Modelling aboveground biomass and nutrient export in South African *Pinus elliottii*

by

Phillip Muyambo

Thesis presented in fulfilment of the requirements for the degree of Master of Science in Forestry and Natural Resources Management in the Faculty of AgriSciences at Stellenbosch University

Supervisor: Dr David Drew
Co-supervisor: Dr Ben du Toit and Dr Stephen Dovey

March 2017

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2017

ABSTRACT

The objective of this study was to develop an allometric model for *Pinus elliottii* grown in the Tsitsikamma region of the Eastern Cape province in South Africa. 20 trees were destructively sampled were within a chronosequence of three ages in plantations with uniform attributes. In-field data were collected of DBH (diameter at breast height) and height (H). Samples of discs, branches and foliage were collected from the felled trees. Variables collected from the biomass samples were used for biomass and nutrient export modeling. Density of the wood discs and bark was determined by a water displacement technique. Stem biomass was reconstructed using Smalian's volume formula. To develop a set of linear models for biomass prediction, dry mass of the sampled biomass components was regressed against logarithmically transformed predictors that included DBH, H, and DBH^2H. Models were chosen based on goodness-of-fit assessment statistics and parsimony. A two-step process was used to upscale samples to tree level and from tree to stand level using the allometric models. For additivity purposes, logarithmic transformed (ln) DBH was used as a single predictor to determine the aboveground biomass (AGB) at stand level. The estimated AGB for the 16 (522 SPH), 28 (347 SPH) and 33 (380 SPH) years old *P. elliottii* trees were 99, 254 and 205 Mg ha^{-1} respectively. The BEF values of this study which were 0.81, 0.96 and 1.37 for Site 1, 2 and 3. Macro-nutrients export increased with stand age. The estimated N export due to harvesting stemwood and bark alone was 388.7 kg ha^{-1} in younger trees (16 years) and 720.7 kg ha^{-1} in older trees (28 and 33 years). A larger export of micro-nutrients such as Mn, Fe and Zn is potentially through harvesting of needles.

Keywords: *Pinus elliottii*, allometric model, models, DBH, H, AGB, nutrient, nutrient export.

OPSOMMING

Die doel van die studie was om ‘n allometriese model vir *Pinus elliottii* wat groei in die Tsitsikamma area van die Oos-Kaap provinsie in Suid Afrika, te ontwikkel. 20 bome wat destruktief getoets is, is gebruik binne ‘n krono-orde van drie ouderdoms groepe in plantasies met uniforme kenmerke. Veld data was versamel van DBH (diameter by bors hoogte) en hoogte (H). Monsters van stomp skuiwe, takke en blare was versamel van die gesaagde bome. Veranderlikes wat ingesamel is van die biomassa monsters was gebruik vir die biomassa en voedingstowwe uitvoer modelering. Die digtheid van die hout skuiwe en bas was bepaal deur water ‘n verplasing tegniek. Stam biomassa was geherkonstruktireer met behulp van Smalian’s se volume formule. Die droë massa van die biomassa monsters is met behulp van regressive gebruik om ‘n stel lineêre modelle te ontwikkel wat biomassa voorspel teen logaritmies getransformeer voorspellers wat DBH, H, en DBH2H ingesluit. Modelle is gekies deur middel van orde-van-pas analise statistieke en parsimonie. ‘n Twee-stap skaal proses was gebruik om monsters op te skaal tot boom grootte en van boom grootte tot vak grootte, met behulp van alometriese modelle. Logaritmiese (ln) veranderde DBH was gebruik as enkel voorspeller vir die op skalings proses om bo-grond biomassa van ha orde te voorspel. Die berame AGB vir die 16 (522 SPH), 28 (347 SPH) en 33 (380 SPH) jaar oue *Pinus elliottii* bome was 99, 254 en 205 Mg ha^{-1} onderskeidelik. Die BEF waardes vir die studie was 0.81, 0.96 en 1.37 vir ligging 1, 2 en 3. Makro-voedingstowwe uitvoer toegeneem met die stand ouderdom. Die geskatte N uitvoer as gevolg van die oes stemwood en bas alleen was 388,7 kg ha-1 in jonger bome (16 jaar) en 720,7 kg ha-1 in ouer bome (28 en 33 jaar). 'N Groter uitvoer van mikro-voedingstowwe soos Mn, Fe en Zn is potensieel deur die oes van.

Sleutelwoorde: *Pinus elliottii*, allometriese model, models, DBH, H, bogrondse biomassa, voedingstowwe, voedingstowwe uitvoer.

ACKNOWLEDGEMENTS

I would like to thank the following persons and organisations for making this study a reality:

- Dr. David Drew, Dr Ben du Toit and Dr Stephen Dovey for support and guidance during the project formulation, planning of field work and writing of my thesis.

- MTO for providing the needed assistance; inventory data and resources to complete my field work.

- Mr. Deon Malherbe, Mr. Mark February and 2014/15 3rd year Forestry students for assisting me with field and lab work.

- PMSA (Paper Making Association of South Africa for providing the necessary funding the entire project.

- Anonymous Postgraduate students in the Department of Forest and Wood Science for their support.

- Finally, to my Lord Jesus Christ for giving me the grace to undertake this study.

Dedication

I dedicate this piece of work to my loving parents: Chengeto and Guest.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AGB	Aboveground biomass
AIC	Akaike's Information Criteria
BA	Basal Area
BGB	Belowground Biomass
BEF	Biomass Expansion Factor
BGB	Belowground Biomass
C	Carbon
CBD	Convention on Biological Diversity
CL	Crown Length
CBH	Crown Base Height
CF	Biomass Correction factors
CO_2	Carbon dioxide
CV	Coefficient of Variance
DAFF	Department of Agriculture, Forestry and Fisheries
DBH	Diameter at Breast Height
DWAF	Department of Water Affairs and Forestry
FSA	Forestry South Africa
H	Height
IPCC	Intergovernmental Panel on Climate Change
ln	logarithmically transformed
Kg ha^{-1}	Kilogram per hectare
Kg m^{-3}	Kilogram per cubic meter
Kg	Kilogram
m^3	Cubic metre
MAP	Mean Annual Precipitation

MAT	Mean Annual Temperature
Mg ha^{-1}	Metric tonnes per hectare
QGIS	Quantum Geographical Information Services
RMSE	Root Mean Square Error
SE	Standard Error
SI	Site Index
SPH	Stems per hectare
t C ha^{-1}	Tonnes Carbon per hectare
UNCED	United Nations Convention on Environment and Development
UNFCCC	United Nations Framework Convention on Climate Change
VIF	Variance Inflation Factor

Chapter 1: Introduction

1.1 BACKGROUND

Commercially managed forest plantations are considered an opportunity for mitigating the effects of climate change by their potential to sequester atmospheric carbon dioxide (IPCC 2006). Carbon sequestration in plantation forestry is assessed by estimating the size of the carbon stocks and comparing changes in stocks over a given time frame (Picard et al. 2012). Carbon stocks are known to be site specific and are constituted of pools within each facet of the forest ecosystem. The carbon stock includes above-ground biomass (AGB), below-ground biomass (BGB), forest floor litter biomass, dead material biomass, soil carbon and harvested woody product pools (IPCC 2006). Apart from the soil and forest floor, the greatest potential for AGB and carbon storage in forest ecosystems is reported to be within tree biomass components such as stem, branches, and foliage (Peichl and Arain 2006; Pretzsch 2009; Zao et al. 2012). Carbon fluxes of each of the pools vary with climatic, edaphic, biotic and management influences (Bird et al. 2010). Biomass estimates are therefore needed to determine carbon sequestration, biomass growth and competition in forest ecosystems (Parresol 1999; Gonzalez-Benecke et al. 2014). Moreover, increased regional and global expectations in renewable energy, ecosystem services and the need for sustainable forestry practices has led to a rise in the demand of biomass estimation models. In most of the cases this is driven by environmental legislation change which provides a strong incentive for realistic carbon estimates.

Inventory based methods are often used for assessing forest carbon stock and changes (Correia et al. 2010). Biomass assessment is done by either directly employing allometric models that predict tree biomass components based on field measurements of individual trees or by applying multiplication factors that allow to convert or expand stem volume to the required tree biomass components (IPCC 2003). Remote sensing, and geographic information systems are also powerful interrelated technologies for biomass assessment (Parresol 1999; Kunneke et al. 2014).

Furthermore, measuring above-ground biomass is necessary as it is the first step in evaluating site nutrient demands and management practices for rapidly growing stands (Adegbidi et al. 2002; Sanchez et al. 2006; Gonzalez-Benecke et al. 2014). This is

because harvesting of biomass in commercial timber plantations is known to result in significant macro-nutrient content loss which ultimately affects nutrient reserves. It is therefore important to understand the status of biomass and nutrient stocks to secure a continued supply of tree biomass components (long-term productivity). The productivity and commercial importance of *P. elliottii* makes it a key component of the carbon balance in South Africa. It is noteworthy to mention that biomass estimation is key to the South African forestry industry. The contribution of the commercial forestry industry in South to the Gross Domestic Product (GDP) is estimated to be 1.27% (DAFF 2011). Planted forests constitute close to 1.27 million hectares of land and are across different site types. A significant amount of the planted forest area is under *Pinus elliottii*, a Pine sub-species (FSA 2011).

Thus, the goal of the study is to develop a species-specific model for AGB estimation of *P. elliottii* by testing a variety of model types. The study also aim to develop other biomass quantification methods such as expansion factors. The developed allometry model is useful in inventories especially in the carbon off-setting potential of forest plantations under similar environmental conditions. Furthermore, the study seeks to determine the exported macro and micro-nutrients of *P. elliottii* at stand level.

1.2 PROBLEM STATEMENT

While several biomass studies have been published in South Africa on species such *P. patula* and *P. radiata* (van Laar and van Lill 1978; van Laar 1982; Carlson and Allan 2001; van Zyl 2015). It is therefore important to note that *Pinus elliottii* lacks a biomass estimation model despite its commercial and ecological relevance to South African forestry industry. Species-specific models for estimating AGB lead to more accurate estimates than generalised functions which rely on diameter at breast height (DBH) (Gholz and Fisher 1982; van Lear et al. 1984) or DBH and Height (van Lear et al. 1986; Baldwin 1986).

1.3 RESEARCH OBJECTIVES

1.3.1 Main objective

The main objective of the study is to develop a model for the estimation of stand level AGB and nutrient export for *P. elliottii*.

1.3.2 Specific objectives

1. To develop and assess a range of models and coefficient sets for estimating stand-level AGB.
2. To estimate total AGB and formulate estimators such as biomass expansion factors (BEFs) for *P. elliottii* in South Africa.
3. Based on the best AGB model, to develop models which estimate potential nutrient export.

Chapter 2: Literature Review

2.1 DRIVE TOWARDS CARBON ESTIMATION

In the context of global climate change, the capacity of forest ecosystems to sequester carbon has attracted increasing attention (IPCC 2006). Like many other countries, South Africa resolved to voluntarily align and conform to the United Nations Framework Convention on Climate Change (UNFCCC) in 2002. In the succeeding years, it signed agreements with affiliated regulatory bodies which include; Reducing Emissions from Deforestation and Forest Degradation (REDD+) and the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2003; DEAT 2006; UNFCCC 2009). The objective of the bodies is to reduce greenhouse gas (GHG) emission, and spearhead climate change mitigation and adaptation strategies (UNFCCC 2011).

Quantifying biomass is needed for site productivity assessment, which entail stand, tree growth and yield studies (Madgwick and Satoo, 1975). Estimates of biomass components such as the crown, provide detailed understanding on the quantity of harvesting residues and fuel load which is essential for planning prescribed burning and accounting for biomass for bio-energy production (Gonzalez-Benecke et al. 2014). Estimates of biomass removals are also necessary as they reflect the effects of biomass removal on site productivity and nutrition depletion (Shan et al. 2001; Sanchez et al. 2006).

Of late, the forest industry in South Africa was subjected to tax implications because of its active role in sequestering atmospheric carbon dioxide (CO_2) and storage of carbon (C) in tree biomass, dead organic matter and soil carbon pools (West 2009; Zao et al. 2012). The carbon sequestration capacity of forests is strongly correlated to forest carbon stock, which is equal to forest biomass multiplied by carbon content factor (CCF) (Zao et al. 2012).

2.1.1 Key carbon pools and fluxes in forest ecosystems

Forestry ecosystems are known to be sanctuaries for carbon storage. They are constituted of several pools which include AGB, BGB, under-storey vegetation, dead organic matter, and the soil (Figure 2.1).

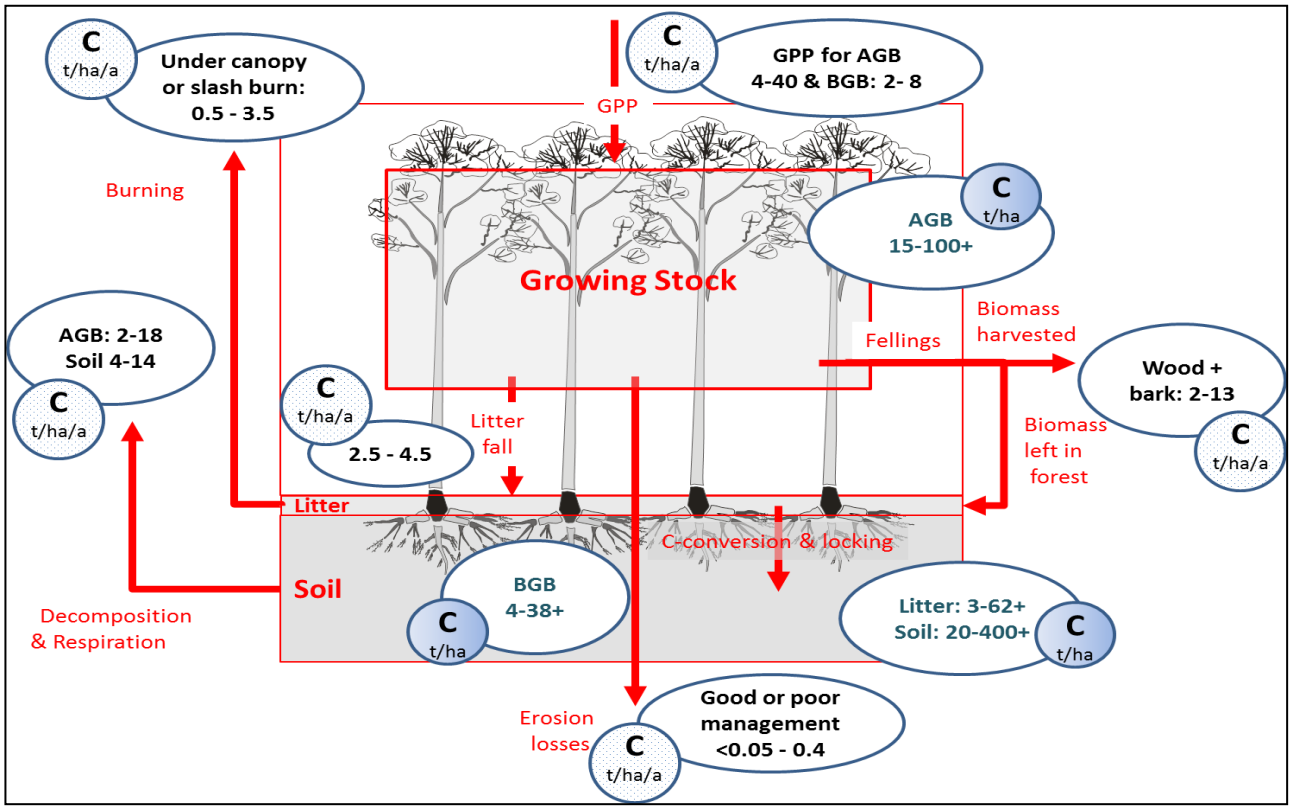

Figure 2.1: Major carbon and fluxes in forest ecosystems. The carbon pools are represented by filled circles (measurements in t C ha^{-1}) and the fluxes in dotted circles (measurements expressed in t C ha^{-1} annum^{-1}). The ranges given are typical ranges compiled from several sources found mostly in South African pine and eucalypt plantation forests (du Toit et al. 2016).

It is essential to measure and monitor the amount of C kept in AGB pools stock and its change over time (IPCC 2006). This is because emission and carbon capture that may result due to land use change, management, forest growth or site degradation can be examined (Gibbs et al. 2007). IPPC (2006) proposed a method to determine annual change in carbon stocks in forest plantations by summing changes in living biomass, dead organic matter and soil pools.

2.1.2 Carbon estimation

Carbon in the growing portion of a stand (living trees) is estimated using mathematical equations that convert tree or stand inventory data to biomass and to carbon. These are normally allometric equations that convert tree diameter and tree height to biomass, or biomass expansion factors that convert standing volume to biomass (IPCC 2006). Forest biomass estimation has become a central facet of measuring capacity of forest ecosystems to sequester carbon (Zao et al. 2012). Even though IPCC Tier 1 proposed

international level default values to estimate plantation C stocks at a country wide level (IPCC 2006), it is important to note that IPCC methods are viewed as generic, implying that they are not specific to local conditions. Moreover, they lack the desired precision for South African C accounting and taxation systems (du Toit et al. 2016). Progression towards higher resolution country-specific Tier 2 and regional specific Tier 3 estimates are encouraged for reporting and essential for taxation systems (IPCC 2006; Bird et al. 2010).

2.2 ESTIMATION METHODS FOR TREE BIOMASS

2.2.1 Measuring aboveground biomass

Allometry is the measure and study of growth or size of a part in relation to an entire organism (Parresol 1999). Estimates of AGB, for practical reasons, are frequently based on easily made measurements, such as tree diameter, and a suitable predictive equation. These functions reflect total AGB, or some component thereof (Nemeth 1973; Ritchie et al. 2013). As Parresol (1999) notes, biomass estimating models of a forest stand involve prediction of individual tree biomass and summation of the quantities to obtain per-hectare stand biomass.

It is important to note that there are various methods for assessing AGB (Parresol 1999; van Laar and Akça 2007; Samalca 2007; Picard et al. 2012; Seifert and Seifert 2014). These methods include; field measurements, remote-sensing, and inventory assessments. Though remote sensing is expensive, some studies have reported that it generally produces more accurate estimates than other conventional options (Samalca 2007; Picard et al. 2012). Principally, this study focused on *in situ* sampling, which is a destructive and direct biomass measurement technique (van Laar and Akça 2007; Picard et al. 2012; Seifert and Seifert 2014; Magalhães 2016). The method is described in the sections that follow and in Chapter 3.

2.2.2 Plot area-basis biomass estimation

In situ biomass sampling method is divided into; bulk sampling and biomass component sampling (with regression) (Seifert and Seifert 2014). As noted by Seifert and Seifert (2014), the bulk sampling method is more commercially practical than *in situ* sampling as it is determined based on in-field chipping. The method is often useful when determining biomass value per area of invasive woody vegetation (Seifert and Seifert 2014; Magalhães 2016). Biomass component sampling involves harvesting trees or tree components on an

individual tree or on a plot area, measuring key metrics, drying the material, and then (fresh and dry) weighing the biomass components (Gibbs et al. 2007; Seifert and Seifert 2014).

2.2.3 Single tree-basis biomass estimation

When developing biomass models; the *in situ* destructive biomass determination method is recommended (Parresol 2001; Husch et al. 2003). This is because the method precisely caters for tree-specific biomass measurements at an extensive scale (GTOS 2009). However, the non-destructive biomass measurement does not need felling of tree; hence, it employs developed biomass models and biomass expansion factors (BEF) to infer biomass to unit areas (Pearson et al. 2007). Amongst, the two measurement methods, the regression models generate more accurate biomass predictions (IPCC 2003). Usually, regression models are site specific and they mimic the distribution of trees of a site especially if they are derived from a large enough and representative number of trees (Husch et al. 2003).

2.3 SAMPLING AND UPSCALING OF BIOMASS

The first sampling phase involve selection of trees normally in randomly located circular plots. There are several ways to randomly select these plots. The Hawth's Tools in ArcGIS software has been employed in some studies to select plots (Magalhães and Seifert 2015). After the plots are marked, a sub-set of trees for destructive measurement of biomass is selected from the pre-sampling enumeration data trees (first sampling phase) representing a stratified DBH range for each plot. Individual trees are felled and often divided into stemwood and crown (branches and needles) biomass components. Tree components are then sampled and the dry weights estimated. Section 2.4 highlights the procedure followed in measuring biomass components.

2.4 MEASURING BIOMASS COMPONENTS

The AGB of trees is usually divided into three main components, namely: stemwood, stem bark and the crown (Parresol 1999). The crown component is often separated into two components, which are: branches and needles (van Laar and Akça 2007; Seifert and Seifert 2014).

2.4.1 Branches

A sampling with regression procedure proposed by Seifert and Seifert (2014) is commonly used to sample branches. Regression models are developed to estimate biomass based on the sampled branches in the second phase to increase the size of the sample (Saint-André et al. 2004). Since 75% of the destructively sampled trees in this study were mature trees, the sampling procedure recommended by Seifert and Seifert (2014) was used for sampling the branches of all the trees. However, in the case of younger trees, the entire branches can be weighed in-field because of the relatively small size of the trees. The predictor variables for regression models typically include; branch diameter, branch length and basal area (van Laar and Akça 1997; Seifert and Seifert 2014). Although compound variables may improve models, it is important to note that metrics of these variables are cumbersome to collect hence sometimes a single variable is used.

2.4.2 Needle

Like the branch biomass components, needles are separated from the branches and oven-dried until a constant mass is achieved (Litton 2003; van Laar and Akça 2007). The process of removing needles from branches of mature trees is time consuming and labour intensive. Thus, needle biomass samples are regressed with the branch diameter or basal area as proposed by Parresol (1999) and Saint-André et al. (2004) to determine needle biomass of the entire tree. In this study, a sampling with regression approach was also employed for the needle biomass.

2.4.3 Stemwood

Stemwood biomass measurement is normally done in two phases: volume measurement and density determination. The derived basic density is multiplied with the sectional volume to determine the biomass of the stem section. Sectional volume of stems is often determined by using the CT-scanner or a water displacement method. The weight of the water replaced after full immersion, denotes the volume of the sample in cm^3 (American Society for Testing and Materials 2008). The two density methods are not feasible for the entire merchantable stem since they are associated with a high capital cost. Thus, wood discs or stem portions are used (van Laar and Akça 2007; Picard et al. 2012).

For practical purposes, stem volume equations are commonly and widely applied to estimate the total and merchantable volume of stems from limited diameter measurements

along the stem (van Laar and Akça 2007). These equations are practicable for the calculation of frustums of different forms. Smalian and Hubert's formula can be applied when the frustums are that of a paraboloid while Newton's formula can be applied to all the frustums. The geometric formula is often used to calculate the volume of the truncated cone (Seifert and Seifert 2014). Volume formulas generally used to calculate the volume of stem sections are shown below (van Laar and Akça 2007; Seifert and Seifert 2014).

Smalian's formula: $V = \frac{g_u + g_l}{8} \cdot l$ (2.1)

Huber's formula: $V = g_m l$ (2.2)

Newton's volume formula: $V = \frac{g_u + 4g_m + g_l}{6} \cdot l$ (2.3)

Geometric formula: $V = \frac{\pi l}{3} (R^2 + Rr + r^2)$ (2.4)

Where:

g_m = cross sectional area at the midpoint of the stem section (cm^2)

g_u = cross sectional area at the upper end (cm^2)

g_l = cross sectional area at the lower end (cm^2)

l = length of stem sections (m)

R = diameter at thick end of log (cm)

r = diameter at thin end of log (cm)

V = volume (m^3)

2.4.4 Variability in density

Stem volume and basic density calculation are central for the successful determination of stem biomass. Plantation trees are known to differ considerably in wood density within the stem in radial and longitudinal direction and between trees and sites (Seifert and Seifert 2014). Therefore, information on density gradients is fundamental in determining biomass of most softwood trees. As noted by Seifert and Seifert (2014), employing literature derived density values is a crude method which does not factor in density variability and generates biased biomass predictions. Upscaling from sample disc entails a measurement component where basic density is determined at disc level. This is followed by a modelling

exercise which is typically based on the estimation of fresh weight to dry weight ratios or a regression approach to obtain information for the entire stem (Seifert and Seifert 2014).

2.4.5 Bark

Like stemwood biomass determination (Section 2.4.3), the collected stem discs are also considered for the bark density determination. Bark volume is measured by subtracting volume under bark from volume over bark. Alternatively, bark is removed from each disc to measure its weight (Saint-André et al. 2004). Functions for bark-thickness, such as those developed by Deetlefs (1957), can also be used to calculate the bark volume which is later multiplied by a single oven-dry to green-weight ratio. However, this technique will only be useful if estimation errors related with bark thickness model are negligible (van Laar and Akça 2007).

2.5 STATISTICAL PROCEDURE

2.5.1 Biomass modelling

Biomass modelling is an upscaling process which is based on statistical procedures which entail use of regression models (Seifert and Seifert 2014).

2.5.2 DBH-Height models

Stem diameter at breast height (DBH) and tree height (H) are commonly used measures of tree growth. Several models forms which include the inverse DBH and ln-transformation DBH are used to explain the height to DBH relationship. These include: compound variables, linear and polynomial functions (Chave et al. 2005; Feldpausch et al. 2011; Sileshi 2014). In other studies, site factors such as MAT, MAP, BA, SPH, age and DBH have also been considered (Bollandsås 2007; van Laar and Akça, 2007; Feldpausch et al. 2011; van Wyk et al. 2013).

2.5.3 Models for biomass components

Regression analysis is a common method for predicting biomass in forest stands. Standard least squares techniques are commonly used in fitting regression lines with different parameters (Parresol 1999; Picard et al. 2012). These models are frequently logarithmically (ln) transformed linear models (Seifert and Seifert 2014). Non-linear correlations of predictors are often logarithmically transformed to attain the linearity while

satisfying the assumptions of homoscedasticity. Linear regression models forms used to estimate biomass include: simple linear and multiple linear and multiple linear.

Simple linear regression (Picard et al. 2012): $Y = \beta_0 + \beta_1 X + \in$ (2.5)

ln-transformed (Picard et al. 2012): $\ln(Y) = \beta_0 + \beta_1 \ln(X) + \in$ (2.6)

Multiple linear regression (Parresol 1999): $Y = \beta_0 X_1 \beta_1 X_2 \beta_2 \ldots X_j \beta_j + \in$ (2.7)

Multiple linear (ln) (Parresol 1999): $\ln(Y) = ln\beta_0 + \beta_1 \ln(X_1) + \cdots + \beta_j \ln(X_j) + \in$ (2.8)

Where:

Y = Tree component mass (kg)

X = Tree dimensional variables

β_j = Model parameter

β_o = Intercept value

β_1 = Slope value

2.5.4 Biomass Expansion Factors

Biomass expansion factors (BEFs) are calculated as the ratio between the mass of the whole tree and stem volume. BEFs are usually applied at the stand level and allometric functions at the tree level. This is because they are default ratios which are applied on inventory data (volume of stand). BEFs are frequently applied for upscaling biomass. National and regional AGB estimates are often calculated based on BEFs (Schroeder et al. 1997). Local commercial forest biomass can be estimated from BEFs by applying them to forest inventory data (Brown 2002; West 2009). AGB estimates are often derived from calculated stem volume from forest inventories and default BEFs (Brown 2002). However, variations in tree age, size and site conditions may result in unreliable BEFs estimates (Brown et al. 1989; Sanquetta et al. 2011). In contrast to these findings, a biomass modelling study on *Androstachys johnsonii* Prain (Mecrusse Woodlands) in Mozambique showed that the BEFs were weakly related to tree size (Magalhães and Seifert 2015). Other studies have also reported that BEF vary with tree size (Brown et al. 1989; Sanquetta et al. 2011). This study did not attempt to test the independence or weak dependence of BEF values on tree size.

2.6 ADDITIVITY

Additivity is a sought attribute of biomass models (Picard et al. 2012). When all model formulas of biomass components are equivalent to the estimation of the total biomass with one additivity is achieved. Ecosystem productivity, energy and nutrient flow studies often categorise biomass into components thus additivity is essential (Cunia and Briggs 1985). Often different methods to achieve additivity are compared in many studies (Phiri 2015; Magalhães 2016). The additivity process entails use of several linear and nonlinear regression model forms where they are tested for each tree component and for the total tree using weighted least squares (Parresol 1999; Parresol 2001; Saint André et al. 2004; Picard et al. 2012). These weight functions are determined by iteratively finding the optimal parameters that homogenises the residuals, and enhances other fit statistics (Picard et al. 2012). In Magalhães (2016) study, the following independent variables were tested in a multivariate regression; $1/DBH$, $1/DBH^2$, $1/DBH \cdot H$, $1/DBH \cdot LCL$, $1/DBH^2 \cdot H$ and $1/DBH^2 \cdot LCL$, the best (approximation) weight function was found to be $1/D^2H$, for all tree component equations (linear or nonlinear).

Methods such as the SUR which join all components and the total tree biomass model by considering contemporaneous correlations and introducing restrictions on a set of regression equations have been used in the study of AGB and BGB (Saint André et al. 2004; Goicoa et al., 2011). However, it is worth noting that they use non-linear models which are associated with multiplicative errors especially when logarithmic transformed. The main methods of enforcing additivity are: Conventional (CON), Seemingly Unrelated Regression (SUR) with parameter restriction, Isometric Log Ratio (ILR), Composition models and Nonlinear Seemingly Unrelated Regression (NSUR) with parameter restriction (Parresol 1999; Parresol 2001; Seifert and Seifert, 2014). The CON method which was employed in this study consists of using uniform independent variables for all tree component models and the total tree model thereby achieving additivity automatically (Parresol 1999; Goicoa et al. 2011). The most widely used simple linear model form (Equation 2.5) is often used for the tree biomass components and for total AGB. Linear models are preferred over nonlinear models because the conventional method of enforcing additivity is only valid for linear models (Parresol 1999; Goicoa et al. 2011).

2.7 ERROR PROPAGATION

To make correct inferences about long term dynamics in biomass stocks, it is important to understand the uncertainties (errors) associated with the biomass estimation (Samalca 2007). Biomass stock is often assessed by combining the estimates of the first and second phases. Thus, the calculation of the error propagation forms an essential part of estimation. Two main sources of error are accounted for in this calculation. These are; error resulting from plot-level variability (first sampling phase) and error which emanate from the choice of biomass regression equations (second phase).

As reported by Seifert and Seifert (2014), errors in the first phase are largely affected by the sampling design, sample size, type of estimator used and the inherent variation between the sampled trees. Errors due to sampling in the second phase involve regressions. The magnitude of second phase error is mainly affected by the sampling design, the sample size, the estimation procedure and the variation of the biomass value of the regression function (Samalca 2007). Cunia (1986) demonstrated that linear models are preferred because the procedure of combining the error of the first and second sampling phases is limited to biomass regressions estimated by linear weighted least squares. Efforts to reduce first phase errors (inventory) have been made by using random sampling but this does not guarantee unbiased estimates (van Laar and Akça, 1997).

The combination of the two errors in the two phases generates a value for the total error propagated. Samalca (2007) based on the works of Cunia (1986), proposed a method for determining the error propagated (Equation 2.9).

$$S^2 = S^2_{(x)} + S^2_{(y)} \qquad (2.9)$$

Where:

S^2 = total variance

$S^2_{(X)}$ = variance associated with sampling

$S^2_{(y)}$ = variance associated with regression

2.8 GOODNESS OF FIT FOR REGRESSION MODELS

Statistical regression procedures are used to formulate models for scaling dimensional variables of standing trees to biomass (Parresol 1999; Picard et al. 2012). Several

measures for goodness of fit and comparing alternatives between different models (least squares regressions) have been recommended by Parresol (1999).

Akaike's Information Criterion (AIC) is a common measure for comparing models and is used in selecting the best fitted model. The smaller AIC value indicates a better fit for the model. Several biomass studies have used AIC as criterion because it considers the number of parameters in the model when comparing different models and thus ensures parsimony in model selection (Parresol 1999; Ott et al. 2001). The AIC, the residual sum of squares, number of samples and terms used in each regression, thus penalises inclusion of additional parameters into each model (Anderson et al. 1994). In Payne (2015) study, the Wald's test was used to test the effect of dropping terms.

Some of these methods are: Adjusted coefficient of determination (R^2), error of estimates (se), Coefficient of variation (CV) and relative standard error S (%). The se uses the actual units of measurements. Saint-André et al. (2004) and FAO (2012) highlighted that when the value for se is small compared to the value from other models, it means the model has a good fit.

Cook's test statistic, which join the leverage and residual for each data point in the regression is widely employed to detect possible outliers (Cook 1979). In this study, outliers that had a strong influence on the regression outcome was traced back through each raw data-set to ascertain for data capturing or calculation errors before segregation from the analysis. For visual assessment: residual scatter, leverage and Cook's statistics plotted against fitted values are used to ascertain normality and heterogeneity (Payne 2015). The 95% Confidence limits of coefficients and intercepts were estimated using the product of the standard error, t-test statistic and coefficient estimates for regression equations as reported by Payne (2015).

Variance inflation factor (VIF) is another measure of assessing the goodness of fit of a model. VIF also known as tolerance. Studies have proposed different VIF values as the maximum. For instance, a maximum VIF value of 10 was recommended by Neter et al. (1989). Others scholars have recommended a maximum VIF value of 5 and even 4 (Allison 2012). Therefore, it would appear, that most studies can use whichever VIF bound they wish to help enhance substantial and important or new information about the predicting variables.

2.9 TRANSFORMATION BIAS CORRECTION

Extensive literature has been published on how to comply with various model assumptions, especially when data transformations are involved prior to the fitting procedure (Seifert and Seifert 2014). To minimise heteroscedasticity, dimensions of organisms inherently require logarithm transformation prior to the testing of hypothesis on regression analysis (Baldwin 1986). Logarithmic transformed DBH is usually selected for statistical procedures such as upscaling branch and needle biomass. Schroeder et al. (1997) found nonlinear models to perform better than the linear ones. However, values from the logarithm regression results in biased estimates (Phiri 2015). Because of this biasness, a formula (Equation 3.6) shown in detail in Chapter 3, Section 3.7.2.1 was developed by Baskerville (1972) for the corrections of error in biomass inventories.

2.10 NUTRIENT EXPORT

The demand for biological resources such as forest products, including saw timber, pulpwood and wood chips continue to rise especially with the ever-increasing demand of South African forest products in Asian markets. The drive towards renewable energy such as bio-energy also continue to put pressure on plantation forest resource base in South Africa. This has led to more forest resources being harvested from industrial plantations which already face numerous environmental and socio-political influences (Dovey 2009). The operational consequences is often pressure on production, hence frequently forestry practices may be altered to suit the ever-rising market demands. This has prompted prompt research initiatives that assess the impact of biomass removal (harvesting) on site nutrient reserves (Dovey 2009) which by far has the greatest impact on nutrient fluxes and reserves in South African plantation forestry (Binkley 1986, du Toit and Scholes, 2002). When additional biomass components are harvested (foliage and bark) with together with primary biomass (stemwood) nutrient pools are at risk because of accentuated nutrient export.

2.11 FACTORS INFLUENCING NUTRIENT RESERVES AND EXPORT

Several other factors influence nutrient reserves and export. These include: tree species, site, age, biomass component harvested, harvesting method, rotation length, climate, soil, atmospheric deposition, and mineral weathering (Binkley 1986; du Toit and Scholes 2002; Saint Andre et al. 2006; Dovey 2009). In addition, when productivity increases because of

site management practices, the rotation length for plantations is lowered leading to increased nutrient export through improved quantity and frequency of AGB extraction (Binkley 1986; Dovey 2009). In Binkley (1986) view, the economic imperative leading to reducing rotations further exacerbates site quality due to nutrient export. However, rapid export of vital nutrients may not be detected on sites with well-buffered soils and massive nutrient capital, but may speedily diminish unproductive sites. Zululand coastal plain of South Africa with minimum clay and organic carbon content, have a narrow nutrient-holding capacity and hence have low nutrient reserves (du Toit and Dovey 2002; Dovey 2009). Soils of similar quality are in the Tsitsikama region where biomass samples of this study were collected have shown to have the same high risk of nutrient depletion under poor management.

2.12 FOREST BIOGEOCHEMICAL CYCLE

Nutrients are found in forest ecosystems in several pools which include the above and below-ground biomass, the forest floor and in the soil. The biogeochemical cycling of nutrients is fundamentally fluxes of nutrients from plant forms in the soil into the biomass (stand uptake), and eventually back to the forest floor as litterfall and harvesting residue where nutrient-rich material undergoes decomposition and return to the soil as nutrient-containing organic or mineral compounds. Fine root turnover plays a major role in contributing to fluxes via living biomass to soils.

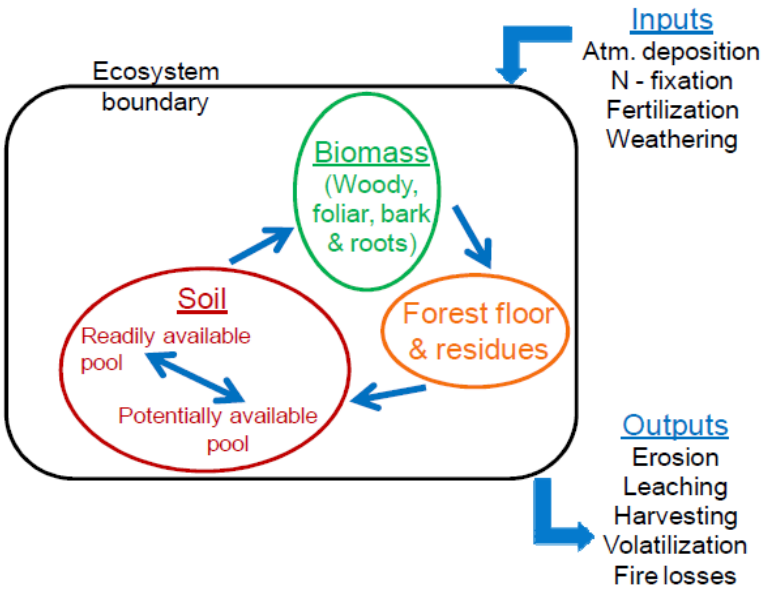

Figure 2.2: Schematic representation of the forest biogeochemical cycle (nutrient pools and fluxes within a forest ecosystem) (Ackerman et al. 2013).

From the illustration in Figure 2.2, nutrients can be added to the forest ecosystem, primarily by weathering, atmospheric deposition, fertilisation and nitrogen fixation. Nutrients can be removed from ecosystems, mainly through leaching, erosion, fire-induced losses, volatilisation, and harvesting removals (du Toit and Scholes 2002). Moreover, metamorphosis during the cycling of each nutrient element in the various soil pools are complex and specific to each individual nutrient (Ackerman et al. 2013). It is noteworthy mentioning that certain pools of nutrients may be readily available for plant uptake, while other pools are only potentially available for plant uptake in the long term, once they have been transformed to plant-available form (Fisher and Binkley 2000).

2.13 THE SOUTH AFRICAN FORESTRY INDUSTRY

Plantation forests in South Africa represent 1.27 million hectares and 1% of total land area geographically spread between 23° and 34° South latitude (FSA 2011). The planted forests are within climatic regions with a mean annual temperatures (MAT) ranging between 12.0 and 22.5 °C, mean annual precipitation (MAP) between 500 and 2000 mm, altitudes between 0 and 2200 m above sea level, and on soils derived from 23 major parent materials (Schulze et al. 1997). Different silvicultural management techniques are employed on these diverse sites types to grow a diverse range of wood and fibre products. Of the Pine species, 15.6% is planted to long rotation and 12.8% to short rotation regimes (FES 2011; FSA 2011). These rotation lengths vary from short (6-12 years) to long (up to 35 years). The long-rotation regimes are constituted of pine species grown for veener (plywood), solid wood (sawn-log) and short rotation mainly grown for pulp and wood chips. Rotation lengths vary with tree growth and site productivity, with felling age generally determined by market forces and management goals.

2.13.1 The genus *Pinus elliottii*

Pinus elliottii (Engelmann), commonly known as slash pine, is an introduced species grown typically in even-aged commercial plantation forests in South Africa. It is native to the South Eastern United States; predominantly found in the coastal plains of North and Central Florida. However, its dominance extends into neighbouring states as well (Poynton 1979). *P. elliottii* has also been planted in many countries mainly for timber production and pulpwood. These countries include; Argentina, Australia, Venezuela, Brazil, China, New Zealand, Uruguay and USA (Gonzalez-Benecke et al. 2014).

2.13.2 *Pinus elliottii* in South Africa

In South Africa, it has a relatively long history of use in the commercial forestry sector, with seeds first imported in 1916 and extensive expansion occurring since. *Pinus elliottii* has a very wide planted range in both the summer and all-year rainfall regions, including a very wide altitudinal gradient. It is known as a hardy, relatively slow growing species that is adaptable to many different site conditions (du Toit 2012). Softwoods (pines) is 44% of total plantation area (1 273 357ha) in South Africa. As shown in Figure 2.2, *P. elliottii* is the second most commercially grown softwood (after *P. patula*) covering a planted area of 196 575 ha equivalent to 15.4 % of forest land in South Africa (Dovey 2014).

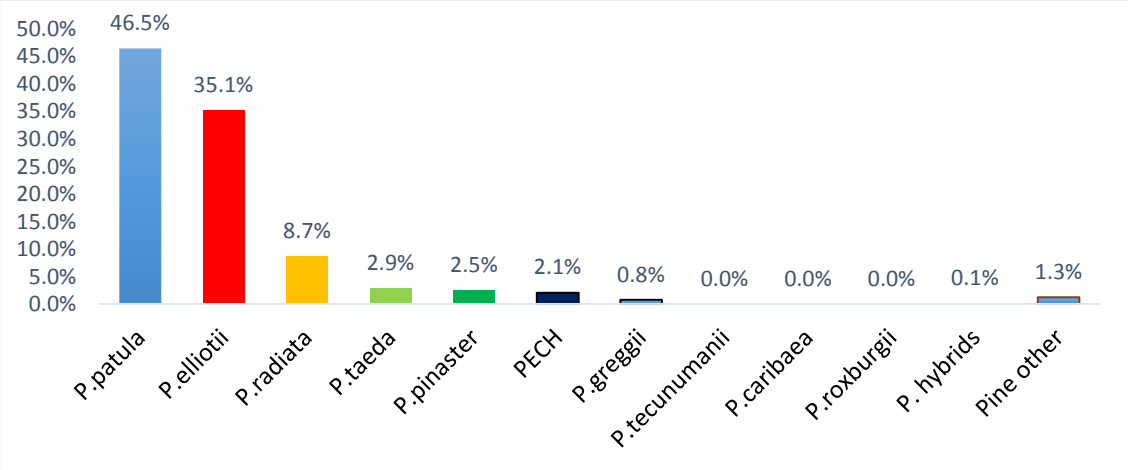

Figure 2.2: Pine species commercially grown in South Africa in terms of Pines planted area.

2.13.3 Factors affecting *Pinus elliottii* choice in South Africa

Pinus elliottii is noted to have a fair resistance against *Diplodia pinea*, which is a major disease that cause dieback and stem cankers. *P. elliottii* is also considered as one of the species which resist *Fusarium circinatum* (pitch canker fungus) and *Sirex noctilio* when it is crossed with *P. caribaea* (du Toit 2012). In addition, *P. elliottii* is amongst the pine species that is known to withstand severe frost and exposure to cold winds (Polynton, 1979, du Toit 2012). The species has a superior resistance to waterlogging; being able to withstand near-permanent waterlogged conditions (Polynton 1979; Schultz 1997; Chmura et al. 2007). The idle MAT for *P. elliottii* is above 14°C and the optimum MAT range is South Africa is between 17°C and 22°C. The minimum MAP (mm) of cool temperate (< 16°C) and all-year zones is 700 mm, whilst Sub-tropical zones (> 19°C) is 900 mm. *P. elliotti* grows poorly in cool temperate climate (du Toit 2009) such as the Tsitsikamma region

where this study was carried out. Furthermore, *P. elliottii* is regarded as fire resistant from a young age. *P. elliottii* grows across all sites, from very low productivity sites to the highly productivity sites (MAI > 20) (du Toit 2012). However, the species productivity on high altitude sites is reported to be low (du Toit 2012).

2.13.4 Wood properties of *P. elliottii*

The pine resource supply has always been generally accepted by sawmilling sector because of its relatively good wood properties and qualities. *P. elliottii* is preferred because it does not manifest any specific direction in spiral grain (du Toit 2012). The core wood is the least spiral amongst South African commercial pines (Banks 1969). However, the South African *P. elliottii* is associated with resin shakes. The species is known to be quite resinous as its ducts usually respond quickly and sometimes abruptly to any form of damage (Malan 1994). Resin shakes and infiltration also occur in *P. elliottii* x *P.caribaea* hybrid but rarely occur in other South African grown pines (du Toit 2012). Although in-roads have been made to develop a better understanding of the phenomenon and its effect on processing and end-product value, no solutions towards the reduction in severity or elimination of resin shakes in *P. elliottii* have been forthcoming (du Toit 2012).

2.14 BIOMASS MODELS FOR LOCAL PINE SPECIES

P. elliottii is an important plantation species internationally, as well as in South Africa. However, there is lack of published allometry functions for the species. Table 2.1 shows studies that have been reported on *P. patula* in Swaziland (Morris 1986; Morris 1992; Carlson and Allan 2001) and *P. radiata* across a range of site conditions in the southern regions of South Africa (van Laar and van Lill 1978; van Laar 1982; van Zyl 2015).

Table 2.1: Summary of Pine biomass studies carried out in South Africa (du Toit et al. 2016).

Species	No. Trees	No. Sites	Age (years)	SPH (trees/ha)	DBH (cm)	H (m)	Elevation (m)	Rainfall (mm)	Temperature (°C)	Source
P. patula	65	16	1-28.5	443-1612	0.8-33.4	1.6-27.1	761-1520	825-1645	15.5-19.5	Morris (1986) Morris (1992) Carlson and Allan, (2001)
P. radiata	52	6	25-40	222-417	11.4-60	12.4-41.1	30-750	1000-1300	13.5-18.5	van Laar and van Lill (1978) van Laar (1982) van Zyl (2015)

van Laar and van Lill (1978) published allometric coefficients are:

- ln(oven-dry AGB) = 8.51584 + 2.19497*ln(DBH)

van Zyl (2015) reported:

- ln(oven-dry AGB) = -1.83 + 2.24*ln(DBH)

van Zyl (2015) biomass estimates of 63.2 - 255.2 Mg ha^{-1} corresponds van Laar and van Lill (1978) 184.9 Mg ha^{-1}. It is worth mentioning that the biomass datasets in Table 2.1 were built using a comparable biomass sampling approach involving destructive harvesting of trees and their components selected to represent the tree size distribution across each study site. The biomass components of van Laar and van Lill (1978) and van Zyl (2015) studies were weighed in the field to ascertain the wet mass and sub-samples were oven-dried to constant mass to develop dry to wet mass ratios similar to Seifert and Seifert (2014) recommendations.

2.15 EXTRAPOLATION OF PUBLISHED BIOMASS MODELS

Different methodologies (on wood weight determination), high variability of sites and species are a challenge to extrapolation of biomass models (Ackerman et al. 2013). For instance, differences were noticed in biomass component drying temperatures. van Zyl (2015) biomass samples were dried at 105°C standard to dry *P. radiata* components, while van Laar and van Lill (1978) and van Laar (1982) dried *P. radiata* at 80°C. Therefore, a standardised sampling approach, analysis and reporting guideline is essential to compare results. To apply available biomass functions, a drying study is necessary to attain species-specific correction factors for determining weight of wood using different temperatures (Ackerman et al 2013; Phiri 2015). Recently, a drying study was carried out on South African Eucalyptus trees where sub-sample were subjected to different drying temperatures in a series between 60 and 105 ºC (Phiri 2015). Stemwood had the largest percentage change of 6% when drying from 60 ºC to 105 ºC while foliage had the lowest percentage change of less than 2%. As reported by Phiri (2015) samples dried at temperatures less than the standard drying temperature of 105 ºC lead to a proportional over-estimation of biomass. Therefore, this may generate biased results when extrapolating. Published functions for *P. patula* which covers the full age spectrum was recommended to apply to adjacent areas in South Africa (Ackerman et al. 2013). At present, *P. radiata* functions cover a wider climatic range though in the confines of the

Western and South Cape provinces. Therefore, it is necessary to test the model. However, van Zyl (2015) cautioned that failing to consider site variations may result in poor estimations.

2.16 RELEVANCE OF INTERNATIONAL MODELS

As reported by Dovey (2014), equations developed internationally can be used as a potential resource for equation comparison or as interim measure whilst developing locally relevant carbon equations. This is because equations produced in the literature are useful for prescribed conditions, hence they cannot be extrapolated outside their geographic and age limits. However, it is noteworthy mentioning that they are exceptions to the application of fitting generalised models. For instance, if the trade-off between accuracy and cost effectiveness is relatively high.

Several *P. elliottii* models have been published elsewhere. Some of the component and total AGB models are presented in Table 2.2.

Table 2.2: Summary of *Pine elliottii* biomass models with predicting variables: DBH, DBH+1, $(DBH+1)^2$, H, CL, SPH and DBH^2H.

Reference	Component	Formula	R^2(%)	Age	Samples	Location
Cobb et al. (2008)	Branches	$y = 51.4 (DBH^2H) - 0.79$	67	6	45	GA, USA
	Stemwood	$y = 117.0 (DBH^2H) + 1.39$	94			
	Total stem	$y = 152.0 (DBH^2H) + 2.02$	96			
Nemeth (1973)	Total tree	$\ln(y) = -2.08597 + 1.31232 \ln (DBH+1) + 0.15839 [\ln (DBH+1)]^2 + 0.56439 \ln (CL)$	98.5	4 & 8	15	NC, USA
	Main stem	$\ln(y) = -2.67757 + 1.39684 \ln (DBH+I) + 0.11902 [\ln (DBH+1)]^2 + 0.23986 \ln (H)^2$	99.1			
	Stem bark	$\ln(y) = -3.98837 + 1.42810 \ln (DBH+1) + 0.83321 [\ln (H) - 0.37012 (SPH)$	98.5			
	Stemwood	$\ln(y) = -2.96870 + 1.28600 \ln (DBH+ 1) + 0. 15201 [\ln (DBH+ 1)]^2 + 0.26975 \ln (H)^2$	99.2			
	Bole needles	$\ln(y) = +0.21097 + 0.05515 \ln (DBH+1) - 0.24120 (SPH)$	82.5			
	Total branch	$\ln(y) = -3.70861 - 0.93318 \ln (DBH+ 1) + 0.66271 [\ln (DBH+ 1)]^2 + I. 14562 \ln CL + 3.67463 \ln (H) - 1.28437 \ln (H)^2$	94.7			
	Branchwood & bark	$\ln(y) = -4.68738 + 0.49666 [\ln (DBH+1)]^2 + 1.41693 \ln (CL) + 1.94392 \ln (H) - 0.80510 \ln (H)^2$	94			
	Branch needles	$\ln(y) = -4.17512 + 0.49941 [\ln (DBH+1)]^2 + 0.94595 \ln (CL) + 2.93469 \ln (H) - 1.15977 \ln (H)^2$	92.6			
	Dead branches	$\ln(y) = +0. 38503 - 1.54483 \ln (H) + 0.80618 \ln (H)^2 + 0. 19008 (SPH)$	87.7			
Jokela and Martin (2000)	Total aboveground	$\ln(y) = -2.715 + 1.261 \ln (DBH^2)$	95	13	40	FL, USA
	Needles	$\ln(y) = -5.359 + 1.294 \ln (DBH^2)$	70			
	Branch	$\ln(y) = -6.740 + 1.629 \ln (DBH^2)$	88.4			
	Stemwood	$\ln(y) = -3.009 + 1.231 \ln (DBH^2)$	93.5			
	Bark	$\ln(y) = -3.423 + 1.028 \ln (DBH^2)$	95.4			
Jokela and Martin (2000)	Total aboveground	$\ln(y) = -2.264 + 0.802 \ln (DBH^2H)$	98.6	4	25	FL, USA
	Stemwood	$\ln(y) = -3.694 + 0.882 \ln (DBH^2H)$	99.2		34	
Xuanran et al. (2008)	Needles	$y = 5.2255 (DBH^2H)^{0.8529}$	75.8	19	18	JX, China
	Branch	$y = 18.5862 (DBH^2H)^{0.7945}$	73.3			
	Stemwood	$y = 8.6613 (DBH^2H)^{1.0178}$	99.8			
	Aboveground	$y = 2852.04 + 14.6382 (DBH^2H)$	97.5			
Gholz and Fisher (1982)	Aboveground	$\ln(y) = a + b \ln (DBH)$	-	5 to 34	19	FL, USA

Nemeth (1973), expressed the relationships between dimensions (independent variables) and component (biomass) with logarithmic transformed multiple regressions (Table 2.2). Signs on the coefficients of the DBH and height variables in the biomass models (Table 2.2) reflect on the tree growth behaviour (Nemeth 1973). For instance, the negative sign on the linear equation in the branch component model reveal the relationship (a decreasing rate of increase). This was reported to be due to the canopy closure effect. Therefore, the equation mirrors exactly what one would anticipate (Nemeth 1973).

Model form determines the precision of biomass estimates. In the case of Nemeth (1973) in Table 2.2, logarithmic transformed multiple linear model with variables ln(DBH+1), ln(DBH+1^2) and ln(CL) produced excellent results for total AGB (R^2 = 99%). Nemeth (1973) results are not significantly different from Xuanran et al. (2008) simple linear model with variables D^2H (R^2 = 98%). However, a difference was observed on needle and branch biomass components model performance. Other studies have also reported biomass models for *P. elliottii* that ware based on DBH as a single predictor variable, height predictors and age covariates (Baldwin 1986; Albaugh et al. 1998; Chave et al. 2005; Coyle et al. 2008). It is important to note that robust biomass model allow estimates of biomass to be made using easily available stand attributes such as DBH (Gonzalez-Benecke et al. 2014).

2.17 ESTIMATED ABOVEGROUND BIOMASS OF *P. ELLIOTTII*

Available lliterature assist in understanding the estimated AGB of young and mature *P. elliottii* trees. In Chapter 5, the results of this study will be compared with some of the AGB estimates reported in this section. For a typical age like the one under study (16 years), Gonzalez-Benecke et al. (2010) reported stemwood biomass between 65.1 - 72.3 Mg ha^{-1}, branch biomass of 11.8 - 3.4 Mg ha^{-1} and foliage of 9.8 - 10.8 Mg ha^{-1}. Shan et al. (2001) who studied 17 years old trees published a foliage biomass of 4.2 - 6.8 Mg ha^{-1}, branches biomass between 5.7 - 10.2 Mg ha^{-1}, stemwood biomass within 75.6 - 125.6 Mg ha^{-1} and total AGB of 85.5 -142.6 Mg ha^{-1}. In Gholz and Fisher (1982) study on 26-year-old trees, stemwood biomass ranged from 100.1 - 148.8 Mg ha^{-1} and the total AGB was 114.9 - 172.1 Mg ha^{-1}. Furthermore, Vogel et al. (2010) reported a stemwood biomass of 87.8 - 154.2 Mg ha^{-1} and AGB which ranged from 106.0 - 184.2 Mg ha^{-1}. The change in biomass distribution observed over time is attributed to the dynamic processes involved in the development of a forest (Nemeth 1973).

Chapter 3: Materials and Methods

3.1 STUDY AREA

Three sites were considered in this study, all located on the southern coastline of South Africa in the Eastern Cape Province (Figure 3.1). Two of the study sites were at Lottering Plantation and one at Witelsbos Plantation.

Figure 3.1: Map of South Africa showing study area in the Eastern Cape Province of South Africa.

3.2 DESCRIPTION OF STUDY SITES

Table 3.1 summarises the key attributes of the study sites. The study sites are typical of where *Pinus elliottii* is grown in South Africa. Trees were sampled across a chronosequence of three ages in plantations with uniform attributes; Lottering (Site 1), Witelsbos (Site 2) and Lottering (Site 3). Table 3.1 shows the key attributes of each site.

Table 3.1: Main attributes of the three study sites.

	Site 1	Site 2	Site 3
Plantation	Lottering	Witelsbos	Lottering
Compartment number	D65A	B19B	C27A
Coordinates	33°58'41.38"S 23°42'37.43"E	34°0'0.94"S 24°5'58.45"E	33°59'17.32"S 23°47'26.84"E
MAP (mm)	1008	1094	1008
SI_{20} (m)	23.9	23.0	25.6
Age (years)	16	33	28
MAI (m^3/ha/a)	16.5	14.9	19.5
SPH (stems/ha)	522	380	347

All sites have young soils, non-red neocutanics. The site index estimates were based on an inventory done in 2014. MAI, SI and SPH data was recorded in the same year. MAP data was obtained from nearest weather stations in 2015. The study sites did not consider growth gradient. The stand age of Site 2 and 3 were in the normal saw timber clear-fell age range of the region.

3.3 RESEARCH METHODOLOGY

The detail of methods used to identify sample trees and collect individual biomass component metrics are described below. A breakdown of the equipment and tools utilised during the study is listed in Appendix 1.

3.3.1 Sampling approach

The first sampling entailed measuring key metrics of *Pinus elliottii*, and in the second phase; destructive sampling was done on a subset of trees from the first phase. The second phase sampling was done to facilitate regression modelling as recommended by Seifert and Seifert (2014). Twenty trees were sampled in total, 15 from Lottering and 5 from Witelsbos. Financial and time constraints limited the number of trees that could be destructively sampled. The methodological approach of the study sampling exercise was similar across the three sites.

3.3.2 Site enumeration

An enumeration of trees at each site was done to identify sample trees. Caution was taken to ensure that a buffer of 25 m was maintained between plots and the edge of the compartment since edge trees produce relatively larger lateral branches than trees in the interior of the stand.

Each plot constituted 100 trees. The trees in the plot where numbered sequentially for identification and marked with spray paint displaying the number of the tree. A DBH (1.3 m) calliper was used to ensure that DBH measurements were consistently taken at the correct height to the nearest cm. For precision in determining the height of the stem, the upper side of the slope was considered as the base of the tree. A Vertex IV hypsometer (Haglöf) and a 360° transponder was used for tree height measurements on a subset (30 trees) of the measured 100 trees. The subset trees represented the height distribution of the trees in the plot. The basis for the height measurements was to establish the compartment estimate of height range in which the measured heights were used to estimate the heights of the trees measured for DBH only.

3.3.2.1 Sample tree selection

For precise measurements, diameter of all trees in a 100-tree plot were measured as proposed by Kunneke et al. (2014) to get the compartment estimate of DBH distribution, and ultimately for selection of trees for destructive sampling and for upscaling. This was done using the pre-sampling enumeration data trees representing a DBH distribution for each site. Trees with a DBH that was within the DBH range values were selected for destructive sampling. Trees from each site were also selected based on a series of criteria; tree form, noticeable diseases, defects, damage (animal and mechanical) and uniform stocking). However, the specific criteria applied for selection considered healthy trees, it is important to note that resulting allometric model may be inherently biased.

3.4 ABOVEGROUND COMPONENTS

Detailed compositional data of individual trees for regression modelling and reconstruction of stem was carried out by sub-sampling the branches, needles and stem. Consequently, these regression models are then used to scale up the branch diameters for a full tree, where all branch diameters have been recorded after felling.

3.4.1 Tree measurements

Before destructively sampling trees, a north direction mark was put on the trees and DBH was measured. After felling, measurements for taken of tree height (length), diameter (DBH) at 1.3 m, live crown base (to lowest live branch), dead crown base (to lowest dead branch) and pruning height (highest remains of pruning scars). Measurements of height of whorls (cluster of branches within a 0.5 m stem length) were done from tip (whorl 0) to live crown base and marked. All live branch diameters per whorl were measured using a vernier caliper and recorded. In this study, the height of the stump remaining after felling the tree was measured and considered to be part of the AGB.

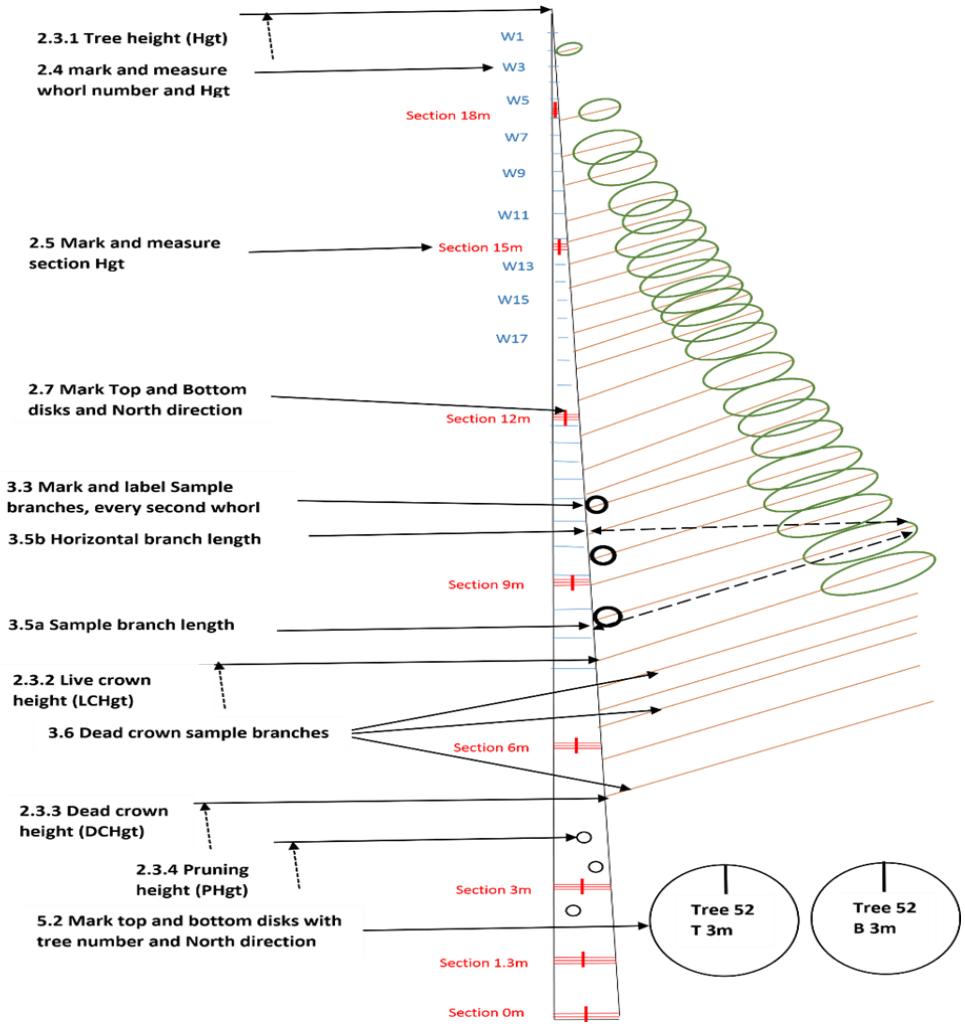

Figure 3.2: Procedure for destructive sampling and measuring key metrics of biomass components.

3.4.2 Stemwood

To reconstruct volume, 3 m sections were marked on the stem from the tree base (0 m) to the tip (whorl 0) of the stem. Figure 3.2 illustrate the procedure taken to measure, mark

and cut samples from the destructive sampling trees. A north direction mark was put on the two discs and as well as the tree number and height. Two discs (25 mm thick) were marked and cut at the lower end of each 3 m section and (DBH) using a chain saw (Figure 3.3). One disc was for density determination and the other one was for volume calculation. Under bark and over bark diameter readings were measured to calculate the bark volume. For detailed measurement steps see Appendix 1.

Figure 3.3: Destructive sampling of biomass in field.

3.4.3 Branches

Branches were selected from a whorl using a random number table. Where necessary, additional branches were randomly selected to ensure the live crown sample branches represented a tree. Measurements on sample branches recorded: vertical and horizontal diameters, branch length and the horizontal length (90° to the stem). These were then cut off and put in sample branch bag Samples of branches were taken to recreate the branch biomass by developing an allometric model of branch biomass versus branch diameter, for upscaling to crown.

3.4.4 Needles

All needles from the sampled branches were removed and packed into labelled paper packets for each sample branch. The remaining wood after stripping the needles of the sampled branches and those on the stem were cut and packed in labelled paper packets

for each branch. The needles were separated from the branches and packed in separate paper bags.

3.5 LABORATORY PROCEDURE

3.5.1 Branches and needles

Samples designated for drying were immediately weighed after transportation from the field. Due to the distance of the research site from University of Stellenbosch Forestry laboratory, the amount of time between sampling and lab weighing was between 96 to 120 hours. The mass obtained was considered as the field wet mass, which was needed to calculate moisture loss. All needle and branch samples (stored in paper packets) were oven dried to 65°C until a constant weight reading was obtained. Sub-samples were dried at 105°C (three sample branches from the top, middle and bottom of the crown). After obtaining a constant mass, moisture loss percentage was calculated based on the laboratory mass and the dry mass (at 105 °C). The ratio was used to establish the dry mass of all the samples.

3.5.2 Stemwood

Volume estimates were made using the water displacement technique on fully saturated discs without bark (American Society for Testing and Materials 2008). The discs (without bark) were submerged for 7-14 days in drums filled with water (until saturation). Subsequent determination of the saturated volume and basic density followed.

$$\frac{W_{water}}{W_{air}} = \frac{(\rho_{sample} - \rho_{water}) \cdot V}{(\rho_{sample} - \rho_{air}) \cdot V} = 1 - \left(\frac{\rho_{water}}{\rho_{sample}}\right) \quad (3.1)$$

Where:

W = weight (g)

ρ = density (g/cm^3)

V = volume (cm^3)

Debarked discs and respective bark were oven dried at 105°C to constant weight. The standard drying temperature in most biomass studies is commonly 105 ºC or 103 ± 2 °C (Ackerman et al. 2012; Seifert and Seifert 2014). Basic density was calculated by dividing the oven dry weight of the discs by the corresponding saturated volume. This study estimated the basic density at the point of geometric centroid where the Smalian volume

formula was used essentially as a weighting approach. The reason for considering a weighting approach was to represent the density of each section in the ultimate biomass calculation (Seifert and Seifert 2014; Magalhães 2016). The procedure on stem-level upscaling is presented in the statistical analysis section.

3.5.3 Bark

The previously described density determination procedure was repeated to estimate the basic density of stem bark at 1.3 m. Stem under bark volume was subtracted from over bark volume to obtain the bark volume. To calculate the biomass of bark, the density of bark is multiplied volume of bark.

3.6 DETERMINING NUTRIENT CONTENT

S, Cl and Mo are not routinely analysed by laboratories as deficiencies of these elements are rare (and hence they were not done in this study either). For chemical analysis of key essential nutrients: sub-samples were taken from each biomass component (see Appendix 1). The branch sub-sample represented the minimum, medium and maximum diameter of the branches. The needle samples represented each individual tree. Biomass components were separately dried at 65 ºC using ovens to minimise loss of volatile nitrogen and sulphur (Seifert and Seifert 2014). The branch, bark and stemwood sample were coarse milled to 30g for each sample. Macro-nutrients: nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg) and potassium (K) were analysed by Bem Lab and reported as a percentage of total dry-matter. Micronutrients: iron (Fe), sodium (Na), zinc (Zn), copper (Cu), aluminium (Al) and manganese (Mn) were analysed and reported as recommended by Kalra (1998). The nitrogen content of samples was determined using Leco CNS-2000 and Leco TruSpec NS analysers. Magnesium perchlorate (anhydrone) was used to remove any moisture from the system and a Cu catalyst for oxygen (O^2) elimination. Concentrations of the inorganic elements: P, K, Fe, Ca, Mg, Na, Zn, Cu, Al and Mn were measured using inductively coupled plasma optical emission spectrometry and the samples were ashed in a furnace at 450 °C overnight and digested using hydrochloric acid.

The mean and standard deviation of nutrient concentrations were calculated for the tree component of each tree (assuming normality). The nutrient concentrations were reported as mean concentrations of nutrients found in individual biomass components of each tree

and expressed in kilograms per hectare (Appendix VII). Biomass components were then multiplied with nutrient concentration to determine the nutrient accumulation (kg/tree). Linear models in Appendix VIII with component biomass as predicting variables were used to predict nutrient per plot (kg/plot) which were then up-scaled to stand level (kg ha^{-1}). The relationship between tree size and concentration was not explored in this study.

3.7 STATISTICAL ANALYSIS

Statistical procedures were employed in both phases of the upscaling process using the R Core Team (2015) and SigmaPlot (2015). The details are presented in this section.

3.7.1 Upscaling I

3.7.1.1 Upscaling of samples

A biomass upscaling procedure was used to upscale from sample to tree level (Upscaling I) and from tree to stand level (Upscaling II) (Seifert and Seifert 2014). The upscaling of the crown and stem was carried out separately. The crown included the foliage and branches. Different parameter estimates were considered, which included mainly transformed variables.

3.7.2 Upscaling of branch and leaf biomass with a regression approach

The best branch and needle biomass models were selected after running potential linear regressions. Logarithmic (ln) transformed regression equations were used and several independent variables were tested. The widely-used power law logarithmic form was used to fit the allometric relationship between the independent variables; d^2*l (branch diameter and branch length) and d (branch diameter) versus dependent variables (branch mass and needle mass). Here, Y in Equation 3.3 can be branch mass and needle mass: X is d^2l and branch diameter (d), $\ln(\beta_0)$ is the intercept, and the slope (β_1) is indicative of the relative growth rate between branch and needle biomass components and d^2l and branch diameter (Pretzsch and Dieler 2012).

$$\ln(Y) = \ln(\beta_0) + \beta_1 \ln(X_1) + \in \quad (3.2)$$

$$\ln(Y) = \ln(\beta_0) + \beta_1 \ln(X_1) + \beta_2 \ln(X_2) + \in \quad (3.3)$$

Where:

Y = biomass component mass (kg)

X_1 = dimensional variables

β_2 = Model parameter

β_o = Intercept value

β_1 = Slope value

3.7.2.1 Correcting estimation bias

The estimated branch and needle biomass was back-transformed to the original unit values by employing the correction factor. The logarithmic transformation induces a systematic bias in the estimation of the response when back transforming to original values. This is because of the log-normal distribution (Baskerville 1972). Therefore, the error was corrected by multiplying the predicted values by a correction factor (CF). The CF is shown in Equation 3.4:

$$CF = \exp * (RSE^2/2) \quad (3.4)$$

Where:

RSE = residual stand error obtained from the model (regression)

The correction factor was applied to back transformation bias correction to obtain unbiased results (Seifert and Seifert 2014).

3.7.3 Upscaling stemwood biomass based on a geometric approach

The volume of stem sections was calculated by employing the geometric formula for a truncated cone (Seifert and Seifert 2014). The lower and upper diameters of all stem sections were measured as indicated earlier in Figure 3.3. Widely used volume calculation formulas were used to determine the stemwood volume. These were the Smalian and Huber's formula reported in Chapter 2 section 2.4.3 (Equation 2.1 and 2.2).

For estimating stemwood biomass of each individual tree, the calculated volumes (m^3) of the measured stem sections were then multiplied with the basic density values (kg m^3) obtained from the discs representing different sections of the tree. It is important to note that wood density varies vertically, hence the weighting of each wood section was necessary to accurately estimate biomass of the section. The total stem wood biomass for each individual tree was obtained by adding all stem sections.

A combined variable linear model using ln($DBH^2 \cdot H$) as a predictor variable (Equation 3.2) was selected based on the actual volume measurements from Smalian and Huber's volume formulas. Predictor variables were logarithmically transformed; DBH, Height, $DBH^2 \cdot H$ and Crown base height (CBH) to linearise the relationship between the predictor variable and minimise stemwood biomass, hence minimising heteroscedasticity.

3.7.4 Upscaling total tree biomass with a regression approach

The total tree biomass model which scored the highest according the goodness of fir statistics was determined by running un-transformed and *ln*-transformed simple linear regression equations with both independent and compound predictors. These were DBH, height (H), $DBH^2 \cdot H$ and DBH and H (compound predictors). The widely-used power law logarithmic form was used to fit the allometric relationship between the independent variables DBH and dependent variables (total tree biomass). For instance, Equation 3.2 and 3.3 were used, with Y as the total tree biomass and X as $DBH^2 \cdot H$. The estimated total tree biomass was back-transformed to the original unit values by employing the correction factor (Equation 3.4).

3.7.5 Upscaling from tree level to stand level

Biomass models were applied at the tree level. It is important to note that this phase of upscaling entail incorporating measured variables such as diameter at breast height (DBH) and total tree height, and then correlate with tree biomass components and the total AGB of the respective trees (Magalhães and Seifert 2015). Stand level estimates were then made using mean tree metrics.

3.7.5.1 Height model

A height model was essential in predicting heights of the plot trees where DBH was measured. Because of the wide difference in stand age, it was necessary to make height-diameter models for younger trees and older trees (28 and 33 years). The study considered and parameterised two height models for Site 1 and Site 2 and 3 (combined) using Equation 3.2. The independent variables in the models were logarithmic transformed (ln)DBH and 1/DBH (inverse DBH). Most studies have explained the relationship between DBH and height using both linear and non-linear regressions (Chave et al. 2005; Sileshi 2014). The power law model is known to be the most parsimonious and widely used

model. This is because in some cases it relates well with biomass allometry principles (van Laar and Akca 2007; Picard et al. 2015).

$$\ln(Y) = \ln\beta_0 + \beta_1 \ln(1/DBH) + \in \quad (3.5)$$

Where:
Y = height
β_o = Intercept value
β_1 = Slope value

The estimated heights of the young and older trees were back-transformed to the original unit values by employing the correction factor (Equation 3.4).

3.7.5.2 Aboveground biomass

A pooled model was used for each biomass component and total AGB (with DBH as predictor) to up-scale the biomass to plot and stand level for the three sampled sites using Equation 3.2. The total plot biomass of each component was multiplied by the stems per hectare to obtain the total biomass per hectare. Biomass estimates obtained were back-transformed to the original unit values by using the correction factor as previously outlined.

3.7.6 Biomass Expansion Factor

BEFs was related to the corresponding biomass of the inventoried volume of the three sites under study as previously outlined in Chapter 2 section 2.5.4. The calculation procedure used in this study defined BEF as the product of volume per hectare (m^{-3} ha^{-1}) and wood density (kg m^{-3}) (Brown at al. 1991). Stem volume was preferred to merchantable volume because merchantable height is sensitive to personal judgment and thus is more subjective than stem height, especially for standing trees. Nevertheless, BEF computed based on biomass can be calculated as a function of BEF computed on volume. BEF's were determined for each site as the proportion of stemwood to total AGB.

3.7.7 Volume models

As stated in the literature review, biomass measurement is typically done in two phases. This entail volume measurement, and wood density determination. At stand level, the derived basic density is multiplied with the stand volume to determine the biomass. Therefore, widely used functions were considered in estimating the volume of 20 trees and

upscaling volume of the rest of the trees in each of the sampled plots. The following models were parameterised for height: Standard Form Factor Model estimated from the segmented polynomial taper function (Max and Burkhart), Combined Variable Model and Schumacher and Hall. The formulas are given below:

Standard Form Factor Model:

$$Vt = \left(\frac{\pi}{40000}\right) \cdot k \cdot DBH^2 \cdot H \quad (3.6)$$

k (0.403405352) derived from coefficients: β_0 (-3.53841), β_1 (1.68878), β_2 (-2.23737), β_3 (89.12748), a_1 (0.69458) and a_2 (0.069477) as proposed by van Laar and Akça (2007).

Combined Variable Model:

The Combined Variable was also considered as an alternative to the Standard Form Factor Model and Schumacher and Hall. The Combined Variable Model is based on a fitted regression against the data of this study. Coefficients for estimation were generated from the data of this study. The coefficients were: β_0 (-11.5394) and β_1 (1.11235).

Schumacher and Hall Model:

$$\ln(V) = \beta_0 + \beta_1 \ln(DBH + f) + \beta_2 \ln(H) \quad (3.7)$$

Where:
ln = natural logarithm to the base e
V = stem volume (m^3, under-bark)
DBH = breast height diameter (cm, over-bark)
f = correction factor
H = tree height (m)

For comparison purposes, widely used Schumacher and Hall volume parameter estimates were used for estimating *P. elliottii*. The coefficients are; β_0 (-10.677), β_1 (1.931), β_2 (1.157) and f (0) (Loveday, unpublished in Bredenkamp 2012).

3.8 MODEL EVALUATION

Least squares regressions were used. Evaluation of model compliance to the assumptions of linear modelling was through goodness of fit evaluation criteria. A criteria for selection of model was used; Coefficient of determination (R^2), standard error of estimates (se), mean standard error (MSE), root mean standard error (RMSE), variance inflation factor (VIF) and the akaike information criterion (AIC) (Akaike 1973; Parresol 1999). Some methods of evaluating are known to be better than others and some are reported together to provide complementary information. The coefficient of determination (R^2) is a well-known and widely used method. The RSE and RMSE add no new information on quantifying total error.

Though AIC is most appropriately used for hierarchical models with greater independent variables. This study used AIC as a secondary criterion, considered in relative terms, in the context of the criteria which, in effect, gave a more absolute indication of goodness of fit. AIC was employed as a method of distinguishing information gain between models, and adds additional insight on the accumulation error. Models with less independent predictors were targeted, as they are more parsimonious (Burnham and Anderson 2002; Sileshi 2014). Sileshi (2014) reported that an increase in model variables result in the accumulation of error. This is because each individual predictor is associated with measurement error and error in the estimation of the parameters (Sileshi 2014).

Since additivity was desirable, a consistent model was selected in which the sum of the components equal the predicted whole (Parresol 1999). This was a conventional approach which automatically ensured additivity was used with the same predictors. The study could not develop a model that relied on wood density for ultimate up-scaling because density data only existed for sampled trees. Even though it was possible to build a conventional model with both DBH and H. This study, opted to use variable DBH for upscaling because it was the simplest model in the additive form.

Chapter 4: Results

4.1 INVENTORY DATA

4.1.1 Mean DBH and mean Height of trees

According to the mixed model results, trees at the youngest site (Site 1) had, as expected, a significantly ($p < 0.001$) smaller DBH than trees at the older sites (Site 2 and 3) ($p = 0.921222$), but there was no difference between the trees at the two older sites (Figure 4.1). Younger trees had a markedly lower mean diameter and height compared to older trees. The mean height for 16, 28 years and 33 years stand age was 19.5 m, 28.9 m and 28.6 m.

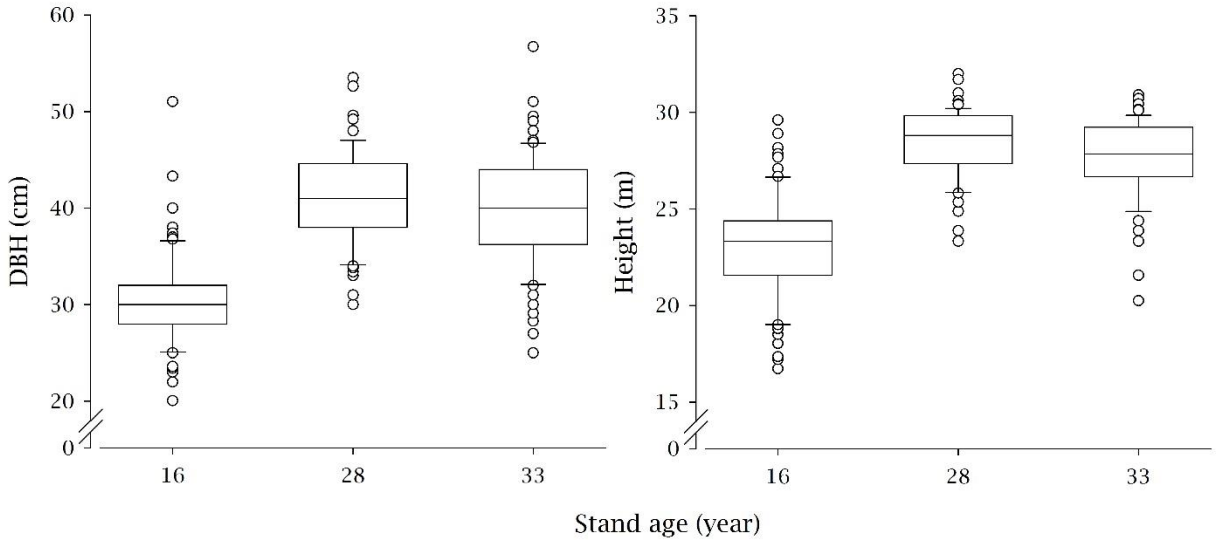

Figure 4.1: Box-whisker plot of DBH and tree height at three stand ages. The line is the median, box represents the first standard deviation, lower and upper whiskers show the range and the circles represent potential outliers.

4.1.2 Diameter distribution of sampled trees

Younger trees showed evidence of skew (Shapiro-Wilk statistic 0.933163, $p < 0.0001$) while Site 2 and 3 were normally distributed (Shapiro-Wilk statistic 0.991619 and 0.988935; $p = 0.7930$ and 0.5794) (Figure 4.2). Overall, there was evidence that DBH was not normally distributed (Shapiro-Wilk statistic 0.960848, $p = 0.00486$) (Figure 4.2).

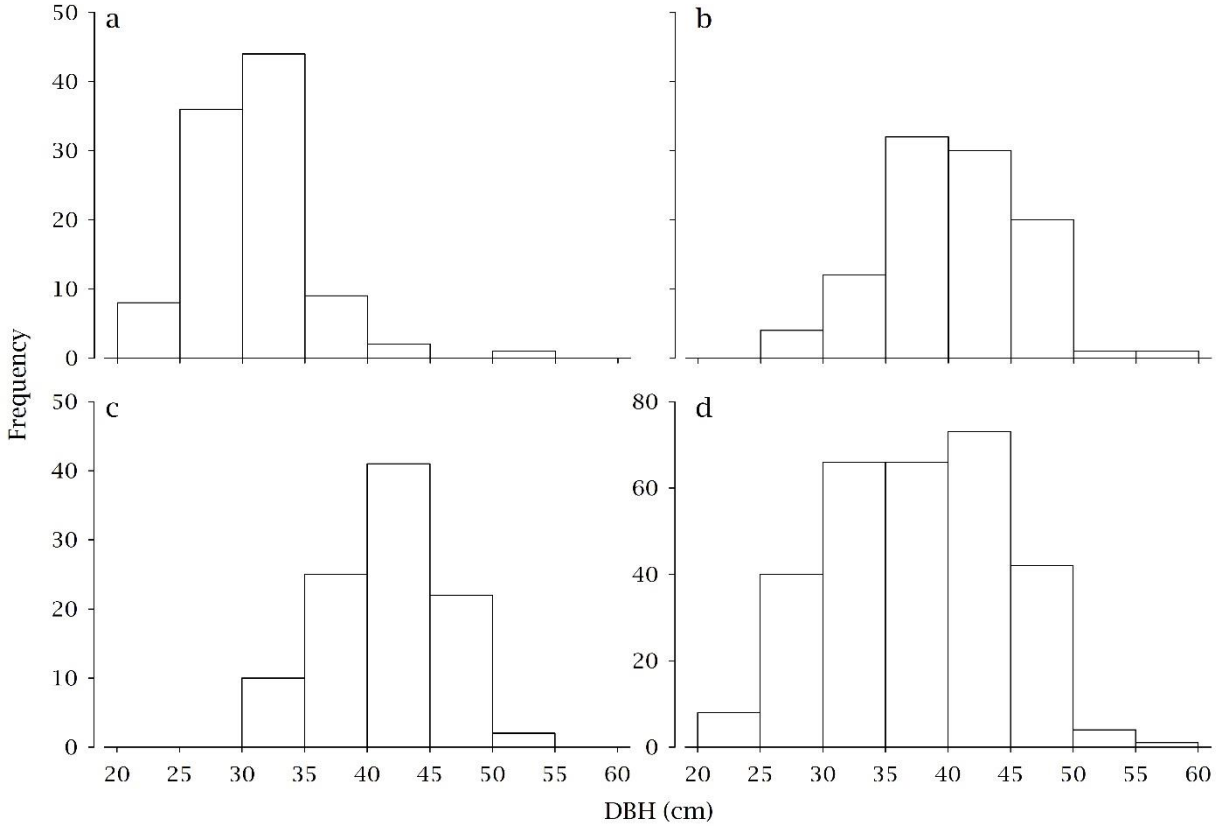

Figure 4.2: Diameter distribution (diameter at 1.3 m from ground level) of the sampled trees at individual sites (a shows Site 1, b shows Site 2 and c shows Sites 3, while d is combined data) for the biomass study.

4.2 HEIGHT MODEL

After fitting a regression for Site 1 and for Site 2 and 3 combined, using inverse DBH as a predictor (Table 4.1) the best models (Model 4.2 and Model 4.4) explained 66.9% and 21.7% of height variation respectively. Site 1 (youngest site), Model 4.2 was preferred as it had a higher coefficient of determination (R^2) than Model 4.1 (Table 4.1). However, several models of forms other than the inverse DBH and ln-transformations were also used, to explain the height to DBH relationship. Model 4.4 with a higher R^2 was used to predict height for Site 2 and 3. The details of the results of Site 2 and 3 model are shown in Table 4.1. Model 4.1 and 4.3 with ln(DBH) predictor variable had a lower R^2, hence it was not selected.

Table 4.1: Summary of diameter-height models.

	Models	Predictors	Parameter	Estimate	SE	*P*	R^2	AIC	RSE	RMSE
Site 1	4.1	Intercept	β_0	1.781	0.265	0.095	64.76	-32.085	0.047	0.043
		ln(DBH)	β_1	0.348	0.079	0.002				
	4.2	Intercept	β_0	3.290	0.076	<0.001	66.86	-32.762	0.046	0.042
		1/DBH	β_1	-9.607	2.088	0.001				
Site 2 and 3	4.3	Intercept	β_0	2.788	0.163	<0.001	20.73	-149.553	0.044	0.043
		ln(DBH)	β_1	0.154	0.044	<0.001				
	4.4	Intercept	β_0	3.517	0.043	<0.001	21.71	-150.115	0.044	0.043
		1/DBH	β_1	-6.298	1.733	<0.001				

H represent height (m) of trees in Site 1 and Site 2 and 3 combined. DBH is given in cm (at 1.3 m from ground level).

4.3 UPSCALING I

4.3.1 Branch and needle samples

Table 4.2 and 4.3 shows key metrics of samples, these include; minimum and maximum length and diameter of branch, branch mass, needle mass, CBH and number of sample per measured parameter. It is worth noting that the range of the branch length and branch diameter was due to the variability in tree architecture. For instance, for Site 1, 2 and 3, the minimum branch length was 20.5 cm, 7 cm, and 10 cm while the maximum recorded was 489 cm, 400 cm and 710 cm respectively.

Table 4.2: Basic statistics of branch biomass samples. Metrics of branch component are given in cm (for diameter and length of branch samples) and m (CBH). SE represents standard error.

	Component	Mean	SE	Minimum	Maximum	Samples
Site1	Branch diameter (cm)	2.8	0.15	0.7	5.4	58
	Branch length (cm)	178.8	13.92	20.5	489	58
	Cbh (m)	12.2	0.19	10	13.2	45
	Branch mass (kg)	0.4792	0.07	0.0003	2.6483	58
Site2	Branch diameter (cm)	2.8	0.14	0.6	6.6	77
	Branch length (cm)	136.3	11.71	7	400	77
	Cbh (m)	17.6	0.17	16.2	19.4	68
	Branch mass (kg)	0.4448	0.07	0.0014	3.4554	77
Site3	Branch diameter (cm)	4.4	0.17	0.9	10	123
	Branch length (cm)	276.2	13.67	10	710	120
	Cbh (m)	15.8	0.17	12.1	18.9	124
	Branch mass (kg)	2.4167	0.25	0.0344	16.3437	124

Table 4.3: Basic statistics of needle biomass samples. Metrics of needle component are given in cm (for diameter and length of branch samples) and m (CBH). SE represents standard error.

	Component	Mean	SE	Minimum	Maximum	Number of samples
Site1	Branch diameter (cm)	2.40526	0.169897	0.65	4.55	38
	Branch length (cm)	148.845	13.8719	20.5	326	38
	Needle mass (kg)	0.199934	0.031391	0.00456	0.66312	38
Site2	Branch diameter (cm)	2.86722	0.201639	0.75	6.55	45
	Branch length (cm)	168.209	15.4731	8.3	400	45
	Needle mass (kg)	0.234694	0.035283	0.00116	1.06551	45
Site3	Branch diameter (cm)	4.32143	0.176824	0.9	10	112
	Branch length (cm)	273.536	13.7689	10	600	112
	Needle mass (kg)	0.722225	0.059454	0.072	2.98886	112

4.3.2 Pooled branch and needle models

Models for estimating branch and needle biomass were fitted using logarithmically transformed branch diameter (d), branch length (l) and d^2l as independent variables (predictors). Compound predictor variable models were also formulated. These are Model 4.8 and 4.12. Tables 4.4 show more details of the models considered.

Table 4.4: Summary of pooled branch and needle model performance.

Models		Predictors	Parameter	Estimate	SE	*P*	R^2	AIC	RSE	RMSE
Branch biomass	4.5	Intercept	β_0	-4.456	0.130	<0.001	77.80	683.516	0.903	0.899
		ln(d)	β_1	3.092	0.103	<0.001				
	4.6	Intercept	β_0	-10.360	0.338	<0.001	75.83	696.299	0.94	0.937
		ln(l)	β_1	1.860	0.066	<0.001				
	4.7	Intercept	β_0	-7.643	0.195	<0.001	83.20	603.479	0.784	0.781
		$\ln(d^2l)$	β_1	0.913	0.026	<0.001				
	4.8	Intercept	β_0	-7.751	0.376	<0,001	83.14	605.366	0.785	0.781
		ln(d)	β_1	1.773	0.168	<0,001				
		ln(l)	β_2	0.947	0.103	<0,001				
Needle biomass	4.9	Intercept	β_0	-3.480	0.108	<0,001	72.59	399.211	0.667	0.663
		ln(d)	β_1	1.922	0.085	<0,001				
	4.10	Intercept	β_0	-7.424	0.366	<0,001	57.74	474.185	0.808	0.804
		ln(l)	β_1	1.190	0.070	<0,001				
	4.11	Intercept	β_0	-5.400	0.202	<0,001	69.54	419.795	0.703	0.699
		$\ln(d^2l)$	β_1	0.553	0.026	<0,001				
	4.12	Intercept	β_0	-2.885	0.562	<0,001	72.62	400.029	0.666	0.661
		ln(d)	β_1	2.146	0.224	<0,001				
		ln(l)	β_2	-0.165	0.153	0,281				

Note: independent variables used in the models are; (d) branch diameter, (l) branch length and (d^2l) is combined variable of branch diameter and length independent variables (predictors).

4.3.2.1 Pooled branch model

Of the tested equations, Model 4.7 was the best fitting model, with the highest R^2 and lowest AIC (Table 4.4). For upscaling, however, this model was not useful, as it did not meet the criteria of parsimoniousity and additivity. Thus, Model 4.5 4 was used for upscaling to tree level. Model 4.5 explained 77.8% of biomass variation and all its parameters were significant ($p < 0.001$).

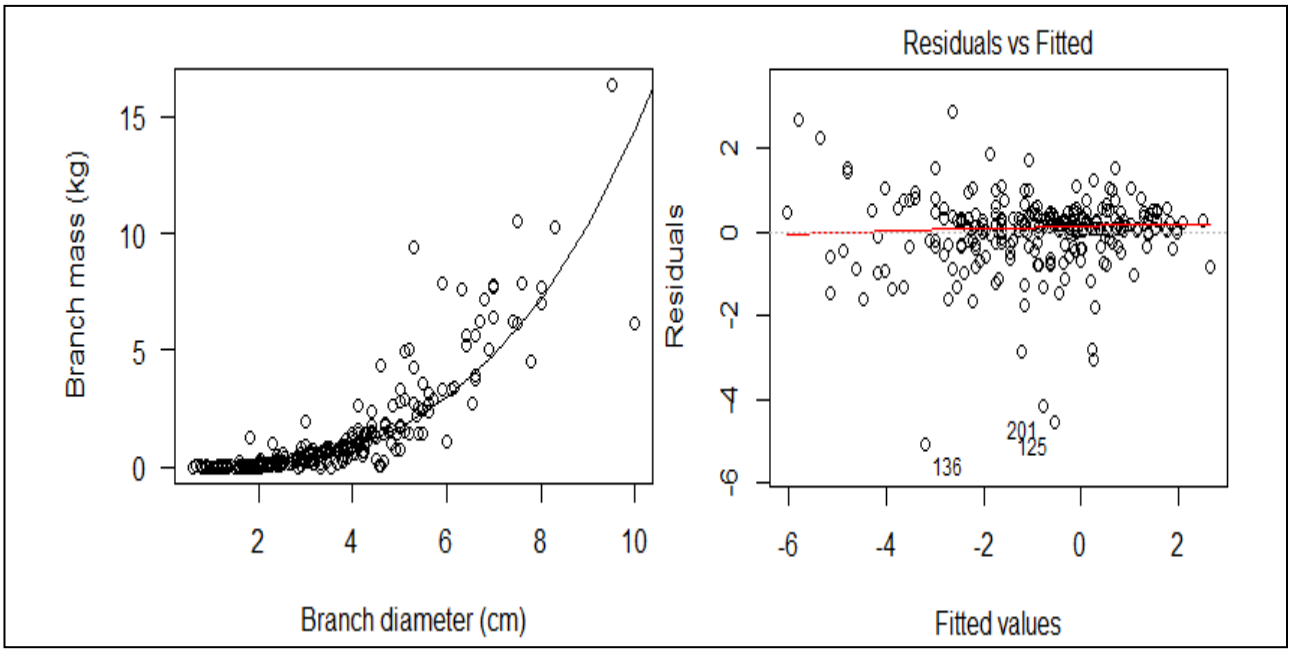

Figure 4.3: (a) Branch biomass and branch diameter relationship (b) model fitted vs. residual plot.

Figure 4.3 shows the relationship between branch diameter and branch mass. Removing the branch sample denoted by the point in Figure 4.3 (with metrics - 10 cm branch diameter, branch length 600cm, mass of 6.146kg) did not have any significant change in slope as shown by the model p-value (< 0.0001). The homoscedasticity assumption was considered by plotting the fitted values against the residuals. Figure 4.3 also shows the residuals plots of the branch biomass model. From the residual vs. fitted plot, it can be observed that observation 125, 136, and 201 as possibly problematic to the model. However, 77.7% of the branch biomass variability could still be explained by Model 4.5.

4.3.2.2 Pooled needle model

Of the models of branch-level foliage biomass, Model 4.9, with branch diameter (d) as predictor, fitted the data equivalently (Table 4.4) to the more complex Model 4.12. Therefore, it was selected for upscaling to tree level.

The plots for the residual against fitted values had no visible pattern, indicating that the homoscedasticity assumption was satisfied (Figure 4.4).

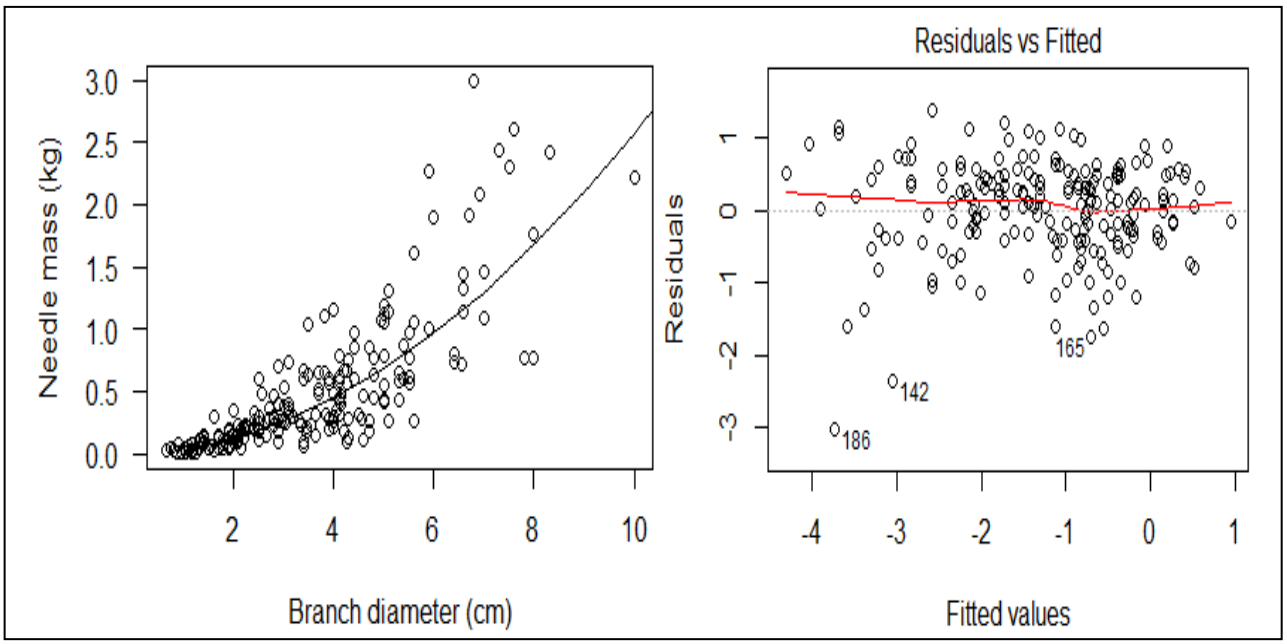

Figure 4.4: (a) Needle biomass and branch diameter relationship and (b) model fitted vs. residual plot.

4.3.3 Stemwood

4.3.3.1 Wood density

The basic density is reported for the section of the stem directly above the felling cut, right where the disc was cut. Figure 4.5 shows the vertical density distribution of the 20 destructively sampled trees. Typical of most pine species, position of sample had an influence on wood density (p = 0.0007). Thus, a gradual drop in density was observed (see trend lines in Figure 6) from the thick end (0 m) right to the tip of the stem (27 m). Furthermore, variability in density was observed across the three sites - illustrated by the three trend lines for each of the sites, especially Site 2 and 3. The lowest recorded density was in Site 3, where density ranged from 187 kg m^{-3} to 676 kg m^{-3}. The mean wood density of site 1, 2 and 3 were 420 kg m^{-3}, 364.7 kg m^{-3}, and 412.4 kg m^{-3} respectively. After testing the effect of site on wood density there was no significant difference (p = 0.4345).

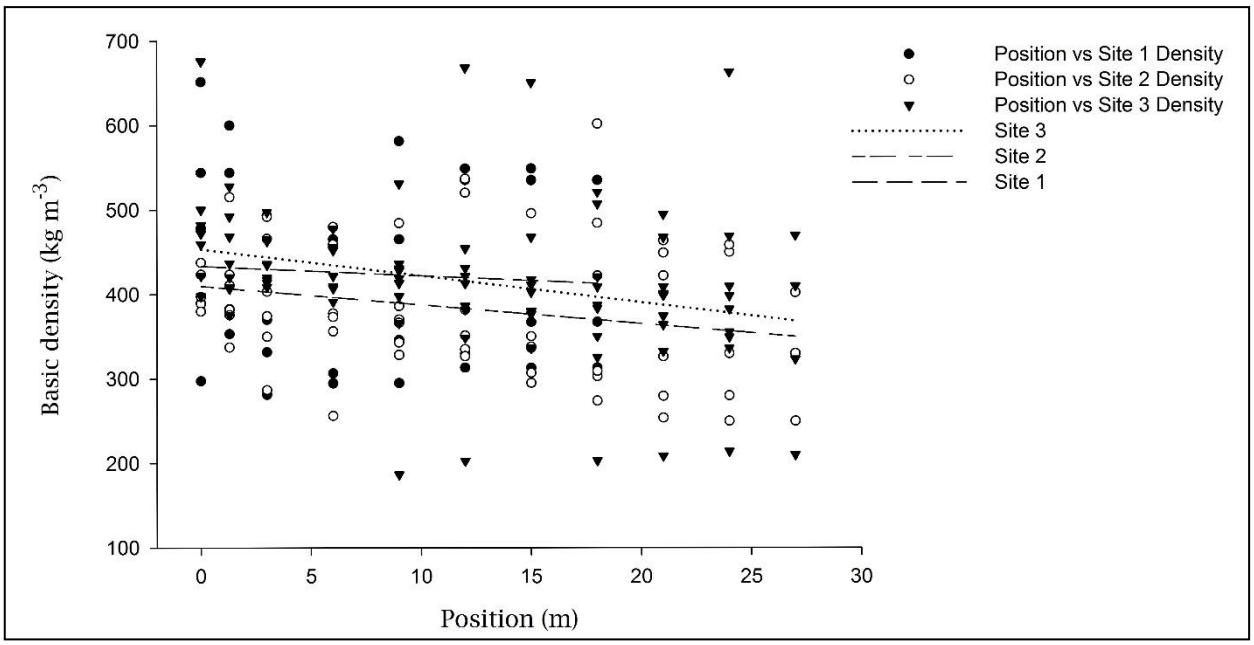

Figure 4.5: Vertical density distribution of sampled wood discs from sites. Trend lines of the three sites are represented by slanting horizontal lines.

A summary of the goodness-of-fit and parameter estimates for a variety of candidate models (see Materials and Methods and Literature Review) is presented in Table 4.4.

Table 4.5: Summary of stemwood model performance.

	Models	Predictors	Parameter	Estimate	SE	*P*	R^2	VIF	AIC	RSE	RMSE
Stemwood biomass	4.13	Intercept	β_0	-3.410	1.132	<0.001	78.61		10.695	0.287	0.272
		ln(DBH)	β_1	2.634	0.313	<0.001					
	4.14	Intercept	β_0	-3.321	1.249	0.016	74.71		14.044	0.312	0.296
		ln(H)	β_1	2.899	0.384	<0.001					
	4.15	Intercept	β_0	-4.717	0.868	<0.001	89.06		-2.722	0.205	0.195
		$\ln(DBH^2H)$	β_1	1.033	0.083	<0.001					
	4.16	Intercept	β_0	4.9E+00	0.135	<0.001	83.31		5.731	0.253	0.240
		DBH^2H	β_1	3.0E-05	0.000	<0.001					
	4.17	Intercept	β_0	-4.964	0.839	<0.001	90.09		-3.840	0.195	0.180
		ln(DBH)	β_1	1.629	0.303	<0.001					
		ln(H)	β_2	1.595	0.341	<0.001					
	4.18	Intercept	β_0	-3.551	1.089	0.005	80.33		9.870	0.275	0.254
		ln(DBH)	β_1	2.814	0.321	<0.001					
		ln(p)	β_2	0.552	0.343	0.127					
	4.19	Intercept	β_0	-5.510	0.314	<0.001	83.74		4.824	0.243	0.222
		ln(DBH)	β_1	2.459	0.285	<0.001					
		ln(CBH)	β_2	1.009	0.338	0.009					
	4.20	Intercept	β_0	-5.074	0.743	<0.001	92.26		-14.146	0.173	0.132
		ln(DBH)	β_1	1.812	0.278	<0.001		2.183			
		ln(H)	β_2	1.573	0.302	<0.001		2.021			
		ln(p)	β_3	0.517	0.216	0.029		1.141			

Note: independent variables used in the models are; DBH (diameter at 1.3 m from ground level), H represents tree height (m), (DBH^2H) is a combined variable, ρ is basic wood density and CBH is crown base height (m).

As for branch and foliage biomass, several models for stem wood prediction were tested, based on findings from the literature. Models with the smallest or negative AIC values were sought. Of the models listed in Table 4.5, Model 4.20, which incorporated DBH, tree height and wood density, fitted the data best. Low variance inflation factors (VIFs), for the correlated variables such as DBH, tree height and wood density were observed in Model 4.20. The study, opted to use variable DBH (Model 4.13) for upscaling because it was capable of predicting stemwood biomass while meeting the parsimoniousness and additivity requirements outlined in Chapter 3, section 3.8.

A strong positive correlation between stemwood biomass and DBH was observed with the R^2 and *p*-value (Table 4.5). Homoscedasticity was assessed by fitting the residuals against the predicted values. Figure 4.6 had no visible pattern demonstrating that the residuals were similar the same across the data.

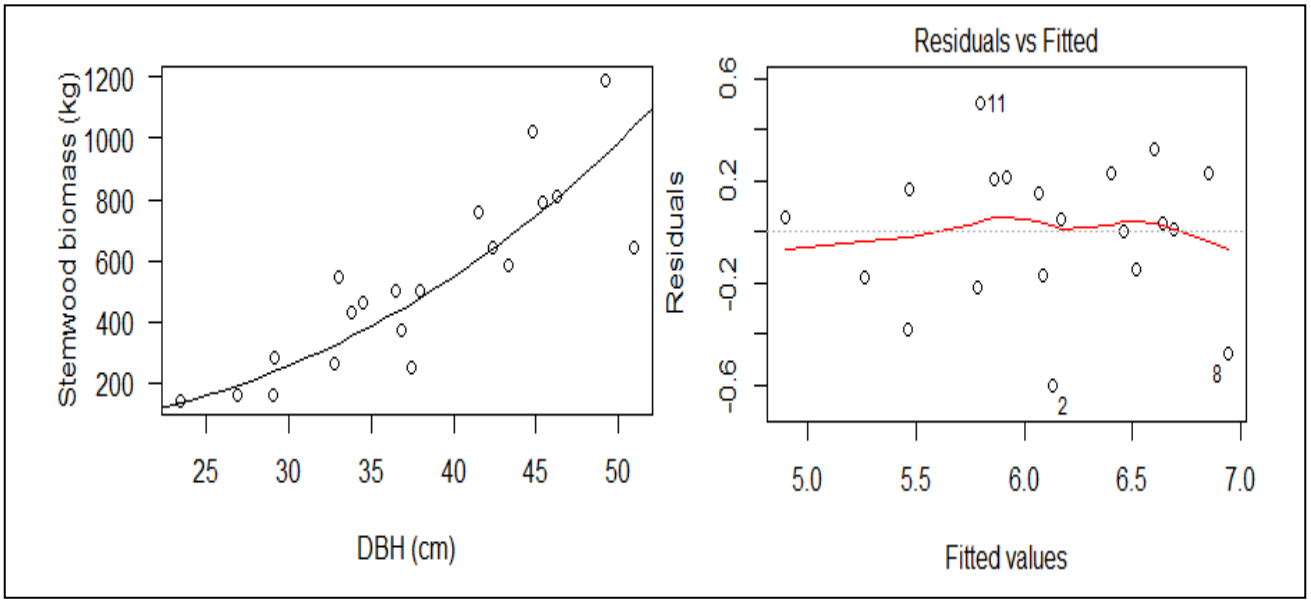

Figure 4.6: (a) Stemwood biomass and DBH and height combined variable (b) model fitted vs. residual plot.

4.3.4 Bark

A summary of candidate models are given in Table 4.6.

Table 4.6: Summary of bark model performance.

Model	Predictors	Parameter	Estimate	SE	*P*	R^2	AIC	RSE	RMSE
4.21	Intercept	β_0	-4.072	1.069	0.00128	74.47	8.3904	0.271	0.257
	ln(DBH)	β_1	2.2196	0.296	<0.001				
4.22	Intercept	β_0	-3.564	1.311	0.014	62.67	15.991	0.327	0.311
	ln(H)	β_1	2.310	0.403	<0.001				
4.23	Intercept	β_0	-4.717	0.868	<0.001	89.06	-2.722	0.205	0.195
	ln(DBH^2H)	β_1	1.033	0.083	<0.001				
4.24	Intercept	β_0	3.0E+00	0.146	<0.001	73.95	8.796	0.274	0.259
	DBH^2H	β_1	2.4E-05	0.000	<0.001				
4.25	Intercept	β_0	-5.860	1.384	<0.001	76.85	6.677	0.256	0.233
	ln(DBH)	β_1	2.110	0.300	<0.001				
	ln(CBH)	β_2	0.803	0.356	0.01811				

Note: independent variables used in the models are; DBH (diameter at 1.3 m from ground level), H represent s tree height (m), (DBH^2H) is a combined variable and CBH is crown base height (m).

Though models using different predictors (Model 4.23 and Model 4.25) performed substantially better than the rest of the models as evidenced by its goodness of fit criteria. Model 4.21 was regarded as the best because of additivity reasons, and the preferable one for the prediction of bark biomass. This is consistent with the criteria stated for selecting models for biomass components in this study. For instance, stemwood biomass (Model 4.13 in Table 4.5). Homoscedasticity for the model was verified by plotting the residuals against predicted values. There was no clear evidence of homoscedasticity in the modelled data (Figure 4.7). Signs of outliers were observed in the bark biomass data; observation 2, 11 and 14.

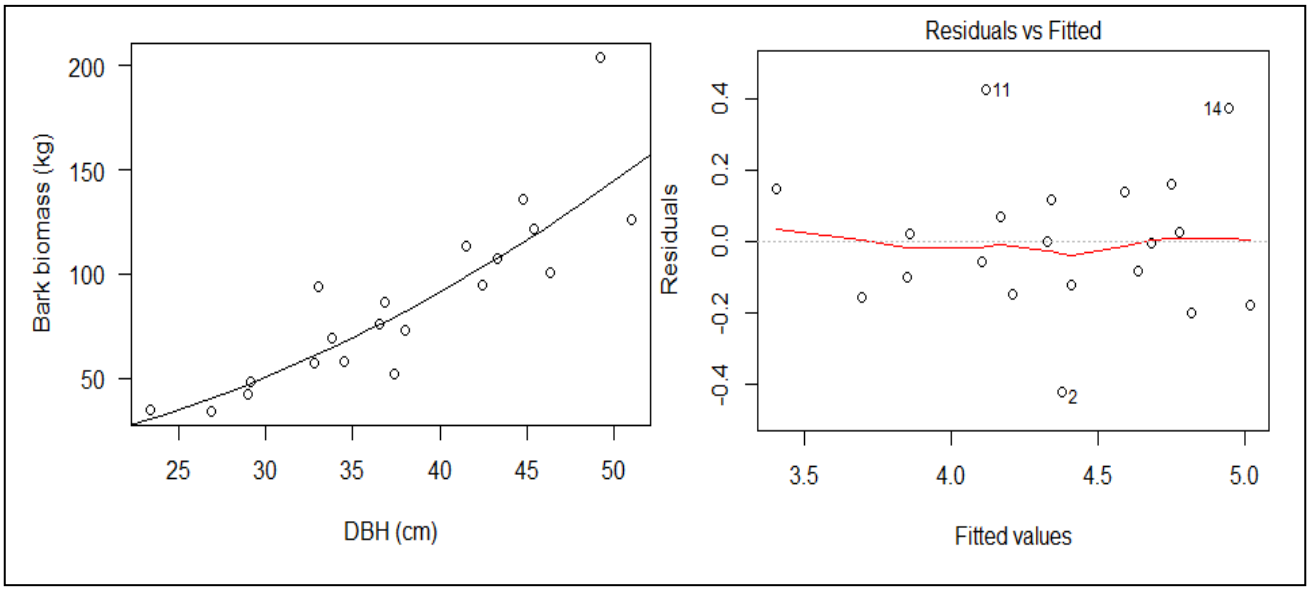

Figure 4.7: (a) Bark biomass and DBH (b) model fitted vs. residual plot.

4.3.5 Tree biomass model

A summary of the goodness-of-fit and parameter estimates for a variety of candidate models for estimating tree biomass is presented in Table 4.7.

Table 4.7: Summary of tree model performance.

	Models	Predictors	Parameter	Estimate	SE	*P*	R^2	AIC	RSE	RMSE
Tree biomass	4.26	Intercept	β_0	-2.684	0.877	0.007	84.8	0.552	0.222	0.221
		ln(DBH)	β_1	2.514	0.243	<0.001				
	4.27	Intercept	β_0	-2.063	1.238	0.113	70.7	13.707	0.309	0.293
		ln(H)	β_1	2.602	0.380	<0.001				
	4.28	Intercept	β_0	-3.847	0.681	<0.001	92.3	-12.187	0.158	0.146
		ln(DBH)	β_1	1.764	0.246	<0.001				
		ln(H)	β_2	1.190	0.277	<0.001				
	4.29	Intercept	β_0	-3.745	0.665	<0.001	92.4	-13.409	0.157	0.149
		$\ln(DBH^2H)$	β_1	0.968	0.063	<0.001				
	4.30	Intercept	β_0	5E+00	1E-01	<0.001	87.6	-3.515	0.201	0.191
		DBH^2H	β_1	3E-05	2E-06	<0.001				

Note: independent variables used in the models are; DBH (diameter at 1.3 m), H represents tree height (m) and D^2H is a combined variable.

Though the combined variable model (DBH^2H) was best model based of the goodness-of-fit statistics, the parsimonious Model 4.26, with DBH as a predictor was used to upscale total tree to plot level. Homoscedasticity was evaluated by plotting the residuals against

the fitted values. The plot showed that Figure 4.8 had no visible pattern demonstrating that the residuals were almost the same across the data.

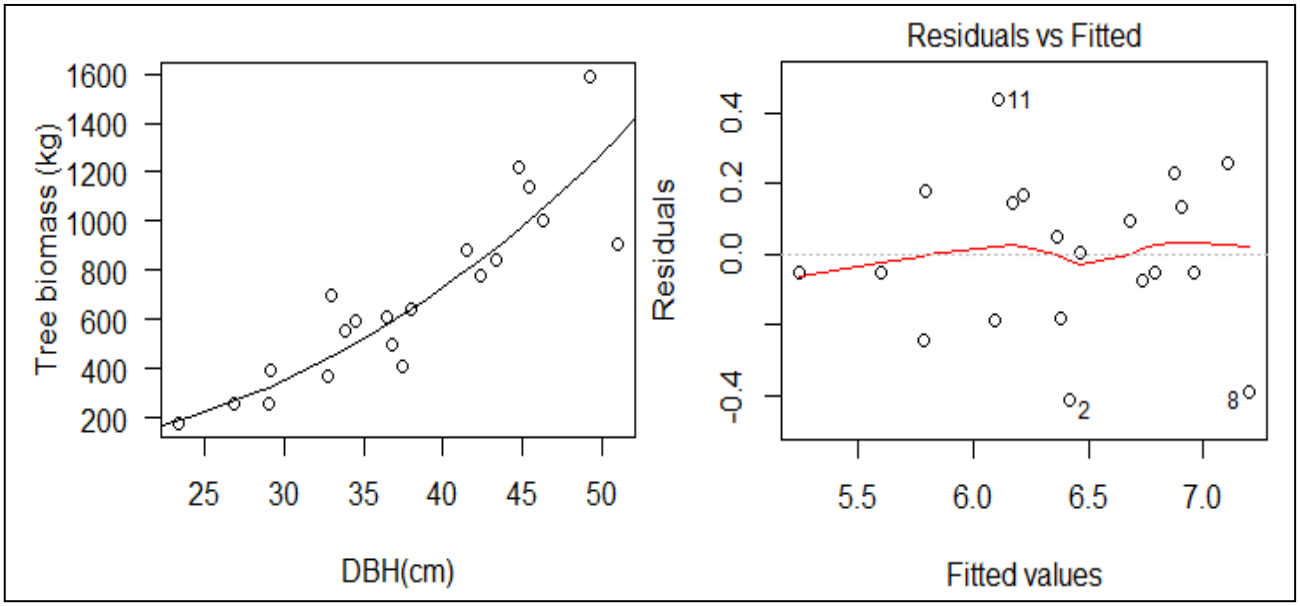

Figure 4.8: (a) Tree biomass and DBH and height combined variable (b) model fitted vs. residual plot.

4.4 UPSCALING II

As discussed in the literature review and material and methods chapters, the conventional method used in this study entails employing uniform independent variables and the same weight functions for all tree component models and the total tree model thereby achieving additivity automatically.

4.4.1 Biomass components

To satisfy the requirements of conventional additivity, models with the same predictor ln(DBH) were used. These are presented in Table 4.7 and Figure 4.10.

Table 4.8: Summary of models for upscaling.

Model	Component	Predictors	Parameter	Estimate	SE	*P*	R^2	RSE	RMSE
4.31	Needles	Intercept	β_0	-1.475	1.328	0.281	38.6	0.337	0.319
		ln(DBH)	β_1	1.321	0.367	0.002			
4.32	Branches	Intercept	β_0	-4.791	1.548	0.006	63.3	0.390	0.370
		ln(DBH)	β_1	2.486	0.428	<0.001			
4.33	Bark	Intercept	β_0	-4.072	1.069	0.00128	74.5	0.271	0.257
		ln(DBH)	β_1	2.2196	0.296	<0,001			
4.34	Stemwood	Intercept	β_0	-3,410	1,132	<0.001	78.6	0,287	0,272
		ln(DBH)	β_1	2,634	0,313	<0.001			
4.35	Total tree	Intercept	β_0	-2.684	0.878	0.006	84.8	0.222	0.211
		ln(DBH)	β_1	2.514	0.243	<0.001			

Note: independent variables used in the models are; DBH (diameter at 1.3 m from ground level).

Logarithmic transformed models selected from the above tables for upscaling the biomass of each component to stand level are summarised in Table 4.8 (Models 4.33, 4.34 and 4.35 from Table 4.4, 4.5 and 4.6). Figure 4.9 shows transformed DBH models and their confidence levels.

4.4.2 Model predictions

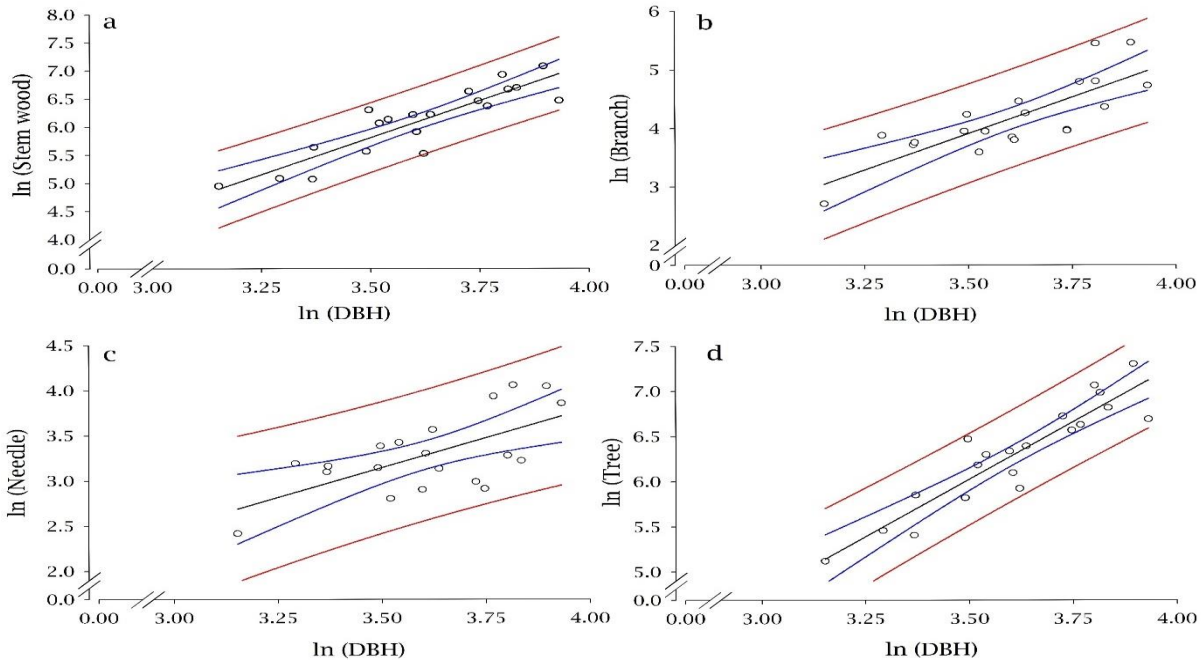

Figure 4.9: Models for estimating tree and biomass components DBH (diameter at 1.3 m from ground level) as the predictor. 95% confidence interval was computed for each sample to observe if 95% of the intervals would contain the population mean. Note: stemwood (a), branch (b), needle (c) and total tree (d).

4.4.3 Predicted biomass

Closeness to the 1-1 line was assessed by plotting the observed values of the biomass components against the predicted values (Figure 4.10). The R^2 coefficient of determination for stemwood, branches, needles and total tree was 70.32, 52.06, 39.04 and 76.73 respectively.

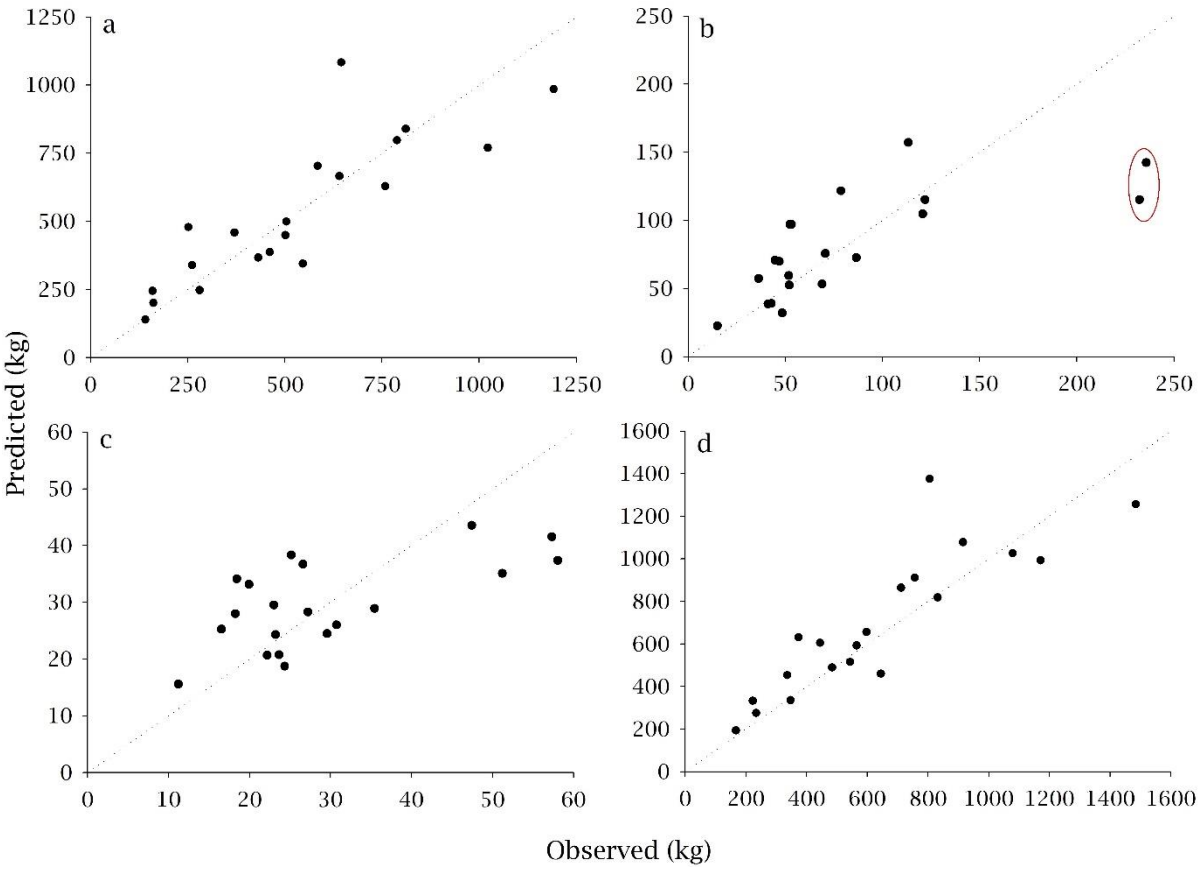

Figure 4.10: Observed versus predicted needle biomass with a 1:1 line (as reference). Stemwood (a), branch (b), needle (c) and total tree (d). Note the point shown on the branch.

Model performance tests indicated that the stemwood and total tree estimates agreed better with observed values. The models were markedly closer to the 1-1 line compared to the branch and needle models. Relationship between predicted and observed values for branch and needle components showed no tendency to over or under estimate the results except for the large branches denoted in red in Figure 4.10. As shown previously in Table 4.2, branch length of the trees sampled across the younger (Site 1) and older sites (Site 2 and 3) ranged from 7 cm to 710 cm while branch diameter ranged from 0.6 cm to 10 cm.

4.5 VOLUME UPSCALING

To upscale volume to plot level, the actual volume measurements used both Smalian and Huber's volume formula to improve the accuracy of the volume measurement of sampled tree sections. It is important to note that the Smalian formula requires two diameter measurements for volume calculation; that is the thick end side (base) and thin end side (tip) while the Huber's formula consider the mid-point diameter. Therefore, to be consistent with the requirements of the volume formulas and the weighting approach discussed in the methodology section, the study used the Smalian formula to calculate volume for the first section at the thick end section of the stem with no measurement at mid-point diameter (0 m to 1.3 m) while the Huber's formula was used for the rest of the stem sections (with a measured mid-point diameter). Predictor variables were transformed; DBH, H, DBH^2Ht and CBH. Table 4.9 provides more detail of the considered models.

Table 4.9: Stem volume model performance.

	Models	Predictors	Parameter	Estimate	SE	*P*	R^2	RSE	RMSE
Stem volume	4.30	Intercept	β_0	-10.652	0.795	<0.001	90.98	0.189	0.179
		ln(DBH)	β_1	2.983	0.221	<0.001			
	4.31	Intercept	β_0	-9.189	1.299	0.016	73.51	0.324	0.306
		ln(H)	β_1	2.851	0.400	<0.001			
	4.32	Intercept	β_0	-11.539	0.453	<0.001	97.34	0.103	0.097
		$\ln(DBH^2H)$	β_1	1.112	0.043	<0.001			
	4.33	Intercept	β_0	-0.154	0.092	0.113	94.06	0.166	0.157
		DBH^2H	β_1	0.000	0.000	<0.001			
	4.34	Intercept	β_0	-12.397	0.820	<0.001	94.55	0.144	0.131
		ln(DBH)	β_1	2.887	0.181	<0.001			
		ln(CBH)	β_2	0.769	0.201	0.002			
	4.35	Intercept	β_0	-11.554	0.466	<0.001	97.19	0.105	0.097
		ln(DBH)	β_1	2.165	0.180	<0.001			
		ln(H)	β_2	1.183	0.190	<0.001			

Note: independent variables used in the models are; DBH (diameter at 1.3 m from ground level), H represents tree height (m), DBH^2H is a combined variable and CBH is crown base height (m).

After considering the parsimoniousness of the Model 4.35 and its goodness of fit. Model 4.32 (Combined Variable) was selected as the best model for upscaling stem volume to plot and stand level.

4.5.1 Volume-DBH relationship

The relationship of the measured volume against DBH of the trees is shown in Figure 4.11.

The residual against predicted (fitted) values plots for volume was consistent on a range of predicted values indicating homoscedasticity of residuals.

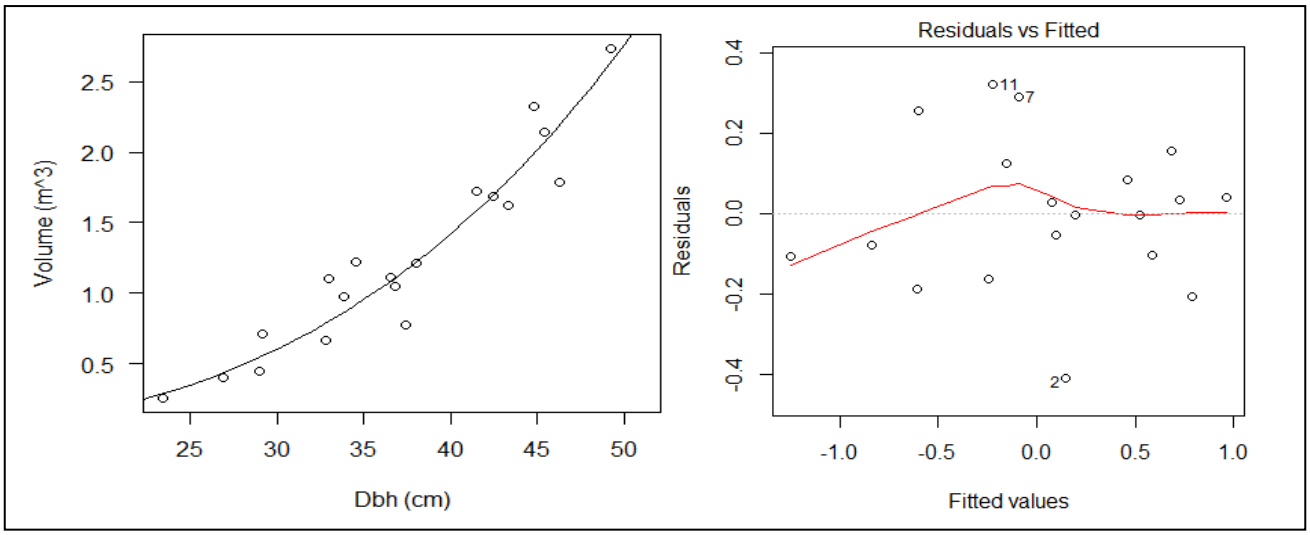

Figure 4.11: (a) Volume and DBH (b) model fitted vs. residual plot.

4.5.2 Parameterising for volume prediction

The widely-used volume models were parameterised for volume prediction (Figure 4.12). These were: Combined Variable, Standard Form Factor Model (based on the Max and Burkhart taper function) and Schumacher and Hall.

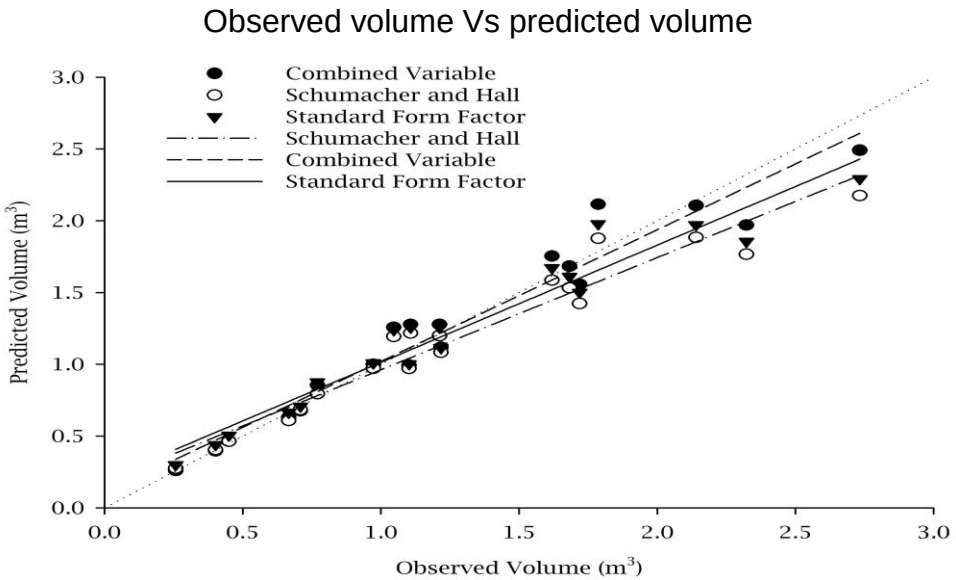

Figure 4.12: Comparison of the three volume models considered with a 1:1 line.

For comparison purposes, widely used Schumacher and Hall and Standard Form Factor Model published volume parameter estimates were used for estimating *P. elliottii*.

However, the Combined Variable Model was the only model fitted with coefficients for estimation that were generated from the data of this study. The Combined Variable Model was selected because it had the highest R^2 value of 94.43 and a markedly significant model p-value ($p < 0.0001$). The Standard Form Factor Model also fitted well, with an R^2 value of 94.08, followed by the Schumacher and Hall which had a lower R^2 value of 93.90.

4.6 ABOVEGROUND BIOMASS ESTIMATION

Table 4.10: Summary of the AGB biomass at stand level.

AGB is reported in Mg ha^{-1}, stand age given in years and stand volume (m^{-3} ha^{-1}).

Stand age (years)	BEF	Stand volume (m^{-3} ha^{-1})	Stand biomass (Mg ha^{-1})
16	0.81	289	98.8
28	1.06	581	253.9
33	0.96	585	204.5

The range in AGB (98 – 253.9 Mg ha^{-1}) varied with stand age.

4.6.1 Biomass allocation

Table 4.11: Summary of the AGB components in kg ha^{-1}. Biomass is reported for each component (needles, bark, branch and stemwood). Percentage (%) of the components to the total AGB are also given.

Stand age (years)		Biomass (Kg ha^{-1})	(%)
16	Needle	11542.382	
28		11374.660	
33		12106.606	
Total		35023.648	6.7%
16	Bark	27964.524	
28		35475.526	
33		35874.041	
Total		25021.220	4.8%
16	Branch	23646.622	
28		33308.315	
33		33416.562	
Total		90371.498	17.2%
16	Stemwood	148916.481	
28		225809.535	
33		222604.340	
Total		374726.016	71.4%

Overall, stemwood had the highest percentage of biomass followed by bark, branch and needles (Table 4.11).

4.7 ESTIMATION OF NUTRIENT CONCENTRATION

Table 4.12 and 4.13 shows a summary of estimated macro and micro nutrient concentration of Site 1 (younger stand), and Site 2 and 3 combined (older stands) in mg kg^{-1} and %. Laboratory results of the concentration are shown in Appendix VII. The variability in nutrient concentrations was relatively small for most nutrients. The highest nitrogen (N) concentration was found in needles, while the stemwood had the lowest concentration. The younger stand had lower concentrations than the older stands.

Table 4.12: Site 1 summary of estimation of nutrient concentration.

Site 1		N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
Component		(%)	(%)	(%)	(%)	(%)	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
	Mean	0.23	0.01	0.13	0.07	0.03	4.40	22.40	1.40	2.00	2.20
Stemwood	SD	0.04	0.00	0.03	0.01	0.01	2.19	6.54	0.55	0.71	0.45
	Mean	0.27	0.02	0.17	0.20	0.07	12.20	34.60	2.20	3.80	5.20
Branches	SD	0.03	0.00	0.02	0.02	0.02	2.17	5.13	0.45	0.84	0.84
	Mean	0.76	0.07	0.53	0.24	0.11	27.75	125.25	3.00	11.50	15.25
Needles	SD	0.34	0.01	0.13	0.03	0.01	6.40	28.79	0.00	2.65	0.50
	Mean	0.24	0.01	0.13	0.10	0.04	4.24	23.50	1.60	4.86	5.85
Bark	SD	0.09	0.01	0.08	0.08	0.04	2.38	4.12	0.00	4.19	2.50

Table 4.13: Site 2 and 3 summary of estimation of nutrient concentration.

Site 2 & 3		N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B
Component		(%)	(%)	(%)	(%)	(%)	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
	Mean	0.26	< 0	0.06	0.09	0.02	6.93	24.07	0.87	2.27	1.13
Stemwood	SD	0.05	0.00	0.01	0.02	0.01	3.01	13.01	0.35	0.96	0.64
	Mean	0.31	0.01	0.10	0.28	0.06	13.73	37.00	1.53	5.27	7.07
Branches	SD	0.04	0.01	0.03	0.07	0.01	4.37	34.08	0.52	2.84	3.88
	Mean	0.89	0.06	0.38	0.58	0.15	119.07	77.57	2.18	18.68	21.14
Needles	SD	0.18	0.01	0.09	0.19	0.04	85.37	23.26	0.46	11.78	5.41
	Mean	0.30	0.02	0.11	0.12	0.03	5.33	27.40	1.73	8.33	5.60
Bark	SD	0.10	0.01	0.05	0.05	0.01	2.19	10.25	0.46	4.01	1.30

Table 4.14: Summary of measured nutrient export of biomass components.

Site	Components	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})	Mn (kg ha^{-1})	Fe (kg ha^{-1})	Cu (kg ha^{-1})	Zn (kg ha^{-1})	B (kg ha^{-1})
1	Bark	70.15	124.70	43.82	119.03	21.34	0.49	0.61	0.06	0.54	0.23
1	Branch	66.77	42.73	29.96	95.09	13.75	0.63	1.26	0.06	0.18	0.39
1	Needles	107.30	7.91	48.19	89.84	17.19	1.52	1.47	0.03	0.99	0.24
1	Stemwood	317.95	137.06	115.41	128.53	25.85	1.30	3.08	0.16	0.60	0.22
1	Total Tree	562.17	312.40	237.38	432.49	78.14	3.94	6.42	0.31	2.32	1.09
2	Bark	113.13	131.12	52.07	125.44	23.30	0.51	0.76	0.08	0.55	0.28
2	Branch	103.70	50.55	38.01	121.07	18.11	0.78	1.56	0.07	0.23	0.45
2	Needles	106.26	7.61	49.16	89.11	16.96	1.48	1.44	0.03	0.91	0.25
2	Stemwood	596.89	168.29	118.27	184.92	25.67	1.75	4.53	0.23	0.78	0.25
2	Total Tree	919.98	357.58	257.52	520.55	84.04	4.52	8.29	0.41	2.47	1.23
3	Bark	114.18	126.80	51.08	121.34	22.63	0.49	0.74	0.07	0.53	0.27
3	Branch	104.19	49.51	37.51	119.50	17.94	0.77	1.54	0.07	0.22	0.44
3	Needles	99.46	75.57	46.10	83.42	15.87	1.38	1.35	0.03	0.85	0.23
3	Stemwood	617.17	167.20	114.76	186.89	24.79	1.75	4.59	0.24	0.78	0.25
3	Total Tree	935.00	419.09	249.45	511.15	81.23	4.40	8.22	0.41	2.38	1.19

4.8 ESTIMATION OF NUTRIENT EXPORT

The nutrient export potential associated with AGB for all the three sites are summarised in Table 4.14. As trees are always debarked off-site, nutrients in bark is always added to stemwood loss. In all sites, stemwood exported more nutrients per kg ha^{-1} than any biomass component. Stand age also influenced the overall nutrient export. Older stands (28 and 33 years) exports more nutrients than the younger stand (16 years).

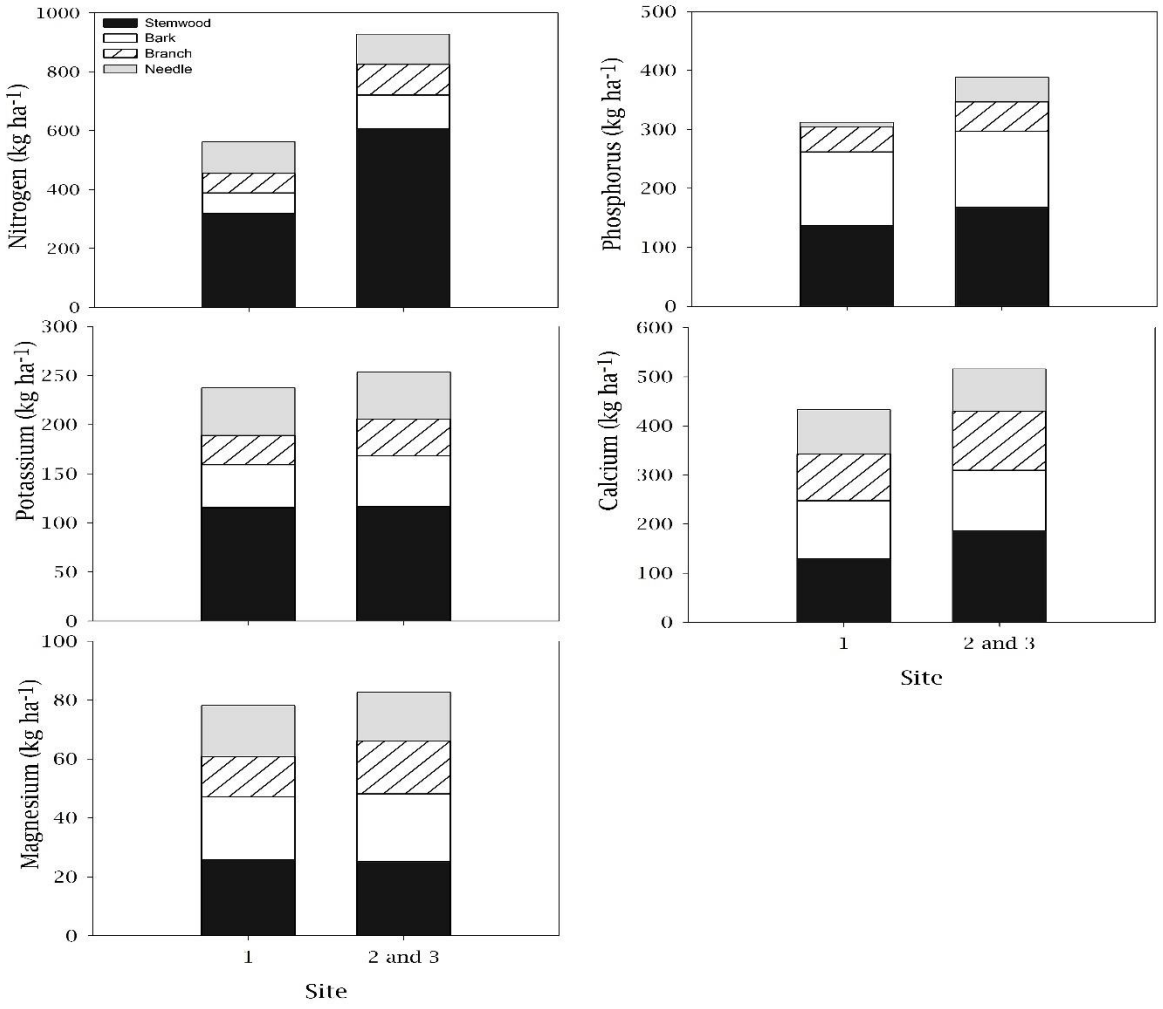

Figure 4.13: Calculated macro-nutrient mass contained in *P. elliottii* biomass components from Site 1 (younger stand) and Site 2 and 3 combined (older stands).

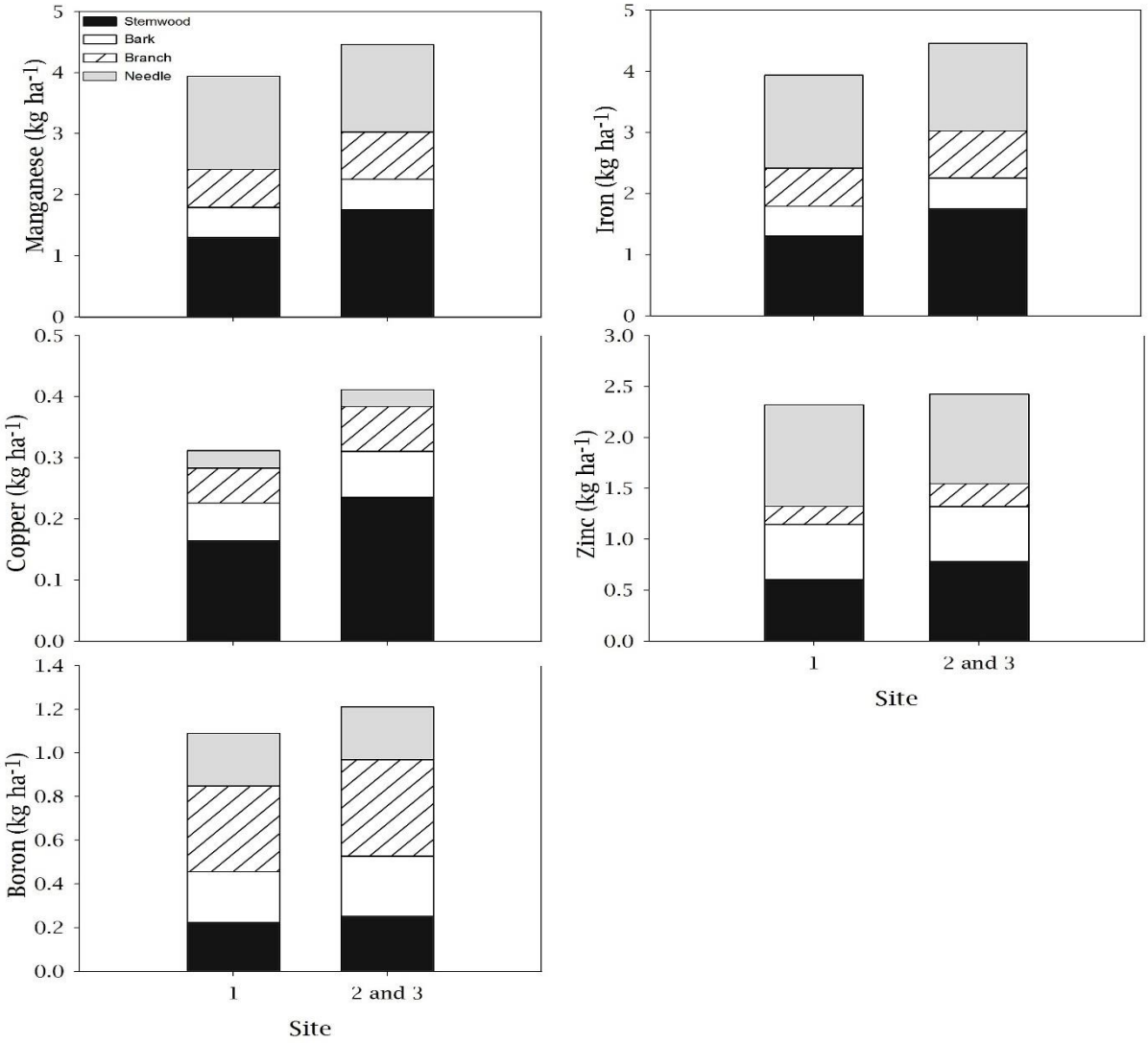

Figure 4.14: Calculated micro-nutrient mass contained in P. elliottii biomass components from Site 1 (younger stand) and Site 2 and 3 combined (older stands).

A general increase in nutrients export in the older stands was observed. Macro-nutrient such as N, Ca and P were exported more in older stands than in the younger stand. However, P and Mg loss was constant across all stand ages. A larger export of micro-nutrients which include Mn, Fe and Zn was also noted. It is important to highlight that as trees are always debarked off-site, nutrients in bark are always added to stemwood loss.

Chapter 5: Discussion

5.1 DBH-Height models

Site-specific height models with independent variables such as ln(DBH) and 1/DBH were practical inputs in biomass modelling (Brown et al. 1989; Chave et al. 2015). Model 4.2 with 1/DBH exhibited a better fit than Model 4.1 (DBH) in predicting height of the Site 1 (younger trees). Model 4.2 explained 66.9% of height variation. As for the older stand, both Model 4.3 and Model 4.4 did not predict well tree heights. Model 4.4 showed less good fits (R^2 = 21.71%) likely because of variation in tree height among sampled trees with the same DBH (Picard et al. 2012). The variation could have also been caused by measurement and recording errors.

5.2 UPSCALING I

5.2.1 Crown

Logarithmic transformed models with variables; d, l, dl and d^2l were explored in the estimation of needle biomass (Table 4.3). Combined variable (d^2l) with R^2 of 83.20% proved to be the best model. Comparing the selected models (Model 4.5 and Model 4.9), for needle and branch biomass, the R^2 (72.59%) of needle biomass was lower than that of branch biomass (77.8%). According to Nemeth (1973), this is because of the relatively shallow regression slope. This shows that there is a strong relationship between DBH and branch biomass than DBH and needles (Figure 4.4). Unlike the branch biomass, the needle biomass has a lower R^2 because of the disproportion in quantity of needles within live crown branches (Saint-André et al. 2004). The general variability in crown material was also proved by the findings of Pienaar (2016), van Zyl (2015) and Mensah et al. (2016). In other studies, the weak relationship between branch dimeter and needles mass was attributed to change of season, diseases, and defoliating events such as fire (Ryan et al. 2006; Gonzalez-Benecke et al. 2014). In this study, Site 1 with the younger trees had lower crown biomass possibly due to late pruning and a fire event which occurred prior to the biomass sampling in 2014.

5.2.2 Stemwood biomass

The combined variable model ln(DBH^2H) was a significant predictor of stemwood as it

exhibited the best fit. However, authors such as Sileshi (2014) caution against employing of compound models with multiple independent variables. Collinearity between DBH, H and density had low VIF values ranging from 1.141 to 2.183 (Table 4.4). This means standard error of the variable may be 2.18 times higher than it would have been if not correlated with others predicting variables. The VIF value has a lower bound of 1 but no upper bound. Studies differ on how high the VIF must be to constitute a problem. Recommendations for acceptable levels of VIF have reported the maximum level of VIF to be 10, 5 and 4 (Neter et al. 1989). Therefore, it seems, that most studies can use whichever maximum VIF limit to help augment their understanding about the predicting variables. On the other hand, Picard et al. (2012) believes that additional variables (such as height and density) have no influence on the predictability of a model and its statistical precision. Nevertheless, it must be specified in this perspective that collinearity overstatedly increase the model p-values and R^2 values, which may mislead interpretation of the predicting variable of the model.

5.2.3 Bark

Amongst the predicting variables explored in this study, DBH^2H performed markedly better (R^2 = 73.95) than the rest of the bark predictors as evidenced by the goodness of fit criteria of Model 4.23. The results of the study showed that ln(H) is not comparable to ln(DBH) in predicting biomass components. Other *P. elliotttii* studies have used combined predicting variables with logarithmically transformed DBH^2 and H (Nemeth 1973; Jokela and Martin 2000).

5.3 WOOD DENSITY

Considering the growing environments of the specific sites (Tsitsikamma region), the mean wood densities were anticipated to be lower as compared to the trees growing in *P. patula* environments (Poynton, 1979; du Toit et al. 2012). A study reported by Stöhr (1980) on 13 year old South African *P. elliottii* trees, density ranged from 315 – 615 kg m^{-3} with a mean density of 420 kg m^{-3}. Therefore, since sampled trees are constituted of low density wood, estimated biomass will be low than when the wood has higher density values.

5.4 UPSCALING II

ln(DBH) was not comparable to ln(DBH^2H) in the general performance of all upscaling models. However, ln(DBH) was used to upscale all biomass components (Table 4.8). ln(DBH) met the desired requirements of parsimony and additivity. To attain additivity, a consistent model was selected in which the sum of the components matched the predicted whole (Parresol 1999). Though it was practical to use ln(DBH^2H), as it performed better than ln(DBH) in upscaling biomass components. This study, opted to use variable ln(DBH) because of its simplicity. Parsimony was a wanted property since it minimised propagation error, especially when a height model was initially employed to predict another variable (H).

5.5 ABOVEGROUND BIOMASS

The allometric relationship established in this study could predict AGB of 20 trees across the three sampled sites. The older trees (28 and 33 years) had significantly more biomass than the younger trees (16 years). Total AGB for the 28 and 33-year-old *P. elliottii* stands was 253.9 Mg ha^{-1} and 204.5 Mg ha^{-1}, respectively. As Gower et al. (1994) notes, there is a strong relation between stand age and biomass growth. The estimated AGB per ha calculated within the present study is different from the findings of Gholz and Fisher (1982) which ranged from 98.3 Mg ha^{-1} to 192.3 Mg ha^{-1} for 33-year-old *P. elliottii*. The estimated total biomass for the 16-year-old stand was 98.9 Mg ha^{-1}. This is in line with Gonzalez-Benecke et al. (2010a) and Shan et al. (2001) studies, who reported a range from 86 to 143 Mg ha^{-1} for a stand with 16 and 17-year-old trees in USA. The results of this study concur with local biomass studies on *P. radiata* done by van Laar and van Lill (1978) and van Zyl (2015). van Laar and van Lill reported AGB of 184.86 Mg ha^{-1} and van Zyl published an AGB which ranged from 63.2 to 255.2 Mg ha^{-1}. The low SPH (347 SPH) due to thinning of the 28-year-old trees in 2014 likely eased resource competition thereby leading to abnormally big branches prone to the natural pruning effect associated with *P. elliottii*. The ripple effect was likely increase in crown growth as evidenced by the branch metrics in Table 4.2.

5.6 BIOMASS EXPANSION FACTORS

The BEF values of 0.81, 0.96 and 1.37 for Site 1, 2 and 3 were within the BEF range reported by FAO (2012) and IPCC (2003) which have a maximum value of 1.3. The BEF results of this study show that they were stand age dependent. The older stands tended to have higher BEF values (0.96 – 1.37) than the younger stand.

5.7 OPTIMUM NUTRIENT RATIOS

Results of this study were compared to international studies by Linder (1995*)* in Sweden and Hockman and Allen (1990) in USA which reported ideal ratios of nutrient to nitrogen.

Table 5.1: Optimum nutrient ratios expressed as percentage of nitrogen. Comparison of the optimum nutrient ratios for Site 1 and Site 2 and 3 was done against Linder (1995) and Hockman and Allen (1990) for *Pinea abies* and Eucalyptus.

Nutrient	Site 1	Site 2 & 3	Linder (1995)	Hockman & Allen (1990)
N	100	100	100	100
P	9.5	7.2	10	8.3
K	68.9	42.3	35	37.1
Ca	31.0	64.4	2.5	32.7
Mg	13.9	16.7	4	11.8
Mn	0.9	4.8	0.05	-
Fe	4.1	3.1	0.2	-
Cu	0.1	0.1	0.03	-
Zn	0.4	0.8	0.05	-
B	0.5	0.9	0.05	-

N and P content in younger trees (Site 1) was within the ratio recommended by Linder (1995*)*. However, Site 2 and 3 (older trees) were not within the reported P ratios. The values of the rest of the nutrients were parallel with published results on other commercial species reported by Linder (1995) and Hockman and Allen (1990).

5.8 NUTRIENTS

5.8.1.1 Nitrogen (N)

Site 1 and Site 2 and 3 (combined) reported N concentration of 0.61% and 0.89%, respectively. The results of this study indicate deficiency of N content when compared to other pine species is comparable. Boardman *et al.* (1997) indicate that the ideal foliage N concentration range for other mature pine species such as *P. radiata and P. taeda* is <1.0% and juvenile (<1.0 to 1.2%). Also, the amount of N that is exported with the biomass components other than the merchantable stems is proportionally lower than the amount that is exported in the merchantable stems. According to the study results, potential for N export in Site 1 is lower (562.2 kg ha^{-1}) than Site 2 with mature trees (920 kg ha^{-1} and 935 kg ha^{-1}).

5.8.1.2 Phosphorus (P)

For both younger (Site 1) and older trees (Site 2 and 3), P concentration of foliage was 0.06 mg kg^{-1}. This value falls short of the marginal (0.75 to 0.08 mg kg^{-1}) reported in Australia by Boardman et al. (1997). However, results of this study are somewhat similar to those reported by van Zyl (2015) in South Africa of a *P. radiata* stand (0.05 mg kg^{-1}). The stemwood and the bark biomass components had the highest P export in both young and mature sites. The amount of P that is removed with the biomass components other than the stem is proportionally greater than the amount that is exported via stemwood.

5.8.1.3 Potassium (K)

Studies is USA and Australia reported that adequate K concentration in *P. elliotti* should be within the range of 0.35 to 0.4% and <0.3% indicate deficiency (Boardman *et al.* 1997). Results for younger trees (0.42%) and older trees (0.38%) are parallel with the proposed adequate range. Younger trees had the lowest K total export potential (237.38 kg ha^{-1}) than the older trees. This was greater than the highest nutrient loss predicted in *P. radiata* (208.30 kg ha^{-1}) by van Zyl (2015).

5.8.1.4 Calcium (Ca)

Site 1 with younger trees had a Ca concentration of 0.19% and Site 2 and 3 were within the expected range (0.58%). There was a relatively similar pattern in Ca loss between the

younger and older trees. Using results from Australia, Spain and Turkey, Boardman *et al.* (1997) indicated that the adequate foliage Ca concentration range for *P. elliotti* is between 0.33 to 0.74%. Ca concentration in needles of younger trees was below the published range. However, comparing younger trees to older trees, nutrient export in younger trees was slightly lower (432.49 kg ha^{-1}) when all the biomass components were summed. The amount of Ca that is removed with the biomass components other than the stem is greater than the amount that is contained in the stemwood. It has been reported that commercial forestry plantations on base-rich soils accumulate more Ca and Mg in the biomass than plantations on leached soils such as those in the Tsitsikamma region (Herbert 2003; Dovey 2009).

5.8.1.5 Magnesium (Mg)

Nutrient concentration results of Mg show that both young trees (0.09%) and older trees (0.15%) were deficient of Mg. For studies done in Australia, Boardman et al. (1997) reported values less than 0.80%. Mg accumulation was similar across older sites (Site 2 and 3), with the younger trees had a marginally lower export potential (78.14 kg ha^{-1}). The Mg export was greater in stemwood and bark components and relatively lower in the branches of younger trees and needles in general.

5.8.1.6 Copper (Cu)

As per the results of the studies done in South Africa and Australia, Cu deficiency is pegged at < 2 mg kg^{-1} and the adequate range lie between 2 to 18 mg kg^{-1} (Boardman *et al.* 1997). Results of this study show that Cu is within the adequate range for both younger and older trees. The mean Cu concentration of younger trees was 9.27 mg kg^{-1} and 21.14 mg kg^{-1} for older trees. The amount of Cu that is removed with the stemwood is more than 50% of the Cu nutrient exported. This implies a great proportion of the Cu is exported through stemwood than in biomass components such as needles.

5.8.1.7 Iron (Fe)

Boardman et al. (1997) recommended that the ideal foliage Fe content range for *P. elliotii* between is 65 mg kg^{-1} and 404 mg kg^{-1}. All sites of this study were within this range. The Fe concentration in younger trees was higher (100.66 mg kg^{-1}) than in older trees (77.57 mg kg^{-1}). It important to point out that Fe concentration in the younger site was by far the

highest observed nutrient as compared to other micro-nutrients analysed. Also, Fe export declined with stand age. The highest export potential was in Site 3 stemwood (4.59 kg ha-1) and the lowest was in the bark of younger trees in site (0.61 kg ha-1).

5.8.1.8 Manganese (Mn)

Mn content for *P. elliottii* in Australia ranged from 284 mg kg^{-1} and the marginal is 21 mg kg^{-1} (Boardman et al. 1997); the sites reported in this study were below the adequate range but within the marginal. The Mn content ranged from 22.39 mg kg^{-1} to 119.07 mg kg^{-1} in the older trees of this study (28 and 33 years). In all the three sites, the highest Mn export was recorded in the stemwood component of the tree. While Mn export of needles decreased with stand age, Mn export in branch and bark components stabilised with age.

5.8.1.9 Boron (B)

B concentration in the needles increased with stand age. Site 1 with younger trees had 12.27 mg kg^{-1} B concentration, while the mean of Site 2 and 3 was 21.14 mg kg^{-1}. Boardman et al. (1997) reports that concentration range of B within the range of 8 to 10 mg kg^{-1} is considered as deficiency. It is important to note that the highest B accumulation in both young and old sites in this study was observed in the branches. The amount of B that is lost with the biomass components other than the stemwood is greater than the amount that is exported in stemwood biomass. Therefore, whole tree biomass harvesting poses a significant threat to B cycling.

5.8.1.10 Zinc (Zn)

Studies have reported that the adequate concentration range of Zn in *P. elliottii* foliage should be between 10 to 68 mg kg^{-1} and deficiency is between 6-10 mg kg^{-1} (Boardman et al. 1997). In the two main stand ages (younger and older) of this study, the Zn concentration was 12.27 mg kg^{-1} and 21.14 mg kg^{-1}. The results show that the sites are not Zn deficient. Zn export results indicate a decrease in accumulation with stand age. For instance, in younger trees the Zn export potential is 0.99 kg ha^{-1} and in older trees it is 0.91 kg ha^{-1}. It is important to note that Zn export is greater in needle, followed by the stemwood, bark and branch components.

Chapter 6: Conclusion and Recommendations

In conclusion, this study has generated allometric models that allow us to accurately estimate AGB and nutrient export of *P. elliottii* based on measurable predictors derived from a destructive sampling approach. Wood basic density equations can be improved upon, should more tree samples be collected across geographical regions and forest sites.

As the *P. elliottii* resource in South Africa represent a far larger portion in terms of plantation ha, the results of this study need to by including different sites. To minimise bias in AGB estimations, the study recommends that the developed allometry model be applied within its valid diameter range as indicated by the inventory data (Table 3.1). Further sampling is essential because it will extend the diameter range of the allometric model thereby increasing the replication and confidence of prediction the entire *P. elliottii* resource which is comprised of; pulp wood, saw-log and peeler logs (> 55 cm).

The IPCC default over-bark BEFs ranging between 1.15 and 3.4 (IPCC (2006) provided for temperate broad leaf and pine plantation trees overestimate total AGB compared to the BEF values of this study which were 0.81, 0.96 and 1.37 for Site 1, 2 and 3.

The results of this study show that harvesting stemwood and bark accentuates the export of nutrients from forest sites by almost two-fold. It is also apparent that the shift to whole tree biomass increase harvestable biomass per hectare and the export of nutrients. To comprehensively appreciate the impacts of the nutrient losses reported in this study, it would be critical to define the nutrient budget of each site against nutrient cycle system as suggested by Payn & Clinton (2005).

The study recommends that future allometry studies on *P. elliottii* should possibly consider increasing study sites and incorporating other significant related variables such as MAP, stand age and site index (productivity) in *P. elliottii* allometric models to determine if they provide more accurate AGB predictions.

REFERENCES

Ackerman P, Ham C, Dovey S, du Toit B, de Wet J, Kunneke A, Seifert T, Meincken M, von Doderer C (eds). 2013. *State of the art of the use of forest residue for bioenergy in southern Africa*. Forest Engineering Southern Africa (FESA) and Institute for Commercial Forestry Research (ICFR) Report No. 03/2013. Pietermaritzburg.

Akaike H. 1973. Information theory and an extension of the maximum likelihood principle. In: B. N. Petrov (Ed.): *Proceedings of the Second International Symposium on Information Theory Budapest*: Akademiai Kiado, 267-281.

Allison P. 2012. Statistical Horizon. *When can you safely ignore multicollinearity*. http://statisticalhorizons.com/multicollinearity.

American Society for Testing and Materials. 2008. D 2395-07: *Standard test methods for specific gravity of wood and wood-based materials*. Available from Canadian Standards Association (CSA), Mississauga, Canada. http://www.csa.ca.

Anderson DR, Burnham K.P, White GC. 1994. AIC Model Selection in Overdispersed Capture-Recapture Data. *Ecological Society of America* 75(6): 1780-1793.

Baldwin VC. 1986. A summary of equations for predicting biomass of planted southern Pines. In: Lohrey RE (ed). *Estimating Tree Biomass Regressions and Their Error, Proceedings of the Workshop on Tree Biomass Regressions Functions and Their Contribution to the Error of Forest Inventory Estimates*, May 26–30, Syracuse NY, For. Serv. Exp. St, pp. 157–171.

Banks CH. 1969. Spiral grain and its effect on the quality of Southern African timber. *Forestry in South Africa* 10:27-33.

Baskerville GL. 1972. Use of Logarithmic Regression in the Estimation of Plant Biomass. *Canadian Journal of Forest Research* 2(1):49-53.

Binkley D. 1986. Forest Nutrition Management. John Wiley and Sons, Inc.

Bird DN, Pena N, Schwaiger H, Zanchi G. 2010. Review of existing methods for carbon accounting. Bogor, Indonesia: *Center for International Forestry Research (CIFOR)*. p. 50.

Boardman R, Cromer R, Lambert M, Webb M. 1997. Forest plantations. In: Reuter, DJ & Robinson, JB. (eds.) *Plant analysis and interpretation manual Australia: CSIRO Publishing*, pp. 505-566.

Bollandsås OM. 2007. Uneven-aged forestry in Norway: inventory and management models. PhD thesis, *Norwegian University of Life Science, Norway*.

Brown S, Gillespie AJR, Lugo AE. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest Science* 35: 881- 902.

Brown S, Gillespie AJR, Lugo AE. 1991. Biomass of tropical forests of South-east Asia. *Canadian Journal of Forest Research* 21: 111-117.

Brown S. 2002. Measuring carbon in forests: current status and future challenges. *Environmental Pollution* 116: 363-372.

Burnham KP, Anderson DR. 2002. *Model selection and inference. A practical information-theoretic approach*, 2nd edn. Springer, Berlin Heidelberg New York

Carlson CA, Allan R (eds). 2001. *A pilot study into the above ground biomass of a mature Pinus patula stand*. Report No. *ICFR Bulletin Series* 20/2001.

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Folster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riera B, Yamakura T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* 145: 87-99.

Chave J, Condit R, Aguilar S, Hernandez A, Lao S, Perez R. 2004. Error propagation and scaling for tropical forest biomass estimates. *Philosphical Transactions. Royal Society Biological Science Journal*, 359: 409 - 420.

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M, Martínez-Yrízar A, Mugasha WA, Muller-Landau HC, Mencuccini M, Nelson BW, Ngomanda A, Nogueira EM, Ortiz-Malavassi E, Pélissier R, Ploton P, Ryan CM, Saldarriaga JG, Vieilledent G. 2015. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology* 20: 3177–3190.

Chmura DJ, Rahman MS, Tjoelker MG. 2007. Crown structure and biomass allocation patterns modulate aboveground productivity in young loblolly pine and slash pine. *Forest Ecology and Management* 243(2): 219-230.

Cook, R. Dennis (March 1979). "Influential Observations in Linear Regression". Journal of the American Statistical Association. *American Statistical Association*. 74 (365): 169–174.

Correia AC, Tome M, Pacheco CA, Faias S, Dias AC, Freire J, Carvalho PO, Pereira JS. 2010. Biomass allometry and carbon factors for a Mediterranean pine (Pinus pinea L.) in Portugal. *Forest Systems* 19(3): 418-433.

Coyle DR, Coleman MD, Aubrey DP. 2008. Above- and below-ground biomass accumulation, production, and distribution of sweetgum, and loblolly pine grown with irrigation and fertilisation. *Canadian Journal of Forest Research* 38: 1335-1348.

Cunia T. 1986. Construction of tree biomass tables by linear regression technique. In: Wharton EN, Cunia T (ed.), Estimating tree biomass and their error. USDA, *Northeastern Forest Experimental Station*, Broomall, Pennsylvania.

Cunia T, Briggs RD. 1985. Forcing additivity of biomass tables: use of the generalized least squares method. *Canadian Journal of Forest Research*. 15(1): 23–28

DAFF. 2011. *A profile of South African Forestry and wood production market value.* Arcadia, South African.

DEAT. 2006. *South Africa Environment outlook: A report on the state of the environment*. Department of Environmental Affairs and Tourism. Pretoria. 42pp.

Dovey SB. (ed). 2014. *Current carbon stock estimation capability for South African commercial plantation forests*. Department of Environmental Affairs. Pietermaritzburg.

Dovey SB. 2009. Estimating biomass and macronutrient content of some commercially important plantation species in South Africa. *Southern Forests Journal* 71(3): 245–251.

du Toit B. 2012. Matching site, species and silvicultural regime to optimise the productivity of commercial softwood species in southern Africa. In Bredenkamp, BV and Upfold, S., (Eds). *South African Forestry Handbook*, Fifth edition. Southern African Institute of Forestry, Pretoria, South Africa. Chapter 2.3, pp 43-49.

du Toit B, Botman I, Kunneke A. 2012. *Tree-based strategies to mitigate climate change whilst providing bio-energy, employment and ecosystem services in the Winelands region, Western Cape, South Africa*. IUFRO Forest Ecology symposium:

Sustaining forests and humans in changing landscapes, 5-12 November 2012, Concepción, Chilé.

du Toit B, Dovey S, Seifert T, Muyambo P, Malherbe D. 2016. *Carbon sequestration in South African plantation forests. Progress report number 1: Techniques to estimate net carbon sequestration carbon at the Tier 2 level using available data from local studies and international literature*. Unpublished manuscript, University of Stellenbosch, South Africa.

du Toit B, Dovey SB, Fuller GF, Job RA. 2004. *Effects of Harvesting and Site Management on Nutrient Pools and Stand Growth in a South African Eucalypt Plantatio*n. In Nambiar EKS, Ranger J, Tiarks A, Toma T (eds). Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Congo July 2001 and China February 2003. Centre for International Forestry Research, Bogor, Indonesia. Pp31-43.

du Toit B, Dovey SB. 2002. Trip report on the 4th workshop in the CIFOR network. Site Management and Productivity in Tropical Forests 9-12 July 2001. *ICFR Bulletin Series 02*.

du Toit B, Scholes MC. 2002. Nutritional sustainability of Eucalyptus plantations: A case study at Karkloof, South Africa. *Southern Africa Forestry Journal*.195:63-72.

FAO. 2012. *Manual for building tree volume and biomass allometric equations from field measurement to prediction*. Springer, Rome, Italy.

Feldpausch TR, Banin L, Phillips OL, Baker TR, Lewis SL, Quesada CA, AffumBaffoe K, Arets EJMM, Berry NJ, Bird M, Brondizio ES, de Camargo P, Chave J, Djagbletey G, Domingues TF, Drescher M, Fearnside PM, França MB, Fyllas NM, Lopez-Gonzalez G, Hladik A, Higuchi N, Hunter MO, Iida Y, K. A. Salim KA, Kassim AR, Keller M, Kemp J, King DA, Lovett JC, Marimon BS, Marimon-Junior BH, Lenza E, Marshall AR, Metcalfe DJ, Mitchard ETA, Moran EF, Nelson BW, Nilus R, Nogueira REM, Palace M, Patiño S, Peh KSH, Raventos MT, Reitsma JM, Saiz G, Schrodt F, Sonké B, Taedoumg HE, Tan S, White L, Wöll H, Lloyd J. 2011. Height-diameter allometry of tropical forest trees. *Biogeosciences* 8: 1081–1106.

FES. 2011. *Report on commercial timber resources and primary roundwood processing in South Africa for the period 2009 to 2010*. Department of Agriculture, forestry and fisheries. Compiled on behalf of the Directorate: Forestry Regulation and Oversight, by Forestry Economics Services CC.

FSA (ed). 2011. *Forestry South Africa. Abstract of South African Forestry Facts for the Year 2010/11*. Forestry South Africa. Pietermaritzburg, South Africa.

Gholz HL, Fisher RF. 1982. Organic matter production and distribution in Slash Pine (Pinus elliottii) plantations. *Ecological Society of America* 63(6): 1827-1839.

Gibbs HK, Brown S, Niles JO, Foley, JA. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Letters* 2: 1-13.

Goicoa T, Militino AF, Ugarte MD. 2011. Modelling aboveground tree biomass while achieving the additivity property. *Environmental and Ecological Statistics* 18: 367-384.

Gonzalez-Benecke CA, Gezan SA, Albaugh TJ, Allen HL, Burkhart HE, Fox TR, Jokela EJ, CA Maier, Martin TA, Rubilar RA, Samuelson LJ. 2014. Local and general above-stump biomass functions for loblolly pine and slash pine trees. *Forest Ecology and Management* 334: 254–276.

Gonzalez-Benecke CA, Martin TA, Cropper Jr. WP, Bracho R. 2010a. Forest management effects on in situ and ex situ slash pine forest carbon balance. Forest Ecology Management. 260, 795–805.

Gower ST, Gholz HL, Kaneyuki N, Baldwin VC. 1994. Production and carbon allocation patterns in pine forests. *Ecological Bulletins* 43: 115-135.

GTOS. 2009. *Assessment of the status of the development of the standards for the terrestrial essential climate variables*. NRL, FAO, Rome.

Hockman JN, Allen HL. 1990. Nutritional diagnoses in loblolly pine stands using a DRIS approach: *North American Forest Soils*. pp. 500-514.

Husch B, Beers TW, Kershaw JA. 2003. *Forest Mensuration*. (4th edn). New Jersey: John Wiley and Sons, Inc.

IPCC. 2006. *IPCC guidelines for national greenhouse gas inventories*, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

Jokela, EJ, Martin TA. 2000. Effects of ontogeny and soil nutrient supply on production, allocation and leaf area efficiency in loblolly and slash pine stands. *Canadian Journal of Forest Research* 30, 1511–1524.

Kunneke A, van Aardt J, Roberts W, Seifert T. 2014. Localisation of biomass potentials In Seifert T. (ed.), Bioenergy from Wood: Sustainable Production in the Tropics, Managing Forest Ecosystems. Dordrecht: *Springer Science and Business Media*. pp 11-41.

Kalra YP. (ed.). 1998. *Handbook of Reference Methods for Plant Analysis*. Boca Raton, Fl: CRC Press.

Linder S. 1995. Foliar analysis for detecting and correcting nutrient imbalances in Norway spruce. *Ecological Bulletins* 44: 178-190.

Litton CM, Ryan MG, Tinker DB, Knight DH. 2003. Belowground and aboveground biomass in young post fire lodge pole pine forests of contrasting tree density, *Canadian Journal of Forest Research* Vol. 33(1): 351–363.

Louw JH, Smith CW. 2012. *Forest site classification*. In Bredenkamp BV (ed) South African Forestry Handbook 5th ed, South African Institute of Forestry, South Africa P 27.

Magalhães TM, Seifert T. 2015. Estimation of tree biomass, carbon stocks and error propagation in Mecrusse woodlands. *Open Journal of Forestry* 5: 471- 488.

Magalhães TM. 2016. *Estimation of tree biomass, measurement uncertainities, and morphological topology of Androstachys johnsonii* Prain. Phd Thesis. University of Stellenbosch, South Africa.

Magalhães TM. 2015. Allometric equation for estimating belowground biomass of *Androstachys jonhsonii* Prain. Carbon Balance and Management 10:16.

Martin TA, Jokela EJ. 2004. Stand development and production dynamics of loblolly pine under a range of cultural treatments in north-central Florida USA. Canadian Journal of Forest Research 30: 1511-1524. *Forest Ecology and Management* 192: 39-58.

Malan FS. The quality and wood properties of 4 provenances of South-Africa-grown Pinus tecunumanii. Annales des sciences forestieres, INRA/EDP Sciences, 1994, 51 (3), pp.203-212.

Mensah S, Kakaï RG, Seifert T. 2016. Patterns of biomass allocation between foliage and woody structure: the effects of tree size and specific functional traits. *Annals of Forestry Research* 59: 1.

Morris AR. 1986. *Soil fertility and long-term productivity of P. patula plantations in Swaziland*. Unpublished PhD thesis. University of Reading. pp 398.

Morris AR. 1992. Dry matter and nutrients in the biomass of an age Series of *Pinus patula* plantations in the Usutu Forest, Swaziland. *Southern Africa Forestry Journal*, 163: 5 - 11.

Nemeth JC. 1973. Dry matter production in young loblolly (Pinus taeda L.) and slash pine (Pinus elliottii Engelm.) plantations. *Ecology Monogram*. 43, 21–41.

Neter J, Wasserman W, Kutner MH. 1989. *Applied Linear regression models*. 2nd Edition. Irwin Homewood IL.

Ott RL, Jackson L, Service P, Walden HM, Rockwell P. 2001. *An Introduction to Statistical Methods and Data Analysis*. 5th ed, Pacific Grove, CA 93950 USA.

Parresol BR. 1999. Assessing tree and stand biomass: a review with examples and critical comparisons. *Journal of Forest Science*, 13:573–593.

Parresol BR. 2001. Additivity of nonlinear biomass equations. *Canadian Journal of Forest Research*. 31(2):865 878.

Paul K, Roxburgh SH., Chave J, England JR, Zerihun A, Specht A, Lewis T, Bennett LT, Baker TG, Adams MA, Huxtable D, Montagu KD, Falster DS, Feller M, Sochacki S, Ritson P, Bastin G, Bartle J, Wildy D, Hobbs T, Larmour J, Waterworth R,. Stewart HTL, Jonson J, Forrester DI, Applegate G, Mendham D, Bradford M, O'Grad A, Green D, Sudmeyer R, Rance SJ, Turner J, Barton C, Wenk EH, Grove T, Attiwill PM, Pinkard E, Butler D, Brooksbank K, Spencer B, Snowdon P, O'Brien N, Battaglia M, Cameron DM, Hamilton S, McAuthur G, Sinclair J. 2015. *Testing the generality of above-ground biomass allometry across plant functional types at the continent scale*. CSIRO Agriculture and CSIRO Land and Water, GPO Box 1700, Australia. doi: 10.1111/gcb.13201.

Payne RW. 2015. *A Guide to Regression, Nonlinear and Generalized Linear Models in Genstat* (18th Edition). Hemel Hempstead, Hertfordshire HP2 4TP, UK: VSN International. p. 85.

Peichl M, Arain MA. 2006. Above and belowground ecosystem biomass and carbon pools in an age-sequence of the temperate pine plantation forests. *Agriculture and Forest Meteorology* 140: 51-63.

Phiri D, Ackerman P, Wessels B, du Toit B, Johansson M, Säll H, Sven-Olof Lundqvist SO, Seifert T. 2015. Biomass equations for selected droughttolerant eucalypts in South Africa. *Southern Forests* 1-8.

Phiri D. 2013. Biomass modelling of selected drought tolerant Eucalypt species in South Africa. MSc. Thesis, University of Stellenbosch, Stellenbosch.

Picard N, Saint-André L, Henry M. 2012. *Manual for building tree volume and biomass allometric equations: from field measurement to prediction*. Food and Agricultural Organization of the United Nations, Rome, and Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Montpellier, 215 pp.

Pienaar LO. 2016. Modeling above-ground biomass of selected tree species within a Mistbelt forest in KwaZulu Natal. MSc. Thesis, University of Stellenbosch, Stellenbosch.

Pretzsch H, Dieler J. 2012. Evidence of variant intra- and interspecific scaling of tree crown structure and relevance for allometric theory. *Oecologia*, 169 (3) (2012), pp. 637–649

Pretzsch H. 2009. *Forest Dynamics, Growth and Yield*. From measurement to model.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07. http://www.rproject.org/contributors.html.

Ritson P, Sochacki S. 2003. Measurement and prediction of biomass and carbon content of Pinus pinaster trees in farm forestry plantations, south-western Australia. *Forest Ecology and Management* 175: 103-117.

Roxburgh SH, Paul KI, Clifford D, England JR, Raison RJ. 2015. Guidelines for constructing allometric models for the prediction of woody biomass: how many individuals to harvest? *Ecosphere*, 6, 1-27.

Ryan MG, Phillips N, Bond BJ. 2006. Hydraulic limitation hypothesis revisited. *Plant, Cell and Environment* 29, 367–381.

Samalca IK. 2007. Estimation of Forest Biomass and its Error A case in Kalimantan, Indonesia. University of Southampton (UK).

Sanquetta CR, Corte APD, da Silva F. 2011. Biomass expansion factor and root-to-shoot ratio for *Pinus* in Brazil. *Carbon Balance and Management*, 6:6.

Schulze RE, Maharaj, M, Lynch S.D, Howe BJ, Melvil- Thomson B. 1997. South African atlas of agrohydrology and climatology. *Water Research Commission*, Pretoria.

Seifert T, Schuck J, Block J, Pretzsch H. 2006. Simulation von Biomasse- und Nährstoffgehalt von Waldbäumen mit dem Waldwachstumssimulator SILVA. *Tagungsband der Jahrestagung der Sektion Ertragskunde im Deutschen Verband Forstlicher Forschungsanstalten*: 208 – 223.

Seifert T, Seifert S. 2014. Modelling and simulation of tree biomass In Seifert T (ed), *Bioenergy from Wood*: Sustainable Production in the Tropics, Managing Forest Ecosystems 26. Dordrecht: Springer Science and Business Media. pp 43-65.

Shan J, Morris L.A, Hendrick R.L. 2001. The effects of management on soil and plant carbon sequestration in slash pine plantations. *Journal of Applied Ecology* 38(5): 932-941.

SigmaPlot 2015. Systat Software, San Jose. California USA.

Sileshi GW. 2014. A critical review of forest biomass estimation models, common mistakes and corrective measures. *Forest Ecology and Management* 329: 237-254.

Somogyi Z, Cienciala E, Mäkipää R, Muukkonen P, Lehtonen A, Weiss P. 2007. Indirect methods of largescale forest biomass estimation. *European Journal of Forest Research* 126:197–207.

Stöhr HP. 1980. Initial Moisture Content and Density and Drying Rate of Three Pine Species Growing in the Natal Midlands. *South African Forestry Journal*, 114: 49-57.

UNFCCC (ed). 2009. Draft decision [-/CP.15] Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries. Subsidiary body for scientific and technological advice. Copenhagen.

UNFCCC. 2011. 17th Conference of the Parties to the United Nations Framework Convention on Climate Change and the 7th Meeting of the Parties to the Kyoto Protocol*2011, Durban Climate Change Conference, November 2011, COP 17*.

van Laar A and van Lear W. 1978. A biomass study in *Pinus radiata* D. Don. *South African Forestry Journal* 107 (1), pp. 71-76.

van Lear DH, Waide JB, Teuke MJ. 1984. Biomass and nutrient content on a 41-year-old loblolly pine (Pinus taeda L.) plantation on a poor site in South Carolina. *Forest Science Journal* 30: 392-403.

van Lear DH, Taras MA, Waide JB, Augspurger MK. 1986. Comparison of biomass equations for planted vs. natural loblolly pine stands of sawtimber size. *Forest Ecology and Management* 14: 205-210.

van Laar A, Akça A. 2007. Forest Mensuration: *Managing Forest Ecosystems*, Vol. 13 Springer Drodrecht.

van Laar A. 1973. A biomass study in Pinus radiata. *South African Forestry Journal*: 71–76.

van Laar A. 1982. Sampling for above-ground biomass for *Pinus radiata* in the Bosboukloof Catchment at Jonkershoek. *South African Forestry Journal,* 123 (1), pp. 8-13.

van Wyk B, van Wyk P. 2013. Field guide to Trees of Southern Africa. Cape Town: Struik Nature. Verwijst T. 1991. Logarithmic transformations in biomass estimation procedures: Violation of the linearity assumption in regression analysis. *Biomass and Bioenergy* 1: 175-180.

van Zyl SJ. 2015. Above-ground allometry and the implications for biomass harvesting potential and nutrient export of Pinus radiata in the Southern Cape region of South Africa. MTec thesis, NMMU, George, South Africa.

Vogel JS, Suau LJ, Martin TA, Jokela EJ. 2010. Long-term effects of weed control and fertilisation on the carbon and nitrogen pools of a slash and loblolly pine forest in north-central Florida. *Canadian Journal of Forest Research* 41: 552-567.

Wang X, Fang J, Tang Z, Zhu B. 2006. Climatic control of primary forest structure and DBH–height allometry in Northeast China. *Forest Ecology and Management* 234: 264-274.

West P. 2009. *Tree and forest measurement*. Dordrecht: Springer.

Xiao CW, Ceulemans. 2004. Allometric relationships for below and aboveground biomass of young Scots pines. *Forest Ecology and Management* 203: 177-186.

Xuanran L, Qijing L, Yongrui C, Lile H, Fengting Y. 2008. Aboveground biomass of three conifers in the Qianyanzhou plantation, Jiangxi Province, China. *Frontiers of Forestry in* China 3: 16.

Zao D, Kane M, Borders B, Subedi S, Akers M. 2012. Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year-old loblolly pine plantations in the Upper Coastal Plain and Piedmont of the southeastern United States. *Canadian Journal of Forest Research* 42(1): 111-122.

APPENDIX I

INSTRUCTIONS FOR ALLOMETRIC MEAUSUREMENTS

Field Work

Note: All samples earmarked for drying goes into paper bags.

bottom dics goes into plastic bags.

Before field trip: measure 10 paper bags of each size and record their weight.

NB!!! Each sample has to be labelled otherwise valuable data is lost. Always label packet before you put anything into it.

Stand Measurements

100 trees will be counted and their diameters recorded on the field form. Determine distribution of diameter / average diameter (compartment estimate). Record stems per hectare against compartment records (Microforest). Measure heights (30 trees) from a subset of the 100 trees. Determine sample trees which represent the distribution of the plot and mark for destructive sampling.

Tree measurements

Mark North direction and DBH on the standing tree

Record basic tree measurements (DBH)

Cut tree down, measure height (length), live crown base (to lowest live branch), dead crown base (to lowest dead branch) and pruning height (highest remains of pruning scars).

Measure height of whorls (cluster of branches within a 0.5m stem length) from tip (whorl 0) to live crown base and mark and number them (blue).

Make 3m sections, and mark them on the stem (black or red) acc. illustration with height in m (0, 3, 6,…) beginning from tree base

Take a handful of mature needle samples from branches in each section (0, 3, 6, 9 etc. not sample branch) for determination of specific leaf area (SLA), put in separate plastic bags and label and place in the cooling box.

Mark 2 adjacent discs at the lower end of each 3m section and at 1.3m, mark NORTH direction per disk!!

All branches

Record all live branch diameters per whorl on the measurement sheet.

Select 1 branch every 2nd whorl as a sample for detailed measurements, use a random number table to select the sample branch. Work from the bottom to top and from north and clockwise from the north mark. Select additional representative branches, if necessary to collect a minimum of 15 live crown sample branches per tree

Label the sample branch with masking tape and identify it on the field form by circling it.

Measure 2 diameters (Vert/hor) on the sample branch

Measure and record the sample branch length and the horizontal length (90° to the stem), then cut it off and put on sample branch heap.

Select three representative dead branches from the top middle and bottom of the dead crown. Label all three branches with masking tape as “dead crown sample branches”

Cut the dead crown sample branches and bulk it in short pierces in labelled paper bags

Cut and remove rest of branches, stack all dead branches on a plastic sheet for weighing in field and stack the rest of the live branches separately from sample branches

Weigh all the dead crown branches including the dead crown sample branches bag with a hand scale in field

Strip all leaves from sample branches and pack into labelled paper packets for each sample branch.

Cut all cones from sample branches and pack into labelled paper packets for each sample branch

Cut all remaining wood of sample branch and pack in labelled paper packets for each branch.

Stem needles and cone measurements

Strip needles from stem and pack separately in paper bag, label for drying in lab

Strip cones from stem and put in paper bags per 3m section. Label bags accordingly.

Sample disks

Cut 2 disks of 2.5 cm thick at the base of each 3m section and at DBH mark. We will call them top disk (T) and bottom disk (B).

Mark cut disks on top side, mark North direction on disks, write tree number and disk height beginning from base to tip, e.g. 3m, 6m 9m etc.

Paint the top side of the base disk (0m) of the top disks with 2,3,5-Triphnyltetrazodium chloride

Separate bottom disks (place in plastic bags) and top disks (place in paper packet)

Checklist

You should have the following sample sets once your tree has been processed:

A set of Top-disks compiled from each stem section plus the dbh disk

A corresponding set of Bottom-disks

A set of SLA needle samples in plastic packets

A set of three packets containing needles, cones and branch-wood from each sample branch

Cone samples and needle samples from the main stem

One bulk sample of representative branches from dead crown

You should also have the following data sets recorded:

Tree dbh, length, crown height and pruning height

Tree whorl heights

Branch diameters (measured in the vertical plane) of all branches per whorl

Branch diameters (measured hor. and vert.) for the sample branches

Laboratory Work

Leaves

Dry all leaf samples from the sample branches (stored in paper packets) to 65°C and record mass on a daily basis until a constant reading is obtained.

Branches

Weigh and record the lab mass (fresh mass, but after transport to lab) of all sample branches including the bulked dead crown sample branches as a first priority in the laboratory.

Remove sub-samples for nutrient analysis (one sub-sample per sample branch):

Use all sample branches for the sub-sample

Cut one thin-, medium- and thick- 5cm long pierces from each sample branch

Record the lab mass of the sub-sample per sample branch.

Bulk all sub-samples into one sample bag.

Place sub-sample in oven to dry at 65 °C and record dry mass daily until constant readings are obtained.

Remove sub-samples for drying to 105°C:

Select three sample branches from the top, middle and bottom of the crown for the sub-sample for drying to 105°C.

Place sub-samples in oven to dry at 105 °C and record dry mass daily until constant readings are obtained.

Calculate the moisture loss % from the lab mass to the dry mass at 105 °C.

On the spreadsheet, convert the total lab mass of all sample branches (including the sub-samples) to total dry mass (at 105 °C) per sample branch.

Dry the bulked dead crown sample branches in oven at 105 °C and record dry mass daily until constant readings are obtained.

Top disks

Measure diameter of disk over- and under bark

Measure diameter of stained heartwood on the base disk (0m) in the N-S and E-W direction

Debark disks, mark new paper bags with disk numbers for bark per disk in separate bags.

Dry bark and debarked disks at 105°C until mass reading is constant.

Weigh and record dry mass.

Bottom disks

Duplicate disk number on two halves.

Split wet disk with bark in 2 halves.

Half bottom disk for water displacement.

Debark disk and discard bark.

Place under water until saturated (for 7 - 14 days)

Measure water displacement with Archimedean principle

Dry half disk to 105°C and record mass until reading is constant.

Sub-samples for Nutrition analysis

Leaves

Within each tree, bulk together all the oven-dry leaf sub-samples per tree

Send one bulked sample per tree to laboratory for chemical analysis of essential nutrients.

Branches

Use branch sub-samples that had been dried at 65 °C.

Grind each sub-sample into powder using the coarse mill.

Send to laboratory for chemical analysis of essential nutrients.

Half bottom disk for nutrition analysis

Mark, and then cut out a wedge (including the bark) with 10 degree angle from each half disk (Mark February).

Debark the wedges and keep all the bark samples together for the whole tree in a paper packet.

Bulk all wedges from one tree together in a paper packet.

Dry the bulked wedges and bark sample in separate paper bags to 65°C until reading is constant.

Mark sample bags for chemical analysis and send to laboratory for chemical analysis of essential nutrients.

Checklist

You should have the following data sets at the end of the lab work sessions:

Dry mass of needles (dried at 65 °C), wood (dried at 105 °C and corrected for sub-sample taken at 65 °C) and cones (dried at 65 °C) *from each sample branch*

Dry mass and surface area of each SLA sample.

Paired data for water displacement and corresponding dry mass of half-disks – we will use this to determine wood density

Woody mass: bark mass ratio of all top disks dried at 105 °C – we will use this to estimate bark mass per tree.

Fresh cone mass of sample branches and stem cones plus the moisture content of a cone sub-sample

Dry mass of stem needles

Dry mass (dried at 105 °C) of dead crown sample

You should also have the following sub-samples per tree that have been prepared for lab analyses:

One bulked leaf sample

One bulked stem wood sample compiled from disk wedges

One bulked branch sample compiled from several small, medium and large branches taken from individual sample branches

One bulked bark sample compiled from the bark of several disk wedges

One cone sub-sample

APPENDIX II

EQUIPMENT AND MATERIAL FOR FIELD AND LAB WORK

- DBH tapes
- 20 m tape (or longer)
- hand held pruning scissors
- large pruning scissors
- clipboards
- pen, pencil and calculator
- small Calipers for branch diameters
- bow-saws
- score sheets
- camera
- first aid kit
- water, soap and paper towels, hand cleaner
- plastic bags
- paper bags with folded sides
- blue refuse bags
- cool box for sample storage and frozen ice bricks
- large plastic sheets
- large cardboard boxes
- box tape rolls
- masking tape rolls
- koki pens (red, blue and black)
- tree crayons
- danger tape
- onion bags
- 2 Chainsaws, serviced.

- chainsaw clothes
- hang scales
- gloves
- hard hats
- safety jackets
- vertex
- spray paint cans
- vessels for wood density determination
- small scales with large plastic weighing bowls
- Kiefer and Forestry lab oven-drying kilns

APPENDIX III

DBH AND HEIGHT MEASUREMENTS (preliminary plot sampling)

Compartment						
age						
Site						
HGT comp						
Vol/tr comp						
Plot length+width						
Site	DBH	HGT(30)	DBH	HGT(30)	DBH	HGT(30)
Tree Number						
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
.						
.						
.						
.						
.						
.						
90						
91						
92						
93						
94						
95						
96						
97						
98						
99						
100						

APPENDIX IV

MEASUREMENT OF TREE METRICS FORM A

Tree No			Compartment				Date				
Age (yr)			Spacing (m x m)								
DBH (cm)			Height (m)								
Prune height (m)			Dead Crown base (m)				Live Crown base (m)				
Student names:											
Section Height (m)	0m	1.3m	3m	6m	9m	12m	15m	18m	21m	24m	27m
Sub-sample Disk bottom(B) measurements:											
whole disk fresh mass (g)											
Sub-sample fresh mass (g)											
bark whole disk fresh mass (g)											
Sub-sample dry mass (g)											
Density disk displacement (g)											
Density disk dry mass (g)											
Bark whole disk dry mass (g)											
Sub-sample Disk top(T)											
Diameter with bark (cm) N-S											
Diameter with bark (cm) E-W											
Diameter under bark (cm) N-S											
Diameter under bark (cm) E-W											
Circumference of missing bark (cm)											
Diameter heartwood (cm) N-S											
Diameter heartwood (cm) E-W											

Average of 10 paper bags (g)		
Dry mass needles on stem (g)		
Field mass Dead crown all branches (g)		

APPENDIX V

MEASUREMENT OF BRANCH WHORL METRICS FORM

Tree																	
Branch diam.(m)										Sample branches				Fresh mass (g)			
Whorl	ht (m)	Φ 1	Φ 2	Φ 3	Φ 4	Φ 5	Φ 6	Φ 7	Φ 8	L (cm)	hor dist to stem (cm)	Φ vert (mm)	Φ hor (mm)	Needle mass	Cone mass	Woody mass	
1																	
2																	
3																	
4																	
5																	
6																	
7																	
.																	
.																	
.																	
76																	
77																	
78																	
79																	
80																	
81																	
82																	
83																	
.																	

APPENDIX VI

Whorl	RANDOM NUMBER TABLE															
1	6	9	2	3	4	1	0	6	4	5	3	0	4	9	8	2
2	6	1	2	9	9	2	0	9	10	3	1	4	6	4	2	3
3	7	1	3	0	7	3	6	3	8	4	9	4	5	3	4	7
4	6	3	2	6	3	2	2	5	5	5	8	7	0	2	8	2
5	4	0	7	4	7	9	4	9	2	2	8	4	6	3	10	7
6	5	0	1	6	5	3	0	4	5	4	1	2	8	7	0	3
7	9	5	3	7	9	0	4	1	4	4	8	8	2	6	5	3
8	1	2	2	2	8	0	5	0	6	7	4	6	6	8	6	3
9	6	10	7	7	2	10	3	2	4	9	5	2	10	4	6	1
10	2	6	3	6	9	9	1	0	5	6	5	5	5	8	4	7
11	3	7	4	5	7	8	6	4	1	10	1	9	3	4	9	6
12	2	9	4	3	10	2	6	4	7	2	7	10	9	2	0	6
13	9	8	5	9	5	6	9	3	1	1	9	5	1	2	9	1
14	6	5	9	5	7	3	8	3	7	6	2	2	7	4	7	5
15	9	6	2	8	1	10	2	3	6	3	2	5	9	0	4	3
16	6	2	5	7	6	3	6	7	0	1	2	8	7	6	3	7
17	9	8	8	6	5	1	10	9	5	5	8	6	8	6	6	1
18	9	7	2	10	8	8	2	0	2	1	3	1	1	7	8	2
19	7	3	8	6	10	6	1	6	6	4	9	5	6	4	4	3
20	2	6	10	3	3	1	5	9	6	0	4	3	0	7	8	7
21	1	5	2	1	6	4	8	5	2	3	9	6	3	9	8	6
22	8	2	4	8	6	2	4	1	2	1	9	9	1	6	2	4
23	3	10	6	7	2	9	6	8	1	1	9	1	5	7	6	6
24	3	6	1	7	0	6	2	6	5	2	8	5	9	5	0	4
25	6	7	3	6	5	0	1	1	2	8	6	0	2	8	4	5
26	0	6	8	0	1	5	6	1	5	6	8	9	5	4	6	2
27	2	7	8	9	6	5	8	4	8	10	10	0	2	8	10	1
28	2	9	5	9	1	4	9	7	4	0	7	7	2	6	4	1
29	4	4	7	4	1	5	8	7	7	1	9	8	7	6	5	3
30	7	4	2	2	0	1	1	0	10	3	6	6	5	0	8	8
31	5	4	1	6	3	5	8	6	2	0	8	9	5	9	3	6
32	1	6	0	2	4	6	5	4	5	8	1	2	2	1	1	9
33	1	4	10	5	2	1	3	7	3	4	6	2	7	7	6	5
34	10	7	6	2	6	7	1	2	2	8	8	5	5	4	5	3
35	10	1	1	9	6	5	6	0	2	3	2	3	8	1	7	6
36	1	4	6	0	7	3	6	9	1	1	6	7	2	7	7	7
37	6	10	7	1	7	4	6	6	1	7	6	1	3	9	0	5
38	9	6	2	3	7	3	9	8	5	8	0	4	8	8	5	0
39	1	1	2	2	1	7	4	3	3	6	2	2	3	2	0	7
40	4	1	4	5	8	3	4	3	6	1	8	4	1	10	1	0
41	7	0	9	3	0	2	9	8	7	6	6	2	2	4	10	3
42	1	10	7	0	8	5	5	5	3	9	7	6	1	3	0	9
43	2	5	9	2	6	0	7	9	9	5	3	9	3	6	7	4
44	7	2	10	3	9	4	7	0	6	5	6	4	0	8	0	6
45	2	3	1	6	4	8	5	4	5	4	0	4	1	3	7	1
46	8	9	1	9	2	1	6	7	0	6	7	8	6	1	4	0
47	7	1	7	6	5	6	6	6	3	3	9	1	0	5	2	1
48	2	3	0	7	0	8	0	4	0	5	5	8	7	5	8	5
49	10	8	8	4	5	6	9	4	6	1	7	1	9	0	6	8
50	4	5	1	3	0	5	1	8	9	6	7	8	8	7	4	4

APPENDIX VII

www.bemlab.co.za
deel van die PathCare Groep van maatskappye

Van der Berg Singel 16
Gant's Sentrum
Strand

Posbus 684
Somerset Mall,
7137

Tel. (021) 853-1490
Faks (021) 853-1423

E-Pos admin@bemlab.co.za

Vat Reg. No. 4200161414

Verslag No.: **BL25277_a** *(Vervang verslag no.: BL025277.DOC)*

Mark Februarie
Universiteit van Stellenbosch
Dept. Bos- en Houtkunde

Blaarontledingsverslag

Datum ontvang: 18/11/2014
Datum ontleed: 20/11/2014

Boord	Lab. No.	Vrugsoort	Kultivar	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
				%					mg/kg					
Needles SLA- Tree 50	25277			0.91	0.07	0.45	0.26	0.12	774	35	162	3	12	16
Needles SLA- Tree 51	25278			1.00	0.07	0.57	0.26	0.11	601	21	134	3	15	15
Needles SLA- Tree 52	25279			1.01	0.08	0.68	0.23	0.09	693	24	106	3	10	15
Needles SLA- Tree 53	25280			0.76	0.07	0.40	0.19	0.10	802	31	99	3	9	15
Needles SLA- Tree 61	25281			0.99	0.05	0.36	0.56	0.18	380	185	95	3	38	22
Needles SLA- Tree 62	25282			0.82	0.06	0.29	0.74	0.17	696	94	117	2	16	22
Needles SLA- Tree 63	25283			1.05	0.06	0.25	0.69	0.19	413	381	107	3	40	26
Needles SLA- Tree 65	25284			0.89	0.05	0.29	0.58	0.15	489	80	94	2	33	20
Tree Disc 50	25285			**0.22**	0.01	0.13	0.08	0.03	174	8	29	2	3	3
Tree Disc 51	25286			**0.27**	0.01	0.13	0.08	0.02	150	3	30	1	2	2
Tree Disc 52	25287			**0.18**	0.01	0.09	0.06	0.02	96	3	19	1	2	2
Tree Disc 53	25288			**0.26**	0.01	0.16	0.06	0.04	142	5	17	1	1	2
Tree Disc 54	25289			**0.20**	0.01	0.12	0.06	0.03	81	3	17	2	2	2
Tree Disc 61	25290			**0.20**	0.00	0.07	0.09	0.02	82	12	11	1	2	2
Tree Disc 62	25291			**0.18**	0.00	0.06	0.08	0.01	64	5	11	1	1	1
Tree Disc 63	25292			**0.26**	0.00	0.08	0.09	0.01	58	11	22	1	2	2
Tree Disc 64	25293			**0.20**	0.01	0.08	0.09	0.02	84	4	14	1	2	2
Tree Disc 65	25294			**0.21**	0.00	0.07	0.08	0.01	52	3	33	1	1	1
Tree Branches 50	25295			**0.28**	0.02	0.16	0.22	0.07	213	14	37	2	4	6
Tree Branches 51	25296			**0.27**	0.02	0.15	0.18	0.05	217	9	28	2	3	4
Tree Branches 52	25297			**0.29**	0.02	0.18	0.20	0.06	268	13	31	2	5	5
Tree Branches 53	25298			**0.28**	0.02	0.21	0.19	0.09	266	14	36	3	4	6
Tree Branches 54	25299			**0.22**	0.02	0.16	0.22	0.08	200	11	41	2	3	5
Tree Branches 61	25300			**0.29**	0.01	0.08	0.34	0.05	173	21	39	2	8	3
Tree Branches 62	25301			**0.28**	0.01	0.09	0.31	0.05	168	13	39	1	3	3
Tree Branches 63	25302			**0.25**	0.01	0.09	0.19	0.04	222	23	32	2	3	3
Tree Branches 64	25303			**0.23**	0.02	0.17	0.25	0.06	157	13	51	2	5	4
Tree Branches 65	25304			0.32	0.02	0.13	0.29	0.06	199	14	32	2	7	4
Tree Bark 50	25305			**0.24**	0.01	0.08	0.08	0.03	246	4	19	2	4	6
Tree Bark 51	25306			0.37	0.03	0.27	0.24	0.11	323	8	27	2	12	11

Hierdie laboratorium neem deel aan die Agrilasa gehalte skema

Boord	Lab. No.	Vrugsoort	Kultivar	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
				%					mg/kg					
Tree Bark 53	25307			**0.19**	0.02	0.12	0.07	0.05	202	3	27	2	3	6
Tree Bark 54	25308			**0.17**	0.01	0.13	0.07	0.02	122	3	21	2	4	6
Tree Bark 61	25309			**0.14**	0.01	0.05	0.15	0.02	72	4	17	2	5	4
Tree Bark 62	25310			**0.14**	0.01	0.07	0.15	0.02	107	4	24	2	4	6
Tree Bark 63	25311			**0.18**	0.01	0.07	0.05	0.01	76	4	19	2	6	5
Tree Bark 64	25312			**0.16**	0.01	0.06	0.16	0.02	79	4	18	2	5	6
Tree Bark 65	25313			**0.19**	0.01	0.09	0.09	0.03	106	5	16	2	11	6
Metodes#				3127	3102	3102	3102	3102	3102	3102	3102	3102	3102	3102

Waardes in **swartdruk** is kleiner as die laagste kwantifiseerbare konsentrasie.

D = Tekort; L = Laag; H = Hoog; B = Baie hoog; T = Toksies;

#Verwys na BemLab werkinstruksies

Verklaring: Monsters ontvang in goeie toestand. Die gerapporteerde resultate is slegs van toepassing op die monster(s) ontvang. Enige advies wat by hierdie verslag ingesluit is, is op die aanname gebaseer dat die monster(s) verteenwoordigend is van die blok waaruit dit geneem is.
Bestel no.: 234593669

Dr. Pieter Raath
.....
namens BemLab

02-12-2014
.....
Datum gerapporteer

EINDE VAN VERSLAG

bemlab
www.bemlab.co.za
part of the PathCare Group of companies

16 Van der Berg Crescent
Gant's Centre
Strand

P O Box 684
Somerset Mall,
7137

Tel. (021) 853-1490
Fax (021) 853-1423

E-Mail admin@bemlab.co.za

Vat Reg. Nr. 4200161414

Certificate of Analyses

Report No.: **NR993**

Mark Februarie
Universiteit van Stellenbosch
Dept. Bos- en Houtkunde
Stellenbosch
7600

Analyses Report

Date received: 09/05/2016
Date tested: 13/05/2016

Reference No.	Lab. No.	N %	P mg/kg	K %	Ca %	Mg %	Na mg/kg	Mn mg/kg	Fe mg/kg	Cu mg/kg	Zn mg/kg	B mg/kg
T1 Branches Biomass	993	0.31	262	0.16	0.44	0.10	556	14	154	2	12	12
T2 Branches Biomass	994	0.35	159	0.14	0.29	0.06	399	15	42	2	6	12
T3 Branches Biomass	995	0.36	106	0.07	0.27	0.06	407	14	25	2	8	11
T4 Branches Biomass	996	0.33	62	0.07	0.36	0.05	417	19	23	1	2	11
T5 Branches Biomass	997	0.33	108	0.11	0.25	0.05	454	12	22	2	5	11
T6 Branches Biomass	998	0.32	76	0.06	0.24	0.05	496	10	26	1	3	10
T7 Branches Biomass	999	0.28	51	0.07	0.17	0.04	384	8	11	1	3	10
T8 Branches Biomass	1000	0.34	135	0.11	0.26	0.06	440	9	24	1	8	5
T9 Branches Biomass	1001	0.33	134	0.10	0.29	0.05	494	9	19	1	3	4
T10 Branches Biomass	1002	0.30	68	0.09	0.22	0.05	490	12	16	1	3	3
T1 Disc Biomass	1003	0.21	67	0.05	0.13	0.03	387	6	64	1	2	1
T2 Disc Biomass	1004	0.26	63	0.05	0.12	0.02	370	7	32	1	3	2
T3 Disc Biomass	1005	0.30	48	0.05	0.13	0.03	392	10	30	1	2	1
T4 Disc Biomass	1006	0.31	58	0.04	0.08	0.01	25	7	24	1	3	1
T5 Disc Biomass	1007	0.28	33	0.04	0.07	0.01	32	11	23	1	2	1
T6 Disc Biomass	1008	0.26	29	0.05	0.07	0.02	42	4	23	0	2	1
T7 Disc Biomass	1009	0.32	32	0.04	0.07	0.01	25	5	16	1	2	1
T8 Disc Biomass	1010	0.29	31	0.05	0.06	0.01	28	3	21	0	5	0
T9 Disc Biomass	1011	0.28	53	0.06	0.10	0.02	35	8	16	1	3	1
T10 Disc Biomass	1012	0.32	44	0.06	0.07	0.02	21	8	21	1	2	0
T1 Bark Biomass	1013	0.42	256	0.17	0.12	0.05	137	7	48	2	17	7
T2 Bark Biomass	1014	0.36	204	0.17	0.14	0.04	143	9	38	2	15	8
T3 Bark Biomass	1015	0.34	132	0.08	0.11	0.03	130	6	25	2	8	4
T4 Bark Biomass	1016	0.38	202	0.11	0.26	0.05	56	11	21	2	13	7

Reference No.	Lab. No.	N %	P mg/kg	K %	Ca %	Mg %	Na mg/kg	Mn mg/kg	Fe mg/kg	Cu mg/kg	Zn mg/kg	B mg/kg
T5 Bark Biomass	1017	0.33	114	0.07	0.06	0.02	89	5	44	1	4	4
T6 Bark Biomass	1018	0.38	163	0.11	0.08	0.04	71	4	37	1	6	4
T7 Bark Biomass	1019	0.35	158	0.12	0.08	0.03	86	3	32	1	8	5
T8 Bark Biomass	1020	0.37	192	0.17	0.12	0.03	98	4	18	1	8	6
T9 Bark Biomass	1021	0.41	207	0.22	0.13	0.04	60	4	27	2	9	7
T10 Bark Biomass	1022	0.36	148	0.14	0.10	0.03	103	6	27	2	6	5
LAI Needles- Tree 1	20561	0.86	688	0.34	0.73	0.20	565	104	66	2	13	17
LAI Needles- Tree 2	20562	0.78	706	0.47	0.31	0.11	290	85	52	2	15	18
LAI Needles- Tree 3	20563	0.83	636	0.26	0.51	0.13	454	91	66	2	12	14
LAI Needles- Tree 4	20564	0.67	602	0.43	0.56	0.09	322	97	70	2	12	18
LAI Needles- Tree 5a	20565	0.72	569	0.36	0.40	0.10	585	128	60	2	9	22
LAI Needles- Tree 6b	20566	0.98	628	0.31	0.51	0.14	420	61	61	1	6	15
LAI Needles- Tree 7	20567	0.72	610	0.46	0.31	0.09	513	47	72	2	12	12
LAI Needles- Tree 8	20568	0.96	609	0.48	0.23	0.11	208	59	52	2	33	26
SLA- T5b	20569	0.77	575	0.36	0.35	0.10	580	116	65	2	10	23
SLA- T6a	20570	0.65	548	0.28	0.46	0.13	683	28	81	1	5	15
SLA- Tree 9	20571	0.67	609	0.34	0.63	0.13	325	102	43	2	9	23
SLA- Tree 10	20572	0.86	544	0.33	0.89	0.18	873	81	58	2	6	22

STUDENT: P. MUYAMBO
TSITSIKAMA PLANTATION - SPECIES: P ELLIOTTII

Statement: The reported results may be applied only to samples received. Any recommendations included with this report are based on the assumption that the samples were representative of the block from which they were taken.
Samples received in good condition.

16-05-2016
Date Reported

Dr. Pieter Raath
PhDAgric. (Soil Science)
General Manager

END OF REPORT

APPENDIX VIII

		Parameter	Estimate	SE	R^2 (%)		Paramete	Estimate	SE	R^2 (%)
Stemwood	N	β_0	-0.3038	0.096	95.46	Mn	β_0	-5E-04	5E-04	81.04
		β_1	0.0032	0.000			β_1	7E-06	9E-07	
	P	β_0	-0.0914	0.045	80.46	Fe	β_0	-2E-04	2E-03	75.83
		β_1	0.0006	0.000			β_1	2E-05	3E-06	
	K	β_0	0.1355	0.028	75.03	Cu	β_0	3E-05	2E-05	98.28
		β_1	0.0003	0.000			β_1	1E-06	3E-08	
	Ca	β_0	0.0180	0.001	77.86	Zn	β_0	-3E-04	2E-04	83.54
		β_1	0.0008	0.001			β_1	3E-06	3E-07	
	Mg	β_0	0.0324	0.006	76.21	B	β_0	2E-04	4E-05	89.97
		β_1	0.0001	0.300			β_1	8E-07	7E-08	
Needles	N	β_0	0.0375	0.028	82.74	Mn	β_0	-7E-04	4E-04	85.29
		β_1	0.0076	0.001			β_1	1E-04	1E-05	
	P	β_0	0.0041	0.003	81.03	Fe	β_0	-6E-04	1E-04	69.47
	1_2	β_1	0.0005	0.000			β_1	1E-04	2E-05	
	P	β_0	0.0080	0.006	92	Cu	β_0	1E-05	6E-06	84.82
	2_3	β_1	0.0064	0.001			β_1	2E-06	2E-07	
	K	β_0	0.0083	0.021	69.94	Zn	β_0	-8E-04	2E-04	75.23
		β_1	0.0038	0.001			β_1	5E-05	7E-06	
	Ca	β_0	-0.0306	0.034	66.08	B	β_0	2E-05	8E-05	78.54
		β_1	0.0064	0.001			β_1	2E-05	2E-06	
	Mg	β_0	0.0064	0.007	60.1					
		β_1	0.0012	0.000						
Branches	N	β_0	-0.0261	0.011	97.75	Mn	β_0	-3E-04	1E-04	86.09
		β_1	0.0034	0.000			β_1	2E-05	2E-06	
	P	β_0	-0.0275	0.019	68.48	Fe	β_0	-6E-04	3E-04	91.37
		β_1	0.0012	0.000			β_1	4E-05	3E-06	
	K	β_0	0.0121	0.013	70.46	Cu	β_0	-2E-05	1E-05	90.48
		β_1	0.0010	0.000			β_1	2E-06	2E-07	
	Ca	β_0	-0.0372	0.025	88.34	Zn	β_0	-7E-05	6E-05	81.11
		β_1	0.0032	0.025			β_1	6E-06	7E-07	
	Mg	β_0	0.0037	0.004	88.28	B	β_0	-3E-04	8E-05	93.18
		β_1	0.0005	0.000			β_1	1E-05	8E-07	
Bark	N	β_0	-0.0799	0.047	79.15	Mn	β_0	-4E-04	1E-04	83.13
		β_1	0.0040	0.000			β_1	1E-05	1E-06	
	P	β_0	-0.0956	0.023	89.66	Fe	β_0	1E-04	3E-04	74.44
		β_1	0.0026	0.000			β_1	2E-05	3E-06	
	K	β_0	-0.0143	0.021	67.23	Cu	β_0	-1E-05	1E-05	92.03
		β_1	0.0214	0.000			β_1	2E-06	2E-07	
	Ca	β_0	-0.0941	0.031	77.88	Zn	β_0	-5E-04	2E-04	74.56
		β_1	0.0025	0.000			β_1	1E-05	2E-06	
	Mg	β_0	-0.0141	0.005	84.72	B	β_0	-7E-05	7E-05	82.19
		β_1	0.0005	0.000			β_1	7E-06	7E-07	