepal" is my original work and the information is exclusively based on primary and secondary data collection. All sources of information wherever used are thus, acknowledged accordingly.

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## Letter of Acceptance

The M. Sc. dissertation work entitled **"Taper and volume equations for Sal (*Shorea robusta)* in the Western Terai, Nepal"** submitted by **Ramesh Silwal** has been accepted as a partial fulfillment for the requirement of Masters of Science in Forestry.

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# ABSTRACT

A volume equation for predicting individual tree volume, and a taper function for describing a stem profile were developed for *Shorea robusta*Gaertn. f. in the western Terai, Nepal. The species has high commercial value and makes an important contribution to the local economy because of its high quality timber. Current interest in multiple-product timber harvesting generated a need for improved volume prediction for individual trees and yield prediction for stands. We now need to know what portion of a tree can be used for specific products, and need to identify the entire array of products can be obtained from the stand. Therefore estimation through modeling might be viable option where such models are available. This study was conducted in Saljhandi forest of Rupandehi district and Basanta forest of Bardia district with the main objective of testing the stem volume equatation for *S. robusta* using DBH, height, crown diameter and site as a predictor variables; and developing a stem taper model for *S. robusta* using a destructive sample of 33 trees.

Mean diameter at breast height, tree height and crown volume of the sampled trees were 46.86cm, 26.02m and 719.375 $m^3$ respectively. Trees were purposely selected with some criterion like trees without forks below mid-height; avoid overlapped canopy, diseased and malformed tree and coverage of a full range of tree sizes. Measurement was undertaken only on over-bark diameters. Data regarding diameter at breast height and crown diameter were collected before felling and diameter at eight different sections of bole, tree height were collected after felling the tree. The diameter at different heights along the main stem and the height of the trees were measured by a diameter tape and linear tape respectively whereas crown diameter was measured by plumb bob.

Data were fitted in candidates' model and evaluated by using the significance of the parameter values, adjusted coefficient of determination, root mean square error and distribution of residuals. The results showed that the best fit model for stem volume is $\mathrm{Ln(V)} = \left(-9.1664 + \mathrm{a}_{\mathrm{i=BR,BT}}\right) + \mathrm{bLn(DBH)}$ and stem tapper is $\mathrm{D} = \sqrt{\left[\mathrm{DBH}^{2.03} * \left(\frac{\mathrm{TH-HAG}}{\mathrm{TH-1.3}}\right)^{1.68}\right]}$. These models for this species will help the manager, planners, users and decision makers for better management and utilization of *S. robusta* forest in a long run.

**Key words:** *Stem volume, Stem taper, Model, Height, Diameter*

# ACRONYMS

| | |
|---|---|
| Adj.$R^2$ | Adjusted Coefficient of Determination |
| AFO | Assistant Forest Officer |
| CD | Crown Diameter |
| cm | Centimeter |
| CTA | Chief Technical Advisor |
| DBH | Diameter at Breast Height |
| DC | Degree Celsius |
| DDG | Deputy Director General |
| DFO | District Forest Office |
| DG | Director General |
| DFRS | Department of Forest Research and Survey |
| FAO | Food and Agriculture Organization |
| FRP | Forest Research Project |
| H | Height |
| HAG | Height above Ground up to Point of Interest |
| IoF | Institute of Forestry |
| Ln | Natural Logarithm |
| LRMP | Land Resource Mapping Project |
| m | Meter |
| $m^3$ | Cubic Meter |
| mm | Millimeter |
| RMSE | Root Mean Square Error |
| Spp | Species |
| STA | Senior Technical Advisor |
| TH | Total Height |
| VDC | Village Development Committee |

# CHAPTER ONE: INTRODUCTION

## 1.1 Background

Tree volume and taper equations are useful and important for forestry, and they are lacking for commercial species in developing nations. They are the simple methods and the tools that can be used to obtain individual tree volume and the volumes of entire stands. Such information is vital for forest management.

Volume equations have been used to estimate tree and stand volume, and have played a crucial role in forest inventories and management for more than a hundred years. Studies of tree volume began in the early nineteenth century. Around 1804 Heinrich Cotta was the first forester to introduce the concept of a volume table (Clark 1902). However, an extensive study to collect data for constructing the first volume table was carried out many years later. This early study was mainly of Norway spruce.

Taper functions were introduced and used much later. The advantage of taper functions over volume equations is that taper functions can describe changes in diameter up a tree stem, and therefore provide estimates of dimensions of logs that might be cut from stems. Volumes of any specific log length can be obtained by integrating a taper function. In many cases, this is more convenient than volume ratio equations that are usually limited to a particular height such as commercial height.

Even though both volume equations and taper functions have been studied for many years, they continue to attract forest research. One reason is that there is no single theory in volume and taper equations that can be used satisfactorily for all tree species (Clutter *et al.* 1983; Muhairwe 1999), and no single taper model is best for all purposes (McClure and Czaplewski 1986; Cao *et al*. 1980). Another reason is that both volume and taper equations are required to be increasingly accurate and flexible in their predictions. Forest measurement needs to be improved because market requirements for timber have become more specific in recent years.

Volumes of current growing stock and future growth potential are both vital information for forest management. The former can be obtained through forest inventories and the latter can be estimated or projected from a current inventory by growth and yield models (Methol 2001). Individual tree volumes are primary data for estimating stand volume per hectare (or stand volume for a fixed area), and are directly linked to forest inventory. Effective tools for estimating individual tree volume are volume equations and taper functions. They are acceptably accurate, easy and cheap methods (Philip 1994). While most volume equations developed can limitedly provide total and/or merchantable stem volume, wider ranges of information can be obtained from taper functions. According to Methol (2001) taper functions can be used to estimate the tree variables for instance diameter at any point of the stem; height at which a given diameter occurs along the stem; total volume; merchantable volume to any merchantable height or minimum upper-stem diameter and from any stump height; and individual log volumes.

Volume and taper functions have been scarcely studied in Nepal. Elsewhere, a considerable amount of work on volume and taper has been done (Clutter *et al.* 1983; Kozak *et al*. 1969; Max and Burkhart 1976; Newnham 1988). Limited volume equation and no taper equation for any species in Nepal have been published.

Tree species that have been the focus for past studies, particularly for taper equations, are softwoods (Max and Burkhart 1976; Cao *et al*. 1980; Fang *et al*. 2000). Relatively small numbers of taper equations have been developed for hardwoods. Examples of such equations are the study of Appalachian hardwoods conducted in locations in the United State of America (Jiang *et al*. 2005).

Building volume and taper equations warrants study, particularly when the methodology is applied to species which have not been previously studied in this way.

***Shorea robusta*** **Gaertn. f.** is a subject species for the study described here. The species is an angiosperm, and belongs to Dipterocarpaceae family. More details about it are left for the literature review section (section 2 of this paper). Scientific knowledge about the species is very limited, particularly in Nepal, even though *S. robusta* has important social and high commercial value. *S. robusta* is mainly valued for the strong and durable construction timber, and it is also used as fuel, fodder, leaf plate and resin. Also, seed-oil is produced from *S. robusta* (Jackson 1994b).

## 1.2 Rationale of the study

Current interest in multiple product timber harvesting has generated a need for improved volume prediction for individual tree and yield prediction for stands. Knowledge of total volume is no longer sufficient. Now we need to know what portion of a tree can be used for specific products, and we need to identify the entire array of products that can be obtained from specific stands. However, direct stem volume estimation is tedious, laborious, and costly.

When available, empirical data will provide some of the answers, however, such information will generally be restricted to existing product specifications. Therefore, to interpolate and extrapolate empirical data, and to provide greater flexibility with changing specifications and with new products, a more generalized approach is needed (Martin 1981).

Although various methods of developing taper/volume equations have been proposed (Kozak and others 1969; Kozak and Smith 1966; Max and Burkhart 1976; Fries and Matern 1965; Bennett and Swindel 1972; Goulding and Murray 1976; Demaerschalk 971, 1972, 1973a, 1973b; Burce and others 1968; Ormerod 1973; Clutter 1980; Cao and others 1980; and Demaerschalk and Kozak 1977), the information is either theoretical or limited primarily to softwood species (Martin 1981).

Most equations developed for volume and upper bole diameter estimates are of an empiric, rather than geometric, origin. As such, these equations are of limited use. For instance, in volume table construction for different utilization standards, separate computations, and possibly different models, are required for each standard. A general stem profile model, that can be integrated to give a volume equation, is desirable (Ormerod, 1973).

Sharma and Pukkala  (1990) have developed biomass equation for different species of Nepal including *S. robusta*, need to be calibrated by recent data. The volume models and their counterparts for volume prediction developed by Tamrakar (2000) and Anon( 2006) are limited to large-sized trees. It is not clear how widely and profoundly the good practices based on the earlier instructions (Applegate et al.,1985 & Pukkala et al.,1990) have been applied in data collection, storing, processing and documentation.. There are no published and compatible models available for tapering function of *S. robusta* in Nepal. One of the most important elements in such a circumstance is reliable taper and volume equations for the species in question. Such equations enable users to estimate the diameter at any point on the bole, the height to any predetermined diameter and the volume between any two points on the bole (Martin 1981).

## 1.3 Study objectives

**General**

The overall objective of this study was to develop the stem volume and taper models for *S. robusta* using destructive samples from the western Terai, Nepal

**Specific**

The specific objectives of the study were to:

- To test the stem volume equitation for *S. robusta* using DBH, height, crown diameter and site as predictor variables;
- To develop a taper model for *S. robusta;*

## 1.4 Limitation of the study

As I had to obtain the samples from the tree felling site of the District Forest Office, Rupandehi where the small sized trees were not found, it was not possible to make representation of small sized trees (i.e. less than 37.5 DBH) in the case of Saljhandi forest of Rupandehi district.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 Tree profile and log volumes

Modelling individual stem volume is a critical foundation of forest mensuration, growth and yield estimation, and forest valuation. Individual stem volume equations are used to translate forest inventory measurements of height and diameter at breast height into wood volume and to generate predicted volumes from modelled estimates of future heights and diameters at breast height. In addition, taper equations, models of profiles of stems, are critical for estimating the sizes and shapes of logs that might be obtained from a tree, and these estimates are required to compute log value. It is essential that volume and taper models are as unbiased and accurate as possible.

Trees have various sizes, forms and shapes. A single stem also consists of different geometric segments. Some portions of a stem may be cylindrical, while others may be conoid or other geometric solids. Some parts of a stem may be also affected by irregular forms such as butt swell. Stem volume, therefore, is difficult to estimate accurately. However, foresters usually treat tree stems as common geometric solids of which the volumes can be calculated using the ordinary existing volume formulae. Three common solids of revolution applied to the tree stems are neiloids, conoids and paraboloids (Avery and Burkhart 1994). Volumes of these solids of revolution can be calculated using formulae as follows:

$$\text{paraboloid} = \frac{A}{2}L$$

$$\text{conoid} = \frac{A}{3}L$$

$$\text{neiloid} = \frac{A}{4}L,$$

where: A is cross-sectional area, and L is log length.

The lower bole portion is generally assumed to be a neiloid frustum, the middle portion a paraboloid frustum, and the upper portion a cone (Hush *et al.* 1972).

According to Avery and Burkhart (1994), the principal problem encountered when computing log volumes is that of accurately determining the elusive average cross-sectional area, because volumes for all solids of revolution are computed from the product of their average cross section and length. Two commonly used formulae (Huber's formula and Smalian's formula) define average cross-sectional area in different ways. Huber's formula treats cross-sectional area at the midpoint as the average, and thus:

$$V_{log} = A_{1/2}L$$

where $V_{log}$ is log volume, and L is as previously defined.

Smalian's formula, on the other hand, uses cross-sectional areas of both ends of the log. Therefore, the average cross section is the mean of two end cross-sectional areas, and thus:

$$V_{log} = \frac{A_1 + A_2}{2}L$$

where A1 and A2 are cross-sectional areas at large end and at small end, respectively, and other notations are as previously defined.

One other log volume formula occasionally used for log volume estimation is Newton's formula. The average cross-sectional area used in this formula is slightly more complicated than those used in the previous two formulae. This formula is more difficult to apply in practice. It requires three measurements, one at both ends plus the midpoint of the log and thus:

$$V_{log} = \frac{A_1 + A_{1/2} + A_2}{6}L$$

where all notations are as previously defined.

All three formulae can provide identical results if logs are perfectly cylindrical (Avery and Burkhart 1994). In addition, when logs are short it is also found that the volumes estimated by three formulae are essentially equivalent.

Of the three formulae, Smanlian's formula is the easiest to apply, but it can be shown to be inaccurate with some irregular shapes of logs. Avery and Burkhart pointed out that the formula introduced errors when it was used to estimate volumes of butt logs having flared ends. Some problems are shared by both Smalian's formula and Huber's formula. If the log is not a frustum of a quadratic paraboloid and not a cylinder, then the use of either Smanlian's formula or Huber's formula will introduce errors (Philip 1994). However, given some problems encountered by the other two formulae, Smalian's formula is usually preferred by researchers. The use of midpoint cross sectional area by Huber's formula and Newton's formula can cause a problem in practice. Even though Newton's formula is more accurate than the other two methods and preferred to apply.

## 2.2 Volume tables and equations

A volume table is a tabulation that can be used to obtain the estimated volumes of single trees of given dimensions (Avery and Burkhart 1994). In modern practice, equations are generally used to predict tree volumes rather than hardcopy tables. An early volume equation was introduced during 1930's by Schamacher *et al.* (Laar and Akca 2007). The form of equation is:

(1) $$V = \beta_o D^{\beta 1} H^{\beta 2}$$

Where: V is stem volume, D is diameter at breast height, H is total height, and $\beta_{o-2}$ are estimated parameters.

This equation is a non-linear volume equation that can be linearized by a logarithmic transformation of the dependent and independent variables. The resultant equation is:

(2) $$\ln(V) = \beta_0 + \beta_1 \ln(D) + \beta_2 \ln(H)$$

Nowadays there are many different forms of volume equations of both linear and non-linear form. One of the most common forms is Spurr's volume equation for a linear combined variable model (Bi and Hamilton 1998). This equation has a form:

(3) $$V = \beta_0 + \beta D^2 H$$

One merely substitutes the combined variable of 'diameter squared times height' for the quantity X in the basic equation for a straight-line relationship. Solution of the equation is by simple linear regression techniques. Regression methods are favoured over other traditional methods like tabular and graphic methods that have become obsolete for several reasons (Laar and Akca 2007). One is that it eliminates the necessity to read off the estimated volume from a graph or to interpolate in a table. More importantly, the parameters of the equation can be stored in the memory of a computer and retrieved for volume calculation anytime.

In most cases estimates and profiles of under-bark volume are required, but there are cases where over-bark volume is essential, such as when trees are used for fuel.

## 2.3 Classification of volume tables

Even though nowadays stem volumes are commonly calculated with volume equations, the term 'volume table' has persisted in forestry usage as a generic term meaning tabulations or equations that show the contents of standing trees (Laasasenaho, *et al*. 2005, and Avery and Burkhart 1994). According to (Laar and Akca 2007) volume tables (equations) can be classified based on the number of entries to the table and predictor variables of the volume function:

- Single-entry volume table (one-way table)
- Multiple-entry volume table (two-way table and three-way table)

A single-entry volume table was first developed towards the end of 19th century for all-aged forests in France and adapted for management of mixed unevenaged forests of Switzerland (Laar and Akca 2007). The term "local table" is sometimes used to refer to this kind of volume table. Normally diameter at breast height (D) or basal area (G) is required for constructing a single-entry volume table. The relationship between tree volume and D for many species has been well documented. Generally, Tree volumes have a curvilinear relationship with D but are approximately linearly related to D squared (Avery and Burkhart 1994). Therefore, the volume-basal area line is actually a simple, linear relationship of volume on basal area and the equation can be expressed:

$$(4) \qquad V = \beta_0 + \beta_1(D^2) \qquad \text{or} \qquad V = \beta_0 + \beta_1(G^2)$$

Most single-entry volumes are simple and easy to apply, but their uses are limited to local conditions. Tree dimensions that are more difficult to measure such as height or form are usually not required. Thus, single-entry tables are particularly useful for quick forest inventories and are low cost in use (Philip 1994). Elimination of height and form determinations also tends to assure greater uniformity in volume estimates, particularly when two or more field parties are cruising within the same project area (Avery and Burkhart 1994).

Because trees of a given diameter class, particularly those from different stands, can vary in their heights and forms, use of single-entry volume tables can introduce bias. Thus most volume tables of this type have to be restricted to a small range of diameters in a specific stand at a specific age (Philip 1994). It is usually necessary to construct single-entry tables for each broad site class encountered when soils and topography are notably varied.

Multiple-entry volume tables include double-entry and triple-entry volume tables. The former is sometimes referred to as 'standard volume tables'. The standard volume tables use both 'D' and 'H' as table entries, while triple-entry volume tables have a third variable of tree's dimensions such as form, diameter at a particular height or taper. Some papers reported that the addition of a third predictor variable reduced the amount of unexplained variation and improved the accuracy of volume estimates, while other studies found that the addition of a third predictor variable did not significantly improve the quality of prediction (Laar and Akca 2007). It is clear, however, that triple-entry volume tables are not as widely available as double-entry volume tables.

Double-entry volume tables are probably the most common form of volume table (Philip 1994). A large number of volume equations, which are linear in their parameters, have been proposed with D, $D^2$, H, $H^2$ and interaction terms as independent variables, and individual tree volume as the dependent variable. The volume equations in Table 2.1 are taken from a list of candidate volume equations obtained from the available literature that will be tested with the data set created for this study. A full list of them is in the method section. All but equations 8, and 9 are linear in their parameters.

**Table 1:** Examples of double-entry volume equations

| Equation no. | models | References |
|---|---|---|
| 5 | $V = b_1D^2H$ | Clutter *et al*. (1983) |
| 6 | $V = b_0 + b_1D^2H$ | |
| 7 | $V = b_0 + b_1D^2 + b_2H + b_3D^2H$ | |
| 8 | $V = b_1D^{b2}H^{b3}$ | |
| 9 | $V = b_0 + b_1D^{b2}H^{b3}$ | |
| 10 | $V = D^2/(b_0 + b_1H^{-1})$ | |
| 11 | $V = b_0 + b_1D^2H + b_2D^3H$ | Bi and Hamilton (1998) |
| 12 | $V = b_0 + b_1D^2H + b_2D^3H + b_3D$ | |
| 13a | $V = b_0 + b_1D^2H + b_2D^2H^2$ | |
| 13b | $V = b_1D^2H + b_2D^2H^2$ | |
| 14 | $V = b_0 + b_1D^2H + b_2D^2H^2 + b_3H$ | |
| 15 | $V = b_0 + b_1D^2H + b_2D^3H + b_3D^2H^2$ | |
| 16 | $V = b_0 + b_1D^2H + b_2D^3H + b_3D^2H^2 + b_4D$ | |
| 17 | | |
| 18 | | |

The equations included in Table 1 consist of all three categories of double-entry volume equations defined by Philip (1994):

- simple combined variable model
- multiple regressions with powers of D and H
- logarithmic forms

These three categories of volume equations have been used frequently. Each category has some advantages and limitations. One of the advantages of a logarithmic form is that it can directly handle heterogeneity of the variance, while ordinary least squares techniques cannot.

## 2.4 Linear and non-linear volume equations

Performances of non-linear or logarithmic volume equations are not affected by non-homogeneity of the variance. Using this form of volume equation can surmount the problem of non-homogeneity of the variance that exists in most tree volume data. Because volume data usually include different sizes of trees from very small ones to very large ones, deviations from the regression function of the volumes of the large trees have a disproportionate effect on the estimation of the least squares regression coefficients from a sample (Cunia 1964). In other words, one of the common assumptions underlying least squares methods of regression, that all data points contribute equally to the estimation of the regression coefficients, is not satisfied. Even though heterogeneity of variance does not necessarily introduce bias, it may increase model statistics such as the standard errors of regression coefficients and imply that estimates for small trees are less precise than they actually are. In addition, when the residual error increases with the size of prediction, estimates for small trees may be biased because measurements of small trees would have less influence on estimated coefficients than those of large trees. This may be one reason that unweighted least squares techniques are fully efficient only in the absence of heteroscedasticity, a term denoting a correlation between average error magnitude and the magnitude of the predicted value of a model (Furnival 1961).

## 2.5 Weighted least squares

Cunia (1964) argued that using the logarithms of tree volume equations was not the best option to surmount the problem of heterogeneity of variance. One important drawback of this method is that by taking logarithms the estimation of the arithmetic mean is automatically replaced by the estimation of the geometric mean. Because the first one is always larger than the second, the results are definitely biased. An alternative common technique to combat the non-homogeneity of the variance in tree volume construction is to use weighted least squares. A common weight factor for volume that uses both variables as predictors D and H (interaction term of $D^2H$) is $(\frac{1}{D^2H})^2$. That is because the variance of stem volume tends to increase in proportion to $D^2H$ as reported by Furnival (1961) and Meng and Tsai (1986). For single-entry volume tables, on the other hand, Meng and Tsai (1986) suggested that the weight factor of $\frac{1}{D^2}$ is more appropriate than $\frac{1}{D^4}$ which was used by some authors.

## 2.6 Taper

Taper can be defined as the rate of narrowing in diameter along the tree stem of a given form (Gray 1956). It can be expressed as a function of height above ground level, total tree height, and diameter at breast height (Clutter *et al.* 1983). Taper equations are very useful as they can provide information about diameter at any height, and height at any diameter based only on commonly taken tree measurements (Byrne and Reed 1986). They can be also used to predict individual log or sectional volumes to any height along stem. Therefore, merchantable heights and volumes can be estimated directly using a taper equation. Furthermore, taper equations can be used to derive volume equations by integration when the equation is rotated around the longitudinal axis of a tree (Bruce *et al.* 1968), Byrne and Reed (1986). They can be also compatible to volume equations that are used to estimate single tree volumes. A compatible taper equation developed from volume-taper equation system assures that estimated volume obtained by integrating the taper equation is equal to the estimate obtained with a volume function.

## 2.7 Classification of taper equations

During the past century, form and taper have been studied widely all over the world. Many different forms of taper equations have been developed for various species, particularly for softwoods. A simple form of taper depicts the entire stem profile with a single equation. A complex taper model usually consists of sub-models that attempts to describe different portions of the tree profile with different sub-models, and uses complicated variable predictors.

According to Methol (2001) taper equations can be grouped into four categories; namely, single functions, segmented polynomial models, within-tree variable form (or variable exponent equation), and between-tree variable form functions. Single function include the form of polynomial equations that represent the whole bole with one single continuous function. The taper models by Bruce *et al.* (1968), Ormerod (1973), Hilt (1980), and Gordon *et al.* (1995) are examples of this kind. Segmented polynomial taper models consist of sequence of grafted sub-models describing different segments. A taper model by Max and Burkhart (1976) is an example of this kind. The other two types of taper equations, within-tree variable form (or variable exponent equation), and between-tree variable form functions have not widely used. This study will not examine any equation of these latter two types.

## 2.8 Single functions

An equation presented by Kozak *et al*. (1969) is an example of the relatively simple parabolic function with three estimated parameters. This equation is one of the candidates model tested with data set in this study (model 19).

$$(19) \qquad d^2 = D^2\left(\beta_1\left(\frac{h}{H}-1\right)+\beta_2\left(\frac{h^2}{H^2}-1\right)\right)$$

This taper equation was developed based on the basic relationship of a parabolic function. It was conditioned by $\left(\frac{h}{H}-1\right)$and $\left(\frac{h^2}{H^2}-1\right)$ as predictor variables so that when h equals H, estimated diameter is exactly zero. The related model without imposing such a condition has the form:

$$d^2 = D^2\left(\beta_0+\beta_1\frac{h}{H}+\beta_2\frac{h^2}{H^2}\right)$$

By imposing the condition, bias generated by the model can be reduced because unexplained variation at the top of a tree is restricted. Other candidate taper equations of single form will be examined in the studies described here, including models 20 by Sharma and Oderwald (2001), 21 by Ormerod (1973), and 22 (polynomial series model):

$$(20) \qquad d^2 = D^2\left(\frac{h}{h_D}\right)^{2-\beta}\left(\frac{H-h}{H-h_D}\right)$$

$$(21) \qquad d = D\left(\frac{H-h}{H-h_D}\right)^{\beta}, \beta > 0$$

$$(22) \qquad d = D\left(\beta_0+\beta_1\left(\frac{h}{H}\right)+\beta_2\left(\frac{h}{H}\right)^2+\cdots\beta_n\left(\frac{h}{H}\right)^n\right)$$

Equations 20, and 21 are so conditioned that when h = H, d= 0, and when h = $h_D$ ($h_D$ is breast height equal to 1.3 m), d = D. For equation 21, when b takes on a value of one, the resulting tree profile is conic and when b is one-half the resulting tree profile is parabolic (Reed and Byrne 1985). When b is greater than one but less than one-half i.e. three-fourths, a tree shape is also between a cone and a parabola 'paracone'.

Another common form of single taper functions is a polynomial series. Equation 22 represents the general form of this kind. Even though very high degree polynomials have been used in some studies the most common ones are around fifth-degree polynomial (Figueired-Filho *et al*. 1996). Volume equations with additional complex powers i.e. an equation by Bruce *et al.* (1968) can improve the standard error of estimate (Kozak *et al*. 1969). However, Kozak *et al*. (1969) argued that, for practical purposes it appeared that the real advantage of complex taper equations was little.

Relatively simple taper equations can effectively describe the general taper of trees, however, they often fail to describe the entire stem profile well (Max and Burkhart 1976; Newnhan 1992). Some equations are better for describing the profile along the mid stem portion of the tree, but they are inadequate for describing the area near the butt and at the very top sections of the tree (Jiang *et al*. 2005). Martin (1981) indicated that although no single equation form was best at predicting diameter, height and volume the Max and Burkhart segmented polynomial was best overall. This model was also ranked best amongst six models evaluated by Cao *et al*. (1980).

Taper equations are compatible with tree volume equations if they are derived from each other. The coefficients of the derived volume equations can be written in terms of the taper equation coefficients (Byrne and Reed 1986). Compatible volume and taper equations can also written by derived the expression of taper from an existing total volume equation (Goulding and Murray 1976), and from an existing volume ratio equation (Clutter *et al.* 1983; Reed and Green 1984). The theory of compatible taper and volume systems was first introduced in the early 1970s (Demaerschalk 1972). Before his introduction of the concept it was common that tree volume and taper equations were both in use for a given population, and that volumes obtained from the tree volume equation were not equal to volumes obtained by integration of the taper equation (Methol 2001). The process used for deriving compatible taper equations (equation 23) is described in the methods section.

(23) $$d^2 = \frac{V_{ml}(\beta_1 Z_1 + \beta_2 Z_2 + \beta_3 Z_3 + \beta_4 Z_4 + \beta_5 Z_5)}{kH}$$

Where $Z_n = (n+1)\left(\frac{H-h}{h}\right)^n$

k = constant number $\frac{\pi}{40{,}000}$

$Vml$ = volume of a tree estimated by the volume model

other notations are as previously defined

## 2.9 Segmented taper models

Segmented taper models were first introduced by Max and Burkhart (1976). This type of taper model may provide a better description of the stem profile than that provided by single taper models, especially in the high-volume butt region (Cao *et al*. 1980). As previously described, it is generally assumes that a tree stem can be divided into three geometric shapes (form the top to bottom: a cone shape, a frustum of a paraboliod and a frustum of a neiloid). Segmented models describe these shapes by fitting each one with a different equation and then mathematically joining them to produce an overall segmented function (Diéguez-Aranda *et al*. 2006). Equation 24 was the classic segmented model proposed by Max and Burkhart (1976). It is one of the popular taper models of this kind.

(24) $$d^2 = D^2\left(\beta_1\left(\frac{h}{H} - 1\right) + \beta_2\left(\frac{h^2}{H^2} - 1\right) + \beta_3\left(a_1 - \frac{h}{H}\right)^2 I_1 + \beta_4\left(a_2 - \frac{h}{H}\right)^2 I_2\right)$$

$$I_1 = 1\ if\ \frac{h}{H} \leq a_1 \text{ and } I_1 = 0 \text{ otherwise}$$

$$I_2 = 1\ if\ \frac{h}{H} \leq a_2 \text{ and } I_2 = 0 \text{ otherwise}$$

While taper and volume equations are very common in developed countries, they are less common in developing countries. The study described here involved developing a volume and taper equations for a native species (*S. robusta)* that has high potential value in timber for commercial uses in Nepal. The Ormerod function was used due to following reason:

Write: why did we use Ormerod function for *S. robusta*?

1. Simplicity, easy to use for mid-level technician in the field
2. Parsimonious
3. It explained relatively the high proportion of the observed variability

## 2.10 *S. robusta*

### 2.10.1 General information

*S. robusta* is one of the major forest types in South Asia comprising the geographical range from southern slopes and lower foothills of the Himalayas to river plains, river slopes and valleys. It is situated in Nepal, Bangladesh, India, Bhutan and South China between $75^0$ and $95^0$ E longitude and $20^0$ to $32^0$ N latitude (Gautam, 1990; Fu, 1994; Zhao et al., 1994; Gautam, 2001; Gautam and Dove, 2006).

*S. robusta* forests in Nepal are broadly classified into two types; hill *S. robusta* forest and lower tropical or mixed broadleaved *S. robusta* forests (Stainton, 1972; Anon., 2002). The lower tropical *S. robusta* forests tend to dominate the entire vegetation cover over *Treminalia alata* Heyne ex Roth., *Terminalia bellerica* (Geartn.) Roxb., *Terminalia chebula* Retz., and *Syzygium cumini* L. Skeels (Anon., 2002). *S. robusta* trees in lower tropical forests can grow up to 40 m in height where as other emergent tree species normally reach upto 35 m (Gautam and Devoe, 2006). Most of the regeneration stock in *S. robusta*-dominated mixed forests normally originates from re-sprouting through root suckers (Suoheimo, 1999).

*S. robusta* has been described as ‘the most gregarious and aggressive’ tree species of the forest (Troup, 1921). It is a multipurpose tree species that can be extensively used for timber production due to high value of timber (Gautam and Devoe, 3006) as well as fuel and fodder. Therefore, it is considered as a particularly important and attractive tree species (Jackson, 1994).

In Nepal natural *S. robusta* forests have been highly acknowledged for their economic potential (Rautiainen and Suoheimo, 1997). More than 80% of the Terai rural population of Nepal depends on such forests to meet their subsistence needs (Sapkota, 2001).The economic potential of *S. robusta* play a vital role in GDP contribution of the country. However, there is a widespread belief that the management of forest in Nepal is not sustainable and there is a continuing loss of forest cover accounting approximately 1.3% per annum (Suoheimo, 1999) in Terai. However, in recent years, efforts have been made towards the application of an effective and sustainable forest management practice in Nepal through the mechanism of community forestry, collaborative forestry and leasehold forestry. Suoheimo (1999) indicated that *S. robusta* forests in Terai are not able to meet the increasing local pressure for fuel-wood and timber unless the remaining forests are managed in a sustainable way. Moreover, it has also been realised that there is a lack of appropriate technical information needed for sustainable forest management (Acharya, 2002; Shrestha, 2001)

### 2.10.2 Species characteristics and ecology

Of the 2 factors of habitat, climate and soil, the former decides the general distribution of *S. robusta*; among the climatic factors, rainfall is by far the most important. Annual precipitation normally comes with a dry season lasting 4-8 months (monsoon climate). At higher elevations, *S. robusta* can be damaged by frost.

*S. robusta* occurs in both deciduous dry and moist forests and in evergreen moist forest. Fire is normally responsible for its frequent occurrence in pure stands or as the dominant species of mixed stands, as *S. robusta* is better equipped to survive conflagrations than other tree species.

### 2.10. 3 Previous research

In Nepal, scientific study of *S. robusta* is rare and only undertaken in recent years. The Forest Resource Assessment Nepal Project under the Department of Forest Research and Survey has drafted a field manual for collecting stem and tree data for modeling biomass and volume components at the tree-level in 2011. A Forest Research Leaflet was published on Biomass and Volume Tables for Terai *S. robusta* Forest of Nepal under Department of Forest Research and Survey in 2003. The research was carried out in two sites. One was Butwal of Rupandehi district and the next was Dharan of Sunsari district. Volume Equation and Biomass Prediction of Forest Trees of Nepal was published in 1990 by Sharma and Pukkala. A compilation has also been done by Tamrakar, P. R. in 2000 on Biomass and volume tables with species description for community forest management under the financial support of the Natural Resource Management Sector Assistance Programme.

Moreover, the different research has conducted at individual level on the species. Some of them are listed here for instance modelling the growth of *S. robusta* using growth ring measurements by Sapkota and Meilby in 2009. Likewise research on simple coppice management options for the *S. robusta* Gaertn. f. forests in the Terai of Nepal was carried out by Ojha et al., in 2008. Similarly, a research on regeneration of *S. robusta* in tropical forest of Palpa district, Central Nepal was carried out by Devkota *et al*., 2011. A review on ecological and anthropogenic niches of *S. robusta* Gaertn. f. forest and prospects for multiple-product forest management was carried out by Gautam and Devoe in 2006.Moreover, a Ph. D. research was conducted by Sapkota, 2001 on Species diversity, regeneration and early growth of *S. robusta* forest in Nepal: Responsess to inherent disturbance regimes.

# CHAPTER THREE: STUDY AREA AND METHODOLOGY

## 3.1 Study area

### 3.1.1 Geographical

The data used in this study was taken from two research sites. Site 1 was at Lumbini Collaborative Forest of Saljhandi VDC, Rupandehi district and site 2 was government managed forest and Chandak Chatiya Mahila Community Forest of Bagnaha VDC, Bardia district which represent all management regime and geographical area of the *S. robusta* forest of Western Terai of Nepal.

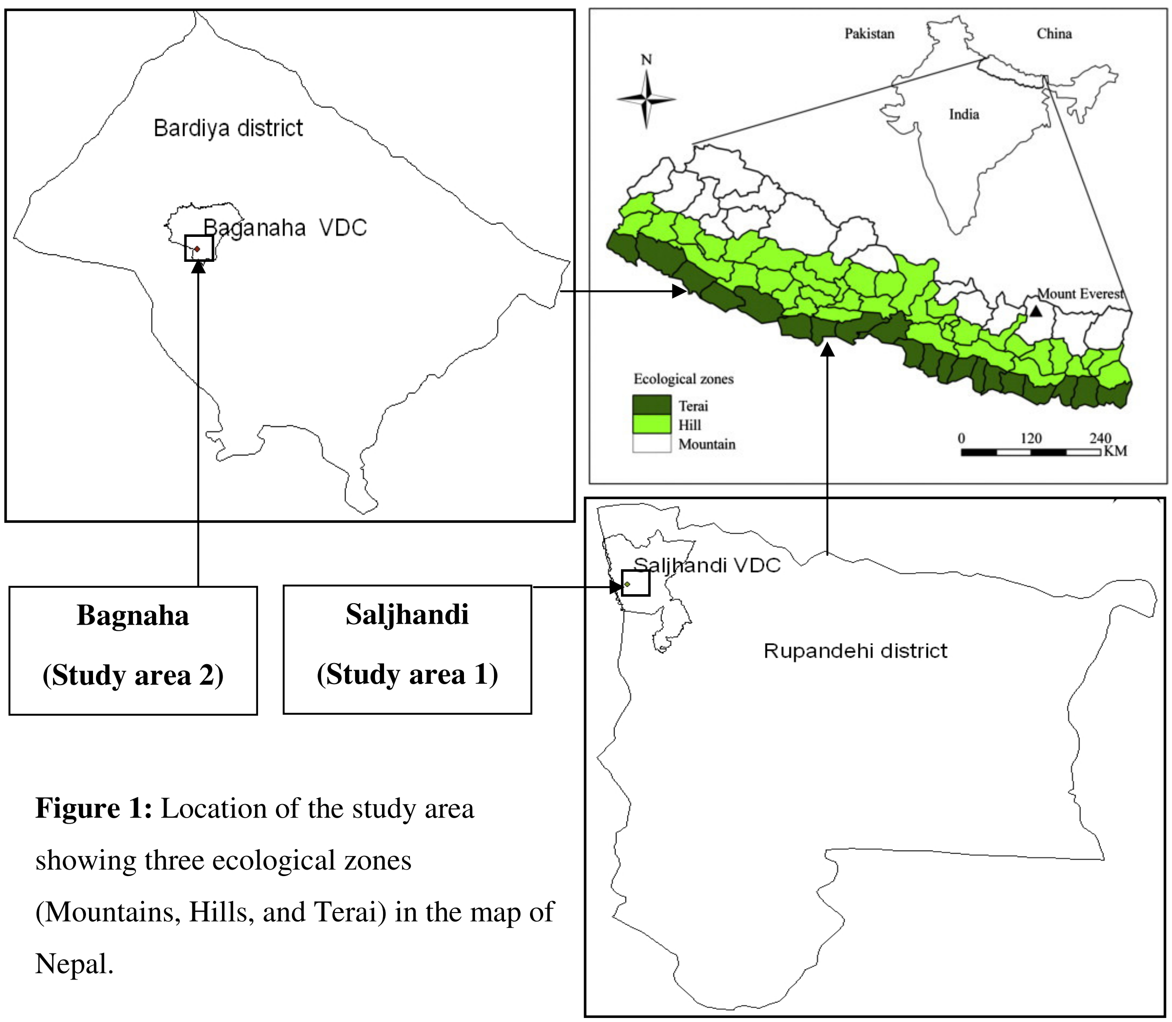


**Figure 1:** Location of the study area showing three ecological zones (Mountains, Hills, and Terai) in the map of Nepal.

### 3.1.2 Climate, soil and vegetation

**Saljhandi Site**

Climate: The climate is sub-tropical and sub-humid with regular monsoon between June-August. Frost occurs seldom and the annual average number of days with minus temperature is 0 (Jackson, 1994). Mean total annual precipitation is 2452 mm of which more than 80% falls from June to September. Monthly mean maximum and minimum temperature are 31.4°C and 17.7°C respectively with an absolute minimum of 4.3°C (Jackson 1994).

Soil: Saljhandi site is flat and fertile. The soil is loamy, deep, well drained and has adequate nutrient capability. According to the map of the Land Resource Mapping Project (LRMP), this area belongs to the class I, most suitable land for agriculture and forestry. Actual landuse for this area is shown as degraded tropical mixed hardwood forest. Soil physical and chemical properties are exceptionally good for forestry use (FRP 1989).

Vegetation: *S. robusta* forest diversity consists of more than 80 percent sal (*Shorea robusta*). Other associated tree species in this forest are bajhi (*Anogeissus latifolia),* asna *(Terminalia alata)*, amala *(Phyllanthus emblica),* barro *(Terminalia belerica),* bhalayo *(Semicar pus anacardium)* botdhairo *(Lagestroemia parviflora),* harro *(Terminalia chebula)*, jamun (*Syzygium cumini),* kalikath *(Myrsine semiserrata),* karma *(Adina cordifolia),* raj briksha *(Cassia fistula)* and sindure *(Mallotus philipinensis) (*Ojha *et al.,* 2008*).*

**Bagnaha Site**

**Climate**

Bagnaha site has a sub-tropical monsoon climate with three distinct season in the annual cycle: hot season (March-June), Monsoon (July-October) and winter (October-February). About 90% of the precipitation occur during the month of July, August and September. The absolute maximum temperature of $41^0$C and minimum temperature of $3.1^0$C were recorded in May 1996 and January 1987 respectively. The highest rainfall of 2798 mm and lowest rainfall of 1592 mm occurred in the year 1990 and 1992, respectively. Mean annual rainfall at Chisapani, at the foot of the Churias, is 2230mm and at Gularia, in an agricultural area to the south of the Study site, 1560mm.

**Vegetation**

More than 70% of the forest is covered by *S. robusta* (S. robusta) forest. Other associate species were classified according to following. A vegetation study conducted by Dinerstein (1979) classified six major vegetation types. This was later modified by Jnawali and Wegge (1993) to seven major vegetation types. These are:

1. *S. robusta* forest is dominated by *S. robusta* in association with *Terminalia tomentosa* and *Buchanania latifolia*.
2. Khair-Sissoo forest is composed of *Dalbergia sissoo* and *Acacia catechu* and restricted to major water courses and flood plain islands.
3. Moist riverine forest comprises *Syzigium cumini*, *Mallotus phillippensis, Bombax ceiba* together with shrub species like *C. macrophylla* and *M. koenigii*.
4. Mixed hardwood forest grows on well drained flat land, *Adina cordifolia, Casearia tomentosa, Mitragyna parviflora* are some species of this type of forest.
5. Wooded grassland forest is more or less Savana type in which the area is covered by grass with sparsely distributed trees. The common grasses are *Saccharum spontaneum, Imperata cylindrica, Erithrina ravennae,* with sparsely distributed tress of *Bombax ceiba, M. phillippencis, A. cordifolia.*
6. Phantas are the previously cultivated fields which in due course of time revegetated into open grasslands. *Imperata cylindrica, Saccharum spontanum* and *Narenga perphrocoma* are the dominating grass species of the phantas.
7. Flood plain grassland is the tall grasses of the flood plain along the Geruwa river. The dominating species of these grasslands are *Saccharum spontanum, S. bengalensis, Phragmatis karka a*nd *Arundo donax*.

## 3.2 Data collection

Sample data were collected from 33 trees in two different locations (Appendix 1) where destructive nature of the data collection technique was applied. Both sites were natural forests and were located 276 km apart from each other (see map 1). Fifteen trees were selected from Saljhandi (Site 1) and eighteen trees were form Baghnaha (Site 2). Tree was selected on the basis of (1) representative of DBH classes, varied size of crown diameter and open to close canopy density, stand and site conditions (2) tree without forks below mid-height (Martin, 1981) (3) avoided over lapped canopy, diseased and malformed tree.


**Figure 2**: Measuring stem profile data at field

Before the trees were felled down, DBH (1.3 m above ground level), and crown diameter of the sample trees were measured and also a photograph was taken. Then the trees were felled and measured other tree characteristics as per following.

### 3.2.1 Definitions of various terms

**Stem volume**

Volume of all living trees more than 10 cm diameter at breast height over bark measured from stump to top of bole (FAO 1998a).

**Taper** can be defined as the rate of decrease in diameter along the tree stem of a given form (Gray 1956).

**Model** is formal expression of relationship between defined entities in physical and mathematical term.

### 3.2.2 Crown

Crown diameter (CD) was measured on the basis of assumption that the horizontal projection of a tree crown is approximately circular (Strub et al., 1975). Crown diameter in four perpendicular directions, beginning with the widest diameter of the subject tree, was measured (Hamilton, 1969). Similarly crown base height and crown length also measured separately to calculate crown volume of the tree.

### 3.2.3 Measurement on the main stem

The height of the trees was measured from base to top and the stump height was added to get total height. Also the tree height from base to point on the bole was measured separately where the size of the bole was 10cm and 20cm diameter. Stem profi1e data (diameter outside bark and height above ground) was obtained at eight points on the bole: stump (30 cm above ground) and at approximately 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, and 7/8 of total height (Martin, 1981). The stem section of the tree (*i.e.,* total height minus stump height) was divided into maximum three meter length sub-sections and measured the diameter at three points (*i.e.* diameter at two ends and middle of the sub-section). The large branches were treated as poles and measured by using above process for volume estimation in the stem analysis.

## 3.3 Data analysis

Individual tree volumes were the sum of volume sections. The volume sections were calculated by using Newton's formula ($V = \frac{A_1+A_{1/2}+A_2}{6}L$). The horizontal projection area of crown was determined using the relationship: $S = \frac{\pi}{4}W^2$

Where, S= crown projection area ($m^2$), W= average CD (m) and $\pi$= constant.

The data of DBH, stem profile data, total height, stem volume and crown volume were analyzed by using RStudio software. The data of DBH, total height CD and site was subjected to previously developed models (Table 2). Different models used to fit the taper and volume models relationship given in Table 3.

## 3.4 Parameter estimation and model evaluation

The commonly used following two modeling approaches were utilized. Firstly; fitting the candidate models; secondly; evaluation of the fitted models. In the first step, candidate models were fitted by regression analysis.

**Table 2**: A list of candidate volume equations

| no. | Models | References | Type |
|---|---|---|---|
| 1 | $\ln(V) = b_0 + b\ D$ | Laar and Akca 2007 | single-entry |
| 2 | $\ln(V) = b_0 + b\ \ln(D)$ | | |
| 3 | $V = b_0 + b\ D^2$ | | |
| 4 | $V = b_0 + b\ D + b_2 D^2$ | | |
| 5 | $V = b_1D^2H$ | Clutter *et al*. (1983) | double-entry |
| 6 | $V = b_0 + b_1D^2H$ | | |
| 7 | $V = b_0 + b_1D^2 + b_2H + b_3D^2H$ | | |
| 8 | $V = b_1D^{b2}H^{b3}$ | | |
| 9 | $V = b_0 + b_1D^{b2}H^{b3}$ | | |
| 10 | $V = D^2/(b_0 + b_1H^{-1})$ | | |
| 11 | $V = b_0 + b_1D^2H + b_2D^3H$ | Bi and Hamilton (1998) | |
| 12 | $V = b_0 + b_1D^2H + b_2D^3H + b_3D$ | | |
| 13a | $V = b_0 + b_1D^2H + b_2D^2H^2$ | | |
| 13b | $V = b_1D^2H + b_2D^2H^2$ | | |
| 14 | $V = b_0 + b_1D^2H + b_2D^2H^2 + b_3H$ | | |
| 15 | $V = b_0 + b_1D^2H + b_2D^3H + b_3D^2H^2$ | | |
| 16 | $V = b_0 + b_1D^2H + b_2D^3H + b_3D^2H^2 + b_4D$ | | |
| 17 | $V = b_0 + b_1D^2H + b_2D^3H + b_3D^2H^2 + b_4H$ | | |
| 18 | $V = b_0 + b_1D^2H + b_2D^3H + b_3D^2H^2 + b_4D$ | | |

**Table 3**: A list of candidate taper equations

| no. | Models | References |
|---|---|---|
| 19 | $d^2 = D^2\left(\beta_1\left(\frac{h}{H}-1\right)+\beta_2\left(\frac{h^2}{H^2}-1\right)\right)$ | Kozak *et al.* (1969) |
| 20 | $d^2 = D^2\left(\frac{h}{h_D}\right)^{2-\beta_1}\left(\frac{H-h}{H-h_D}\right)$ | Sharma and Oderwald (2001) |
| 21 | $d = D\left(\frac{H-h}{H-h_D}\right)^{\beta_1}$, $\beta_1>0$ | Ormerod (1973) |
| 22 | $d = D\left(\beta_0+\beta_1\left(\frac{h}{H}\right)+\beta_2\left(\frac{h}{H}\right)^2+\ldots\beta_n\left(\frac{h}{H}\right)^n\right)$ | |
| 23 | $d^2 = \frac{V_{ml}(\beta_1 z_1+\beta_2 z_2+\beta_3 z_3+\beta_4 z_4+\beta_5 z_5)}{kH}$,<br>where $V_{ml}$ is volume estimated by volume model<br>*Note*: In this study, two functional forms of $V_{ml}$ were tested:<br>(i) **23a** with ***volume model 4*** and;<br>(ii) **23b** with ***volume model 13a***. | Goulding and Murray (1976), and Gordon (1983). |
| 24 | $d^2 = D^2\left(\beta_1\left(\frac{h}{H}-1\right)+\beta_2\left(\frac{h^2}{H^2}-1\right)+\beta_3\left(a_1-\frac{h}{H}\right)^2 I_1+\beta_4\left(a_2-\frac{h}{H}\right)^2 I_2\right)$<br>*where* $I_1 = 1$ if $\frac{h}{H}\le a_1$ and $I_1 = 0$ otherwise<br>$I_2 = 1$ if $\frac{h}{H}\le a_2$ and $I_2 = 0$ otherwise | Max and Burkhart (1976) |

The second step, i.e. evaluation of the fitted models was carried out using following criteria such as:

1. Adjusted coefficient of determination ($R^2_{adj}$): It shows a proportion of total variance explained by the model with the adjustment of the number of parameters, $p$ and the number of non-missing observations, $n$. It was estimated as: $R^2{}_{adj} = 1-(1-R^2)\frac{(n-1)}{(n-p)}$,
2. Significance of the parameter values: Parameter estimates should be significantly different from zero ($p<0.05$).
3. Homogeneity of the residuals: Plotting of the residuals from the model over predicted values or independent variables should show a random, constant variance pattern around a residual value of zero (Clutter et al. 1983).

4. Distribution of residuals, i.e. histograms of residuals were plotted to display the distribution (normal or abnormal) patterns of the residuals.
5. Root Mean Squared Error (RMSE): RMSE determines the accuracy of model predictions and it is considered one of the most important model evaluation criteria. RMSE was calculated using following formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n-p}}$$

   Where $Y_i$ and $\hat{Y}_i$ are the observed and predicted values respectively; $n$ is the total number of observations used to fit the model; and $p$ is the number of parameters.
6. Visual examination of the fitted curves overlaid on the scattered plots of the observed data. It is the most important part in modeling.

# CHAPTER FOUR: RESULT AND DISCUSSION

## 4.1 Descriptive statistics

Following table shows number, mean, minimum size and maximum size of height, diameter and crown volume for each study site including average annual rainfall in millimeter and temperature degree celsius.

**Table 4**: Showing a summary of the data.

| Site | No. of tree | DBH (cm) | | | Height (m) | | | Crown (m3) | | | Average annual rainfall (mm) | Average annual temperature (DC) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mean | min | max | mean | min | max | mean | min | max | | |
| Saljhandi, Rupandehi | 15 | 55.04 | 37.5 | 91 | 30.97 | 24.96 | 36.62 | 1046.12 | 225.59 | 2779.38 | 2196 | 24 |
| Basanta, Bardia | 18 | 38.69 | 5.2 | 92.57 | 21.07 | 4.45 | 34.25 | 392.63 | 0.90 | 1543.32 | 2230 | 19.5 |

Summary of the height and diameter is presented in following figure where x-axis stand for the diameter at breast height in centimeter and y-axis stand for tree height in meter.

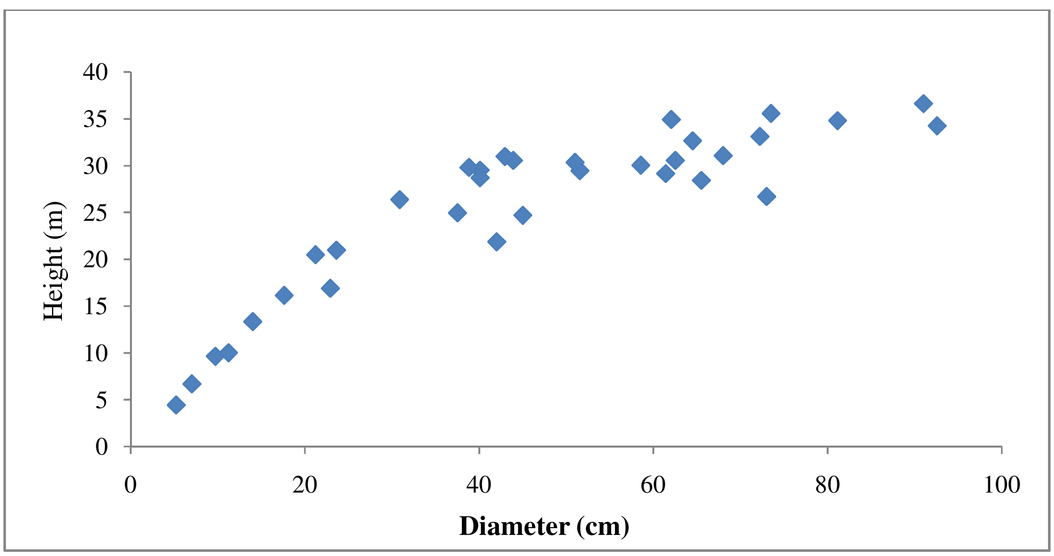


**Figure 3**: Plots of height against diameter at breast height

## 4.2 Candidate model tested for volume

Most equations were directly obtained from the available literature. Models taken from Sharma and Pukkala was modified specifically for the study and found as following:

$$\mathrm{Ln(V)} = \left(\mathrm{a} + \mathrm{a}_{\mathrm{i=BR,BT}}\right) + \mathrm{bLn(DBH)} + \varepsilon_{\mathrm{ij}}$$

Where,

| | | | |
|---|---|---|---|
| V | =Volume | $\varepsilon_i$ | =Residual error |
| DBH= | Diameter at breast ht. | BR | =Bardia |
| | | BT | =Rupandehi |
| | | a and b= | parameter |

### 4.2.1 Model selection process

Model selection is the task of selecting a statistical model from a set of candidate models, given data. In the simplest cases, a pre-existing set of data is considered. However, the task can also involve the design of experiments such that the data collected is well-suited to the problem of model selection. Given candidate models of similar predictive or explanatory power, the simplest model is most likely to be correct. This study included tests on various volume equations of four parameters limited to the functional forms *V = f* (*DBH, Height, CD, Site*). At the first step, CD was insignificant but site was significant at 90% confidence level where total height and DBH was significant at 99% and 99.9% confidence level respectively. Then further analysis was carried out dropping insignificant variable. At the second step, Site was significant at 95% confidence level and adjusted R-square value was 0.8784.

However, diagnostic plot for the general model shows that variances of residuals were not found equal i.e. hetero-scedastisity (Figure 4).

Then the further analysis was carried out taking log-log transformation and site was found significant at 99% confidence level but the total height was insignificant.

Further analysis after dropping the insignificant variable i.e. total height, DBH and site were found significant at 99.9%. The final model did not seriously violate the assumptions of the regression analysis (Figure 5).

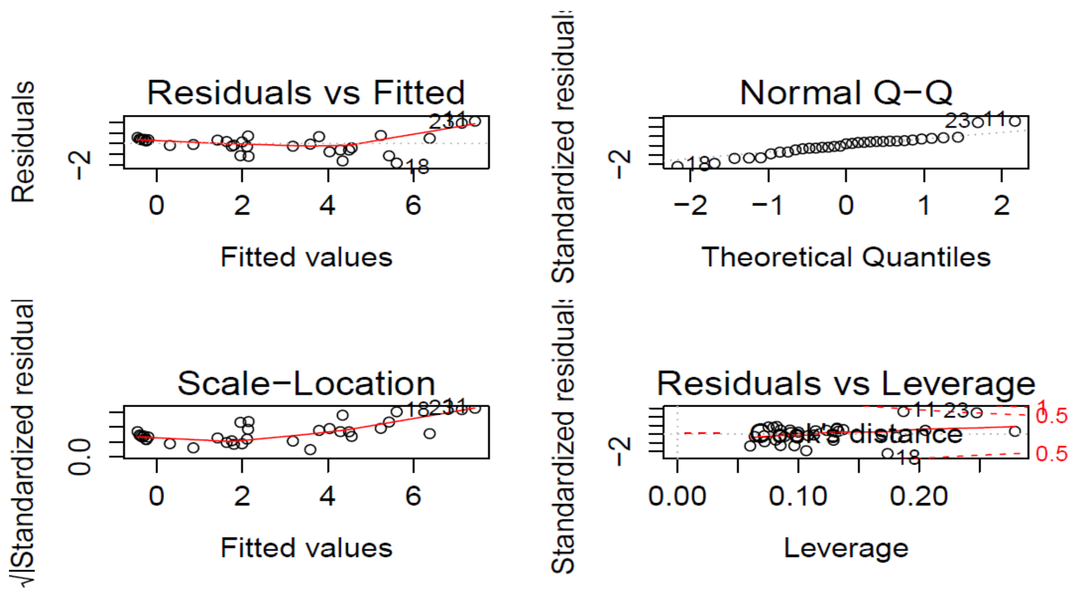


**Figure 4**: Diagnostic plots for the general model

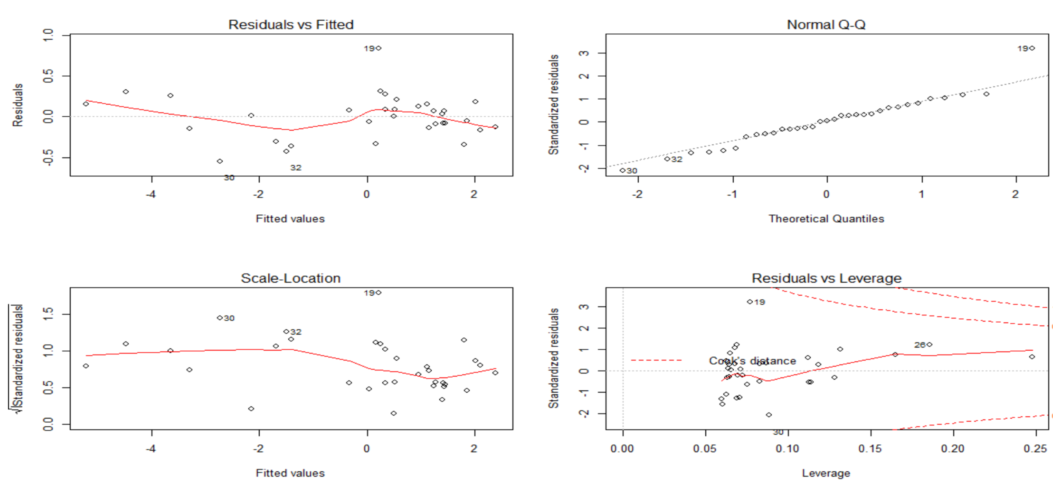


**Figure 5**: Diagnostic plots of final model

The final model was also used to predict the volumes of the different sized trees. These volumes were plotted against the corresponding tree DBH to check the biological realism of the model. Plot (Figure 6) shows that the model predicts the volumes of the different sized trees logically.

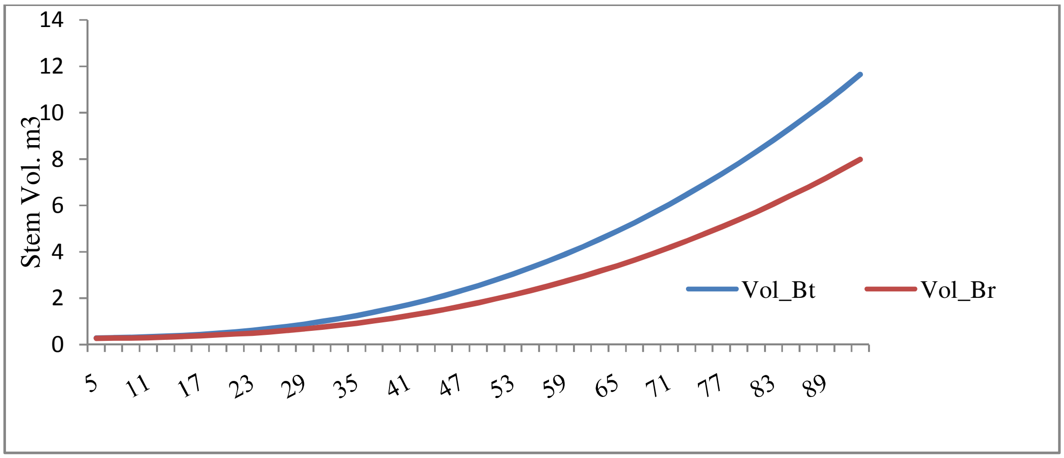


**Figure 6**: Prediction of stem volume

On the other hand, adequacy of the final model was also checked plotting observed volume versus the predicted volume (Figure 7). The plot shows that the model adequately explain the observed range of variability.

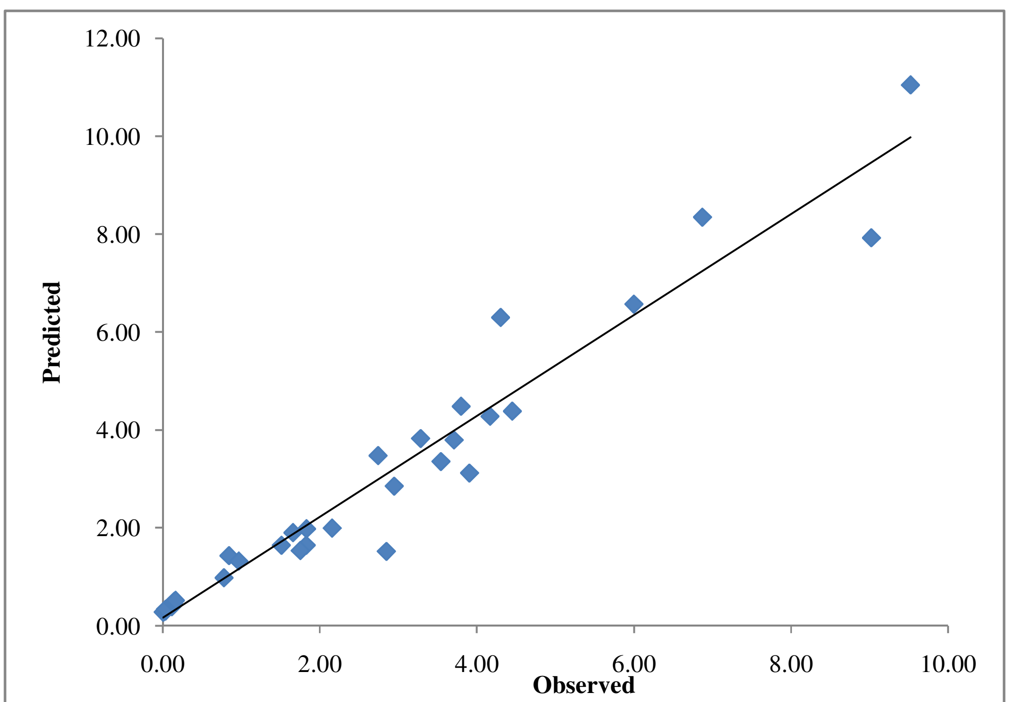


**Figure 7**: Comparison between the measured and predicted stem volume

## 4.3 Candidate model tested for stem taper

Ormerod function was calibrated to develop the taper equation for *S. robusta*:

$$D = \sqrt{\left[DBH^{b} * \left(\frac{TH-HAG}{TH-1.3}\right) \hat{} c\right]} + \varepsilon_{ij}$$

Where,

D =Diameter

TH =Total height of tree

HAG=Height above ground up to point of interest

b and c = parameter

Once the model was fitted, assumption of the regression analysis were checked. The plot for the standardized residuals versus the fitted values showed that the residuals were found to be distributed symmetrically along the zero line when the residuals were weighted by $1/D^2$ (Figure 8).

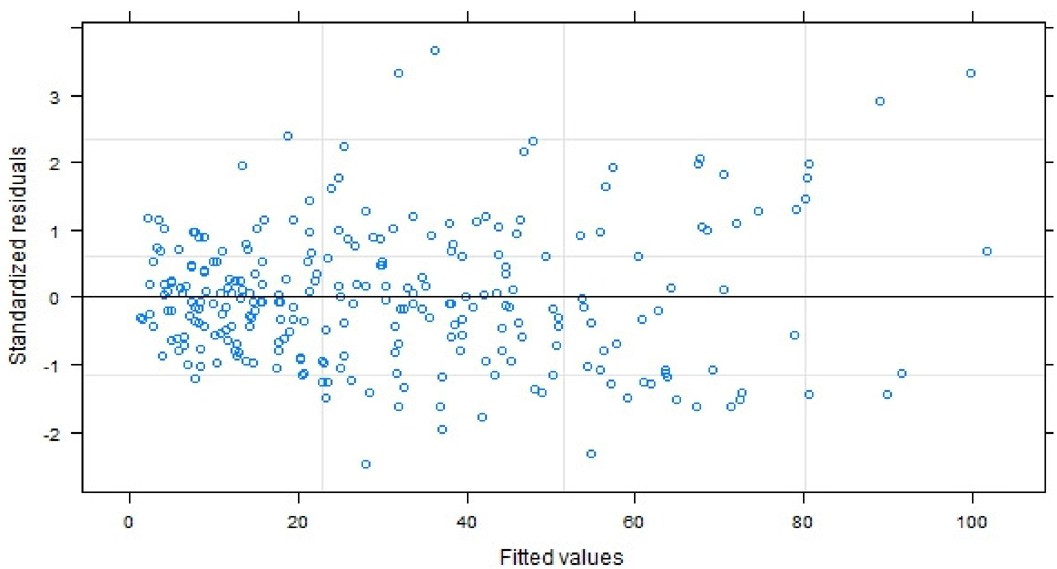


**Figure 8**: Distribution of residual for stem Taper

The distribution of the residuals were also found to be more or less normal (Figure 9).

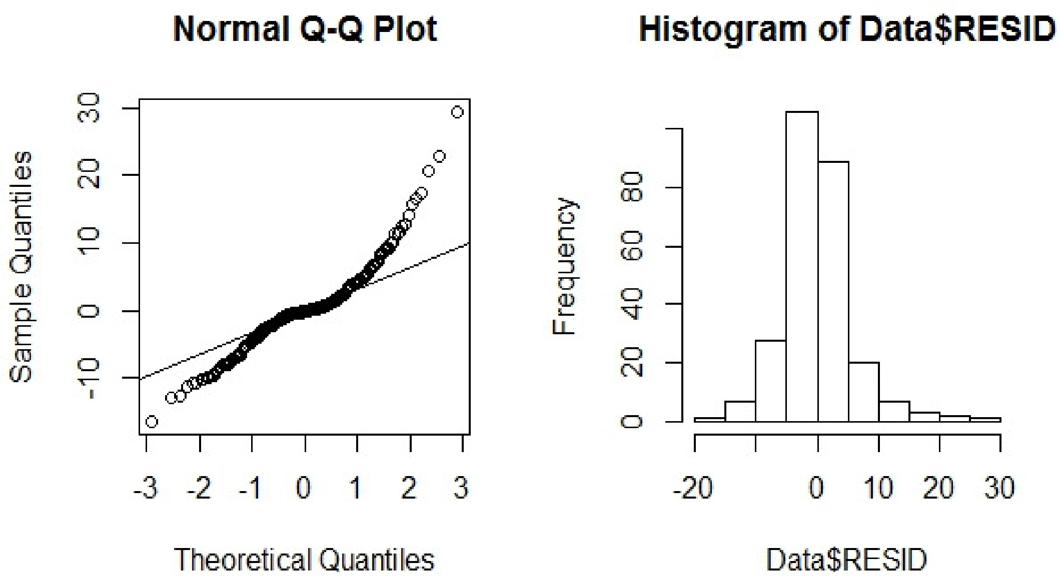


Figure 9: Normality of residuals

The predicted versus the observed diameter plot shows that the taper model adequately explain the observed variability (Figure 10).

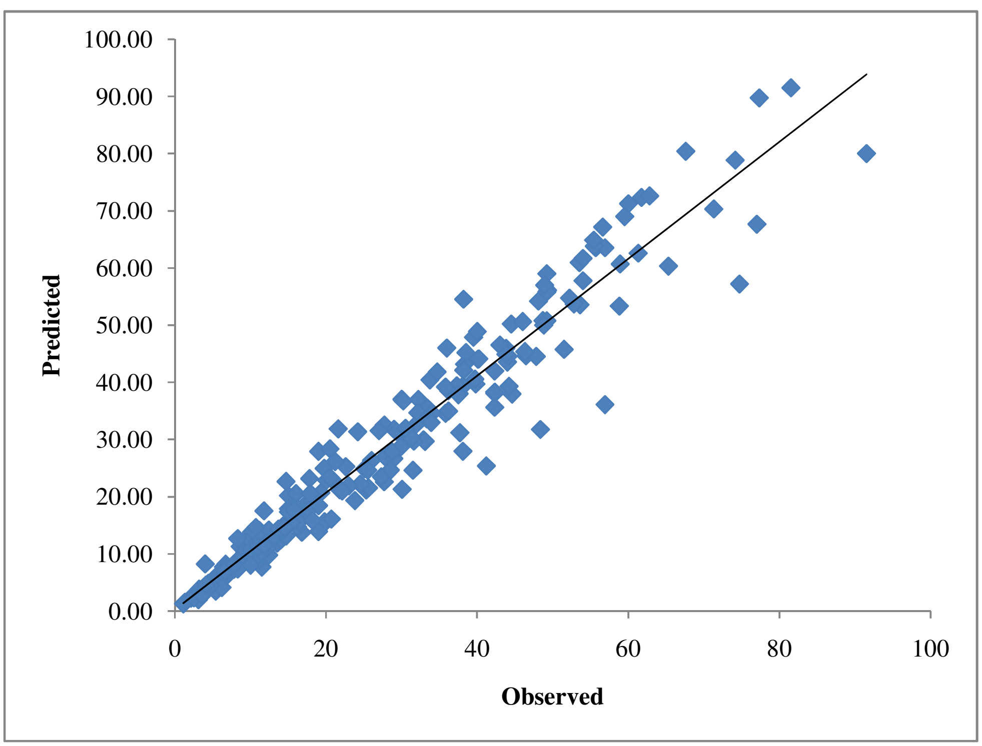


**Figure 10**: Comparison between the measured and predicted diameter at different heights along the stem

The final model was also used to predict the diameter of the different sized trees along the main stem. These diameter values were plotted against the height diameter measurement from the ground to check the biological realism of the model. Plot (Figure 11) shows that the model predicts the diameter of the different sized trees logically from tree base to tree top.

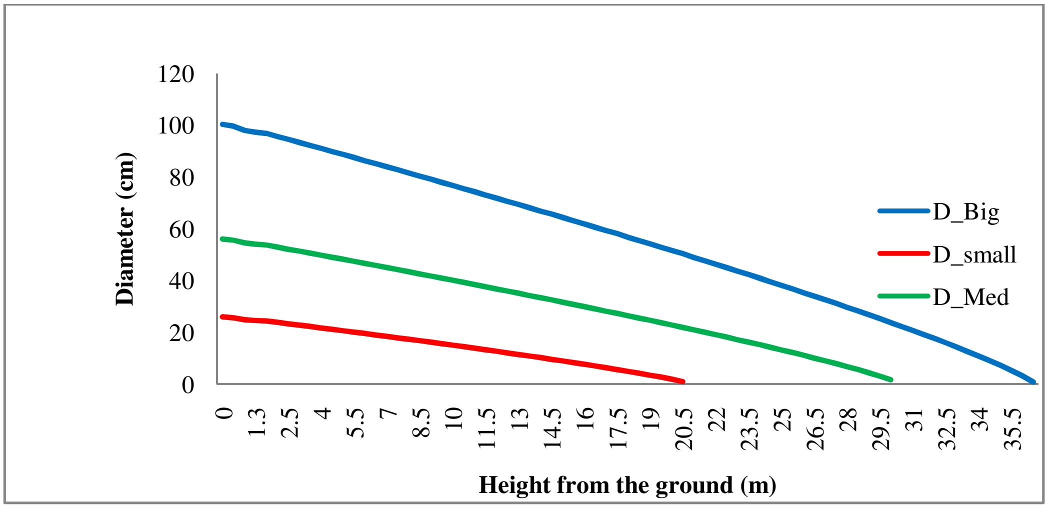


Figure 11: Prediction of stem taper

The model parameters of the stem volume and taper equations are presented in table (5). Adjusted R2 for the stem volume equation was found to be 0.94 and stem taper equation was also 0.94. The models parameters were found to be statistically significant ($p<0.01$). The RMSE values for stem volume equation and stem taper equation were 0.056 was 1.68 respectively.

Table 5: Model parameter estimates and fit statistics

| **Model** | **$R^2$ adj.** | **RMSE** | **Parameter** | **Parameter value** | **P** |
|---|---|---|---|---|---|
| Stem volume | 0.94 | 0.056 | a | -9.1664 | <0.01 |
| | | | b | 2.5163 | |
| Stem taper | 0.94 | 1.68 | b | 2.03 | < 0.01 |
| | | | c | 1.68 | |

# CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

It is concluded that the model for stem volume is $\mathrm{Ln(V)} = \left(-9.1664 + \mathrm{a_{i=BR,BT}}\right) + \mathrm{bLn(DBH)}$ was found site specific as well as simple to use compared to other existing counterparts. The model explained quite high proportion of the observed variability ($R^2$=0.94). Similarly, the model for stem tapper is( $\mathrm{D} = \sqrt{\left[\mathrm{DBH}^{2.03} * \left(\frac{\mathrm{TH-HAG}}{\mathrm{TH-1.3}}\right)^{1.68}\right]}$ ) found to be unbiased, parsimonious with the high predicting ability ($R^2$=0.94). It is easy to use for the mid-level technicians in the field level too. These models for *S. robusta* will help the manager, planners, users and decision makers for better management and utilization of *S. robusta* forest in a long run.

## 5.2 Recommendation

- The derived models are recommended to make taper and local volume table of *S. robusta* in Rupandehi and Bardiya District.
- These models can be applied to similar stand condition (basal area, canopy cover, stand age) from where the study data were obtained.
- The future study for the volume equation should be concentrated into larger areas and representative of small tree in the case of Rupandehi district.
- As this is the first model for *S. robusta* stem taper, it is recommended to test in other sites.
- Care must be provided when using these model in other sites and predicting beyond the observed range of tree size.

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# ANNEX

**Annex 1: Selection control matrix for collecting the analysis trees by diameter classes of *S. robusta* in the study site.**

| Frequencies by DBH classes, cm | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **<10.1** | **10.1–20.0** | **20.1–30.0** | **30.1–40.0** | **40.1–50.0** | **50.1–60.0** | **60.1–70.0** | **70.1–80.0** | **80.1–90.0** | **90.0 >** | **Total no.** |
| 3 | 3 | 3 | 3 | 6 | 3 | 6 | 3 | 1 | 2 | 33 |

## Annex 2: Data collection field formats

| **Field Format 1: Main Stem** | | | | | | |
|---|---|---|---|---|---|---|
| Tree no. | Dbh (cm) | Crown dia. (m) | | Stump height (cm) | Tree height without stump (m) | Total tree ht. (m) |
| | | Longest ($D_1$) | Shortest ($D_2$) | | | |
| 1 | | | | | | |
| 2 | | | | | | |
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| 31 | | | | | | |
| 32 | | | | | | |
| 33 | | | | | | |

| Field Format 2: Main Stem (Taper) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Tree no. | Diameter (cm) | | | | | | | |
| | Stump ht (30 | 1/8 of total | 1/4 of total | 3/8 of total | 1/2 of total | 5/8 of total | 3/4 of total | 7/8 of total |
| 1 | | | | | | | | |
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| 31 | | | | | | | | |
| 32 | | | | | | | | |
| 33 | | | | | | | | |

| Field Format 3: Main Stem (Segment) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Tree no. | Segment no. | Dia. of Segments (cm) | | | Length of segments | Sample Disc | |
| | | D1 | Dm | D2 | | Weight | Volume |
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | | | | | | | |
| 4 | | | | | | | |
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