GROWTH PERFORMANCE AND CARBON SEQUESTRATION POTENTIAL OF TWELVE-YEAR OLD *UAPACA KIRKIANA* PROVENANCES AND FAMILIES AT NAUKO IN MACHINGA, MALAWI

Master of Science in Environmental Science Thesis

By

MICHAEL FREEMAN CHIRWA

Bachelor of Education - University of Malawi

Submitted to the Faculty of Science, University of Malawi, in partial fulfillment of the requirements for the Master of Science Degree in Environmental Science

UNIVERSITY OF MALAWI

CHANCELLOR COLLEGE

September, 2013

DECLARATION

I the undersigned hereby declare that this thesis/dissertation is my own original work which has not been submitted to any other institution for similar purposes. Where other people's work has been used acknowledgements have been made.

Michael Freeman Chirwa

Signature

Date

Certificate of Approval

The undersigned certify that this thesis represents the student's own work and effort and has been submitted with our approval.

Signature: __________________________Date:__________________________

S. Chiotha, PhD (Professor)

Main Supervisor

Signature: __________________________Date:__________________________

J.J. Namangale, PhD (Associate Professor)

Member, Supervisory Committee

Signature: __________________________Date:__________________________

T. Chanyenga (Forestry Research Scientist)

Member, Supervisory Committee

Dedication

This thesis is dedicated to all my family members.

ACKNOWLEDGEMENTS

All course work and research leading to this thesis was fully sponsored by United Nations Development Programme (UNDP). I am greatly indebted to this institution. It was through an impromptu request for me to benefit from this facility of capacity building in the Forestry Department of Malawi hence my special gratitude to the Director of Forestry, Dr. Dennis Kayambazinthu and Mrs Nyuma Mughogho, the Assistant Director of Forestry responsible for Extension, for all the efforts made in facilitating the sponsorship. Special thanks go to my supervisors namely Prof. S. Chiotha, Dr. J. Namangale and Mr. T. Chanyenga, for all the energies expended in perfecting this work. It has been my pleasure and great personal privilege to work with them. My heartfelt gratitude to all those who assisted me in data collection. Messrs W. Sagona, H. Jenya, O. Kachala, E. Makawa, H. Banda, I. Jamali and K. Likunda from FRIM deserve special mention.

To my wife Carol, it is too demanding to be by one's side offering moral support for two solid years. Muchenge, my son, your mere presence throughout the days of my studies gave me joy and hope to excel. I hope we will trade positions in the due course of our lives. To the whole of my family, the pride I take in you urges me to excel. I would do great injustice if I do not acknowledge the unwavering support from my workmates.

May God bless you all.

ABSTRACT

Uapaca kirkiana (Muell. Arg) is an important multipurpose indigenous fruit tree in the Zambezian ecoregion whose studies are limited. Six *U. kirkiana* provenances and their families were studied from a 12-year old alpha-lattice designed provenance trial at Nauko in Machinga, Malawi for their growth and carbon sequestration potential. Growth performance variables height, crown width, diameter and survival were assessed. Allometric models were also developed for estimation of carbon stocks through wholesome destructive sampling of trees.

Phalombe provenance (4.7 ± 0.87m) outgrew all the other provenances in height with Dedza (4.43 ± 1.06m) attaining the least height growth. No significant differences were detected amongst the mean heights for the provenances ($F = 2.06$, $p = 0.069$). Family height however differed significantly, varying between 3.06 ± 1.05m and 5.95 ± 1.08m ($F = 1.60$, $p = 0.001$). Widest crown was observed in Dedza provenance (2.27 ± 0.86m) while Luwawa produced the narrowest (1.98 ± 0.85m) and the variation between the two crowns was the only significant difference ($F = 2.75$, $p = 0.018$). No significant differences were detected amongst the family means signifying low genetic control of crown traits ($F = 1.02$, $p = 0.438$). Phalombe provenance (8.59 ± 2.19cm) was again the most superior performer in diameter growth, significantly varying from other provenances such as the least performer, Kasungu (7.6 ± 2.42cm; $F = 4.49$, $p = 0.000$). Diameter growth at family level also varied significantly ranging between 5.2 ± 1.11cm and 10.7 ± 1.89cm ($F = 1.65$, $p = 0.000$). Provenance survival rates ranged between 54 and 69% for Litende and Luwawa provenances respectively while the overall survival for the provenances was 64%.

Allometric models generated were able to explain between 54.6% and 92.4% of variation in all the response variables. Total carbon estimated from lines of best fit for the provenances varied between 10.09 ± 6.64kg $tree^{-1}$ for Luwawa and 12.47 ± 6.94kg $tree^{-1}$ for Phalombe (F = 2.67, p = 0.021). When survival rates were considered, Phalombe was estimated to sequester 774kg ha^{-1} with Litende the least carbon sequestering provenance at 135kg ha^{-1}. Dedza was the second prolific provenance, sequestering 745kg ha^{-1}. Significant differences were detected in the carbon sequestered by the component parts of the provenances and families.

Phalombe was generally the overall superior provenance in terms of growth and carbon sequestration potential by the six provenances. Some best performing families were also from this provenance. However there is still need to conduct further multi-locational studies to establish how the provenances would perform in other environmental conditions and make the models predictive in a wider range of conditions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND ACRONYMS

AGB	Aboveground Biomass
AGC	Aboveground Carbon
BEF	Biomass Expansion Factor
CH_4	Methane
COMESA	Common Market for Eastern and Southern Africa
CO_2	Carbon Dioxide
DBH	Diameter at Breast Height (1.3m)
FAO	Food and Agriculture Organisation
FRIM	Forestry Research Institute of Malawi
GHGs	Greenhouse Gases
GoM	Government of Malawi
HFC	Hydroflourocarbons
ICRAF	International Centre for Research in Agroforestry
IPCC	Intergovernmental Panel on Climate Change
N_4H	Nitrous Oxide
PRESA	Pro-poor Rewards for Environmental Services in Africa
REDD	Reduced Emissions from Deforestation and Forest Degradation

DEFINITION OF TERMS

Allometry

A relation whereby one measured parameter is a good estimate of another unmeasured parameter in the same organism (Janssens *et al.*, 2003).

Biomass

Organic material both above-ground and below-ground, and both living and dead, e.g., trees, crops, grasses, tree litter, roots and so on (FAO, 2004; in Samalca, 2007).

Carbon sequestration

Carbon sequestration is the capture and secure storage of carbon dioxide that would otherwise be emitted to or remain in the atmosphere. Terrestrial carbon sequestration is carbon stored in the biomass created by perennial vegetations such as root systems and tree trunks **(**Schleizer, 2008)**.**

Family

Individuals that are more closely related to each other than to other individuals in a population (Zobel *et al.,* 1984). In this thesis it is used interchangeably with treatment.

Provenance

Original geographic area from which seed or other propagules were obtained (Zobel *et al.*, 1984).

Wood density

Oven dry weight per unit of green volume (Philip, 1994).

CHAPTER ONE

GENERAL INTRODUCTION

1.0 Background Information

Uapaca kirkiana (Muell.-Arg), locally known as *masuku*, is an important multi-purpose fruit tree in the Zambezian eco-region that belongs to the family *Euphorbiaceae*. The fruit of *U. kirkiana* which is of high nutritional value can be eaten raw, made into jam, sweetmeat or used to produce a refreshing drink and a variety of wines (Mwamba, 1989). In some instances like in Ruvuma, Zimbabwe, sweet beer is also produced from its fruits (Ngulube, 1996). The fruit is also one of the most reliable forest products in providing a safety net in times of hunger. The wood also has the attributes to produce high quality charcoal and firewood. It is a termite resistant species whose wood is fairly durable, straight-grained with white sap wood and red-brown figured heartwood which can be used as timber to make furniture. Utensils such as spoons can also be made from its wood. Its various parts are also used in traditional medicine and the species is a good source of income to rural people (Saka and Msonthi, 1994 in Mwase *et al.*, 2008). The root has been widely reported to treat indigestion. However, it should also be acknowledged that this indigenous fruit tree, just like all other trees also plays a role in provision of other ecosystem services such as carbon sequestration.

Climate change is undoubtedly one of the major environmental problems facing the world. According to Forster *et al.* (2007), human activities are discernibly the major causes of global climate change with most activities that result in emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), Hydroflourocarbons (HFCs) and other greenhouse gases.

Suggestions for mitigation of climate change have ranged from setting greenhouse gas emission limits to using mechanisms of removing GHGs from the atmosphere through such options as carbon capture and storage. The latter mechanisms have again taken several forms. One major form of carbon capture is that, through technological means, carbon be removed from the atmosphere, consigned to underground stores in the earth's geology, and contained within them. The other such mechanism is carbon sequestration by plants. It is the later form that has resulted in financing mechanism such as carbon trading that have added further value to tree planting and domestication of fruit trees.

To improve the access of rural communities to indigenous fruit trees such as *U. kirkiana* their domestication by small-scale farmers has been encouraged in the *miombo* eco-region of southern Africa (Maghembe, *et al.*, 1994 in Mwase *et al.*, 2006). In view of the potential, the domestication and cultivation of this indigenous fruit tree species on farmland is being promoted to further exploit its economic and nutritional potential. The domestication process involves the characterization, selection, production and adoption of desirable tree germplasm in a process that involves farmers' participation in research (Akinnifesi *et al.*, 2006 in Mwase *et al.*, 2006). In a priority setting exercise, involving researchers and farmers in southern Africa *U. kirkiana* was the most preferred indigenous fruit tree species among a list of ten priority species (Maghembe *et al.*, 1994 in Mwase *et. al*., 2008).

1.1 Research Problem

U. kirkiana has high potential for improving the nutrition and income of small-scale farmers through production, sale and consumption of fruits (*Mwase et al.,* 2006).

Besides fruits, the tree also provides other products and services such as timber, fuelwood, medicine, fodder, construction poles and shade. The emergence of carbon markets and financing in the region in an effort to abate climate change, means besides benefiting from diverse products and services from the trees, farmers could further supplement their income through carbon trading, further adding value to an already highly valued multi-purpose tree species. Examples of such carbon initiatives in the region include:

- Government of Malawi Tree Planting for Carbon Sequestration Programme
- PRESA (ICRAF) Initiative
- Clinton-Hunter Foundation Carbon Initiative
- COMESA Carbon Poverty Reduction Initiative
- REDD initiatives in Tanzania and Zambia

Several problems are impeding the generally impoverished local farmers from fully benefiting from such initiatives. The national mean land holding size for Malawi, for example, has been decreasing over time from 1.53 ha in 1968/69 to 0.80 ha in 2000 (Halle and Burgess, 2006). Corresponding to this decrease, there is an increase in smallholder households from 885,000 to 2,090,690 during this period. It is therefore imperative to optimize productivity within such limited land holdings through promotion or planting of multi-purpose tree species that do not only provide products and nutritive security but can also offer saleable products and services.

Multi-purpose species such as *U. kirkiana* are good for boundary planting, one system of tree planting in some initiative such as the Clinton-Hunter Foundation Carbon Iniative in Malawi. There is therefore need to improve as much as possible the commercial traits of such species. Mwamba (1989) revealed large variations exist *U. kirkiana* in Zambia revealed that in tree vigour, flowering, fruiting, yield, sweetness and pulp colour of the fruits. Other studies on fruit, seed and seedling variation from natural populations in Malawi have also revealed significant differences (Ngulube, 1996). Chirwa *et al.* (2007) also found significant differences in the growth of six year old *U. kirkiana* at Nauko in Machinga, Malawi. This signifies differences in growth and development aspects of the species.

Despite such extensive information being generated for the species, information on long-term performance of such indigenous species and their provenances and families remain scanty and is sometimes discontinuous. Such studies ensure the success of tree planting by guiding the choosing of superior species, provenances and families for domestication or determining traits that would need improvement to optimize benefits to the farmer. Another area as noted by Henry (2010) is that very few allometric equations for carbon estimation exist for sub-Saharan Africa tree species and as a result generalized allometric equations, often established for forests in other continents, are used by default.

1.2 Objectives of the Study

1.2.1 General Objective

The general objective of the study was to evaluate the performance of six 12 year old *U. kirkiana* provenances and their families at Nauko in Malawi, in terms of their growth and carbon sequestration potential.

1.2.2 Specific Objectives

The specific objectives of this study were:

1. To compare the growth performance of six *U. kirkiana* provenances and their families.
2. To construct simple allometric models for estimation of *U. kirkiana* carbon stocks.
3. To quantify carbon sequestered by the six *U. kirkiana* provenances and their families.

1.2.3 Hypotheses for the Study

The study tested the following null hypotheses:

1. There are no significant differences in growth of the provenances and families at 12 years of growth.
2. The allometric models to be developed do not vary in strength from one another.
3. Provenance-to-provenance and family-to-family variations of scarbon sequestered at age 12 by *U. kirkiana* at Nauko are not significantly different from one another.

1.2.4 Research Questions

The objectives of this research were based on the following question:

1. What is the current growth status of the provenances?
2. Which provenances and families are contributing more to carbon sequestration than others?
3. Are there any variations in carbon sequestration of the component parts of the provenances and families?
4. What traits would need to be improved if these provenances and families are to be domesticated by only considering their growth and carbon sequestration potential?

1.3 Justification for the Study

Miombo woodlands are endowed with diverse tree species of which some have never been thoroughly studied. One area that remains to be critically looked at is the long-term performance of these species that include multifunctional fruit tree species that have remained integral to the livelihoods of local communities living within their vicinity and sometimes even beyond. The domestication of indigenous fruit trees, let alone carbon trading has further underscored the importance of such studies.

This study will therefore not only generate information about the growth performance of one of the highly prioritized species in the region but it will assist in understanding how best the provenances under study can be partly improved for enhanced benefits to the local farmer. It will also assist in determination of families that could be sources of more viable seed for domestication purposes. Above all, the study will generate allometric models that could be used in estimation of carbon that could be sequestered by the species or provenances, more especially in similar environmental conditions and diameter class range or age. Furthermore, the models generated for the component parts may be used in valuation studies of various functions the component parts may be subjected to by being used specifically in determining carbon stock for the component parts.

1.4 Organization of the Thesis

This thesis has five chapters. The first chapter provides a general background to this study including the problem statement, objectives of the study and its justification. Chapter two is a review of relevant literature to the study while chapter three describes the research methodology. Results are presented and discussed in chapter four. Conclusion and recommendations are made in chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

Studies on growth performance and carbon sequestration of other equally important tree species have been conducted in various sites across the world. Although they may have had different objectives altogether to the current study, applicability of the methods to the current study is inevitable. This chapter presents various methods used in such studies. General description of the species is however also discussed as it is inevitable to study a species without understanding the characteristics that may be significantly influential to its behaviour.

2.1 General Description about *U. kirkiana*

2.1.1 Ecology and Distribution

U. kirkiana's occurrence in the Zambezian ecoregion covers Angola, Southern Democratic Republic of Congo, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe (Ngulube, *et al.*, 1995 in Mwase *et al*, 2008). It is generally limited between an altitude of 500 and 2000m above sea level (Ngulube, 1996). But it has also been reported in high elevation areas of even up to 2400m such as in Benguela Highlands (Angola) and Mbeya Highlands (Tanzania). Rainfall range for its growth is between 400 and 1400m per annum and monthly daily maximum temperatures between 25 and 31^{0}C and corresponding minimum temperatures range between 8 and 17^{0}C (Mwase *et al*., 2006).

U. kirkiana which is a gregarious species usually associated with tree species from such genera as *Parinari, Protea, Ochna, Burkea, Albizia, Brachystegia, Isoberlinia,* *Monotes, Pericopsis* and *Pterocarpus*, grows on a wide range of soils but its prevalence is on ferrasols and luvisols (Ngulube, 1996). The most suitable soils for *U. kirkiana* are generally characterized by low cation exchange capacity, low organic matter content and macro nutrients: nitrogen, potassium and phosphorus, and with a soil pH ranges between 4 and 6 although 5-5.5 is considered optimal (Mwamba, 1983 in Mwase *et al*., 2006).

2.1.2 Propagation Techniques, Plant Parts and Phenology of *U. kirkiana*

U. kirkiana is a deciduous and out-crossing species, propagated through seeds, cuttings, wildlings, root suckers, coppices and regeneration. Ngulube (1996) indicated that it also dispersed by animals because of the edible sugary pulp which forms 40-60% of fresh fruit, making it attractive to a wide range of mammals and birds. The seed has around 50% of moisture content. It flowers and fruits during the rainy season and fruits ripen from September to December and sometimes through February (Mwase *et al*., 2006). Like all tree species, it is prone to droughts and frequent fires which retard its fruiting age and maturity. Its fruit load has been reported as high as 2000 in some instances in Zambia and Zaire (Ngulube, 1996).

Foliage plays a vital role in photosynthesis process in a plant and resultantly carbon sequestration potential of a plant. Foliage and buds for *U. kirkiana* are dark shiny green with short grey to rust-coloured curly hairs beneath when young but become almost glabrescent on approaching maturity (FAO 1983, White 1962 and Pardy 1951, in Ngulube 1996). Generally most leaves have been reported to fall within the range of 12-36cm in length and 8-24cm in width and are generally described as sub-circular in shape with a rounded apex. It has a prominent midrib and 12-24 pairs of prominent parallel secondary nerves. Its petioles are velvety, short (up to 3.5cm long) and stout; while the stipules are evenly pubescent, 3-4mm long, and tardily deciduous (Mwase *et al*., 2006).

Plate 2.1: Prominent leaves of *U. kirkiana* that play a vital role in the photosynthesis process

Mature fruit is yellowish–brown which may however be faintly different in some natural populations between individual trees ranging between yellowish-brown and reddish (Hans, 1981 in Ngulube, 1996). Although fruit weight at maturity may vary with site, it usually ranges between 10 and 27g fresh, with a volume of up to 27cm^3 (Mwamba 1989). The fruits would generally contain 3-5 whitish seeds whose length can reach up to 2cm long and width up to 1.4cm (FAO 1983 in Ngulube, 1996).

One major outlook of a mature *U. kirkiana* is that it has a short trunk and is enormously branched, a characteristic which gives it a dense rounded top. Heights of 5-10m are common (Shorter, 1989 and Palgrave, 1981, in Ngulube, 1996). It is further reported that large individuals within natural population may even achieve as much as 13m while clear trunks can reach up to 9m. Diameters for mature trees are generally within a range of 15-25cm but in exceptional cases they may grow as far as 40cm. According to Ngulube (1996), its root system is scarce but with a mass of small laterals and central sinkers emerging from the base of the stem without organization.

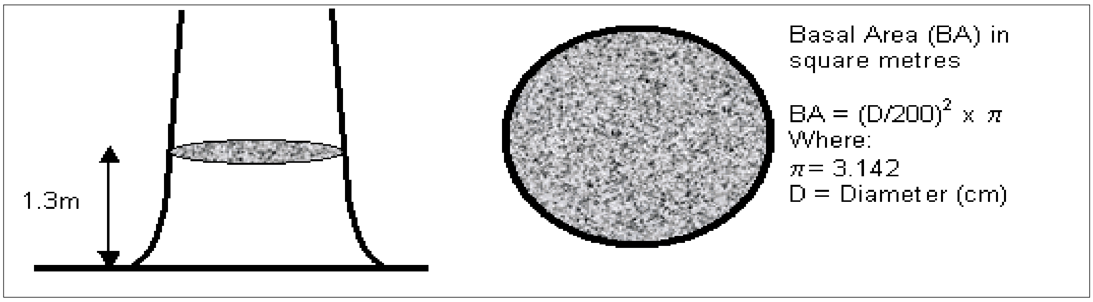
2.1.3 Growth Characteristics of *U. kirkiana* in Planted Stands

Survival figures following field planting of *U. kirkiana* vary between 28 – 100% up to 4yrs and for seedlings inoculated with ectomycorrhizae in nursery, 100% survival has been achieved (Ngulube, 1996). It is a slow growing species under limited or no management but grows relatively faster when it has been suitably inoculated and clean weeding is conducted (Mwase *et al*., 2006), developing multiple stems as early as three years (2-6 stems/plant) and fruiting within 9-10yrs. According to Ngulube (1996), for more viable growth, seedlings from natural regeneration are considered better than monocultured seedlings.

2.2 Assessment of Growth Performance and Carbon Sequestration Potential of Trees

2.2.1 Assessing Growth Performance of Trees

Assessment of growth performance of trees mostly involves the direct measurement of growth parameters amongst them height, dbh, crown width and bole height. It is from these parameters that other secondary variables like volume and basal area are then calculated (as in Figure 2.1). Tree survival has often been used in the assessment of growth performance of trees as it has an effect on the overall performance of a species, provenance or stand.



(Source: Farm Forest Line, 2008)

Figure 2.1: Illustration of basal area, one secondary parameter computed from primary variables like DBH

Ofori *et al.* (2007) studied provenance variation in *Khaya ivorensis* and *anthotheca* species for growth and resistance to shoot borer *Hypsipyla robusta*. The parameters they assessed for growth were dbh, height and survival of the species' provenance. Results showed no significant ($P > 0.05$) variation in growth among provenances of two species. They, however, observed significant variations ($P < 0.05$) in growth parameters among progenies of both species. Height and dbh of the highest-ranking progenies of the two species were twice those of the lowest-ranking progenies. *K. anthotheca* had a high heritability ($h^2 = 0.74$) for height growth compared to that of *K. ivorensis* ($h^2 = 0.51$) which they observed to suggest an inherent degree of higher genetic control in height growth for *K. anthotheca* than *K. ivorensis*.

2.2.2 Methods for Estimation of Carbon Stocks

2.2.2.1 Direct Carbon Estimation

Direct methods for estimation of carbon stocks, which are usually referred to as the destructive methods, involve complete harvesting of a tree or stand to determine biomass or carbon through the actual weighing of each of its components, thus roots, stem, branches, and foliage. These tree components are oven dried and weighed. Total biomass is the total dry weight of all the components while aboveground biomass is the total biomass with the exclusion of root biomass which is actually referred to as belowground biomass. The dry biomass can be converted to carbon content by taking half of the biomass weight, thus carbon content is 50% of biomass (Westlake, 1966; in Gibbs *et al.* 2007). Occasionally, carbon is measured directly by burning the samples in a carbon analyzer (Losi, 2003).

2.2.2.2 Indirect Carbon Estimation

Indirect methods are commonly used since it is always costly, tedious and less environmental friendly to use the direct method to estimate carbon stocks as there is complete harvest of a tree stand,. These take several forms like destruction of a representative sample of a population which is either processed as a whole sample for carbon determination or further sub-sampled. The latter involves collection of smaller samples from each component part of the tree to determine dry weight to fresh weight ratios that are further extrapolated to the samples in the field which would have been wholesomely fresh weighed. The estimated dry weights are assumed to be the biomass of the sample trees. Allometric models are then developed to determine carbon for standing trees.

Biome averages, forestry inventories and remote sensing are among various techniques that could be used cross-cuttingly to obtain data under these two major broad categories. In some instances however tree volumes and specific gravity of the species are also used to attain carbon estimates, albeit they may be either direct or indirect.

2.2.2.2.1 Forest Inventory and Carbon Quantification

This method relates ground-based measurements of tree diameters or volume to estimate carbon stocks using allometric relationships (Gibbs *et al.,* 2007). The benefit of using this method is that generic relationships may readily be available hence it can be relatively less expensive as compared to other methods.

2.2.2.2.2 Biome Average and Carbon Quantification

In this category, Gibbs *et al.* (2007) in their review of various methods for monitoring and estimating tropical forest carbon stocks cited this as a method that involves estimation of averages for forest carbon stocks for various categories of forests based on a variety of input data sources. These could range from available ground based measurements for a particular stand to remotely sensed data. However biome here refers to broad categories of plant communities with similar geographic and climatic conditions, and therefore the method is mostly suitable at landscape level biomass or carbon quantification where other methods maybe considered inappropriate (Klein, 1998). However this method has high uncertainty at country-level as there is high generalization as data sources are not properly sampled to describe large areas (Gibbs *et al.*, 2007). Despite this, the method is viewed to be less costly than other methods of data collection as data is immediately available, sometimes at no cost.

2.2.2.2.3 Remote Sensing and Carbon Quantification

Remote sensing involves several techniques such as aerial photography, optical parameters and radar (Ravindranath and Ostwald, 2008). The latter two are widely categorized into optical remote sensors; very high-resolution airborne optical remote sensors; radar remote sensors; and laser remote sensors. Optical remote sensors use visible and infrared wavelengths to measure spectral indices and correlate to ground-based forest carbon measurements while very high resolution airborne optical remote sensors use images with very high resolution (approximately 10-20cm e.g. Landsat) to measure tree height and crown area, and allometry to estimate carbon stocks.

Examples of images for this method include 3-dimension digital aerial imagery. Radar and satellite remote sensors use microwave or radar signal to measure forest vertical structure; and laser light to estimate forest height or vertical structure of a stand respectively. The former has often been used synonymously with Synthethic Aperture Radar (Goetz *et al.*, 2009). Although remote sensing has been mainly used to estimate biomass or carbon for mainly forest stands, Popescu (2007) used airborne lidar to successful estimate biomass individual *Pinus taeda* in the southeastern United States. Further benefits and limitations of these remote sensing methods are as indicated in Table 2.1.

2.2.2.3 Key Principles in Carbon Estimation

2.2.2.3.1 Stratification and Random Selection

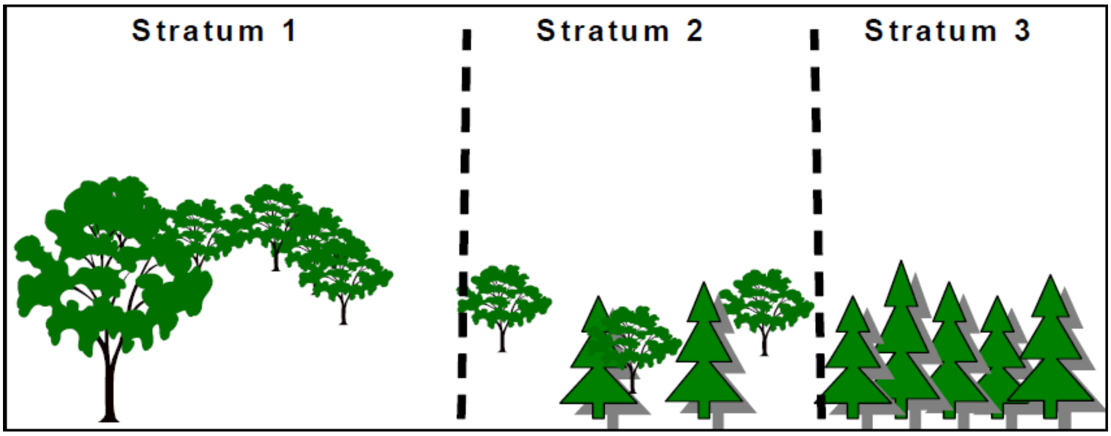
According to Klein (1998), stratification is a sampling procedure where the population of interest is subdivided into homogenous subunits or strata that may apply different or same sampling method in each stratum.

Table 2.1: Benefits and limitations of remote sensing methods to estimate carbon stocks

Method	**Benefits**	**Limitations**	**Uncertainty**
Optical remote sensors	• Satellite data routinely collected and freely available at global scale • Globally consistent	• Limited ability to develop good models for tropical forests • Spectral indices saturate at relatively low biomass/carbon stocks • Can be technically demanding	High
Very high-resolution airborne optical remote sensors	• Reduces time and cost of collecting forest inventory data • Reasonable accuracy • Excellent ground verification for deforestation baseline	• Only covers small areas (10 000s ha) • Can be expensive and technically demanding • No allometric relations based on crown area are available	Low to medium
Radar remote sensors	• Satellite data are generally free • Can be accurate for young or sparse forest	• Less accurate in complex canopies of mature forests because signal saturates • Mountainous terrain also increases errors • Can be expensive and technically demanding	Medium
Laser remote sensors	• Accurately estimates full spatial variability of forest carbon stocks • Potential for satellite-based system to estimate global forest biomass/carbon stocks	• Airplane-mounted sensors only option • Satellite system not yet funded • Requires extensive field data for calibration • Can be expensive and technically demanding	Low to medium

(Source: Gibbs *et al.*, 2007)

Klein (1998) categorized forest-related stratification into geographic and subject matter classification. Geographic classification includes such criteria as forest type (as in Figure 2.2); ecozones; site and soil types; and topographic conditions. The latter includes criteria as species; species group (e.g. commercial and non-commercial); as well as is the case for this study – provenances or families. Stratification enhances that the within-stratum variance is small than when the population is sampled as one (Philip, 1994). Whether in systematic or random sampling schemes, survey efficiency is greatly increased by reducing unnecessary sampling and ensuring that major variations have been captured (Gibbs *et al.*, 2007).



(Source: Project Team KYOTO, 2009)

Figure 2.2: Depiction of stratification by forest type

2.2.2.3.2 Drying Process and the Generic Fifty-percent Carbon Assumption

In determination of biomass and carbon estimates, varying drying times and temperature have often been used. Zabek and Prescott (2006), in developing biomass equations and quantifying aboveground leafless biomass of hybrid poplar in Coastal British Columbia, oven-dried sub-samples to constant dry weight at a temperature of 70 ± 2^{0}C while Dias *et al.* (2006) oven-dried their sub-samples at 60^{0}C. Again, generally most studies, as indicated earlier, assume that the concentration of carbon in different tree parts is generally 50% of dry weight. Losi *et al.* (2003) analyzed these assumptions on species-specific stand level estimates of carbon stock for *Anacardium excelsum* and *Dipteryx panamensis* growing in 7-year-old mixed-species plantations in Panama.

Results indicated that the drying time, the number of sub-samples taken, and whether or not carbon was measured directly had only a small effect on the estimate of carbon stock for the entire cohort of trees. None of the methods developed using the same sample of Panamanian trees gave stand level estimates of carbon stock that differed by more than 10% from the best estimate for either species. Measured carbon content of dry bole samples were about 50% of the dry mass, thus 47.8% for *A. excelsum* and 48.5% for *D. panamensis* species.

2.2.2.3.3 Volume and Wood Density

Often times there has been use of volume and wood density or specific gravity in estimation of carbon stocks. In such situations, tree dimensions are measured and the volume of the stem and larger branches is calculated using formulas for volume such as the commonly used forms of Smalian and Huber.

$$v = \frac{L(g_1+g_2)}{2} \quad \text{(Smalian's formula, in Philip, 1994)}$$

$$v = Lg_m \quad \text{(Huber's formula's, in Philip, 1994)}$$

where:

v = volume of log (m^3),

L = log length (m),

g_1= cross-sectional area at base of log (m^2),

g_2= cross-sectional area at top of log (m^2)

and g_m= cross-sectional area at mid-length of log (m^2).

These volume formulae have often been used over others because of their simplicity. Subsequently volumes generated are then used to calculate the biomass using specific gravity or wood density.

2.2.2.3.4 Allometry and Carbon Quantification

There are some tree characteristic variables that are desirable but are very difficult to be measured. In such instances Klein (1998) states that relationships can be established between the desired variables and hard-to-measure variables (e.g. volume) with direct and easily measurable variables (e.g. DBH). Again, as it has been noted, direct harvesting techniques for estimating carbon are labour intensive, time consuming and expensive. Recent global recognition of trees as carbon sinks that should be sustainably managed and conserved to mitigate climate change even renders destructive methods implausible. The development of allometric models was therefore imperative as the method does not always require harvesting of sample trees.

Using allometry, stand level biomass or carbon is frequently calculated from linear and nonlinear regression models established by species with field measurements (Crow and Schlaegel, 1988; Hahn, 1984; Ohmann & Grigal, 1985; Smith, 1985 in Zheng 2004). So besides establishing mere relationships in terms of proportions, equations linking tree parameters, their biomass and carbon sequestration ability can be generated for further use in other studies besides the study they would have been generated for.

Allometry and Ratios

Using allometry, ratios have been developed to quantify biomass or carbon in components of plants. The most common however are the root-shoot ratios. Root-shoot ratios have usually been developed to avoid tedious root excavation process or even the unattainable task of extracting extensive root systems all the time carbon is to be quantified. Laclau (2003) reported that root biomass constitutes an important component of total carbon storage, more especially in a pine plantation, and so the need for it to be included as part of total carbon. A study was therefore conducted on *Ponderosa* pine, the most common tree species planted in northwest Patagonia, Argentina. Field research was conducted on *Ponderosa* pine samples of roots from two differently aged stands of similar site quality to develop regression equations relating root dry weight, root volume, and carbon storage as functions of tree DBH.

Laclau (2003) found that root biomass and volume can be highly explained by DBH in the *Ponderosa* pines. Root–shoot ratios calculated for sampled trees ranged in average 0.21–0.24 and 0.23–0.25 for the 10- and 20-year-old stands respectively which augured with other similar studies on temperate conifers' biomass. Such has been the case with various other studies that root-shoot ratios have become integral to biomass or carbon quantification studies.

Allometry and Models

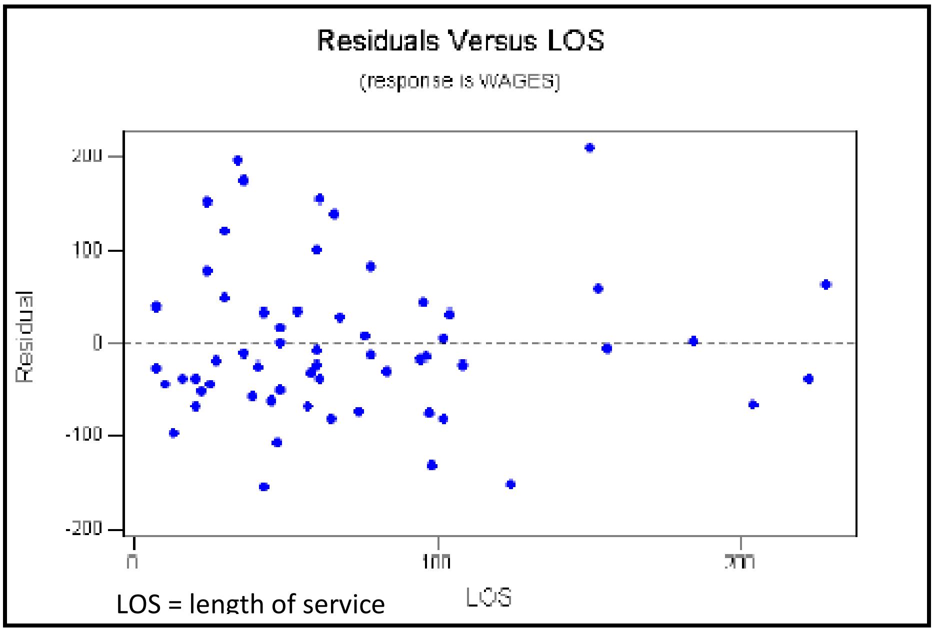
Allometric modeling has mainly taken two forms. One such form is whereby the models are developed directly from the harvested tree samples while the other has involved the use of already tested standard forms to generate specific equations for the case under study. Least square method is then used to develop the regression equation either using one explanatory variable (simple regression) or more (multiple regression). The method minimizes the sum of squares between the regression line and the real data. Variance for the data is assumed to be constant for the continuous independent variable while the data is assumed to have normal distribution in each class of the independent variable (Klein, 1998). When these are not tested in the initial stages of generation of the models, testing after development of the models can be done using residual plots. Graphical residual analysis can be used to test the appropriateness of the model, normality of data and constancy of the variance (Sullivan, 2004). Figure 2.3 shows one of such graphs.

If a plot of residuals against the predictor variable shows the residuals increasing or decreasing as the predictor increases, then a strict requirement of constant error variance of the linear model is violated (Sullivan, 2004). Test statistics, as the co-efficient of determination (R^2) and standard error of estimate ($S_{y.x}$), are used to test the effectiveness of the model. However it should be noted that residual plots can also be used prior to generation of models in order to find out whether data should be transformed or not.

In the use of already developed standard forms, Spetch and West (2003), on estimation of biomass and carbon sequestered on farm forest plantations in northern New South Wales in Australia, employed an allometric model commonly used in literature to describe the relationship between tree oven-dry biomass (*W* kg) and tree diameter at breast height over bark (*D* cm), thus:

$$W=aD^b,$$

where *a* and *b* are constant parameters.



(Source: Moore *et al.*, 2003)

Figure 2.3: Plot of residuals against predictor variables

The model is usually fitted to the data using ordinary least-squares regression analysis after logarithmic transformation of the model to a straight line (Spetch and West, 2003). Nath *et al.* (2003) in studying aboveground biomass and carbon storage in various bamboo species in North East India used the allometric form that involved logarithmic transformation of data:

$$\log Y = a + b \log X,$$

where:

Y = component dry weight (g),

X = diameter at breast height (cm),

and a and b are the regression coefficients.

Fang *et al.* (2006) developed allometric models for biomass production and carbon sequestration of poplar plantations in Baoying County in China directly without the use of standard forms. Using linear and curve regression models (including logarithmic, inverse, quadratic, power, growth and exponential functions), regression equations for predicting biomass production of poplar plantations were fitted respectively choosing stand age×planting density, stand age×*ln*(planting density), *ln*(stand age×planting density), and stand age×(*ln*(planting density))^2 as independent variables.

The final models developed through the study using curve regression for different components had R^2 values between 0.57 for leaf and 0.98 for total biomass (Figure 2.4) and all were highly statistically significant ($p \leq 0.001$). The proxy volume variable ad^2 (a = sstand age; d = *ln*(planting density)) accounted for 57–98% of the variation in biomass in all plantations. To validate the effectiveness of the models Fang *et al.* (2006) used plots of predicted versus observed biomass and these indicated good fit and high predictive ability across plantations. In many cases, several sample trees, in larger diameter classes, should be destructively harvested to test the validity of resultant equations (Brown, 2002).

Components	Models[a]	B_0	B_1	R^2	*F*-value
Stem biomass	$Y=B_0x^{B_1}$	0.0022	1.7988	0.959	976.06
Branch biomass	$Y=e^{(B_0+B_1/x)}$	3.7498	−252.15	0.915	450.14
Leaf biomass	$Y=e^{(B_0+B_1/x)}$	2.1215	−147.80	0.569	55.46
Above-ground biomass	$Y=e^{(B_0+B_1/x)}$	5.3363	−285.98	0.961	1032.72
Root biomass	$Y=e^{(B_0+B_1/x)}$	3.9534	−292.01	0.897	365.83
Total biomass	$Y=e^{(B_0+B_1/x)}$	5.5690	−288.14	0.975	1643.83

[a] x=stand age×(*ln*(planting density))^2

Figure 2.4: Results of regression for biomass predictive equations by Fang *et al.*

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Study Site

The trial site, which was established in 1997 by Forestry Research Institute of Malawi (FRIM) and ICRAF, is located at Nauko (35°23’ S, 15°10’ E) in Machinga District in Malawi. It is on the southern foot of Liwonde Forest Reserve, about 10km on the eastern side of Machinga Boma; and about 25km to the western side of upper Lake Chilwa (Figure 3.1). The site is located in silvicultural zone C of the country with soils that are mainly of ferrallitic type. It lies at an altitude of 1000m above sea level and experiences mean annual rainfall of 840–960mm.

3.2 Plantation Design

This study was superimposed on an already established alpha lattice experimental design that was laid out at the site in the planting year of 1997 with seven provenances (six from Malawi and one bulked from Mozambique), 20 replications and 100 treatments representing families for the different provenances (Chirwa *et al.*, 2007). Each family or treatment formed a tree line plot with four trees from which data for this study was collected. A spacing of 2m within treatments and 4m between treatments was used in the layout. Figure 3.2 illustrates this design for a single planting block of 100 treatments. Five such blocks are available at the site. However due to time and financial limitations, three blocks were used for the study. The blocks were selected randomly after the blocks had been allocated random codes between one and five.

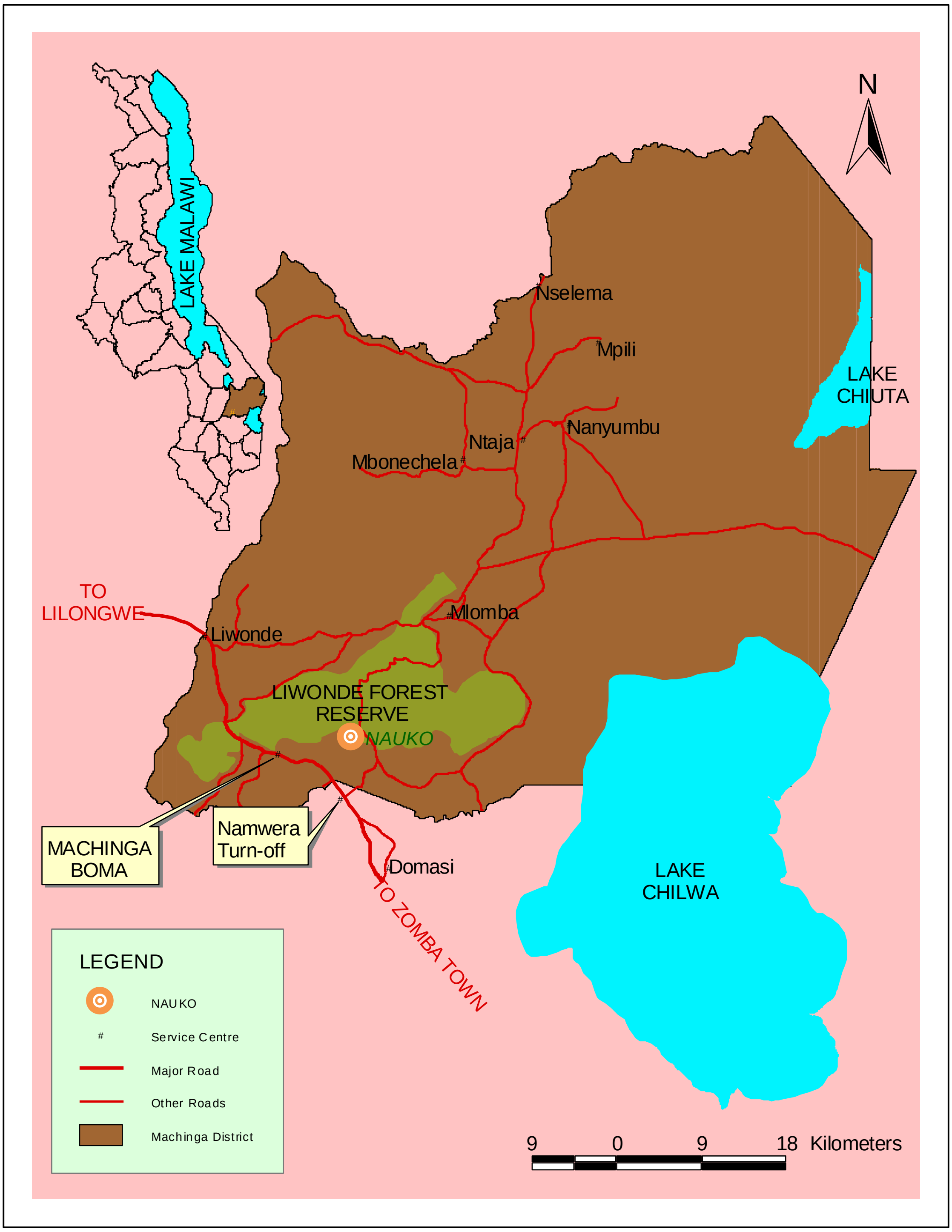


Figure 3.1: Location of the study site

According to Chirwa *et al.* (2007), the goal of establishing these provenance trials was to promote the domestication and wider growing of indigenous fruit trees by farmers in southern Africa. The study's initial aim was to evaluate the performance of *U. kirkiana* provenances and families from Malawi and Mozambique seed sources in order to sample the genetic variation existing in the natural populations and learn more about the biology of the species (Chirwa *et al.*, 2007). However, the current study was mainly focused on the indigenous provenances of Malawi namely Phalombe, Dedza, Luwawa, Kasungu, Litende and Thazima which are traceable as their coordinates are available. Seed for the 6 provenances and families were collected by the Malawi National Tree Seed Centre, Zomba and the codes for the provenances and their respective families are as indicated in Appendix 1. Location of origins of seed for the trial is shown in Appendix 2.

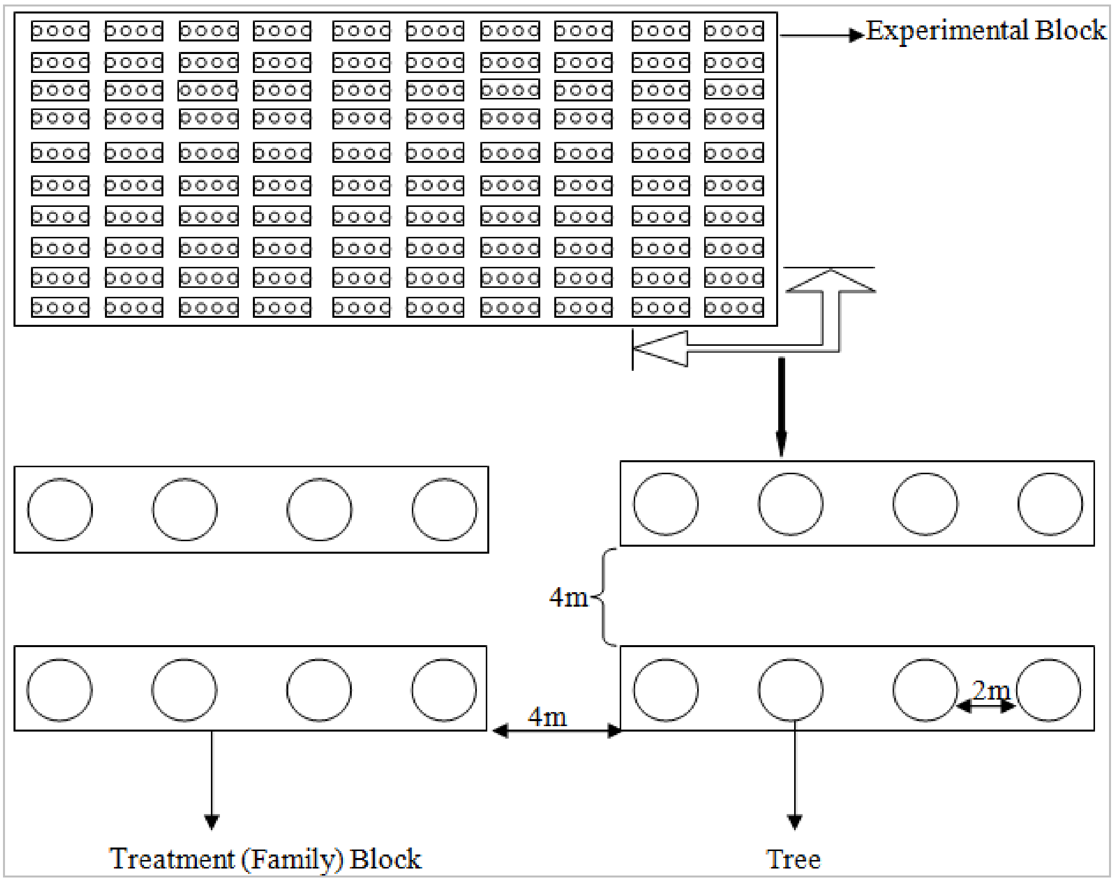


Figure 3.2: Layout of each experimental block

3.3 Data Collection Methods

3.3.1 Assessment of Primary Field Variables

Trees in each of the tree line plots were assessed for diameter at breast height (DBH), thus diameter at 1.3m from the ground; crown width; and height. Crown width was measured as the average vertical projection of the crown in the north-south and east-west orientations.

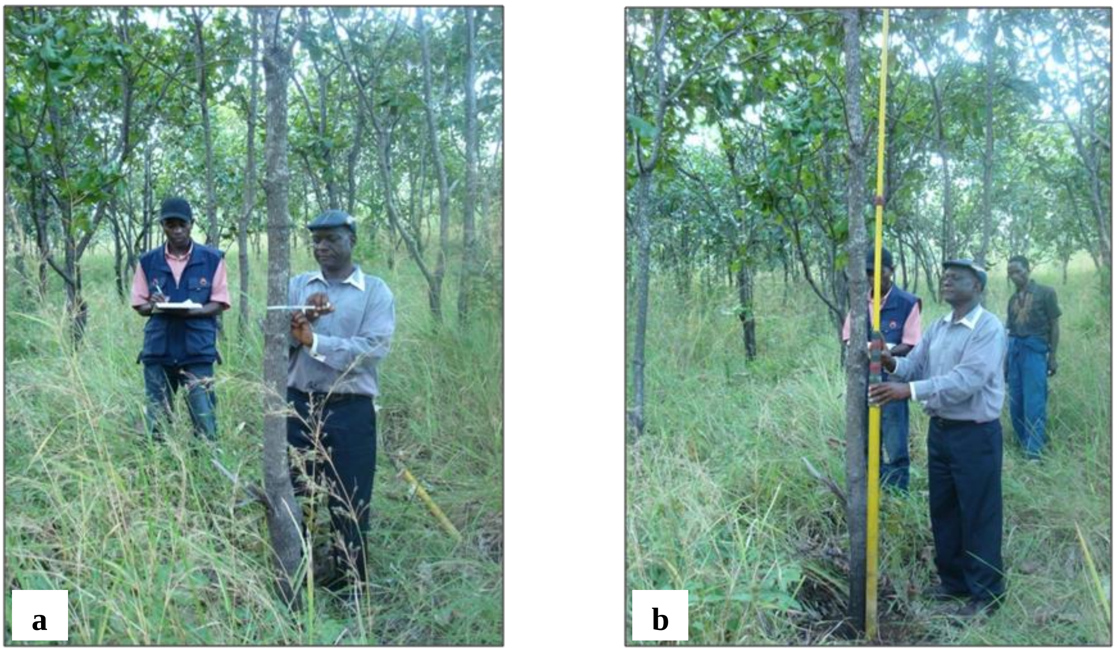


Plate 3.1: Reading of field measurements: a) diameter at breast height (dbh), b) height

3.3.2 Collection of Data for Carbon Estimation

Development of allometric equations that would be used to calculate carbon stocks locked by these provenances and families initially involved destructive sampling of trees from the population. As recommended by Pearson *et al.* (2005) for trees in a plantation with low variability and at about the same spacing, 26 trees were selected to represent the full range of the diameter classes. However only 24 sample trees were used in the study as 2 trees were later reported missing. This did not however affect the construction of allometric models as the maximal diameter (3-17cm) of the study was still proportionally covered in a manner similar to their presence.

Multi stage sampling engaging diameter class and provenance dominance as first and second stage sampling units respectively was employed. Thus contribution of each diameter class or provenance was proportional to its dominance in the data that was collected in the main survey for establishment of provenance growth. The former covered a maximal diameter range of 3 to 17cm as per data collected from the main survey. The sub-sample trees were then selected randomly depending on the codes that trees were allocated in each diameter class.

The selected trees were then harvested to the ground and divided into component parts namely the trunk, branches and foliage. The trunks and branches were cut into smaller logs that would easily fit into the ovens. The foliage was carefully pruned and packed into holed plastic bags at the site and dispatched to laboratories for oven drying. The component parts were indelibly numbered with codes for easy identification. The component parts were then oven dried to constant weight and measured for their dry mass which is the biomass content. The amount of carbon was computed by multiplying the biomass by 50% (Munishi *et al.,* 2010; Westlake, 1966; in Gibbs *et al.* 2007; Losi *et. al.,* 2003).

Plate 1.2: The tree-felling process

Plate 3.3: Some tree branches and trunks ready for oven-drying to constant weight

Plate 3.4: Weighing of samples after oven drying: a) trunk, b) foliage

3.4 Data Analyses

3.4.1 Growth Performance of the Provenances and Families

The provenances were compared for their differences in growth aspects with regard to the parameters measured in the main survey namely DBH, height and crown width. Mean DBH, height and crown widths were calculated at individual provenance level and family level. Analysis of variance (ANOVA) tests were done to compare provenance and family means and computation of descriptive statistics for the variables was conducted in Minitab Version 13 analytical software. As the provenances and families were unbalanced, thus they had unequal number of observations, Tukey’s pairwise comparison was used to detect whether differences in the means were significant or not.

3.4.2 Development of Allometric Equations

Allometric equations for carbon were also constructed in the same Minitab 13 analytical package using the data for the 24 oven-dried sample trees. The following standard forms as most commonly used by various authors were used in the construction of the allometric models:

$y = a + b\,D + c\,D^2$	(1)	$\ln y = a + b\,D^2H$	(6)
$y = a + b\,D$	(2)	$y^{0.5} = a + b\,D^2H$	(7)
$\ln y = a + b \ln D$	(3)	$\ln y = a + b \ln D + c \ln H$	(8)
$y^{0.5} = a + b\,D$	(4)	$y^{0.5} = a + b\,D + c\,H$	(9)
$y = a + b\,D^2H$	(5)	$y^{0.5} = a + b\,D^2 + c\,H + d\,D^2H$	(10)

where: *y* represents carbon content; *D* is the tree diameter at breast height; *H* is tree height; *a, b, c* and *d* are regression coefficients; and *ln* indicates the natural logarithm (Jayaraman, 2000).

The best fitting equations were selected based on the highest adjusted coefficient of determination (R^2), a lower Adjusted R^2 and a low standard error of estimate ($S_{y.x}$). Normal probability plots of residuals, and residuals versus predictor were used to test compliance with assumptions of least-squares regression, thus normality of distribution and homogeneity of variance.

3.4.3 Estimation of Carbon Stocks

The best fitting allometric equations that were developed from data for the sub-samples were used to estimate carbon of the rest of individual unharvested trees in the trial. Carbon sequestered by the provenances and families on a hectare basis were then computed from the carbon stocks obtained for the individual standing trees. Total aboveground biomass was regarded as the sum of trunk, branch and foliar carbon while belowground carbon was equivalent to root carbon.

Similar to the analysis in growth performance of the provenances, ANOVA was conducted to assess the differences in carbon stocks amongst the provenances, with their means compared using the Tukey's pairwise method. Procedural structure for the whole study is summarized in Figure 3.3.

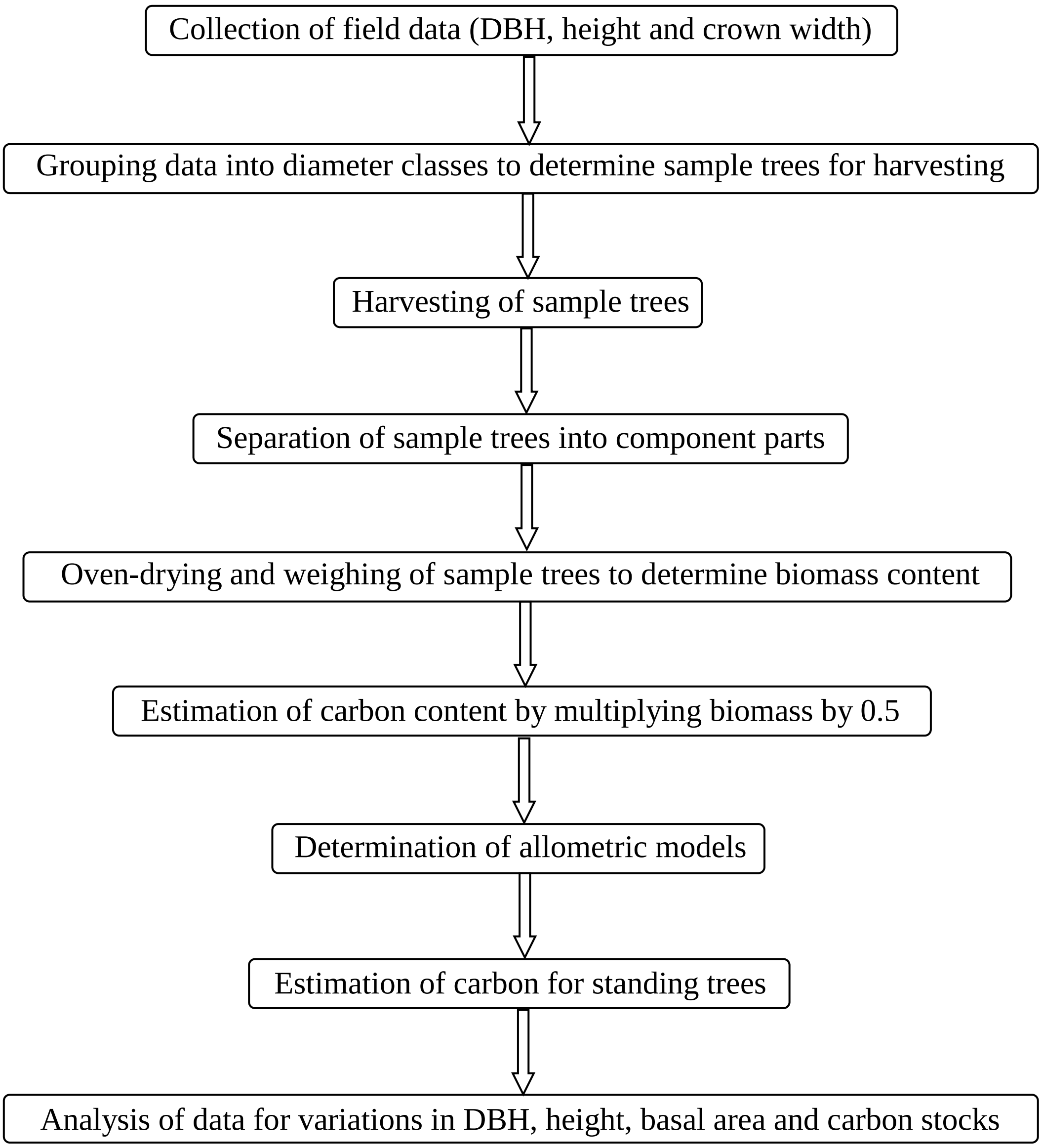


Figure 3.3: Methodological framework for the study

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Growth Performance of the Six *U. kirkiana* Provenances and Families

4.1.1 Survival

Overall survival for the provenances in the 12^{th} year of growth was 64%. However the survival for individual provenances registered above half of the trees planted for each provenance ranging between 54 and 69% for Litende and Luwawa provenances respectively (Figure 4.1). Ngulube (1996) reported survival rates between 28 and 100% for *U. kirkiana* up to 4 years, although these 12 year old provenances and families still fall within the same range.

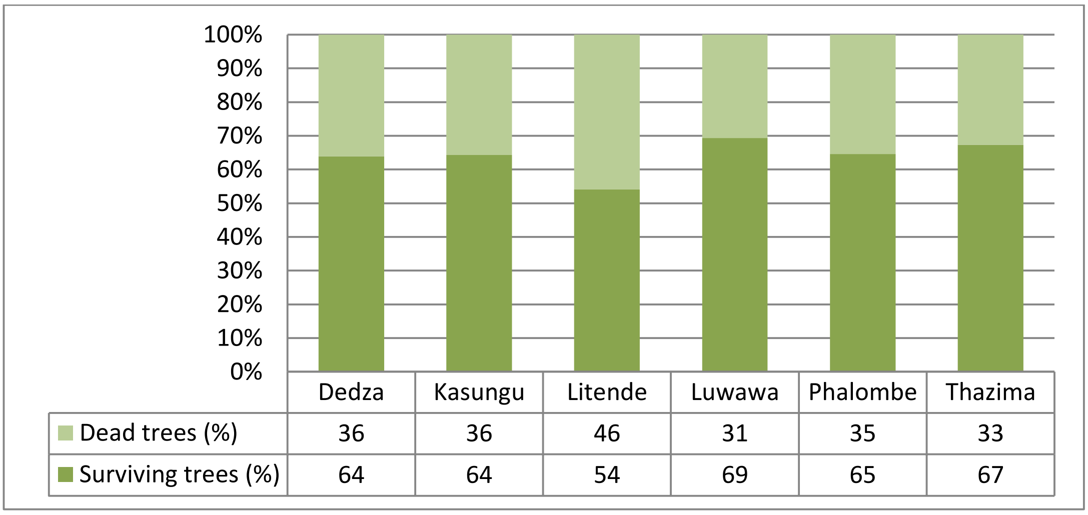


Figure 4.1: Survival of the provenances at 12 years of age

Previous results on survival of the provenances are limited to year three where the survival ranged from 76% for Litende to 87% for Thazima (Chirwa *et al.*, 2007). Despite that there seemed to be favourably high survival in the third year of growth, the low survival for Litende may have continued over time resulting in a further lower survival in the 12th year of growth. Dedza and Phalombe registered survivals of 83% each while Kasungu and Luwawa had 81 and 86% respectively.

4.1.2 Height

Phalombe (4.7 ± 0.87m tree^{-1}) outgrew the other provenances in terms of height (Figure 4.2). The least performing provenance was Dedza (4.43 ± 1.06m tree^{-1}). However none of the paired Tukey's comparisons for the mean heights yielded a significant difference between any pair (F = 2.06, p = 0.069, Appendix 3a). All the pairs of intervals in Tukey's pairwise comparison included value zero (0) or had the upper and lower bounds with different terms signifying that their corresponding means were not significantly different from one another. Mean height by family differed significantly, varying between 3.06 ± 1.05m tree^{-1} for Family 48 from Thazima provenance, and 5.95 ± 1.08m tree^{-1} for Family 68 from Kasungu provenance (F = 1.60, p = 0.001, Appendix 4a).

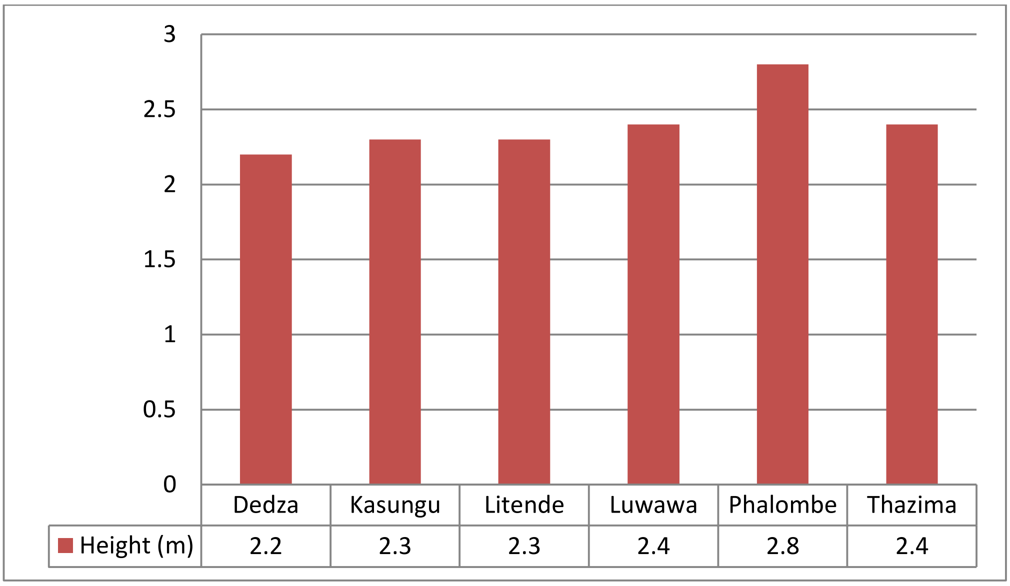
```
One-way ANOVA: Height (m) versus Provenance

Analysis of Variance for Height (
Source     DF        SS        MS        F        P
Provenan    5     10.85      2.17     2.06    0.069
Error     743    783.21      1.05
Total     748    794.06
                                 Individual 95% CIs For Mean
                                 Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
Dedza     207     4.428     1.063         (-----*-----)
Kasungu    54     4.687     1.185               (----------*----------)
Litende    39     4.446     1.166   (------------*------------)
Luwawa    158     4.447     1.113         (------*-----)
Phalombe  186     4.696     0.870                    (-----*-----)
Thazima   105     4.436     0.928        (------*-------)
                                   ------+---------+---------+---------+
Pooled StDev =    1.027                 4.25      4.50      4.75      5.00
```

Figure 4.2: Minitab output for ANOVA for height

An earlier study of growth performance of the same trial at age six by Chirwa et al. (2007) found significant differences in height growth of the provenances with

Phalombe standing out (Figure 4.3). Overall growth of the provenances has however remained steady with other provenances slowly picking up.



(Data Source: Chirwa *et al.*, 2007)

Figure 4.3: Growth of height for *U. kirkiana* provenances at Nauko at 6 years

4.1.3 Crown Width

ANOVA results for crown width showed that there were no significant differences between pairs of crowns for all the provenances except between Luwawa and Dedza which had the least and widest mean crown of 1.98 ± 0.85m and 2.27 ± 0.86m $tree^{-1}$ respectively (F = 2.75, p = 0.018; Figure 4.4). Jayaraman (2000) indicated that even though results may statistically be significant, there is still need to compare whether that difference is practically significant. The difference in the two means (0.29m) is practically not significant when growth especially of the crown is considered as it can be easily attained.

```
Analysis of Variance for Crown W
Source     DF        SS        MS        F        P
Provenan    5    10.342     2.068     2.75    0.018
Error     743   559.262     0.753
Total     748   569.604
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
Dedza     207    2.2652    0.8585                          (-----*-----)
Kasungu    54    2.0500    0.8053          (-----------*-----------)
Litende    39    1.9859    0.8409  (-------------*------------)
Luwawa    158    1.9791    0.8531           (------*------)
Phalombe  186    2.1742    0.9248                     (------*-----)
Thazima   105    2.2238    0.8420                       (-------*--------)
                                   -------+---------+---------+---------
Pooled StDev =   0.8676                  1.80      2.00      2.20
```

Figure 4.4: Minitab output for ANOVA for crown width

Family 40 from Dedza provenance had the widest mean crown (3.1 ± 0.26m tree^{-1}) with Family 91 from Litende provenance as the least (1.34 ± 0.83m tree^{-1}; Appendix 4b). None of the paired comparisons of crown width at family level yielded a significant difference between one family and the other (F = 1.02, p = 0.438). Lambeth and Hubert (1997, in Chirwa *et al.*, 2007) in their study of inheritance of crown traits and their relationship to growth rate in *Pinus* species of south-eastern USA reported very low genetic control (<0.2, heritability values) of crown width. A previous study on the same provenances at age 6 by Chirwa *et al.* (2007) also showed lack of significant differences in growth of the crown.

4.1.4 Diameter at Breast Height (DBH)

Significant differences were detected in the DBH of the provenances (p = 0.000, F = 4.49; Figure 4.5). Phalombe was the most superior provenance (8.59 ± 2.19cm tree^{-1}) in growth of this trait. Multiple comparison of the mean showed Phalombe's mean DBH significantly different from the rest of the provenances. Although all the other provenances did not significantly differ from one another, Luwawa had the least mean DBH (7.53 ± 2.31cm tree^{-1}). Growth performance in DBH amongst families showed significant differences between means of the various families (F = 1.65, p = 0.000;

Appendix 4c). The DBH range for the families was 5.2 ± 1.11cm tree^{-1} (Family 27, Dedza provenance) to 10.7 ± 1.89cm tree^{-1} (Family 11, Phalombe provenance). Phalombe has almost similar altitudinal and rainfall range with Nauko (Appendix 2). This does not however consider other conditions as differences in soil characteristics and temperature. Tree growth is interplay of various site conditions as well as hereditability (Dangasuk *et al*., 2001) and/or gene-environment interactions (Jayaraman, 2000).

```
One-way ANOVA: DBH (cm) versus Provenance

Analysis of Variance for DBH (cm)
Source     DF        SS        MS        F        P
Provenan    5    119.27     23.85     4.49    0.000
Error     743   3951.40      5.32
Total     748   4070.66
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
Dedza     207     7.892     2.408              (-----*----)
Kasungu    54     7.598     2.417   (----------*---------)
Litende    39     7.603     2.629   (----------*----------)
Luwawa    158     7.532     2.305       (-----*-----)
Phalombe  186     8.588     2.188                          (----*-----)
Thazima   105     7.753     2.116         (------*-------)
                                   ------+---------+---------+---------+
Pooled StDev =    2.306                7.20      7.80      8.40      9.00
```

Figure 4.5: Minitab output for ANOVA for DBH

4.2 Carbon Allometry

4.2.1 Root Carbon Models

All prediction equations together with their respective test statistics, thus coefficients of determination (R^2) and standard error of estimate (S) are presented in Table 4.1. The results show that the predictor variables were able to explain variation in the dependent variable within a range of 54.6% to 76.8%. The line of best fit was presented by the equation:

$Y = 1.20 - 0.333D + 0.0495D^2$

where Y = carbon (kg) and D = diameter at breast height (cm).

Table 4.1: Allometric equations for root carbon

Root Carbon		
Regression Equation	R^2	$S_{y.x}$
$Y = -2.15 + 0.519\ D$	70.1%	0.8767
$Y = 1.20 - 0.333\ D + 0.0495\ D^2$	76.8%	0.7906
$lnY = -3.97 + 2.14\ lnD$	63.5%	0.5517
$Y^{0.5} = -0.088 + 0.176\ D$	68.1%	0.3109
$Y = 0.180 + 0.00563\ D^2H$	75.7%	0.7902
$lnY = -0.500 + 0.00272\ D^2H$	54.6%	0.6148
$Y^{0.5} = 0.724 + 0.00184\ D^2H$	68.3%	0.3098
$lnY = -4.33 + 1.89\ lnD + 0.609\ lnH$	64.2%	0.5592
$Y^{0.5} = -0.181 + 0.168\ D + 0.036\ H$	68.3%	0.3175
$Y^{0.5} = 0.124 + 0.0138\ D^2 + 0.124\ H - 0.00095\ D^2H$	69.7%	0.3178

As regards standard errors of estimates (S), low figures were generally computed for all models. Residual plots for the lines of best fit for each component are presented in Appendix 5. All the normal probability plots showed reasonable linearity while plots of residual against predictors showed no discernible pattern, below and above the zero (0), signifying equality of variance over classes of the predictor variables.

Ryan et al. (2011) reported that the general assumption is that belowground or root biomass is generally 0.25 of aboveground biomass which equally applies to carbon. Similarly, Cairns et al. (1997; in Ravindranath and Ostwald 2008) reported that root biomass (Y) for tropical forests trees could be calculated using the following equation:

$Y = \mathrm{Exp}\ [-1.0587 + 0.8836 * ln(\mathrm{AGB})]$.

This model was tested for its root carbon against the study's model using the assumption that carbon was 50% of biomass (Figure 4.6). Assumption that root carbon was 0.25 of aboveground biomass was also tested. Significant differences were detected amongst the means (F = 519.35, p = 0.000). Cairns et al.'s model underestimated the mean root carbon by over 80% (0.334 to 1.943 kg tree^{-1}). This may be due to that the model was not specific to a location, forest type and species.

The general assumption by Ryan et al. underestimated the carbon for the *U. kirkiana* provenances by 0.223kg (1.720 to 1.943 kg tree^{-1}). This significance in the differences could be attributed to the fact that this is just a general assumption while this study's model is species specific. The age or maximal diameter range for which the models were developed may also be significant in explaining these differences as models may prove weaker in predicting carbon or biomass for trees outside the maximal diameter they were generated from (Sah, 2004).

One-way ANOVA: Root C (kg), Ryan Assump C, Cairns Model C

```
Analysis of Variance
Source      DF        SS        MS        F        P
Factor       2   1138.14    569.07   519.35    0.000
Error     2244   2458.83      1.10
Total     2246   3596.96
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Level        N      Mean     StDev  -----+---------+---------+---------+-
Root C (   749     1.943     1.214                                  (-*)
Ryan Ass   749     1.720     1.313                              (*-)
Cairns M   749     0.334     0.296  (-*)
                                    -----+---------+---------+---------+-
Pooled StDev =     1.047                0.50      1.00      1.50      2.00
```

Figure 4.6: Comparison between root carbon assumption and the study's model

4.2.2 Trunk Carbon Models

The results show that the predictor variables were able to explain variation in the dependent variable of within a range of 73.8% to 88.7% (Table 4.2). The latter represented the logarithmic equations:

$$\ln Y = -2.83 + 1.72 \ln D + 0.492 \ln H$$

The standard error of estimate varied between 0.2396 and 2.5260.

Table 4.2: Allometric equations for trunk carbon

Trunk Carbon		
Regression Equation	R^2	$S_{y.x}$
$Y = -4.31 + 1.15 D$	84.6%	1.2630
$Y = -0.25 + 0.113 D + 0.0601 D^2$	87.1%	1.1860
$\ln Y = -2.54 + 1.93 \ln D$	87.9%	0.2425
$Y^{0.5} = 0.064 + 0.255 D$	87.0%	0.3109
$Y = 0.936 + 0.0121 D^2H$	86.9%	1.1670
$\ln Y = 0.599 + 0.00242 D^2H$	73.8%	0.3576
$Y^{0.5} = 1.26 + 0.00260 D^2H$	83.4%	0.2878
$\ln Y = -2.83 + 1.72 \ln D + 0.492 \ln H$	88.7%	0.2399
$Y^{0.5} = -0.233 + 0.229 D + 0.116 H$	87.8%	0.2524
$Y^{0.5} = -0.357 + 0.0293 D^2 + 0.360 H - 0.00355 D^2H$	87.8%	0.2587

Munishi et al. (2010) developed the following carbon models for trunks for two forest reserves in old-growth miombo woodlands of Southern Tanzania where *U. kirkiana* was one of the most dominant species and diameter for the trees ranged from 5cm:

$_{0.0069}DBH^{2.9756}$ (Longisonte Forest Reserve)

$_{0.0172}DBH^{2.5702}$ (Zelezeta Forest Reserve).

A comparison of the two trunk model with this study's trunk carbon model showed significant variations among the means (F = 8.73, p = 0.000; Figure 4.7). However the models for the two reserves did not vary. The two models did not consider tree diameters less than 5cm and this may have partially contributed to the variation. However the differences were practically insignificant.

```
One-way ANOVA: Trunk C (kg), Longisonte Trunk C, Zelezeta Trunk C

Analysis of Variance
Source      DF        SS        MS        F        P
Factor       2     177.6      88.8     8.73    0.000
Error     2244   22821.5      10.2
Total     2246   22999.1
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev ----------+---------+---------+------
Trunk C    749     4.739     2.701                     (--------*-------)
Longidot   749     4.136     3.662 (-------*------)
Zelezeta   749     4.150     3.131  (------*-------)
                                   ----------+---------+---------+------
Pooled StDev =     3.189                   4.20      4.50      4.80
```

Figure 4.7: Comparison between Longisonte and Zelezeta trunk models, and the study's model

4.2.3 Branch Carbon Models

Figure 4.8 shows best fit equation for branch carbon. The combined predictor variable (D^2H) for the line of best-fit was able to explain 77.7% variation in carbon stocks for the provenances. The least variation that could be explained by the regression models for branch carbon was for a logarithmic equation with about 57% (Table 4.3). Munishi et al. (2010) developed the following carbon models for branches for miombo species in Longisonte and Zelezeta Forest Reserves:

$_{0.0489}\text{DBH}^{2.1623}$ (Longisonte)

$_{0.5606}\text{DBH}^{2.4067}$ (Zelezeta).

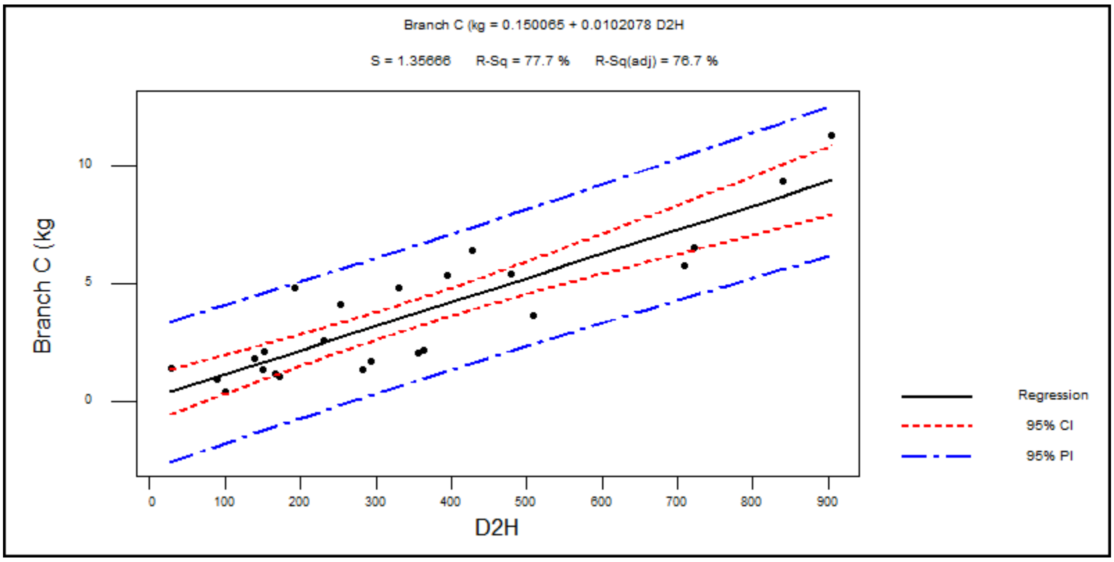


Figure 4.8: Fitted line plot of branch carbon model

Table 4.3: Allometric equations for branch carbon

Branch Carbon		
Regression Equation	R^2	$S_{y.x}$
$Y = -3.92 + 0.922\ D$	69.1%	1.5950
$Y = 2.38 - 0.678\ D + 0.0931\ D^2$	76.5%	1.4240
$lnY = -2.84 + 1.87\ lnD$	57.2%	0.5490
$Y^{0.5} = -0.117 + 0.231\ D$	68.8%	0.4032
$Y = 0.150 + 0.0102\ D^2H$	77.7%	1.3570
$lnY = 0.066 + 0.00273\ D^2H$	64.8%	0.4981
$Y^{0.5} = 0.922 + 0.00251\ D^2H$	74.1%	0.3672
$lnY = -3.25 + 1.58\ lnD + 0.688\ lnH$	58.3%	0.5548
$Y^{0.5} = -0.445 + 0.203\ D + 0.128\ H$	69.8%	0.4063
$Y^{0.5} = 1.04 - 0.0067\ D^2 - 0.010\ H + 0.00374\ D^2H$	74.4%	0.3828

Mean carbon density per tree varied significantly between the branch models for Longisonte and Zelezeta Forest Reserves, and this study's model (F = 368.9 and p = 0.000; Figure 4.9). However the difference between this study's model and Longisonte's model was not as huge as the difference between the former and Zelezeta's. Zelezeta's overestimation of the branch carbon may have been contributed by the fact that it was a very weak relationship, able to explain only 34% of variation in the dependent variable, branch carbon (Munishi et al., 2010).

```
One-way ANOVA: Branch C (kg), Longisonte Branch C, Zelezeta Branch C

Analysis of Variance
Source      DF        SS       MS       F       P
Factor       2   14689.1   7344.5  368.29   0.000
Error     2244   44750.1     19.9
Total     2246   59439.1
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean    StDev  ----+---------+---------+---------+--
Branch C   749     3.564    2.484  (-*)
Longison   749     4.776    3.007        (-*)
Zelezeta   749     9.491    6.679                               (*-)
                                   ----+---------+---------+---------+--
Pooled StDev =     4.466              4.0       6.0       8.0      10.0
```

Figure 4.9: Comparison between Longisonte and Zelezeta branch models, and the study's model

4.2.4 Leaf Carbon Models

The range in explaining variability in the dependent variables for leaf carbon was 61.1% to 85.7% (Table 4.4). The line of best-fit was:

$$Y^{0.5} = -0.292 + 0.0111D^2 + 0.146H - 0.00175D^2H$$

The standard error of estimate ranged between 0.06811 and 0.44440. Calva-Alvarado et al. (2008) also found several nonlinear relationships for biomass in their study of five tropical species in Puerto Viejo, in the north Caribbean lowlands of Costa Rica. However loss of leaves at varying times within the dry season may have contributed to the lack of linearity in the model for *U. kirkiana* at Nauko.

Table 4.4: Allometric equations for leaf carbon

Leaf Carbon		
Regression Equation	R^2	$S_{y.x}$
$Y = -0.212 + 0.0670\ D$	79.6%	0.08779
$Y = -0.090 + 0.0361\ D + 0.00180\ D^2$	80.2%	0.08852
$lnY = -5.23 + 1.93\ lnD$	84.1%	0.28450
$Y^{0.5} = 0.0667 + 0.0599\ D$	81.5%	0.07388
$Y = 0.0998 + 0.000695\ D^2H$	78.6%	0.08988
$lnY = -2.04 + 0.00225\ D^2H$	61.2%	0.44440
$Y^{0.5} = 0.353 + 0.000596\ D^2H$	74.2%	0.08714
$lnY = -5.62 + 1.65\ lnD + 0.654\ lnH$	85.4%	0.27860
$Y^{0.5} = -0.0433 + 0.0505\ D + 0.0428\ H$	83.3%	0.07169
$Y^{0.5} = -0.292 + 0.0111\ D^2 + 0.146\ H - 0.00175\ D^2H$	85.7%	0.06811

4.2.5 Aboveground Carbon

The models generated for aboveground carbon ranged between 77.6% and 88.7% (Table 4.5). Figure 4.10 shows the model of best-fit for aboveground carbon. Ryan et al. (2011) developed the following biomass model for miombo species in Mozambique:

$$Y = {}_{0.0267}D^{2.5996}$$

where Y was biomass and D is diameter at breast height.

Carbon was assumed to be 50% of the biomass. A comparison of means generated by this current study and that generated for miombo species in Mozambique showed that the latter underestimated the carbon by 2.01kg per individual tree ($F = 51.20$ and $p = 0.000$; Figure 4.11). This may therefore significantly underestimate carbon on a hectare basis. However like with differences obtained for root carbon, the difference may practically be insignificant where other models are unavailable and cannot be estimated at all.

Table 4.5: Allometric equations for aboveground carbon

Aboveground Carbon		
Regression Equation	R^2	$S_{y.x}$
$Y = -8.44 + 2.14\ D$	83.2%	2.4830
$Y = 2.04 - 0.529\ D + 0.155\ D^2$	87.8%	2.1660
$\ln Y = -1.81 + 1.85 \ln D$	80.8%	0.3059
$Y^{0.5} = 0.014 + 0.347\ D$	85.1%	0.3768
$Y = 1.19 + 0.0230\ D^2H$	88.7%	2.0320
$\ln Y = 1.15 + 0.00248\ D^2H$	77.6%	0.3308
$Y^{0.5} = 1.62 + 0.00364\ D^2H$	85.7%	0.3687
$\ln Y = -2.15 + 1.61 \ln D + 0.581 \ln H$	81.9%	0.3039
$Y^{0.5} = -0.443 + 0.309\ D + 0.178\ H$	86.1%	0.3725
$Y^{0.5} = 0.377 + 0.0192\ D^2 + 0.286\ H - 0.00051\ D^2H$	87.0%	0.3690

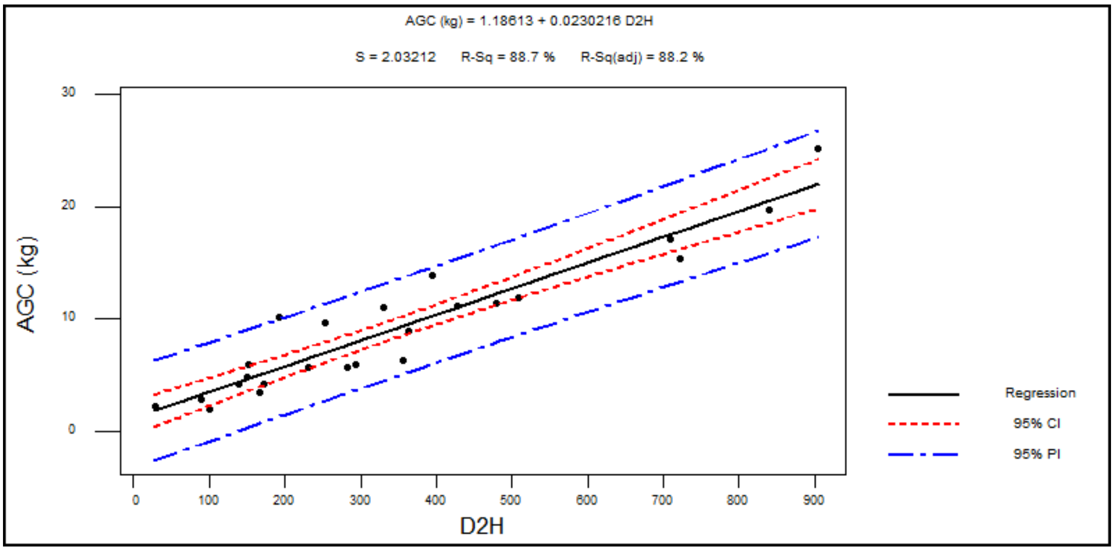


Figure 4.10: Fitted line plot aboveground carbon model

```
One-way ANOVA: AGC (kg), MozAGC

Analysis of Variance
Source      DF        SS        MS        F        P
Factor       1    1510.0    1510.0    51.20    0.000
Error     1496   44120.3      29.5
Total     1497   45630.2
                                     Individual 95% CIs For Mean
                                     Based on Pooled StDev
Level        N      Mean     StDev   ---------+---------+---------+-------
ABC (kg)   749     8.887     5.602                            (----*----)
MozAGC     749     6.879     5.254   (----*----)
                                     ---------+---------+---------+-------
Pooled StDev =     5.431                     7.20      8.00      8.80
```

Figure 4.11: Comparison between Mozambique miombo aboveground carbon model and this study's model

4.2.6 Total Carbon

Best-fit model for total carbon had a coefficient of determination of 92.4% (Figure 4.12). The relatively least fitting model for the total carbon had its coefficient of 79.2% (Table 4.6).

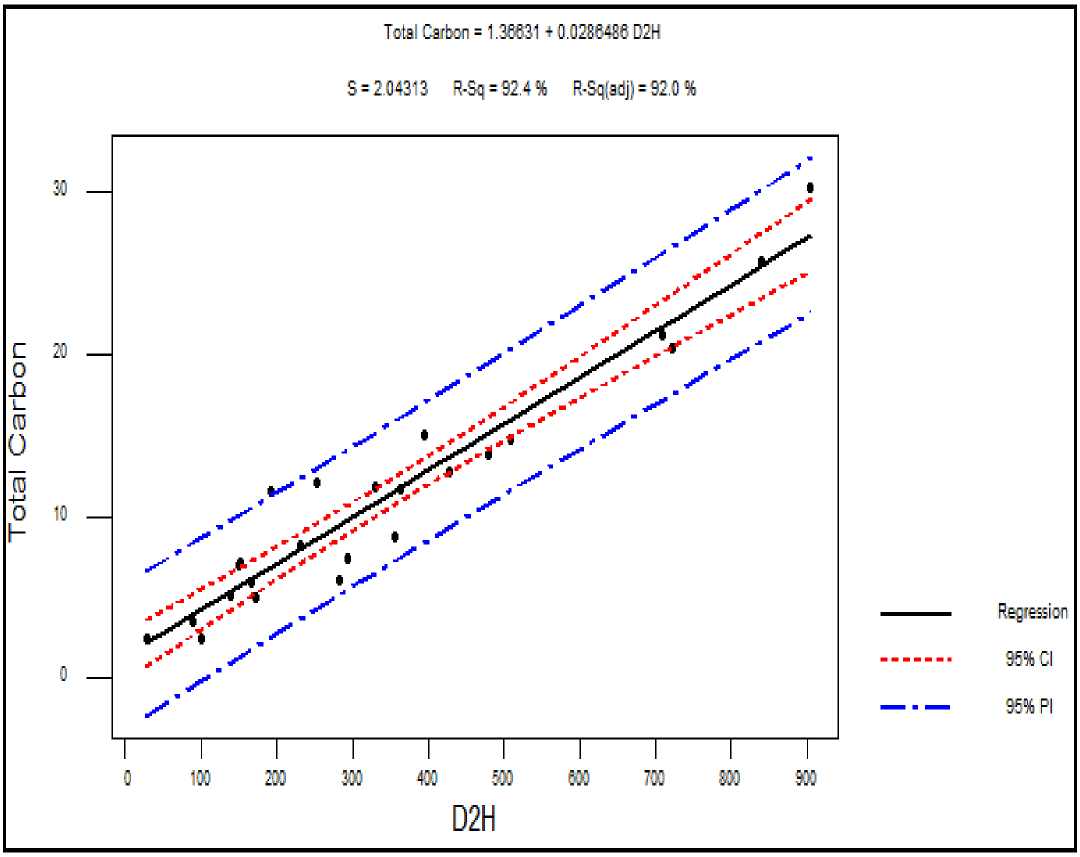


Figure 4.12: Fitted plot line for total tree carbon

Table 4.6: Allometric equations for total carbon

Total Carbon		
Regression Equation	R^2	$S_{y.x}$
$Y = -10.6 + 2.65 D$	86.4%	2.7280
$Y = 3.24 - 0.862 D + 0.204 D^2$	91.7%	2.1730
$lnY = -1.64 + 1.87\ lnD$	84.5%	0.2727
$Y^{0.5} = 0.004 + 0.388 D$	88.5%	0.3621
$Y = 1.37 + 0.0286 D^2H$	92.4%	2.0430
$lnY = 1.36 + 0.00249 D^2H$	79.2%	0.3159
$Y^{0.5} = 1.79 + 0.00406 D^2H$	88.9%	0.3550
$lnY = -1.98 + 1.63\ lnD + 0.580\ lnH$	85.6%	0.2688
$Y^{0.5} = -0.455 + 0.349 D + 0.178 H$	89.3%	0.3568
$Y^{0.5} = 0.378 + 0.0238 D^2 + 0.321 H - 0.00100 D^2H$	90.3%	0.3477

4.3 Carbon Stocks

4.3.1 Root Carbon Stocks

Root carbon for the provenances ranged between 1.762 ± 1.075kg tree^{-1} (Luwawa) and 2.227 ± 1.282kg tree^{-1} (Phalombe; Figure 4.13). Significant differences were detected in the mean carbon stocks for the provenances (F = 3.18, p = 0.08). Phalombe, Dedza, Kasungu and Litende's means were not significantly different from each other. However the latter three provenances were also not significantly different to the other provenances, Thazima and Luwawa making Phalombe a superior provenance in sequestering carbon with roots.

Significant differences were also detected in mean root carbon stocks at family level with Family 11 from Phalombe the most superior family (3.453 ± 1.364kg of root carbon tree^{-1};) and Family 27 from Dedza the most inferior family with 0.854 ± 0.18kg of root carbon tree^{-1} (F = 1.35, p = 0.020; Appendix 6a).

Peichl and Arain (2007) recorded mean belowground tree carbon stocks of 0.1 and 13 kg tree^{-1} in 2 and 15 year-old stands respectively in white pine forests of Ontario, that may also vary by species and site conditions.

```
One-way ANOVA: Root C (kg) versus Provenance

Analysis of Variance for Root C (
Source      DF        SS        MS        F        P
Provenan     5     23.10      4.62     3.18    0.008
Error      743   1080.20      1.45
Total      748   1103.31
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  -+---------+---------+---------+-----
Dedza      207     1.940     1.253              (------*-----)
Kasungu     54     1.812     1.170   (-----------*------------)
Litende     39     1.864     1.561  (---------------*--------------)
Luwawa     158     1.762     1.075      (------*-------)
Phalombe   186     2.227     1.282                        (------*------)
Thazima    105     1.814     1.012      (---------*--------)
                                    -+---------+---------+---------+-----
Pooled StDev =     1.206           1.50      1.75      2.00      2.25
```

Figure 4.13: Minitab output for ANOVA for root carbon stocks

4.3.2 Trunk Carbon Stocks

Phalombe (5.403 ± 2.657kg tree^{-1}) was again the most superior provenance in sequestering carbon through the trunk (F = 3.33, p = 0.006; Figure 4.14). Luwawa had the least ability to sequester carbon through the trunk. However its mean was not significantly different from the other provenances except for Phalombe. General proportional growth to root availability may have accounted for this almost similar pattern in sequestering of carbon in the trunks to the roots. Carbon stocks by family in trunks varied between 1.952 ± 0.773kg tree^{-1} for Family 27 and 8.46 ± 2.742kg tree^{-1} for Family 11. Significant differences were detected in the means for the families (F = 3.33, p = 0.006; Appendix 6b).

Zewdie et al. (2009) studied above-ground biomass production and allometric relations of 11 to 60 year-old Eucalyptus globulus Labill. coppice plantations along a chronosequence in the central highlands of Ethiopia. Stem wood carbon varied between 0.8 and 77.6 kg stem^{-1}. However in addition to the variation in species, altitude for the study site ranged from 2300 to 3200 m above sea level. Average annual temperature was 20 °C while annual mean precipitation ranged from 971 to 1464 mm but also with a bimodal distribution. Soils within the study area were predominantly classified as Nitosols. Montes et al. (2005), in their study of stem growth among provenances of Calycophyllum spruceanum from the Peruvian Amazon found significant variations in their growth with the growth more pronounced in a zone with the most fertile soils and highest rainfall. This resultantly affects the amount of carbon a plant can sequester as it is a function of biomass accumulation.

```
One-way ANOVA: Trunk C (kg) versus Provenance

Analysis of Variance for Trunk C
Source     DF       SS       MS        F        P
Provenan    5   119.75    23.95     3.33    0.006
Error     743  5338.12     7.18
Total     748  5457.87
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----------+---------+---------+------
Dedza     207     4.682     2.808              (-----*-----)
Kasungu    54     4.549     2.809      (-----------*-----------)
Litende    39     4.466     3.142  (-------------*-------------)
Luwawa    158     4.353     2.590        (------*------)
Phalombe  186     5.403     2.657                        (-----*-----)
Thazima   105     4.454     2.324        (-------*--------)
                                   ----------+---------+---------+------
Pooled StDev =    2.680                    4.20      4.80      5.40
```

Figure 4.14: Minitab output for ANOVA for trunk carbon stocks

4.3.3 Branch Carbon Stocks

Significant variations were observed for the provenances in terms of branch carbon stocks. Phalombe was the most superior provenance with mean carbon stock of 4.108 ± 2.475kg tree^{-1} (F = 2.66, p = 0.021; Figure 4.15). The most inferior provenance was again Luwawa with a mean of 3.259 ± 2.369kg of carbon tree^{-1}. However this mean was not significantly different from those for the other four provenances except for Phalombe. Branch carbon significantly differed by family ranging between 1.504 ± 1.074kg tree^{-1} for Family 31 from Dedza provenance and 7.26 ± 2.855kg tree^{-1} for Family 11 (F = 1.38, p = 0.014; Appendix 6c).

```
One-way ANOVA: Branch C (kg) versus Provenance

Analysis of Variance for Branch C
Source     DF        SS       MS       F       P
Provenan    5     81.27    16.25    2.66   0.021
Error     743   4534.47     6.10
Total     748   4615.74
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean    StDev   -------+---------+---------+---------
Dedza     207     3.511    2.592             (-----*----)
Kasungu    54     3.501    2.668       (----------*----------)
Litende    39     3.368    2.885   (------------*------------)
Luwawa    158     3.259    2.369        (-----*------)
Phalombe  186     4.108    2.475                       (----*-----)
Thazima   105     3.267    2.063       (------*-------)
                                   -------+---------+---------+---------
Pooled StDev =    2.470                 3.00      3.60      4.20
```

Figure 4.15: Minitab output for ANOVA for branch carbon stocks

An overall comparison of trunk carbon to branch carbon irrespective of provenance showed an individual tree sequestering an average of 4.651 and 3.502kg respectively, equivalent to 57 and 43% between the two. Munishi et al. (2010) estimated 1.29 and 1.63 tonnes of total carbon for trunks and branches respectively for the miombo of Southern Highlands of Tanzania, representing 44 and 54% respectively. The difference between the proportions might be due to the differences in openness of the natural miombo forest and the plantation which might have influenced the way the branches were growing.

4.3.4 Leaf Carbon Stocks

Phalombe (0.358 ± 0.141kg tree^{-1}) was the superior provenance in sequestering carbon by foliage (F = 4.74, p = 0.000; Figure 4.16). The most inferior provenance was Luwawa at 0.287 ± 0.145kg of foliage carbon. However there was no significant difference between this mean and those for Dedza, Kasungu, Litende and Thazima. The differences in the foliar carbon means were also significant among the families ($F = 1.57$, $p = 0.001$; Appendix 6d). The most superior family was 74 (0.44 ± 0.252kg tree^{-1}) from Luwawa provenance while the least was 27 (0.141 ± 0.072kg tree^{-1}) from Dedza provenance.

```
One-way ANOVA: Leaf C (kg) versus Provenance

Analysis of Variance for Leaf C
Source      DF        SS        MS        F        P
Provenan     5    0.5169    0.1034     4.74    0.000
Error      743   16.1915    0.0218
Total      748   16.7084
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  --------+---------+---------+--------
Dedza      207    0.3072    0.1503            (-----*-----)
Kasungu     54    0.2957    0.1438   (----------*-----------)
Litende     39    0.2995    0.1744  (-------------*------------)
Luwawa     158    0.2869    0.1454     (------*------)
Phalombe   186    0.3581    0.1407                         (-----*-----)
Thazima    105    0.3082    0.1488          (-------*-------)
                                    --------+---------+---------+--------
Pooled StDev =    0.1476                 0.280     0.315     0.350
```

Figure 4.16: Minitab output for ANOVA for leaf carbon stocks

Breman and Kessler (1995; in FAO, 1999) reported the following green foliage weight production per mature tree for species from sub-Saharan Africa: *Acacia senegal* – 1 kg; *Acacia laeta* - 0.8 kg; *Acacia seyal* - 2.9 kg; *Balanites aegyptiaca* - 0.8 kg; *Combretum ghasalense* - 4.5 kg; *Commiphora africana* - 0.9 kg; *Grewia bicolor* - 2.1 kg; *Guiera senegalensis* - 0.2 kg; *Pterocarpus lucens* - 1.85 to 2.3 kg; *Sclerocarya birrea* - 14.3 kg. Oven drying of the foliage may significantly reduce these weights and applying an carbon assumption of 50% of dry weight would mean the 12-year old performing relatively better for their age. However some other species can perform better based on the conditions they are grown. Son and Kim (1998) recorded about 1.2 tonnes of carbon ha^{-1} for 15-year-old *Ginkgo biloba* plantation in Central Korea.

4.3.5 Aboveground Carbon Stocks

ANOVA results in Figure 4.17 indicate that not all means of aboveground carbon stocks for the provenances were significantly similar (F = 2.67, p = 0.021). Phalombe (10.12 ± 5.58kg $tree^{-1}$) was not significantly different from Dedza (8.77 ± 5.85kg $tree^{-1}$), Kasungu (8.75 ± 6.51kg $tree^{-1}$) and Litende (8.45 ± 6.01kg $tree^{-1}$). However Dedza, Phalombe and Litende were also significantly not different from the two most inferior provenances, Thazima (8.22 ± 4.65kg $tree^{-1}$) and Luwawa (8.20 ± 5.58kg $tree^{-1}$). However significant differences were noted in aboveground carbon stocks for the families and the means varied between 3.584 ± 1.153kg $tree^{-1}$ and 17.223 ± 6.437kg $tree^{-1}$ for Family 27 and Family 11 respectively (F = 1.38, p = 0.014; Appendix 6e). This may not be comparable with other species also growing in their natural conditions as white pine forests of Ontario which registered between 0.3 and 54 kg $tree^{-1}$ in 2 and 15 year-old stands respectively (Peichl and Arain, 2007). The species would be expected to be comparable with the older age group. Generally long-lived slow growing trees, with higher wood density, store more carbon than fast growing short-lived trees with low density.

```
Analysis of Variance for AGC (kg)
Source     DF        SS        MS        F        P
Provenan    5     413.7      82.7     2.67    0.021
Error     743   23057.1      31.0
Total     748   23470.8
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
Dedza     207     8.769     5.845              (-----*-----)
Kasungu    54     8.746     6.017        (-----------*-----------)
Litende    39     8.446     6.506    (-------------*--------------)
Luwawa    158     8.199     5.342         (------*-------)
Phalombe  186    10.115     5.581                         (-----*------)
Thazima   105     8.218     4.652        (-------*--------)
                                   -----+---------+---------+---------+-
Pooled StDev =    5.571                7.2       8.4       9.6      10.8
```

Figure 4.17: Minitab output for ANOVA for aboveground carbon stocks

4.3.6 Total Carbon Stocks

Total carbon for the provenances varied between 10.09 ± 6.64kg tree^{-1} for Luwawa and 12.47 ± 6.94kg tree^{-1} for Phalombe (F = 2.67, p = 0.021; Figure 4.18). Total carbon sequestered by families varied significantly amongst the families ranging from 4.346 ± 1.433kg tree^{-1} for Family 27 to 21.308 ± 8.006kg tree^{-1} for Family 11 (F = 2.67, p = 0.021; Appendix 6f). The superiority and inferiority of families such as 11 and 27 respectively may also have been contributed to by proportionality in growth of the component parts. Those that may have a relatively poor root development, especially of lateral roots, may as well have experienced stunted growth.

```
Analysis of Variance for Total C
Source     DF        SS        MS        F        P
Provenan    5     639.4     127.9     2.67    0.021
Error     743   35649.9      48.0
Total     748   36289.4
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
Dedza     207    10.794     7.267             (-----*-----)
Kasungu    54    10.766     7.482       (-----------*-----------)
Litende    39    10.394     8.090   (--------------*--------------)
Luwawa    158    10.086     6.642        (------*------)
Phalombe  186    12.468     6.940                      (------*------)
Thazima   105    10.110     5.784       (-------*--------)
                                   ------+---------+---------+---------+
Pooled StDev =    6.927                 9.0      10.5      12.0      13.5
```

Figure 4.18: Minitab output for ANOVA for total carbon stock

The provenances collectively sequestered 2, 733kg ha^{-1} as a plantation (Figure 4.19). Phalombe and Dedza were the two superior provenances sequestering carbon at 774 and 745kg ha^{-1} respectively. The most inferior provenance was Litende (135kg ha^{-1}). Since it also had the lowest survival (54%), its total carbon had to be consequently lower than other provenances. Despite that Phalombe and Dedza had lower survival rates (65% and 64% respectively) than Luwawa (69%) and Thazima (67%) their carbon density per hectare may have been greater due to greater biomass accumulation compounded by unbalanced planting densities (Appendix 1).

A hypothetical planting scenario considering single provenance stands and the provenances' survival rates, still portrayed Phalombe provenance sequestering more carbon (3, 242kg ha^{-1}) than any other provenance (Figure 4.19). The least carbon sequestering provenance was Litende at 2, 244kg ha^{-1}. Luwawa was second superior with 2, 785kg ha^{-1} due to high survival and increased expansion factor per hectare. In the existing mixed planting scenario, the provenances are able to sequester 2, 733kg ha^{-1}.

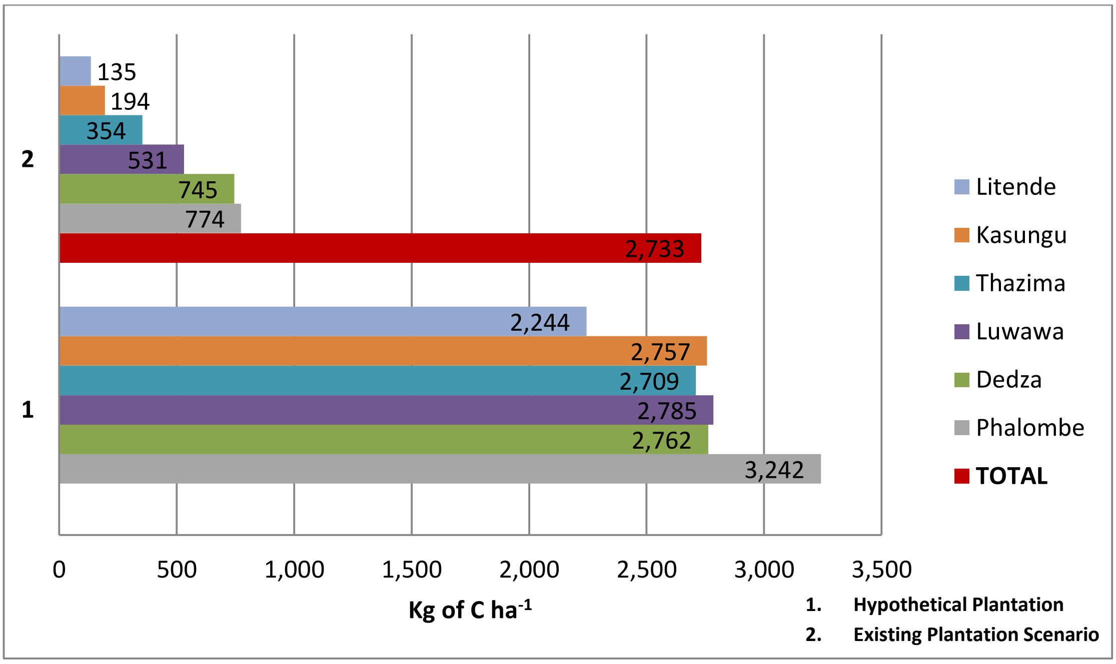


Figure 4.19: Total carbon sequestered by the provenances

Varying carbon densities have been reported across various forest types or species. Noh *et al.* (2010) reported total tree carbon of about 9.2 t ha^{-1} in 10-year-old stand of *Pinus densiflora* in Korea. Sixteen year old re-growing *miombo* in Northern Zambia are able to sequester total carbon stocks as high as 8, 500 kg ha^{-1} (Stromgaard, 1985). Chamshama *et al.* (2004) recorded carbon stocks between 3.28 and 21.78 t ha^{-1} for protected old-growth forest areas in Morogoro, Tanzania, while Munishi (2010) reported *U. kirkiana* sum carbon stocks of 0.65 and 2.12 t ha^{-1} for trunk and stems alone in old-growth *miombo* forest reserves in Southern Highlands of Tanzania where the species was one of the dominants. The effect of extraneous factors, such as human influence, age and species were however not accounted for. As an example, the current study investigated growth of a single species while the former was composed of wildly growing varying species with different growth rates without any tender operations for a regularly spaced plantation.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Summary of the Study

Information on long-term performance of multi-purpose indigenous fruit trees from the miombo biomes has been limited. Although several studies have been conducted on species like *U. kirkiana* gaps have always availed. Long term performance of such species and its carbon sequestration potential are not widely documented let alone allometric models to help in estimation of the carbon stocks without further harvesting of the trees. Their study at provenance and family level remains inevitable if more effective domestication and plantation programmes are to be implemented in such an environment where climate change has become a global problem of primary concern.

Six 12 year-old *U. kirkiana* provenances and their ninety-six families were studied to determine their growth performance and carbon sequestration potential at Nauko in Machinga, Malawi. The study also aimed at generating models for estimation of carbon stocks of *U. kirkiana* provenances and families that may be in similar environments, age or diameter range.

The study was superimposed on an already existing *U. kirkiana* trial. A manageable number of three blocks out of five were randomly selected for the study. Trees in tree line plots of four trees were assessed for height, crown width and diameter at breast height (DBH). Twenty-four trees covering a maximal DBH range of 3 to 17cm were harvested in their entirety for generation of carbon models and determination of carbon stocks for the standing trees.

Phalombe was the most prolific provenance in terms of growth and carbon sequestration. However other provenances are slowly picking up if growth in previous years is considered. Phalombe outgrew the other provenances in terms of diameter growth. Significant differences were detected amongst families in height and diameter growth. Resultantly there were significant differences in carbon stocks sequestered by the provenances and these where highly detected in the families. Luwawa and Thazima provenances would need to be improved in their diameter growth and branching characteristic to be able to sequester more carbon as the other provenances. This also applies to some of their respective families.

Although the provenances and families seem to offer a good sink for carbon, they are still inferior to other fast growing species' provenances and families, especially those from the fast growing species like Ponderosa pines. In the long term, slow growing species are however reported to sequester more carbon. Their domestication potential for climate change mitigation would be however augmented by their nature to provide multiple uses, thus inclusive of being part to a safety net in times of hunger.

Despite that statistically, significant differences were detected in growth of the crown width amongst the provenances, the differences were not practically significant. Amongst families, differences in growth of the crown were insignificant suggesting it to be a weak variable in developing models for carbon estimation.

Models developed through this study are valid for *U. kirkiana* provenances and families growing in similar condition and covering the maximal diameter range of 3 to 17cm despite registering slight differences with those developed for miombo woodlands. Although the models vary in strength, predictor variables were able to explain above 50% variability in the response variables.

5.2 Recommendations

- Multi-locational studies need to be conducted so as to determine the performance of the provenances in different environmental conditions hence the models developed through this study are site specific or fit other sites with similar conditions unless proven otherwise.
- Despite that carbon stocks sequestered by the provenances significantly vary, the variation is highly detected amongst families. This suggests that selection of mother trees for seed sources should be done in two stages, thus at provenance level and then family level, to avoid inferior families in superior provenances being sources of seed. This also applies to tree improvement programmes i.e. breeding programmes. However other variables like fruit load and sweetness would also need to be established.
- Differences in crown width both between provenances and within families were found to be insignificant while carbon stocks vary. It is therefore imperative that models generated based on crown width should be carefully scrutinized on their strength presently that allometric relationship cannot be established between the two variables.
- DBH is the most commonly used and widely available variable for calculating biomass or carbon and consequently other tree variables (Crow and Schlaegel, in Zheng 2004). In cases where the line of best fit has height and dbh as explanatory variables, where there is a large sample and tree height becomes more strenuous to measure or where cost efficiency becomes a priority, only

models with dbh can be used as this parameter is easy to measure and alternative models herein are also explaining significant proportions in total variations in carbon content.

- As important as this multi-purpose indigenous fruit tree is, there is need to keep monitoring performance over long periods so that their overall ability in growth and carbon sequestration ability over time is well documented.
- Although it may not have a very direct link to the current study, there is need to consider litter in studying of such deciduous species as such species lose a lot of leaves towards the dry season hence contributing a lot to soil carbon. It is however difficult where one may want to attribute the litter to a specific tree.
- With differences being detected in growth amongst families, and not only provenances, selection of mother trees for seed collection should be considered critical to tree breeding and improvement. However this needs to be backed up with other studies in fruit sweetness and production.

5.3 Limitations of the Study

Allometric modelling requires that models that are generated are validated using a separate dataset or data for another sub-sample from the same stand whose carbon stocks may have been estimated using the allometric models initially generated. This requires further destructive sampling. The models developed through this study were not validated as such as the trial was established for long term research. Again, the harvesting of sub-sample trees for generation of allometric models and carbon determination was done in dry season. As *U. kirkiana* is a deciduous tree, the trees may have lost their leaves at varying degrees and this may have affected the amount of carbon stocks reported for the foliage.

REFERENCES

Andersen U.S., Córdova J.P.P., Nielsen U.B. and Kollmann J. (2008). Provenance variation in germination and seedling growth of *Abies guatemalensis* Rehder. *Forest Ecology and Management*, 255 (5-6), 1831-1840.

Brown S. (1997). Estimating biomass and biomass change of tropical forests: a primer. (FAO Forestry Paper 134). Rome. FAO.

Calvo-Alvarado J.C., McDowell N.G. and Waring R.H. (2008). Allometric relationships predicting foliar biomass and leaf area: sapwood area ratio from tree height in five Costa Rican rain forest species. *Tree Physiology* 28, 1601–1608.

Carpenter F.L., Nichols J.D. and Sandi E. (2004). Early growth of native and exotic trees planted on degraded tropical pasture. F*orest Ecology and Management* 196 (2-3), 367-378.

Chamshama S.A.O., Mugasha A.G. and Zahabu E. (2004). Stand biomass and volume estimation for Miombo woodlands at Kitulangalo, Morogoro, Tanzania. *Southern Forests, Journal of Forest Science*, 200, 161-169.

Chirwa P.W., Bwanali R.J., and Sagona. W. (2007). Growth and development of a six-year-old *Uapaca kirkiana* provenance trial at Nauko Forest Reserve, Malawi. *Southern Hemisphere Forestry Journal*, 69(1), 55–58.

Dangasuk O.G., Gudu S. and Okalebo J.R (2001). Early growth performance of *Faidherbia albida* in Semi Arid Baringo District of Kenya in '*Sustaining the global farm*', 412-418, Stott D.E., Mohtar R.H. and Steinhahardt G.C. (eds). Purdue.

Dias A.T.C, de Mattos E., Vieira S.A., Azeredo J.V., and Scarano F.R. (2006). Aboveground biomass stock of native woodland on a Brazilian sandy coastal plain: Estimates based on the dominant tree species. *Forest Ecology and Management*, 226 (1-3), 364-367.

Dvorak W.S, Kietzka J.E. and Donahue J.K. (1996). Three-year survival and growth of provenances of *Pinus greggii* in the tropics and subtropics. *Forest Ecology and Management*, 83 (1-2), 123-131.

Dvorak W.S. and Ross K.D. (1994). Three-year growth and stability of Honduran provenances and families of *Pinus tecunumanii* . *Forest Ecology and Management*, 63 (1), 1-11.

Everett R.L. and Thran D.F. (1992). Above-ground biomass and N, P and S capital in single leaf *pinyon* woodlands. *Journal of Environmental Management,* 34 (2), 137-147.

FAO. (1999). Agroforestry parklands in Sub-Saharan Africa. FAO Conservation Guide 34, 8-9. FAO, Rome.

Flombaum P., and Sala O.E. (2007). A non-destructive and rapid method to estimate biomass and aboveground net primary production in arid environments. *Journal of Arid Environments*, 69, 352–358.

Frost, P. (1997). Miombo report: causes and consequences of land use and land cover changes in Southern and Eastern Africa. Accessed on 14th December, 2010, from: http://mediasfrance.org/Reseau/Lettre/10/en/Dossiers/pa1419/pa1419.htm

Gayon, J. (2000). History of the concept of allometry. *Integrated and Comparative Biology*, 40 (5), 748-758.

Gibbs H.K., Brown S., Niles J.O., and Foley A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters* 2 (045023), 63-74.

Ginwal H.S. (2009). Provenance and family variation in growth performance of *Eucalyptus tereticornis* (Sm.) in a provenance cum progeny trial in Midnapore, India. *Forest Ecology and Management*, 258 (11), 2529-2534.

Goetz S.J, Baccini A., Laporte A.T., Johns T., Walker W., Kellndorfer J., Houghton R.A. and Sun M. (2009). Mapping and monitoring carbon stocks with satellite observations: a comparison of methods. *Carbon Balance and Management*, 4 (2), 13-27.

González J.E. and Fisher R.F. (1994). Growth of native forest species planted on abandoned pasture land in Costa Rica. *Forest Ecology and Management*, 70 (1-3), 159-167.

Hazlett D.L. (1989). Provenance, age, and defoliation effects on the growth of *Cordia alliodora* in Central America. *Forest Ecology and Management*, 28 (3-4), 191-202.

Henry M., Tittonell P., Manlay R.J., Bernoux M., Albrecht A. and Vanlauwe B. (2009). Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. *Agriculture, Ecosystems and Environment*, 129, 238–252.

Hodge G.R., Dvorak W.S., Urueña H. and Rosales L. (2002). Growth, provenance effects and genetic variation of *Bombacopsis quinata* in field tests in Venezuela and Colombia. *Forest Ecology and Management*, 158 (1-3), 273-289.

Hu H. and Wang G.G. (2008). Changes in forest biomass carbon storage in the South Carolina Piedmont between 1936 and 2005. *Forest Ecology and Management,* 255 (5-6), 1400-1408.

Janssens M., Denich M., and Pohlan J. (2003). Allometric relations in tropical agroforestry. Bonn. University of Bonn.

Jayaraman, K. (2000). Forestry Statistics and Data Collection: A Statistical Manual for Forestry Research. FORSPA/FAO. Rome.

Kalinganire A. and Hall J.B. (1993). Growth and biomass production of young *Grevillea robusta* provenances in Rwanda. *Forest Ecology and Management,* 62 (1-4), 73-84.

Klein C. (1998). Simple guide to forest inventory. Gottingen. University of Gottingen.

Kuusipalo J., Hadengganan S., Adjers A. and A. Sagala. (1997). Effect of gap liberation on the performance and growth of dipterocarp trees in a logged-over rainforest. *Forest Ecology and Management,* 92 (1-3), 209-219.

Kwesiga F. (1994). Performance of fifteen provenances of *Gliricidia sepium* in eastern Zambia. *Forest Ecology and Management*, 64 (2-3), 161-170.

Laclau P. (2003). Root biomass and carbon storage of ponderosa pine in a northwest Patagonia plantation. *Forest Ecology and Management*, 173 (1-3), 353-360.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R. & Liski, J. Biomass expansion factors (BEF) for Scots pine, Norway spruce and birch according to stand age for boreal forests. *Forest Ecology and Management*, 188, 211-224.

Losi C.J., Siccama T.G., Condit R. and Morales J.E. (2003). Analysis of alternative methods for estimating carbon stock in young tropical plantations. *Forest Ecology and Management*, 184 (1-3), 355-368.

Mahmood K., Marcar N.E., Naqvi M.H., Arnold R.J, Crawford D.F, Iqbal S. and Aken K.M. (2003). Genetic variation in *Eucalyptus camaldulensis* Dehnh. for growth and stem straightness in a provenance–family trial on saltland in Pakistan. *Forest Ecology and Management*, 176 (1-3), 405-416.

Malimbwi R.E., Solberg B. and Luoga E. (1994). Estimation of biomass at Kitulangalo Forest Reserve, Tanzania. *Journal of Tropical Forest Science*, 7(2), 230-242.

Montenegro F., Meneses V. and Wright J.A. (1997). Growth of *Pinus muricata* provenances in the highlands of Ecuador. *Forest Ecology and Management*, 99 (3), 291-294.

Montes C.S, Vidaurre S. and Weber J. (2005). Variation in stem-growth and branch-wood traits among provenances of *Calycophyllum spruceanum* Benth. from the Peruvian Amazon. *New Forests*, 26 (1), 1-16.

Moura-Costa, P. (1996). Tropical forestry practices for carbon sequestration: Dipterocarp forest ecosystems towards sustainable management. *World Scientific*, 111, 308–334.

Mugasha A.G. , Chamshama S.A.O., Iddi S. and Nshubemuki L. (1996). Survival, growth and wood density of *Pinus kesiya* and *Pinus oocarpa* provenances at Kihanga Arboretum, Sao Hill, Tanzania. *Forest Ecology and Management*, 87 (1-3), 1-11.

Munishi P. K. T., Mringi S., Shirima D. D. and Linda S. K. (2010). The role of the Miombo Woodlands of the Southern Highlands of Tanzania as carbon sinks. *Journal of Ecology and the Natural Environment*, 2 (12), 261-269.

Mwamba C.K. (1989). Natural variation in fruits of *Uapaca kirkiana* in Zambia. Forest Ecology and Management, 26, 299-303.

Mwase W.F., Bjørnstad Å, Ntupanyama Y.M., Kwapata M.B. and Bokosi J.M. (2006). Phenotypic variation in fruit, seed and seedling traits of nine *Uapaca kirkiana* provenances found in Malawi. *Southern African Forestry Journal*, 208, 15-22.

Mwase W. F., Ntupanyama Y. M., Stedje B., Kwapata M. B., Bokosi J. M. and Hvoslef-Eide1 A. K. (2008). Indigenous knowledge of rural communities in Malawi on socio-economic use, propagation, biology, biodiversity and ecology of *Uapaca kirkiana* Muell. Arg. *African Journal of Biotechnology*, 7 (14), 2386-2396.

Nath A.J., Das G. and Das A.K. (2009). Above ground standing biomass and carbon storage in village bamboos in North East India. *Biomass and Bioernegy,* 33 (9), 1188-1196.

Ngulube M.R. (1996). Ecology and management of *Uapaca kirkiana* in Southern Africa. Unpublished doctoral thesis. University of Bangor, UK.

Noh N., Son Y., Lee S., Seo K., Heo S., Yi M., Park P., Kim R., Son Y. and Lee K. (2010). Carbon and nitrogen storage in an age-sequence of *Pinus densiflora* stands in Korea. *Science China - Life Sciences*, 53 (7), 822-830.

Oba G., Nordal I., Stenseth N.C., Stave J., Bjora C.S., Muthondeki J.K. and Bii W.K.A. (2006). Growth performance of exotic and indigenous tree species in saline soils in Turkana, Kenya. *Journal of Arid Environments*, 47 (4), 499-511.

Ofori, D.A., Opuni-Frimpong, E., and Cobbinah, J.R. (2007). Provenance variation in *Khaya* species for growth and resistance to shoot borer *Hypsipyla robusta*. *Forest Ecology and Management*, 242 (2-3), 438-443.

Otegbeye G.O. and Samarawira I. (1991). Growth and form of *Eucalyptus camaldulensis* Dehnh. provenances in northern Nigeria. *Forest Ecology and Management*, 42 (3-4), 219-228.

Otegbeye G.O. and Samarawira I. (1992). Correlations of growth and form characteristics of *Eucalyptus camaldulensi*s Dehnh. provenances in northern Nigeria. *Forest Ecology and Management*, 50 (3-4), 275-285.

Parresol, B.R. (1999). Assessing tree and stand biomass: a review with examples and critical comparisons. *Forest Science Journal*, 45, 573-582.

Peichl M. and Arain M.A. (2006). Above- and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. *Agricultural and Forest Meteorology*, 140 (1-4), 51-63.

Philip M.S. (1994). Measuring trees and forests. Cambridge University Press, Cambridge.

Pinyopusarerk K., Doran J.C., Williams E.R. and Wasuwanich P. (1996). Variation in growth of *Eucalyptus camaldulensis* provenances in Thailand. *Forest Ecology and Management*, 87 (1-3), 63-73.

Popescu S.C. (2007). Estimating biomass of individual pine trees using airborne lidar. *Biomass and Bioenergy*, 31, 646–655.

Reed D.D., Pregitzer K.S., Liechty H.O., Burton A.J. and Mroz G.D. (1994). Productivity and growth efficiency in sugar maple forests. *Forest Ecology and Management*, 70 (1-3), 319-327.

Ravindranath N.H. and Ostwald M. (2008). Carbon inventory methods: handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects. Springer.

Redondo-Brenes A., and Montagnini F. (2006). Growth, productivity, aboveground biomass, and carbon sequestration of pure and mixed native tree plantations in the

Caribbean lowlands of Costa Rica. *Forest Ecology and Management*, 232 (1-3), 168-178.

Ryan C.M., Williams W. and Grace J. (2011). Above- and belowground carbon stocks in a Miombo woodland landscape of Mozambique. *Biotropica,* 43 (4), 423–432.

Sabas E. and Nshubemuki L. (1988). *Eucalyptus camaldulensis* provenances for afforestation in Mwanza and Shinyanga regions of Tanzania. *Forest Ecology and Management*, 24 (2), 127-138.

Samalca I.K. (2007). Estimation of Forest Biomass and its Error: A case in Kalimantan, Indonesia. Warsaw.

Segura, M. and Kanninen M. (2005). Allometric Models for Tree Volume and Total Aboveground Biomass in a Tropical Humid Forest in Costa Rica. *Biotropica,* 37 (1), 2–8.

Schleizer B. (2008). A Landowner's Guide to Carbon Sequestration Credits. The Commonwealth Project, Wadena.

Sniezko R.A. and Stewart H.T.L. (1989). Range-wide provenance variation in growth and nutrition of *Acacia albida* seedlings propagated in Zimbabwe. *Forest Ecology and Management*, 27 (3-4), 179-197.

Son Y. and Kim H. (1998). Above-ground biomass and nutrient distribution in a 15-year-old ginkgo (*Ginkgo biloba*) plantation in Central Korea. *Bioresource Technology* 63 (2), 173-177.

Spencer D.F., Liow D., Chan W.K, Ksander G.G., and Getsinger K.D (2006). Estimating *Arundo donax* shoot biomass. *Aquatic Botany*, 84, 272–276.

Spetch T., and West P.W. (2003). Estimation of biomass and sequestered carbon on farm forest plantations in northern New South Wales, Australia. *Biomass and Bioenergy,* 25 (4), 363-379.

Stromgaard P. (1985). Biomass, growth, and burning of woodland in a shifting cultivation area of South Central Africa. *Forest Ecology and Management*, 12, 163-178.

Sullivan M. (2004). Statistics: Informed decisions using data. Prentice Hall, New Jersey.

Thomas S.C., Malczewski G. and Saprunoff M. (2006). Assessing the potential of native tree species for carbon sequestration forestry in Northeast China. *Journal of Environmental Management*, 85, 663–671.

Tschakert P., Oliver T., Coomes O.T. and Potvin C. (2007). Indigenous livelihoods, slash-and-burn agriculture, and carbon stocks in Eastern Panama. *Ecological Economics,* 60 (4), 807-820.

Tuomela K., Otsamo A., Kuusipalo J., Vuokko R. and Nikles G. (1996). Effect of provenance variation and singling and pruning on early growth of *Acacia mangium* Willd. plantation on *Imperata cylindrica* (L.) Beauv. dominated grassland. *Forest Ecology and Management*, 84 (1-3), 241-249.

Wauters J.B., Coudert S., Grallien E., Jonard M. and Ponette Q. (2006). Carbon stock in rubber tree plantations in Western Ghana and Mato Grosso (Brazil). *Forest Ecology and Management* 255, 2347–2361.

Weber J.C., Larwanou M., Abasse T.A. and Kalinganire. (2008). Growth and survival of *Prosopis africana* provenances tested in Niger and related to rainfall gradients in the West African Sahel. *Forest Ecology and Management*, 256 (4), 585-592.

Williams, M. (2004). Inventory of Nhambita Community Forest, Gorongosa District, Mozambique. ICRAF, Mozambique.

Williams M., Ryan C.M., Rees R.M., Sambane E., Fernando J. and Grace J. (2007). Carbon sequestration and biodiversity of re-growing miombo woodlands in Mozambique. *Forest Ecology and Management* 254 (3), 145–155.

Zabek L.M. and Prescott C.E. (2006). Biomass equations and carbon content of aboveground leafless biomass of hybrid poplar in Coastal British Columbia. *Forest Ecology and Management,* 223 (1-3), 291-302.

Zewdie M., Olsson M, and Verwijst T. (2009). Above-ground biomass production and allometric relations of *Eucalyptus globulus* Labill. coppice plantations along a chronosequence in the central highlands of Ethiopia. *Biomass and Bioenergy,* 33 (3), 421-428.

Zheng D., Rademacher J., Chen J., Crow T., Bresee M., Moine L. and Ryu S. (2004). Estimating aboveground biomass using Landsat 7 ETM+ data across a managed landscape in northern Wisconsin, USA. *Remote Sensing of Environment*, 93, 402–411.

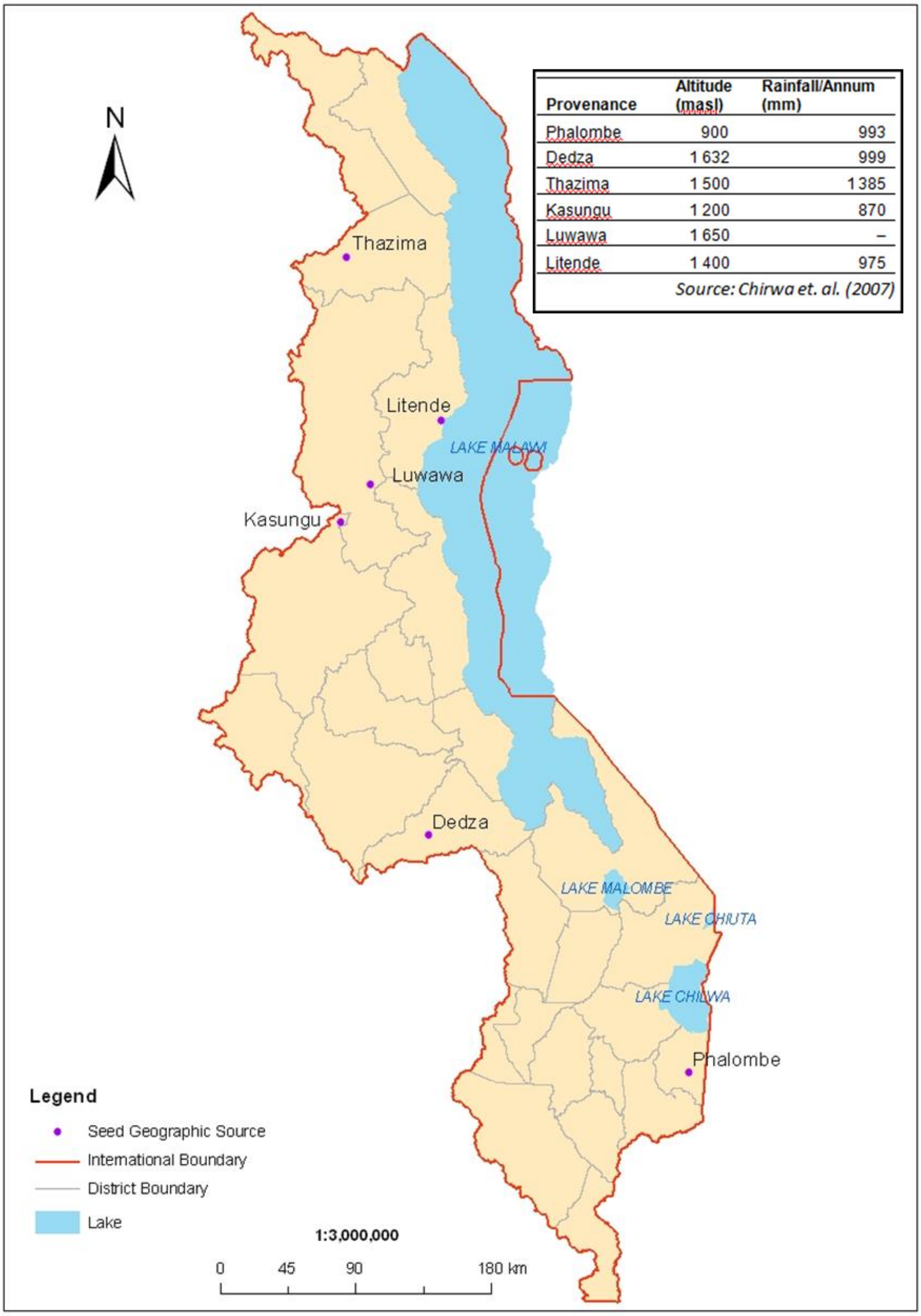
APPENDICES:

Appendix 1: Provenances and their associated families

Provenance	Family Codes
Phalombe	1 to 24
Dedza	25 to 51
Thazima	52 to 64
Kasungu	65 to 71
Luwawa	72 to 90
Litende	91 to 96

(Source: Chirwa *et al.*, 2007).

Appendix 2: Seed geographic sources for the trial



Appendix 3: Tukey's pair-wise comparison matrices

Appendix 3a) Height matrix

```
Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.00450

Critical value = 4.03

Intervals for (column level mean) - (row level mean)

            Dedza        Kasungu      Litende      Luwawa       Phalombe

Kasungu        -0.707
                0.188

Litende        -0.529       -0.374
                0.492        0.856

Luwawa         -0.328       -0.221       -0.524
                0.290        0.701        0.522

Phalombe       -0.564       -0.461       -0.765       -0.566
                0.027        0.443        0.265        0.067

Thazima        -0.359       -0.239       -0.539       -0.358       -0.097
                0.342        0.741        0.559        0.379        0.617
```

Appendix 3b) Crown width matrix

```
Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.00450

Critical value = 4.03

Intervals for (column level mean) - (row level mean)

            Dedza        Kasungu      Litende      Luwawa       Phalombe

Kasungu       -0.1626
               0.5930

Litende       -0.1023      -0.4054
               0.7609       0.6336

Luwawa         0.0249      -0.3188      -0.4853
               0.5473       0.4606       0.3988

Phalombe      -0.1588      -0.5064      -0.6737      -0.4626
               0.3408       0.2580       0.1971       0.0724

Thazima       -0.2548      -0.5878      -0.7515      -0.5560      -0.3514
               0.3376       0.2402       0.1757       0.0666       0.2522
```

Appendix 3c) DBH matrix

```
Tukey's pairwise comparisons

    Family error rate = 0.0500
Individual error rate = 0.00450

Critical value = 4.03

Intervals for (column level mean) - (row level mean)

           Dedza      Kasungu    Litende    Luwawa     Phalombe

Kasungu       -0.711
               1.298

Litende       -0.858     -1.385
               1.436      1.377

Luwawa        -0.335     -0.970     -1.105
               1.054      1.102      1.245

Phalombe      -1.360     -2.006     -2.143     -1.767
              -0.032      0.026      0.172     -0.345

Thazima       -0.649     -1.256     -1.383     -1.048      0.033
               0.926      0.945      1.082      0.606      1.637
```

Appendix 4: Family-level one-way ANOVA for growth variables

Appendix 4a) Height (m) versus Family

```
Analysis of Variance for Height (
Source     DF         SS         MS        F        P
Family     95    150.199      1.581     1.60    0.001
Error     653    643.864      0.986
Total     748    794.063
                                   Individual 95% CIs for Mean
                                   Based on Pooled StDev
Family      N      Mean     StDev  ------+---------+---------+---------+
 1         10    4.7700    0.7875                (---*---)
 2          8    4.7000    0.5264               (---*----)
 3         11    4.8545    1.1553                (---*---)
 4         11    4.6000    1.2434               (---*---)
 5          9    4.7222    0.6037               (---*----)
 6          6    4.5667    0.2503             (----*-----)
 7          7    4.7286    0.6601               (----*---)
 8          7    4.6286    0.8015              (----*----)
 9          9    4.5444    0.7618              (---*----)
10          8    4.9250    1.0068                (----*---)
11          6    5.8500    0.9894                      (----*----)
12          8    4.7875    0.9047               (----*----)
13          7    5.1571    0.9502                 (----*----)
14          9    4.7222    1.0895               (---*----)
15          4    4.0500    0.3416         (-----*-----)
16          5    5.2200    0.9757                 (-----*-----)
17         10    4.4000    0.6532             (---*---)
18          5    4.2800    1.2153           (-----*----)
19          9    4.7778    0.7579                (---*---)
20          4    4.0750    0.6652         (-----*------)
21          8    4.7375    0.9054               (----*---)
22         10    4.6100    0.7490               (---*---)
23          9    4.0778    0.5848           (---*----)
24          6    4.8000    0.7294               (----*----)
25          8    4.4875    0.8626             (----*----)
26          8    4.2375    0.5999            (---*----)
27          5    3.5800    0.7190      (-----*-----)
28          7    4.6143    0.9155              (----*----)
29          5    3.8800    1.1692        (-----*-----)
30          9    4.1444    0.6579           (----*---)
31          5    3.4600    1.2661     (-----*-----)
32          9    4.8889    0.7524                (----*---)
33          9    4.3000    1.0368            (----*---)
34          6    4.8667    0.8548               (----*-----)
35          8    4.9250    0.5036                (----*---)
36          8    4.8875    1.1655                (----*---)
37         10    4.6200    1.2017               (---*---)
38         11    4.5455    1.1387              (---*---)
39          8    4.8500    0.9040                (---*----)
40          3    4.1000    0.5292        (------*-------)
41         10    4.7500    1.1617                (---*---)
42         10    3.4600    0.5758       (---*---)
43          8    4.6250    0.6585              (----*---)
44          9    4.4778    0.9298              (---*---)
45          7    5.3857    0.8688                   (----*----)
46         10    4.6000    1.3064               (---*---)
47          6    4.4000    1.6565            (----*-----)
48          5    3.0600    1.0455   (----*-----)
49          9    4.3000    0.6285            (----*---)
50          9    4.0333    1.3134           (---*---)
51          5    5.0000    1.7464                (----*-----)
52          8    3.8750    0.9809         (----*---)
53          9    4.2667    1.1435            (---*----)
54         10    4.8600    1.2782                (---*----)
55         10    4.2000    0.9499            (---*---)
```

```
56           7    4.8000    0.9256               (----*----)
57           5    4.3400    0.2793           (-----*-----)
58           8    4.7625    0.8245               (----*---)
59           6    4.7167    0.9020              (----*-----)
60           9    4.3111    0.7424            (----*---)
61           9    4.3556    1.1501             (---*---)
62           9    4.2000    0.9950            (---*---)
63          11    4.5909    0.5941               (---*---)
64           4    4.4500    0.3873           (------*-----)
65           8    5.0250    0.6042                 (----*---)
66           7    4.9429    0.7458                (----*----)
67           6    4.7500    0.7342              (-----*----)
68           6    5.9500    1.0784                      (-----*----)
69           7    4.7286    1.7519               (----*---)
70           9    3.9556    1.1013          (---*----)
71          11    4.1273    1.1270            (---*--)
72           7    4.1714    1.1884           (----*----)
73           4    4.6500    0.5745             (-----*-----)
74           4    4.6250    0.6238            (------*-----)
75           8    3.8875    1.0006         (----*----)
76          10    4.5100    1.5308              (---*---)
77           8    4.5875    1.1519              (----*---)
78          10    4.4600    0.9823              (---*---)
79           6    4.9167    0.7910               (-----*----)
80          12    4.6250    1.0914               (---*---)
81           6    4.7000    1.1136              (----*-----)
82          11    4.6182    1.3385               (---*---)
83           7    4.6857    1.3993              (----*----)
84           9    4.2222    1.4455            (---*---)
85          10    5.1100    0.6082                  (---*---)
86           5    4.6600    1.3202             (-----*-----)
87          10    4.5900    0.8556              (----*---)
88           9    4.0556    0.3087           (---*---)
89          11    3.6091    0.7867        (---*---)
90          11    4.3182    1.5587             (---*---)
91           5    3.8000    0.3391        (----*-----)
92           5    3.7800    1.2398       (-----*-----)
93           7    5.8000    1.3342                      (----*----)
94           8    4.1500    0.6990           (----*---)
95           9    4.6889    0.6353               (---*----)
96           5    3.9000    1.4018        (-----*-----)
                                   ------+---------+---------+---------+
Pooled StDev =   0.9930                3.0       4.5       6.0       7.5
```

Appendix 4b) Crown width (m) versus Family

```
Analysis of Variance for Crown W
Source     DF        SS        MS        F        P
Family     95    73.510     0.774     1.02    0.438
Error     653   496.094     0.760
Total     748   569.604
                                   Individual 95% CIs for Mean
                                   Based on Pooled StDev
Family      N      Mean     StDev  -----+---------+---------+---------+-
 1         10    2.2300    0.8957              (----*-----)
 2          8    2.4250    0.8464               (-----*-----)
 3         11    2.0273    0.9961            (----*----)
 4         11    1.6636    1.0347        (-----*----)
 5          9    1.6667    0.6185        (-----*----)
 6          6    1.9500    0.5891          (------*-----)
 7          7    2.5429    1.0737                (-----*------)
 8          7    2.1571    1.1370            (------*-----)
 9          9    2.0444    0.8777            (----*-----)
10          8    1.7500    0.7910        (------*-----)
11          6    2.3833    0.8841              (------*------)
12          8    2.2125    0.9448             (-----*-----)
13          7    2.0714    1.0610           (------*-----)
14          9    2.8000    0.8337                   (-----*-----)
15          4    1.9500    0.7416        (--------*-------)
16          5    2.3000    0.9747            (-------*-------)
17         10    2.3600    0.9168               (-----*----)
18          5    2.0400    1.1589          (------*-------)
19          9    2.5222    0.6438                 (----*-----)
20          4    2.0000    0.9129        (--------*--------)
21          8    1.9625    1.0501           (-----*-----)
22         10    2.0700    0.9604            (-----*----)
23          9    2.5556    1.2350                 (-----*----)
24          6    2.5333    0.8116               (------*------)
25          8    2.1750    0.8892             (-----*-----)
26          8    1.9250    0.9543          (-----*-----)
27          5    1.9000    0.4950        (-------*-------)
28          7    2.5000    1.0424                (-----*-----)
29          5    1.9400    0.6107         (------*-------)
30          9    2.1778    0.6241             (-----*----)
31          5    2.1600    1.2542           (-------*------)
32          9    2.7778    0.9298                   (-----*----)
33          9    2.2444    0.8487              (----*-----)
34          6    2.0667    0.6861           (------*------)
35          8    2.1750    0.7630             (-----*-----)
36          8    2.4750    0.7536                (-----*-----)
37         10    2.7600    0.6703                   (-----*----)
38         11    2.3455    0.7840               (----*-----)
39          8    2.3875    0.9109               (-----*-----)
40          3    3.1000    0.2646                  (---------*---------)
41         10    2.2100    0.6280              (----*-----)
42         10    1.9900    1.0038           (-----*----)
43          8    2.1500    0.6437            (------*-----)
44          9    1.8778    1.3179          (-----*----)
45          7    2.8143    0.7128                   (-----*------)
46         10    2.3700    1.0863               (-----*----)
47          6    1.6333    0.3882      (------*------)
48          5    1.7400    0.4159       (------*-------)
49          9    2.5667    0.5679                 (-----*----)
50          9    2.0556    1.0760            (-----*----)
51          5    2.5600    1.1803               (-------*------)
52          8    2.1250    1.2068            (-----*-----)
53          9    1.8000    0.8529         (-----*-----)
54         10    2.5100    0.5384                 (----*-----)
55         10    2.1300    1.0822             (----*-----)
56          7    2.3571    1.0784              (------*-----)
57          5    2.2800    0.7362            (-------*------)
58          8    1.9375    0.6022          (-----*-----)
```

```
59          6    2.5167    0.6338               (------*------)
60          9    1.8222    0.8941          (----*-----)
61          9    2.4111    0.5555               (-----*-----)
62          9    2.2333    0.9950              (----*-----)
63         11    2.4273    0.7072                (----*----)
64          4    2.6250    0.8770               (-------*--------)
65          8    1.8375    0.7150         (-----*-----)
66          7    2.2571    0.3645             (------*-----)
67          6    2.3667    1.1843              (------*------)
68          6    2.1833    1.0610            (------*------)
69          7    1.7571    0.7934        (------*-----)
70          9    2.2333    0.7246              (----*-----)
71         11    1.8636    0.8201          (-----*----)
72          7    2.0429    0.9126           (-----*------)
73          4    1.4000    0.7394  (--------*--------)
74          4    2.1500    0.8737          (--------*-------)
75          8    1.9000    1.0184          (-----*-----)
76         10    2.3000    0.6481               (----*----)
77          8    1.4625    0.6140      (-----*-----)
78         10    2.1500    0.5778             (-----*----)
79          6    2.5500    1.0173                (-----*------)
80         12    1.6917    1.0698         (----*----)
81          6    1.8500    1.0710         (------*-----)
82         11    1.9909    1.0406            (----*----)
83          7    1.9429    0.9396          (-----*------)
84          9    1.8333    0.9152          (----*-----)
85         10    2.5000    0.7789                 (----*----)
86          5    2.0000    1.0271         (-------*-------)
87         10    1.9000    0.9177           (----*----)
88          9    1.9111    0.7390          (-----*-----)
89         11    1.9182    0.5741           (----*----)
90         11    1.9818    0.7935            (----*----)
91          5    1.3400    0.8295   (------*-------)
92          5    2.0600    1.0574          (-------*------)
93          7    2.5857    0.3132                (------*-----)
94          8    1.9250    0.5445          (-----*-----)
95          9    1.8111    1.0167         (-----*-----)
96          5    1.7400    0.9450       (------*-------)
                                   -----+---------+---------+---------+-
Pooled StDev =   0.8716               1.0       2.0       3.0       4.0
```

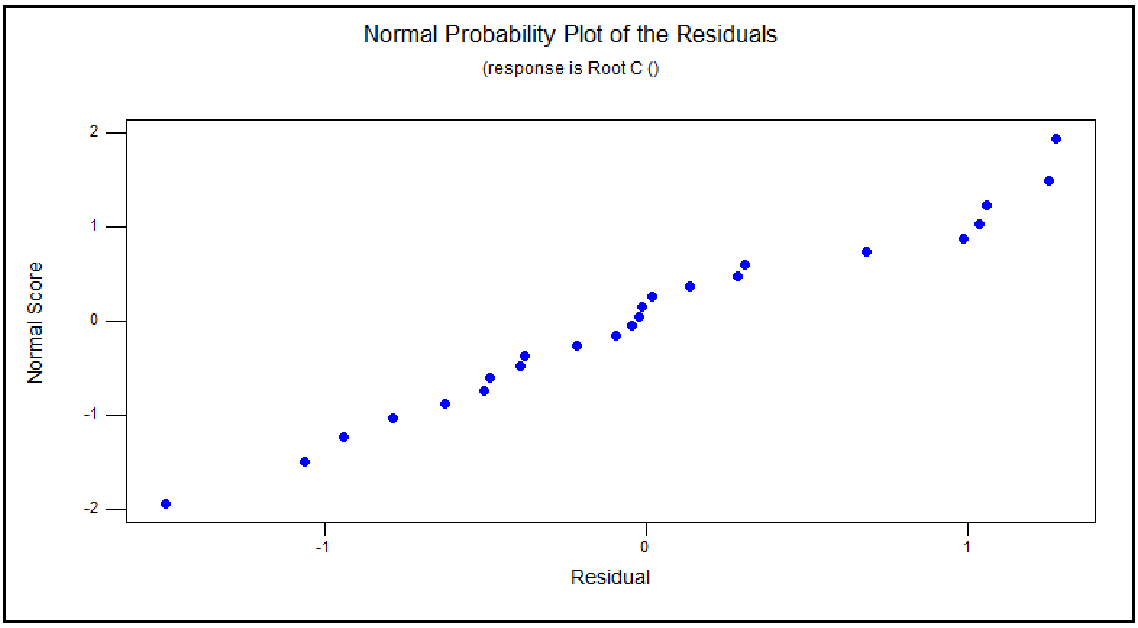
Appendix 4c) DBH (cm) versus Family

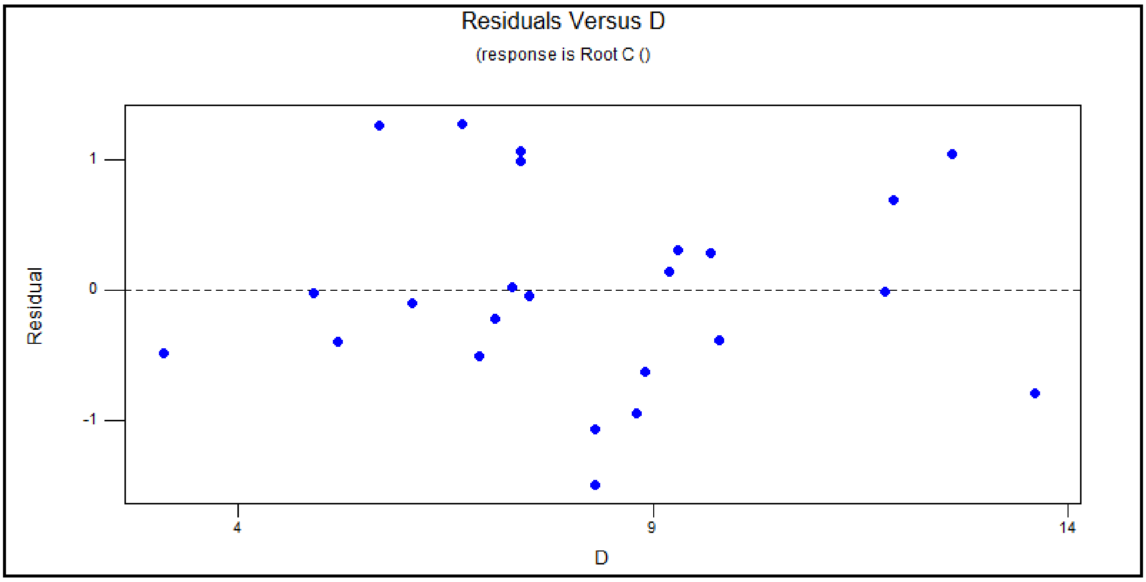
```
Analysis of Variance for DBH (cm)
Source      DF        SS        MS        F         P
Family      95    789.37      8.31     1.65     0.000
Error      653   3281.29      5.02
Total      748   4070.66
                                   Individual 95% CIs for Mean
                                   Based on Pooled StDev
Family      N      Mean     StDev  ----------+---------+---------+------
 1         10     8.830     1.801                 (---*----)
 2          8     9.313     2.171                  (----*----)
 3         11     7.909     1.823              (---*----)
 4         11     8.891     1.833                 (----*---)
 5          9     8.056     2.233              (----*----)
 6          6     8.300     0.822              (-----*-----)
 7          7     8.186     2.376              (----*-----)
 8          7     9.286     2.374                 (-----*----)
 9          9     8.978     2.253                 (----*----)
10          8     8.325     2.147               (----*----)
11          6    10.700     1.889                      (-----*-----)
12          8     8.725     1.628                (----*----)
13          7     8.086     1.227             (-----*----)
14          9     7.578     3.124            (----*----)
15          4     8.275     0.818            (-------*------)
16          5     9.020     1.529                (-----*------)
17         10     9.790     3.477                    (----*---)
18          5     7.660     1.851           (------*-----)
19          9     9.644     1.974                   (----*----)
20          4     7.350     2.634         (-------*------)
21          8     7.387     2.211           (-----*----)
22         10     7.870     2.640              (---*----)
23          9     8.533     2.243                (---*----)
24          6     8.967     1.667                (-----*-----)
25          8     8.725     2.039                (----*----)
26          8     6.813     1.253          (----*----)
27          5     5.200     1.111   (-----*------)
28          7     9.543     2.716                  (-----*----)
29          5     6.920     2.262         (-----*------)
30          9     6.911     2.433          (----*----)
31          5     5.540     1.845    (-----*------)
32          9     9.367     2.194                  (----*----)
33          9     7.111     2.541           (----*----)
34          6     7.033     0.954         (-----*-----)
35          8     8.775     1.150                (----*----)
36          8     8.363     2.563               (----*----)
37         10     7.990     3.232              (----*---)
38         11     9.100     1.785                  (---*----)
39          8     8.300     3.277              (-----*----)
40          3     8.633     1.747            (--------*-------)
41         10     7.850     2.908              (---*----)
42         10     6.600     1.446         (----*----)
43          8     8.975     2.245                 (----*----)
44          9     8.533     2.271                (---*----)
45          7     8.786     1.548                (----*-----)
46         10     8.850     2.441                 (----*---)
47          6     6.433     2.409       (-----*-----)
48          5     5.640     2.413    (------*-----)
49          9     7.411     1.981            (----*----)
50          9     8.089     2.899              (----*----)
51          5     8.540     2.276              (-----*------)
52          8     7.613     2.784            (----*-----)
53          9     7.589     2.578            (----*----)
54         10     7.820     1.737             (----*----)
55         10     6.770     1.998          (----*---)
56          7     8.814     1.620                (----*-----)
57          5     8.760     1.236               (-----*------)
58          8     7.888     1.148             (----*----)
```

```
59          6     9.167     1.398                 (-----*------)
60          9     5.811     1.240      (----*----)
61          9     8.233     3.051               (---*----)
62          9     7.189     2.017           (----*----)
63         11     8.109     1.966               (---*---)
64          4     8.775     2.366              (------*-------)
65          8     7.663     2.237            (-----*----)
66          7     7.857     1.742             (----*-----)
67          6     8.733     2.451               (-----*-----)
68          6    10.300     2.713                    (-----*------)
69          7     7.686     2.553            (-----*----)
70          9     6.544     1.378         (----*----)
71         11     6.100     2.204        (---*----)
72          7     6.543     3.067        (-----*----)
73          4     7.550     0.404          (------*-------)
74          4     9.300     2.814                (------*-------)
75          8     6.188     1.693       (-----*----)
76         10     7.630     2.543             (---*----)
77          8     8.325     2.581               (----*----)
78         10     7.700     1.510             (----*---)
79          6     7.733     1.624            (-----*-----)
80         12     7.617     1.718             (---*----)
81          6     8.183     2.381             (-----*-----)
82         11     7.564     1.927             (---*----)
83          7     7.829     2.935             (----*-----)
84          9     7.844     3.558             (----*----)
85         10     8.840     1.182                 (---*----)
86          5     8.500     3.883              (-----*------)
87         10     7.970     1.273              (----*---)
88          9     6.778     2.456          (----*---)
89         11     6.018     2.022        (---*---)
90         11     6.745     2.501          (---*----)
91          5     7.260     1.610          (-----*------)
92          5     8.520     4.682              (-----*------)
93          7     8.786     2.879                (----*-----)
94          8     6.488     1.512        (-----*----)
95          9     7.978     2.351              (----*---)
96          5     6.480     2.370       (------*-----)
                                   ----------+---------+---------+------
Pooled StDev =    2.242                    6.0       9.0      12.0
```

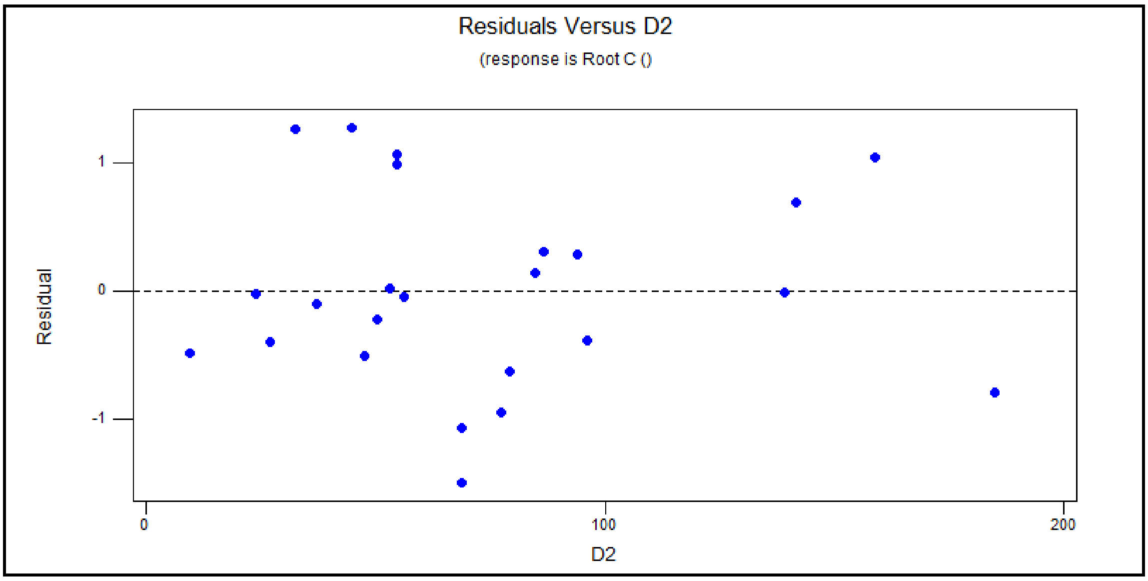
Appendix 5: Diagnostic residual plots for lines of best fit

Appendix 5a) Root carbon

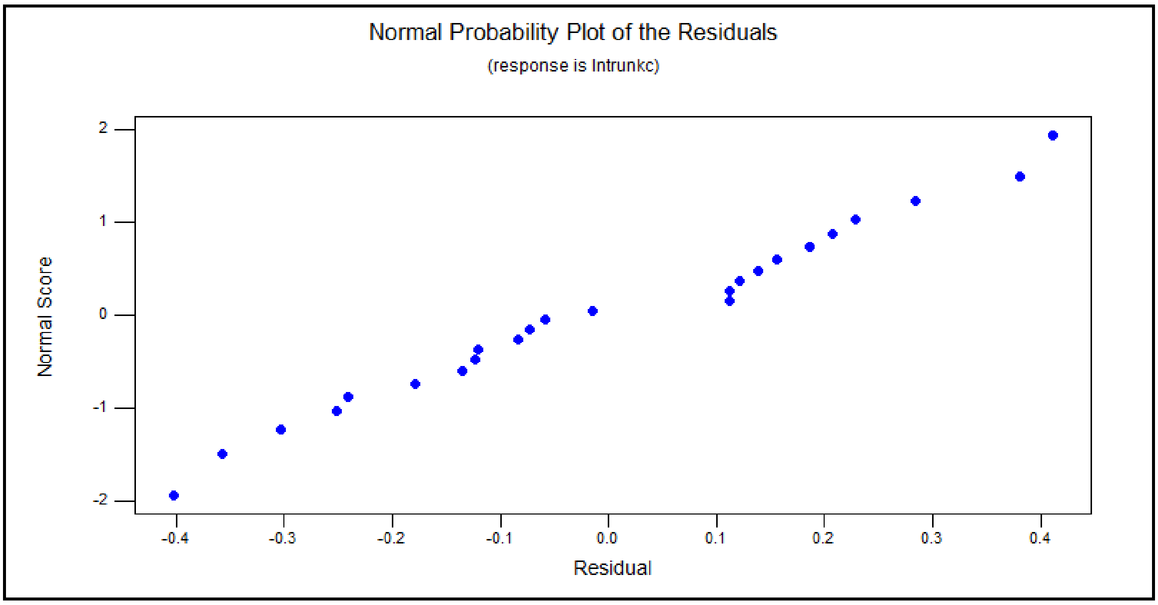


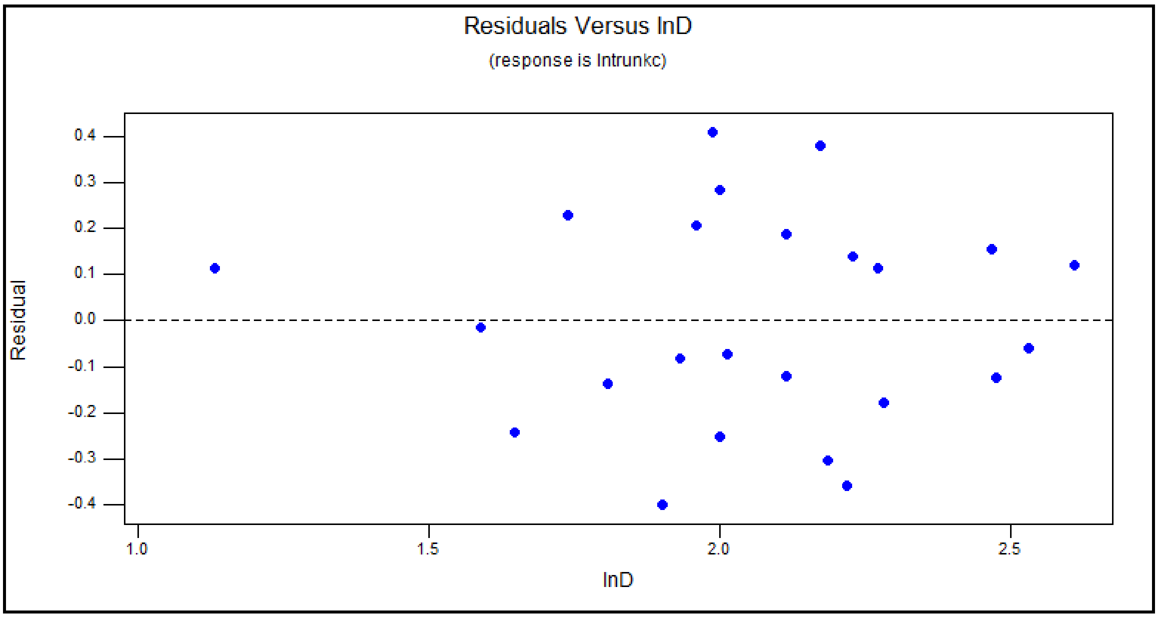


Root carbon – *continued*

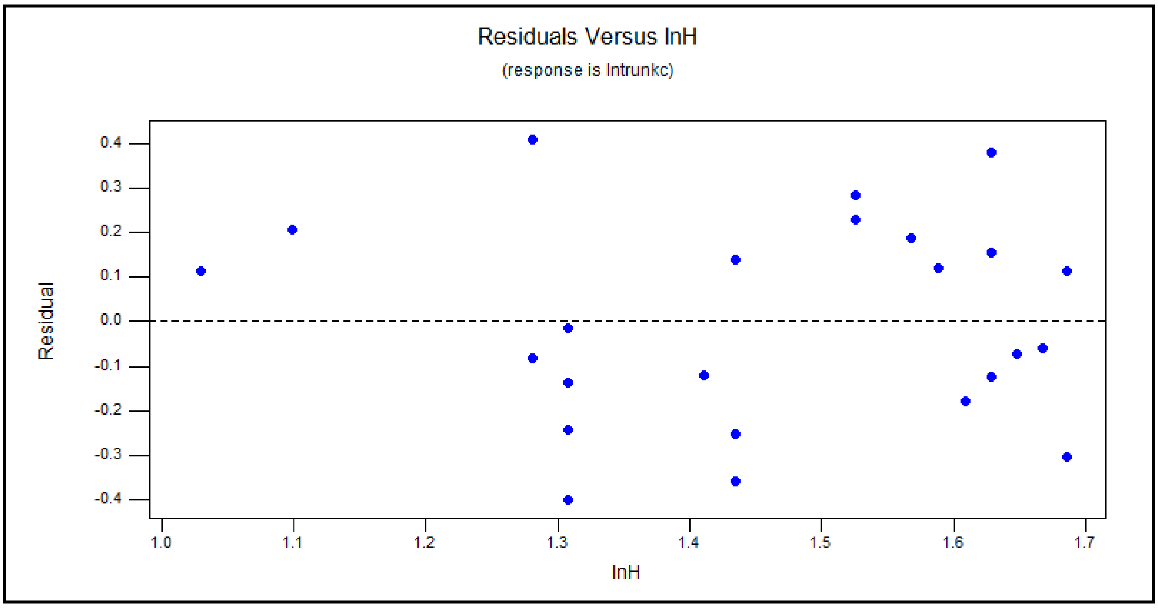


Appendix 5b) Trunk carbon

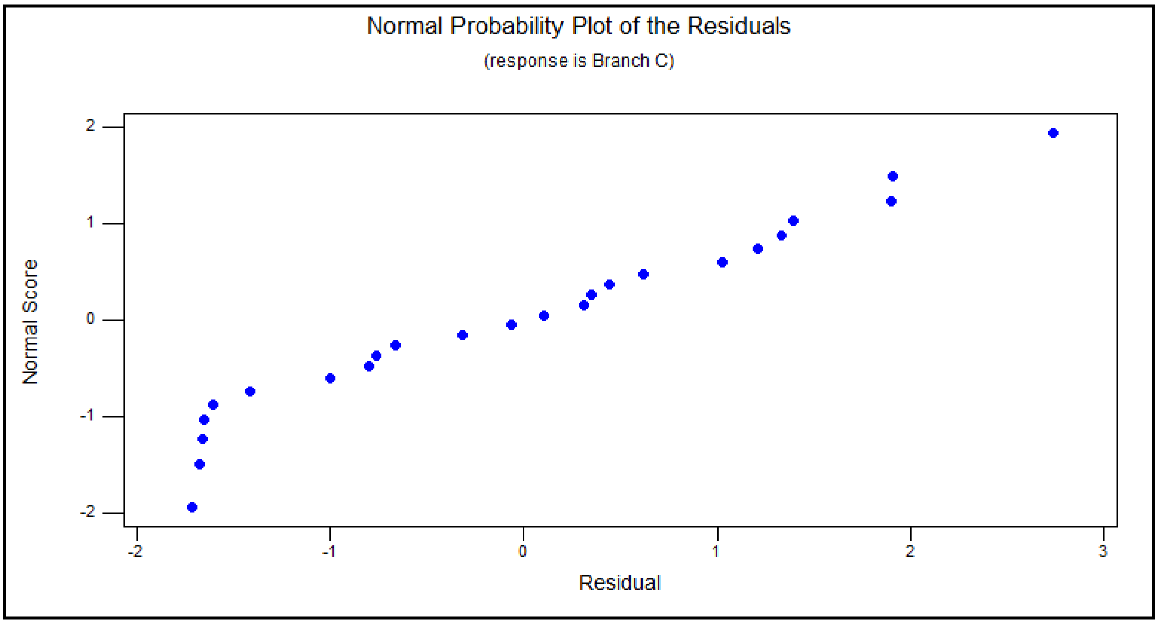


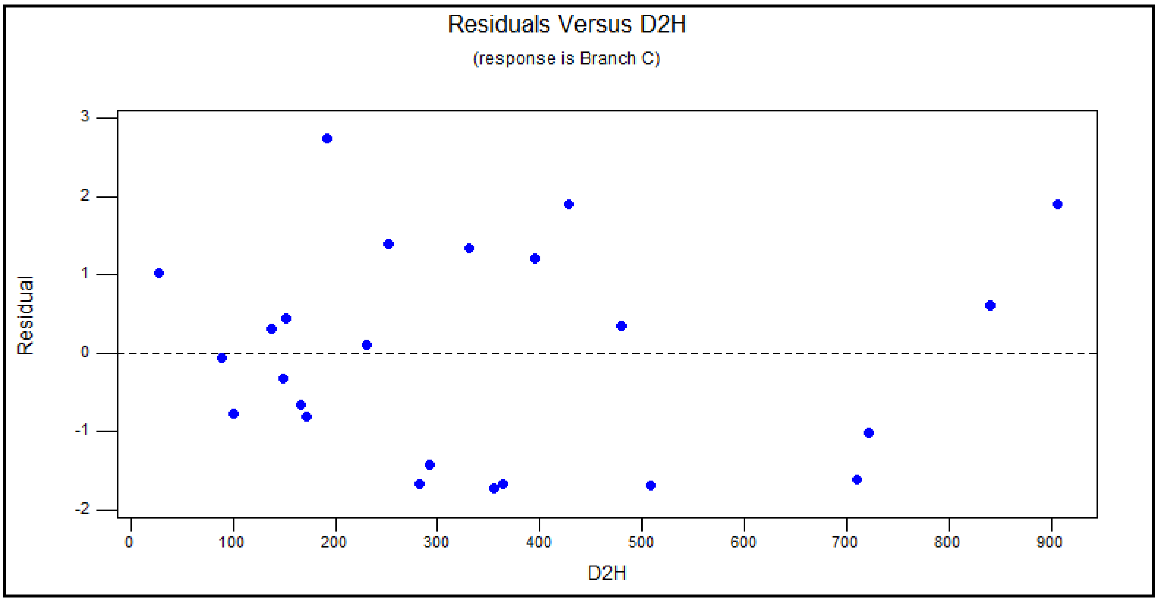


Trunk carbon - *continued*

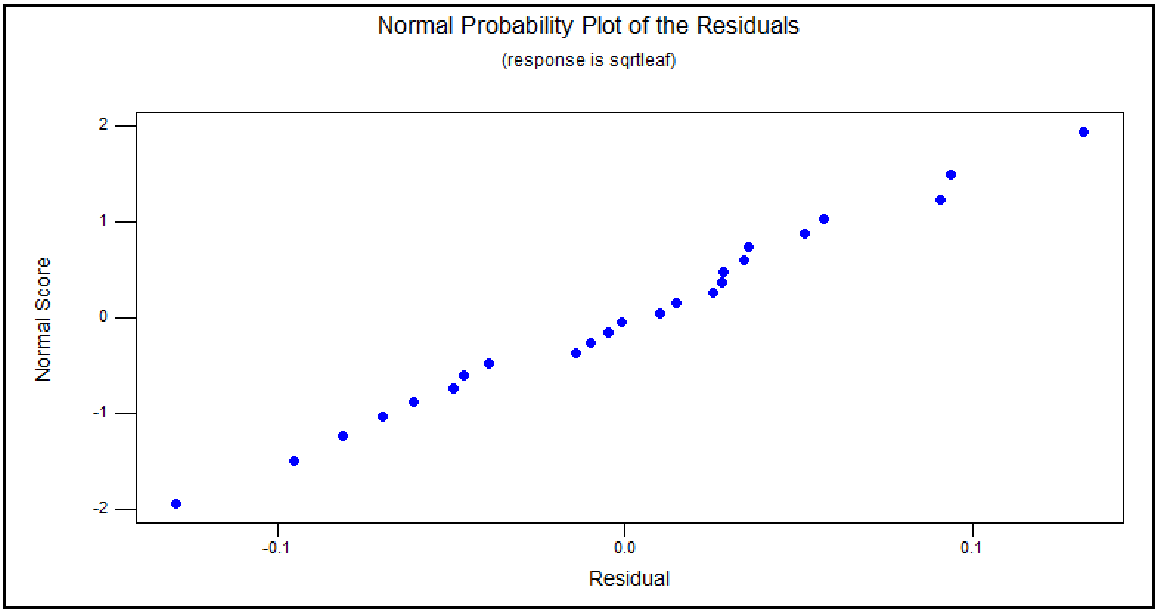


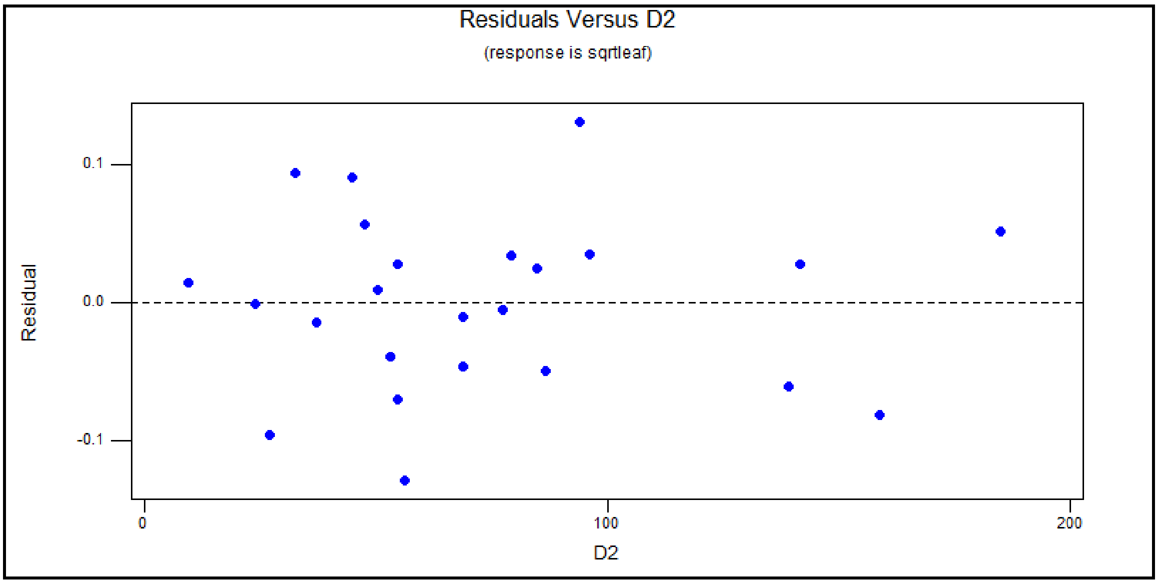
Appendix 5c) Branch carbon



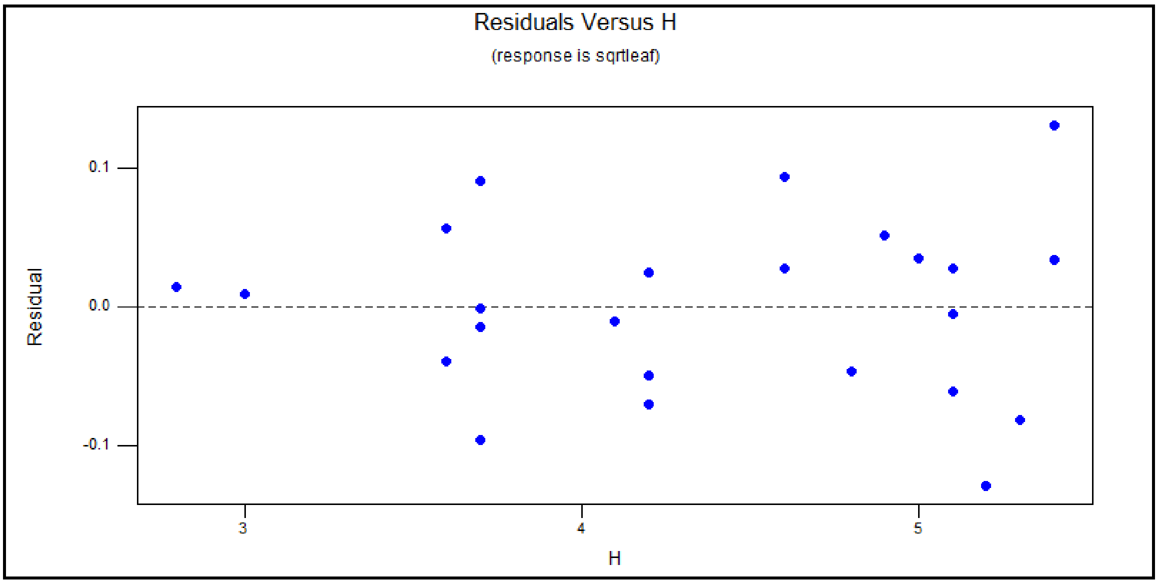


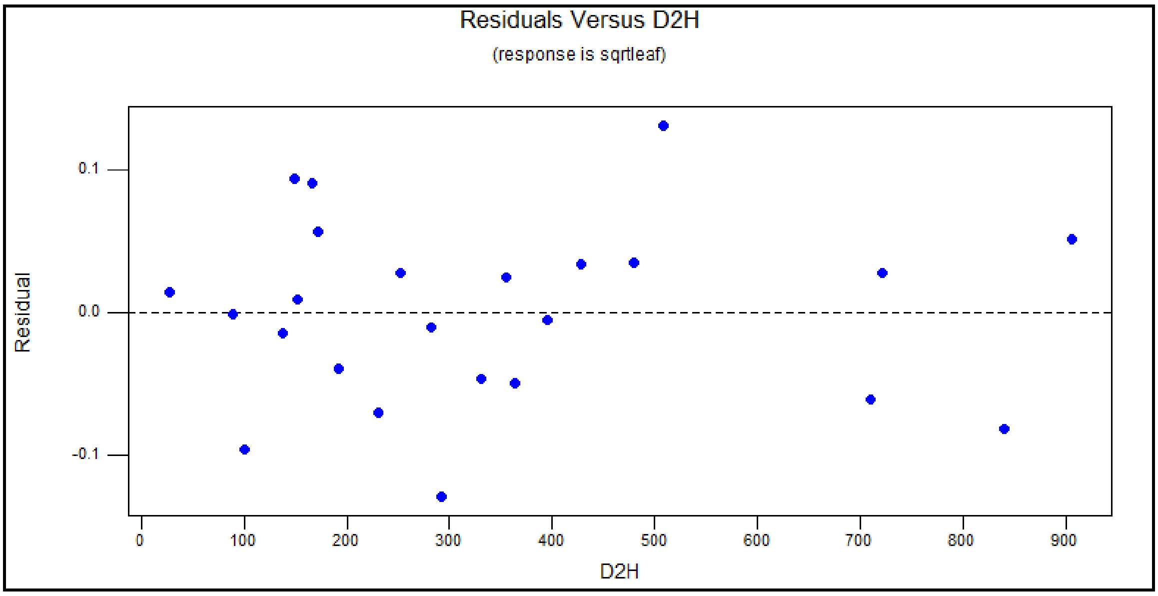
Appendix 5d) Leaf carbon



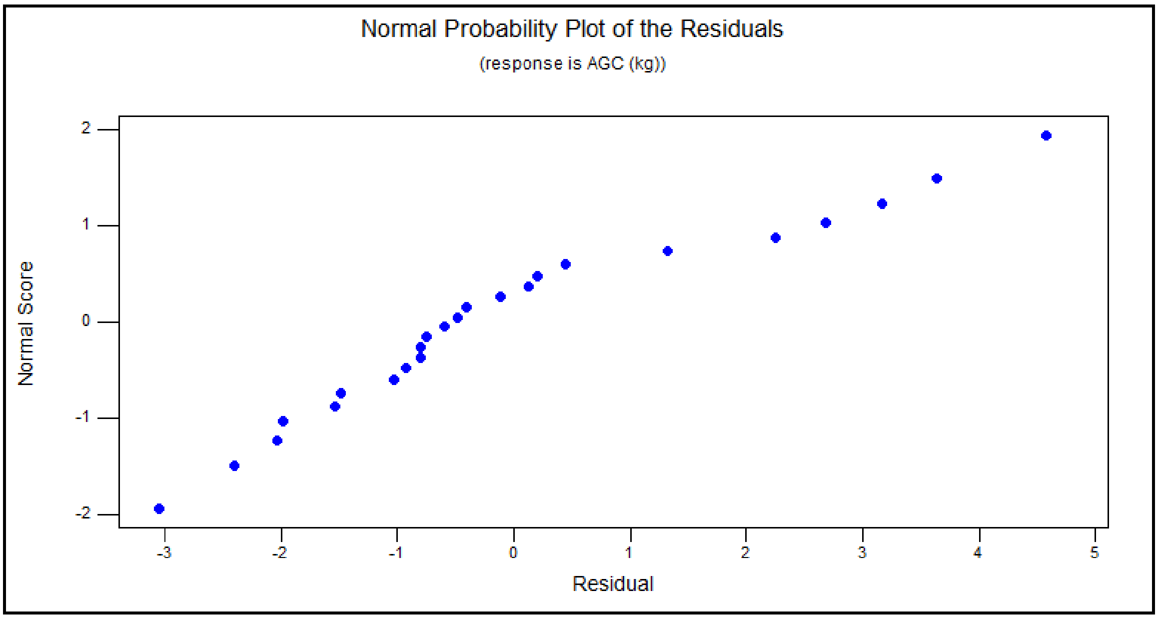


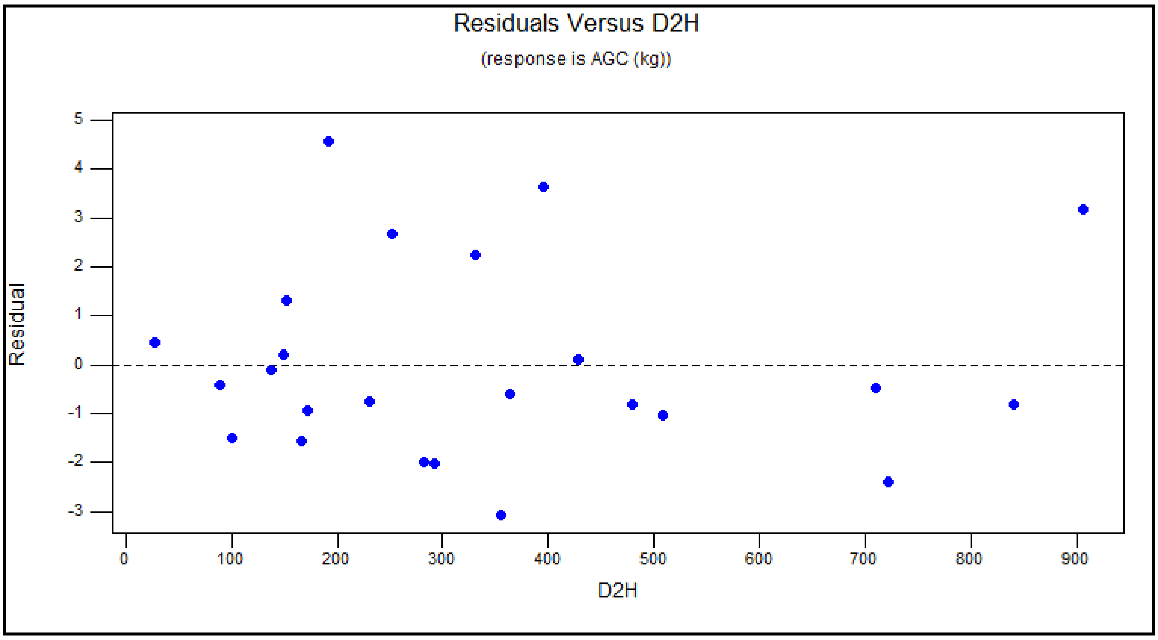
Leaf carbon – *continued*



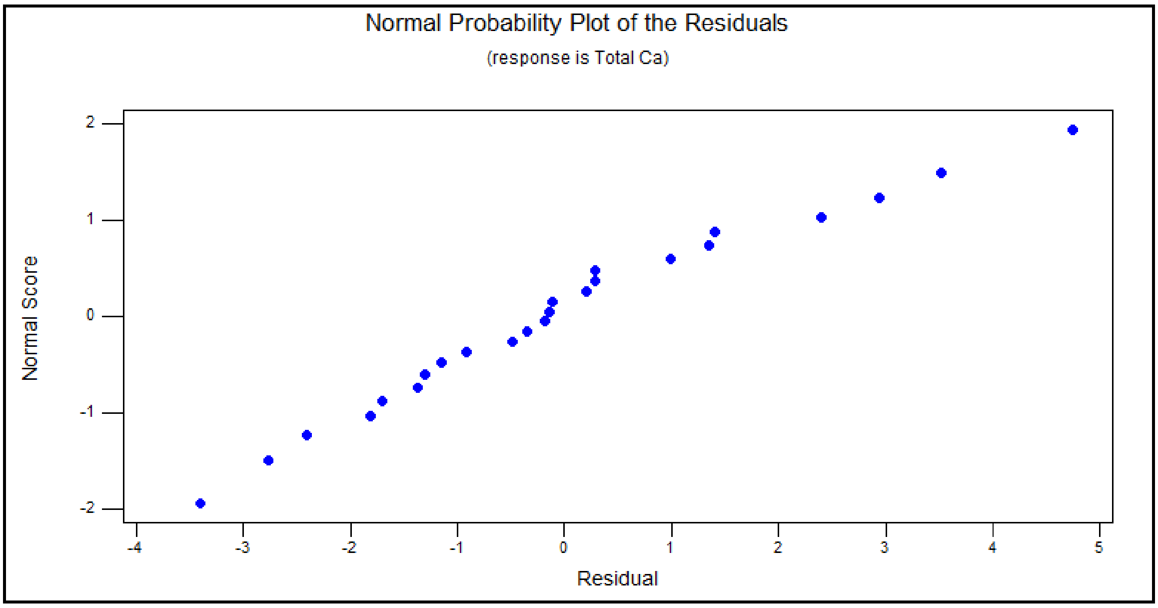


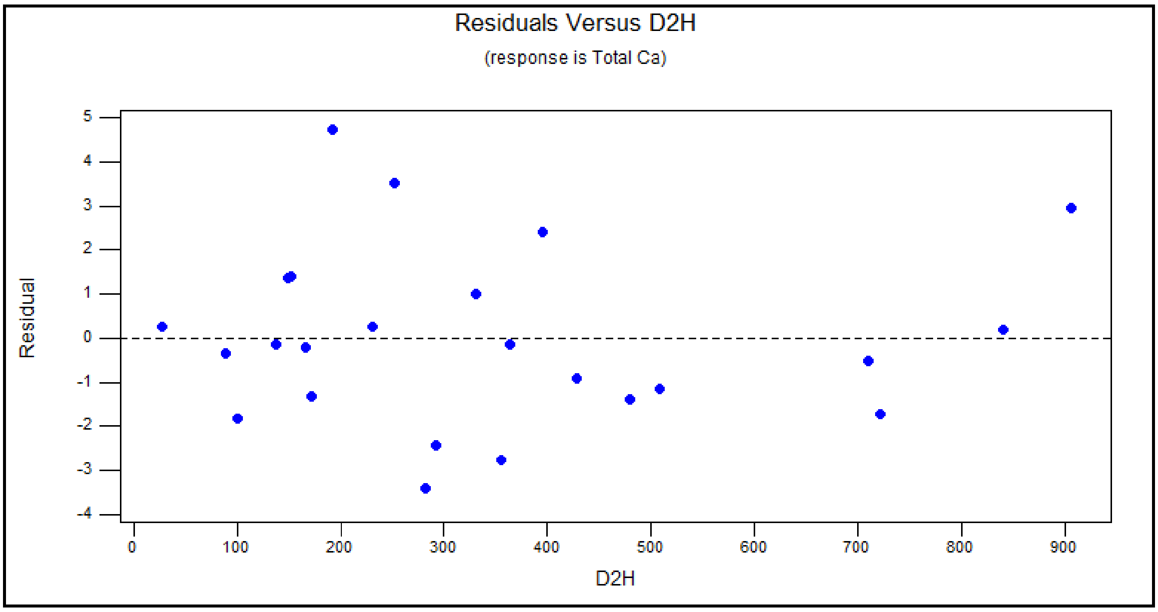
Appendix 5e) Aboveground carbon





Appendix 5f) Total carbon





Appendix 6: Family level one-way ANOVA for carbon stocks

Appendix 6a) Root carbon (kg) versus Family

```
Analysis of Variance for Root C
Source     DF        SS        MS        F        P
Family     95    181.38      1.91     1.35    0.020
Error     653    921.93      1.41
Total     748   1103.31
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Family      N      Mean     StDev  --+---------+---------+---------+----
 1         10     2.265     1.018              (----*----)
 2          8     2.595     1.278                (----*-----)
 3         11     1.813     0.958           (----*----)
 4         11     2.305     1.002               (---*----)
 5          9     1.950     1.176            (----*----)
 6          6     1.875     0.407          (------*-----)
 7          7     2.029     1.306            (-----*----)
 8          7     2.616     1.504                (----*-----)
 9          9     2.423     1.296               (----*----)
10          8     2.059     1.036            (-----*----)
11          6     3.453     1.364                     (-----*-----)
12          8     2.177     0.917             (-----*----)
13          7     1.809     0.544          (-----*-----)
14          9     1.949     1.637            (----*----)
15          4     1.860     0.389         (------*-------)
16          5     2.316     0.757            (------*------)
17         10     3.221     2.742                     (---*----)
18          5     1.690     0.751        (------*------)
19          9     2.764     1.304                 (----*-----)
20          4     1.680     0.930       (-------*-------)
21          8     1.653     0.888          (----*-----)
22         10     1.956     1.350            (----*----)
23          9     2.183     1.483             (-----*----)
24          6     2.308     0.887             (-----*------)
25          8     2.243     0.973             (-----*----)
26          8     1.295     0.351       (-----*----)
27          5     0.854     0.180   (------*------)
28          7     2.843     1.926                 (-----*-----)
29          5     1.470     0.868       (------*------)
30          9     1.522     0.973         (----*----)
31          5     1.008     0.424    (------*------)
32          9     2.634     1.430                (-----*----)
33          9     1.621     1.184          (----*----)
34          6     1.343     0.339       (-----*-----)
35          8     2.146     0.685             (----*-----)
36          8     2.161     1.251             (----*-----)
37         10     2.166     1.705              (---*----)
38         11     2.411     0.923               (----*----)
39          8     2.311     1.799              (----*-----)
40          3     2.117     0.860         (---------*---------)
41         10     2.014     2.011             (---*----)
42         10     1.252     0.539       (----*----)
43          8     2.416     1.336               (----*-----)
44          9     2.190     1.331             (-----*----)
45          7     2.199     0.791             (-----*-----)
46         10     2.395     1.504               (----*----)
47          6     1.345     0.794       (-----*-----)
48          5     1.126     0.693     (------*-----)
49          9     1.623     1.071          (----*----)
50          9     2.114     1.590             (----*----)
51          5     2.172     1.136            (-----*------)
52          8     1.869     1.446           (----*-----)
53          9     1.817     1.184           (----*----)
54         10     1.759     0.724           (----*----)
```

```
55         10     1.393     0.671        (----*----)
56          7     2.221     0.903             (-----*-----)
57          5     2.142     0.643           (------*------)
58          8     1.711     0.437          (----*-----)
59          6     2.387     0.847              (-----*-----)
60          9     1.004     0.326      (----*----)
61          9     2.224     1.725              (----*----)
62          9     1.544     0.826         (----*----)
63         11     1.930     0.967            (----*----)
64          4     2.300     1.451            (------*-------)
65          8     1.770     0.972          (-----*----)
66          7     1.769     0.807          (-----*-----)
67          6     2.317     1.278             (-----*------)
68          6     3.327     2.017                    (-----*-------)
69          7     1.843     0.958          (-----*-----)
70          9     1.226     0.375       (----*----)
71         11     1.230     0.688        (---*----)
72          7     1.540     1.213        (-----*-----)
73          4     1.515     0.171      (-------*-------)
74          4     2.678     1.781              (-------*-------)
75          8     1.160     0.480      (-----*----)
76         10     1.830     1.289           (----*----)
77          8     2.148     1.654             (----*-----)
78         10     1.671     0.720          (----*----)
79          6     1.697     0.616         (-----*------)
80         12     1.668     0.690           (---*----)
81          6     2.022     1.178           (-----*------)
82         11     1.681     0.883           (---*----)
83          7     1.994     1.195           (-----*-----)
84          9     2.191     1.863             (-----*----)
85         10     2.187     0.673              (----*---)
86          5     2.542     2.030              (------*------)
87         10     1.762     0.613           (----*----)
88          9     1.482     1.151         (----*----)
89         11     1.173     0.595       (----*----)
90         11     1.487     0.722         (----*----)
91          5     1.496     0.561       (------*------)
92          5     2.824     3.360                (------*------)
93          7     2.447     1.286              (-----*-----)
94          8     1.223     0.553       (----*-----)
95          9     1.939     1.501            (----*----)
96          5     1.344     0.960      (------*------)
                                   --+---------+---------+---------+----
Pooled StDev =    1.188            0.0       1.5       3.0       4.5
```

Appendix 6b) Trunk carbon (kg) versus Family

```
Analysis of Variance for Trunk C
Source     DF        SS        MS        F       P
Family     95    955.62     10.06     1.46   0.005
Error     653   4502.26      6.89
Total     748   5457.87
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Family      N      Mean     StDev  --+---------+---------+---------+----
 1         10     5.607     2.233                 (-----*----)
 2          8     6.083     2.467                  (-----*-----)
 3         11     4.705     2.362              (-----*----)
 4         11     5.605     2.475                  (----*----)
 5          9     4.861     2.618              (-----*-----)
 6          6     4.782     0.910             (------*------)
 7          7     5.027     2.819              (------*-----)
 8          7     6.094     3.002                  (-----*------)
 9          9     5.700     2.613                 (-----*-----)
10          8     5.203     2.321               (-----*-----)
11          6     8.460     2.742                         (------*------)
12          8     5.461     2.139                (-----*-----)
13          7     4.910     1.494              (-----*------)
14          9     4.758     3.750              (-----*-----)
15          4     4.485     0.905          (--------*--------)
16          5     6.016     1.956                (-------*-------)
17         10     6.842     4.877                     (-----*----)
18          5     4.260     2.160           (------*-------)
19          9     6.494     2.599                    (-----*----)
20          4     3.948     2.250         (-------*--------)
21          8     4.281     2.362            (-----*-----)
22         10     4.748     2.887              (-----*----)
23          9     4.896     2.470               (----*-----)
24          6     5.715     1.974                (------*------)
25          8     5.385     2.243                (-----*-----)
26          8     3.360     1.095         (-----*-----)
27          5     1.952     0.773   (-------*------)
28          7     6.486     3.720                   (------*-----)
29          5     3.534     2.387        (-------*------)
30          9     3.568     2.114          (-----*-----)
31          5     2.296     1.488    (-------*------)
32          9     6.318     2.972                   (-----*-----)
33          9     3.940     2.857           (-----*-----)
34          6     3.705     0.882         (------*------)
35          8     5.481     1.401                (-----*-----)
36          8     5.385     2.949                (-----*-----)
37         10     4.991     3.550               (-----*----)
38         11     5.700     2.180                  (----*----)
39          8     5.478     3.890                (-----*-----)
40          3     4.950     1.902           (---------*--------)
41         10     4.942     4.156               (----*-----)
42         10     2.877     1.168        (-----*----)
43          8     5.709     2.690                 (-----*-----)
44          9     5.238     2.701                (----*-----)
45          7     5.843     1.997                 (-----*------)
46         10     5.762     3.485                  (----*-----)
47          6     3.463     2.556         (------*------)
48          5     2.362     2.031    (--------*-------)
49          9     4.009     2.314            (----*-----)
50          9     4.870     3.580               (----*-----)
51          5     5.608     3.103               (-------*------)
52          8     4.225     3.090            (-----*-----)
53          9     4.359     2.932             (-----*----)
54         10     4.666     2.067              (-----*----)
55         10     3.483     1.923          (-----*----)
56          7     5.594     2.207                (------*-----)
```

```
57          5     5.144     1.316             (-------*--------)
58          8     4.520     1.268             (-----*-----)
59          6     5.737     1.482                (------*------)
60          9     2.597     1.104       (-----*----)
61          9     5.111     3.745               (-----*-----)
62          9     3.848     2.188           (-----*-----)
63         11     4.750     2.011               (----*----)
64          4     5.365     2.647             (--------*-------)
65          8     4.604     2.395             (-----*-----)
66          7     4.660     1.917             (------*-----)
67          6     5.632     2.906                (------*------)
68          6     8.135     4.033                        (------*------)
69          7     4.671     2.787             (------*-----)
70          9     3.079     1.287         (----*-----)
71         11     3.019     2.077         (----*----)
72          7     3.604     3.113          (-----*------)
73          4     4.070     0.507         (--------*-------)
74          4     6.110     3.207                (-------*--------)
75          8     2.833     1.475       (-----*------)
76         10     4.596     3.263              (----*-----)
77          8     5.174     3.632               (-----*-----)
78         10     4.306     1.910             (----*-----)
79          6     4.520     1.698            (------*------)
80         12     4.355     1.957              (----*---)
81          6     5.097     2.949              (------*------)
82         11     4.359     2.346             (-----*----)
83          7     4.951     3.183              (------*-----)
84          9     5.043     4.391               (-----*-----)
85         10     5.677     1.568                 (-----*----)
86          5     5.798     4.415                (------*-------)
87         10     4.515     1.460              (----*----)
88          9     3.387     2.261          (----*-----)
89         11     2.605     1.443       (-----*----)
90         11     3.700     2.235           (----*-----)
91          5     3.544     1.319        (-------*------)
92          5     5.664     6.172               (-------*-------)
93          7     6.349     3.042                   (-----*------)
94          8     3.106     1.523        (-----*-----)
95          9     4.732     2.715              (-----*-----)
96          5     3.248     2.547       (-------*-------)
                                   --+---------+---------+---------+----
Pooled StDev =    2.626            0.0       3.0       6.0       9.0
```

Appendix 6c) Branch carbon (kg) versus Family

```
Analysis of Variance for Branch C
Source     DF        SS        MS         F        P
Family     95    772.36      8.13     1.38    0.014
Error     653   3843.38      5.89
Total     748   4615.74
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Family      N      Mean     StDev  ----+---------+---------+---------+--
 1         10     4.255     2.041               (----*----)
 2          8     4.584     2.128                (----*-----)
 3         11     3.571     2.361             (----*----)
 4         11     4.269     2.392               (----*----)
 5          9     3.648     2.392             (----*----)
 6          6     3.405     0.785           (-----*------)
 7          7     3.806     2.569             (-----*-----)
 8          7     4.650     2.755               (------*-----)
 9          9     4.271     2.270               (----*-----)
10          8     3.979     2.033              (----*-----)
11          6     7.260     2.855                        (-----*------)
12          8     4.133     2.097              (-----*----)
13          7     3.743     1.452            (-----*-----)
14          9     3.786     3.495             (-----*----)
15          4     3.028     0.761        (-------*-------)
16          5     4.752     1.826               (------*-------)
17         10     5.368     4.849                   (----*----)
18          5     3.090     1.989         (------*------)
19          9     5.000     2.459                 (-----*----)
20          4     2.738     1.652       (-------*-------)
21          8     3.225     2.078           (-----*----)
22         10     3.572     2.505             (----*----)
23          9     3.400     2.017            (----*-----)
24          6     4.317     1.759              (-----*------)
25          8     3.985     1.941              (----*-----)
26          8     2.280     0.850        (-----*----)
27          5     1.212     0.515   (------*------)
28          7     5.061     3.553                 (-----*-----)
29          5     2.488     2.056       (------*------)
30          9     2.461     1.577         (----*----)
31          5     1.504     1.074    (------*------)
32          9     4.938     2.931                 (----*-----)
33          9     2.918     2.572          (-----*----)
34          6     2.640     0.728        (------*-----)
35          8     4.109     1.275              (-----*----)
36          8     4.223     2.660              (-----*-----)
37         10     3.827     3.117              (----*----)
38         11     4.249     2.106               (----*----)
39          8     4.355     3.605               (-----*----)
40          3     3.440     1.600        (---------*---------)
41         10     3.955     4.273              (----*----)
42         10     1.779     0.805       (----*----)
43          8     4.285     2.457               (----*-----)
44          9     3.904     2.383              (----*----)
45          7     4.653     1.938                (-----*-----)
46         10     4.535     3.585                (----*----)
47          6     2.640     2.250        (------*-----)
48          5     1.538     1.496    (------*------)
49          9     2.846     2.085          (----*-----)
50          9     3.689     3.297             (----*-----)
51          5     4.532     3.149              (------*------)
52          8     3.021     2.643          (-----*-----)
53          9     3.246     2.685            (----*----)
54         10     3.565     1.906             (----*----)
55         10     2.466     1.582         (----*----)
56          7     4.274     2.143              (-----*-----)
57          5     3.632     1.087           (------*------)
58          8     3.299     1.131           (-----*-----)
```

```
59          6     4.228     1.361              (-----*------)
60          9     1.758     0.894       (----*----)
61          9     3.929     3.582              (----*----)
62          9     2.757     1.927          (----*----)
63         11     3.446     1.648             (---*----)
64          4     3.903     2.206           (-------*-------)
65          8     3.509     2.135            (-----*----)
66          7     3.496     1.670            (-----*-----)
67          6     4.332     2.668              (-----*------)
68          6     7.067     4.372                       (------*-----)
69          7     3.659     2.622            (-----*-----)
70          9     2.071     1.032        (----*----)
71         11     2.168     1.708        (----*----)
72          7     2.709     2.623         (-----*-----)
73          4     2.865     0.507        (-------*------)
74          4     4.615     2.709             (-------*-------)
75          8     1.898     1.128       (----*-----)
76         10     3.607     3.158             (----*----)
77          8     4.009     3.793              (----*-----)
78         10     3.128     1.817           (----*----)
79          6     3.372     1.485           (-----*------)
80         12     3.235     1.769            (----*---)
81          6     3.950     2.748             (-----*------)
82         11     3.291     2.183            (----*----)
83          7     3.913     2.812             (-----*-----)
84          9     4.068     4.164              (-----*----)
85         10     4.362     1.544                (----*----)
86          5     4.664     3.995              (-------*------)
87         10     3.246     1.337            (----*----)
88          9     2.286     1.737        (-----*----)
89         11     1.655     0.949       (----*---)
90         11     2.753     1.790          (----*----)
91          5     2.300     0.949       (------*------)
92          5     4.486     5.841              (------*------)
93          7     5.353     2.711                  (-----*-----)
94          8     2.115     1.272       (-----*-----)
95          9     3.491     2.349            (-----*----)
96          5     2.324     2.177       (------*------)
                                   ----+---------+---------+---------+--
Pooled StDev =    2.426              0.0       3.0       6.0       9.0
```

Appendix 6d) Leaf carbon (kg) versus Family

```
Analysis of Variance for Leaf C (
Source     DF        SS        MS        F        P
Family     95    3.1050    0.0327     1.57    0.001
Error     653   13.6035    0.0208
Total     748   16.7084
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Family      N      Mean     StDev  ----------+---------+---------+------
 1         10    0.3679    0.1194                   (-----*-----)
 2          8    0.4258    0.1580                      (------*-----)
 3         11    0.3174    0.0864                 (-----*----)
 4         11    0.3515    0.1193                    (----*----)
 5          9    0.3292    0.1101                  (-----*----)
 6          6    0.3468    0.0531                 (-------*-------)
 7          7    0.3340    0.1268                 (------*-------)
 8          7    0.4003    0.1538                     (------*------)
 9          9    0.3912    0.1866                      (----*-----)
10          8    0.3593    0.1506                   (-----*------)
11          6    0.4233    0.1187                      (-------*--------)
12          8    0.3585    0.0951                   (-----*------)
13          7    0.3454    0.0741                  (------*-----)
14          9    0.2776    0.1520              (-----*-----)
15          4    0.3290    0.0679               (--------*-------)
16          5    0.3730    0.1077                  (-------*--------)
17         10    0.4315    0.1894                        (-----*-----)
18          5    0.2794    0.1323             (------*-------)
19          9    0.4224    0.1153                       (-----*-----)
20          4    0.2943    0.1776             (--------*--------)
21          8    0.2911    0.1311               (-----*-----)
22         10    0.3235    0.1692                  (----*-----)
23          9    0.3913    0.2560                      (----*-----)
24          6    0.3833    0.1147                    (------*------)
25          8    0.3671    0.1467                    (-----*-----)
26          8    0.2508    0.0868            (------*-----)
27          5    0.1406    0.0719    (-------*-------)
28          7    0.4004    0.1707                     (------*------)
29          5    0.2274    0.1667         (-------*-------)
30          9    0.2800    0.1807               (-----*----)
31          5    0.1606    0.1422     (-------*-------)
32          9    0.3921    0.1019                      (-----*----)
33          9    0.2570    0.1586             (-----*-----)
34          6    0.3057    0.0758               (------*------)
35          8    0.3815    0.0696                     (-----*-----)
36          8    0.3354    0.1548                  (-----*-----)
37         10    0.3519    0.2014                   (-----*-----)
38         11    0.3928    0.1140                      (-----*----)
39          8    0.3354    0.1494                  (-----*-----)
40          3    0.3600    0.1367               (----------*---------)
41         10    0.2765    0.1031               (----*-----)
42         10    0.2054    0.1144          (-----*----)
43          8    0.3935    0.1533                     (------*-----)
44          9    0.3548    0.1814                   (-----*-----)
45          7    0.3661    0.0800                   (------*------)
46         10    0.3224    0.1323                  (----*-----)
47          6    0.2292    0.1696          (------*-------)
48          5    0.1462    0.1665    (-------*-------)
49          9    0.2810    0.1138               (-----*----)
50          9    0.2823    0.1880               (-----*-----)
51          5    0.3100    0.1334              (-------*-------)
52          8    0.2845    0.2072               (-----*-----)
53          9    0.2763    0.1560              (-----*-----)
54         10    0.3094    0.1327                 (----*-----)
55         10    0.2455    0.1377             (----*-----)
56          7    0.3526    0.0956                  (------*------)
57          5    0.3768    0.0948                   (-------*------)
58          8    0.3260    0.0837                 (-----*------)
```

```
59          6    0.4282    0.1457                      (------*------)
60          9    0.2126    0.0910         (-----*-----)
61          9    0.3168    0.2177                (-----*-----)
62          9    0.2570    0.1335            (-----*-----)
63         11    0.3507    0.1369                   (----*----)
64          4    0.3965    0.2016                  (--------*--------)
65          8    0.3274    0.0977                (-----*------)
66          7    0.3329    0.1092                (------*-----)
67          6    0.3550    0.1306                 (------*------)
68          6    0.4155    0.1489                     (------*------)
69          7    0.2941    0.1681              (-----*------)
70          9    0.2227    0.1179          (-----*-----)
71         11    0.2120    0.1518          (----*-----)
72          7    0.2351    0.1881          (------*-----)
73          4    0.3087    0.0368            (--------*--------)
74          4    0.4398    0.2522                     (-------*--------)
75          8    0.2064    0.1269         (-----*-----)
76         10    0.2588    0.1479             (----*-----)
77          8    0.3121    0.1331               (------*-----)
78         10    0.2884    0.1003              (-----*-----)
79          6    0.3233    0.1022               (------*------)
80         12    0.2945    0.1264               (----*-----)
81          6    0.3038    0.1413              (------*------)
82         11    0.2846    0.1357              (-----*----)
83          7    0.2943    0.1798              (-----*------)
84          9    0.2458    0.1743           (-----*-----)
85         10    0.3771    0.0514                    (-----*----)
86          5    0.3454    0.2278                (-------*-------)
87         10    0.3280    0.0832                 (-----*----)
88          9    0.2720    0.1825             (-----*-----)
89         11    0.2016    0.1281         (-----*----)
90         11    0.2655    0.1749             (-----*----)
91          5    0.2616    0.1031          (-------*-------)
92          5    0.3322    0.3072               (-------*-------)
93          7    0.3777    0.1416                   (------*-----)
94          8    0.2266    0.1034          (-----*-----)
95          9    0.3543    0.1802                  (-----*-----)
96          5    0.2128    0.1722       (-------*-------)
                                   ----------+---------+---------+------
Pooled StDev =   0.1443                    0.16      0.32      0.48
```

Appendix 6e) Aboveground carbon (kg) versus Family

```
Analysis of Variance for ABC (kg)
Source     DF        SS        MS        F        P
Family     95    3926.8      41.3     1.38    0.014
Error     653   19544.0      29.9
Total     748   23470.8
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Family      N      Mean     StDev  --+---------+---------+---------+----
 1         10    10.446     4.602              (----*----)
 2          8    11.188     4.804               (----*----)
 3         11     8.900     5.326            (----*---)
 4         11    10.479     5.396              (----*----)
 5          9     9.080     5.393            (----*----)
 6          6     8.527     1.768          (-----*-----)
 7          7     9.434     5.789            (----*-----)
 8          7    11.339     6.209              (-----*-----)
 9          9    10.480     5.115              (----*----)
10          8     9.829     4.586             (----*----)
11          6    17.223     6.437                       (------*-----)
12          8    10.173     4.736             (-----*----)
13          7     9.293     3.277           (-----*-----)
14          9     9.392     7.877            (----*-----)
15          4     7.675     1.717       (--------*--------)
16          5    11.570     4.123              (------*-----)
17         10    12.955    10.933                  (----*---)
18          5     7.820     4.486        (------*-------)
19          9    12.126     5.544                (----*----)
20          4     7.030     3.728      (--------*-------)
21          8     8.126     4.686          (-----*----)
22         10     8.908     5.649            (----*----)
23          9     8.519     4.549           (----*----)
24          6    10.588     3.968             (-----*-----)
25          8     9.841     4.375             (----*----)
26          8     5.995     1.919       (-----*----)
27          5     3.584     1.153  (------*------)
28          7    12.261     8.011                (-----*----)
29          5     6.462     4.634      (------*------)
30          9     6.401     3.559        (----*----)
31          5     4.242     2.420   (------*------)
32          9    11.986     6.613                (----*----)
33          9     7.431     5.798          (----*----)
34          6     6.802     1.641       (------*-----)
35          8    10.119     2.873             (----*-----)
36          8    10.376     6.006             (-----*----)
37         10     9.476     7.027             (----*---)
38         11    10.435     4.750              (----*----)
39          8    10.670     8.126              (----*-----)
40          3     8.617     3.605       (---------*--------)
41         10     9.772     9.634             (----*----)
42         10     4.864     1.814      (----*----)
43          8    10.508     5.542              (----*----)
44          9     9.652     5.376             (----*----)
45          7    11.347     4.372              (-----*-----)
46         10    11.078     8.085               (----*----)
47          6     6.807     5.074       (------*-----)
48          5     4.320     3.374   (------*------)
49          9     7.267     4.701         (----*----)
50          9     9.173     7.434            (----*----)
51          5    11.072     7.100             (------*------)
52          8     7.666     5.962          (----*----)
53          9     8.167     6.054           (----*----)
54         10     8.890     4.298            (----*----)
55         10     6.412     3.568        (----*----)
56          7    10.487     4.837             (-----*-----)
57          5     9.038     2.445          (------*------)
58          8     8.294     2.554          (-----*----)
```

```
59          6    10.385     3.067             (-----*-----)
60          9     4.814     2.012      (----*----)
61          9     9.711     8.075             (----*----)
62          9     7.068     4.342         (----*----)
63         11     8.624     3.719            (---*----)
64          4     9.653     4.973          (-------*------)
65          8     8.761     4.811           (-----*----)
66          7     8.734     3.765           (----*-----)
67          6    10.623     6.017             (-----*-----)
68          6    16.787     9.862                      (-----*-----)
69          7     9.100     5.913           (-----*-----)
70          9     5.524     2.329       (----*----)
71         11     5.742     3.855        (---*----)
72          7     6.959     5.916        (-----*-----)
73          4     7.315     1.149       (------*-------)
74          4    11.258     6.109            (-------*-------)
75          8     5.128     2.544      (----*-----)
76         10     8.987     7.125            (----*----)
77          8     9.886     8.550             (----*-----)
78         10     7.904     4.101          (----*----)
79          6     8.455     3.347          (-----*-----)
80         12     8.145     3.987           (----*---)
81          6     9.760     6.195            (-----*-----)
82         11     8.271     4.921           (----*---)
83          7     9.680     6.339            (-----*-----)
84          9    10.024     9.389             (----*----)
85         10    10.687     3.479              (----*----)
86          5    11.368     9.010             (------*------)
87         10     8.171     3.014           (----*----)
88          9     6.003     3.918       (-----*----)
89         11     4.583     2.140      (----*---)
90         11     7.059     4.034         (----*----)
91          5     6.038     2.137      (------*-----)
92          5    10.966    13.174             (------*------)
93          7    12.917     6.118                 (----*-----)
94          8     5.624     2.869       (----*----)
95          9     8.721     5.300           (----*-----)
96          5     6.096     4.913      (------*------)
                                   --+---------+---------+---------+----
Pooled StDev =     5.471           0.0       7.0      14.0      21.0
```

Appendix 6f) Total carbon (kg) versus Family

```
Analysis of Variance for Total C
Source     DF         SS         MS        F        P
Family     95     6071.9       63.9     1.38    0.014
Error     653    30217.5       46.3
Total     748    36289.4
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Family      N       Mean     StDev ---+---------+---------+---------+---
 1         10     12.879     5.724               (----*----)
 2          8     13.801     5.975               (-----*-----)
 3         11     10.957     6.620             (----*----)
 4         11     12.921     6.708               (----*----)
 5          9     11.179     6.707            (-----*-----)
 6          6     10.495     2.202          (------*------)
 7          7     11.623     7.198            (------*-----)
 8          7     13.990     7.719               (-----*------)
 9          9     12.923     6.362               (----*-----)
10          8     12.109     5.701             (-----*-----)
11          6     21.308     8.006                        (------*-----)
12          8     12.540     5.887              (-----*-----)
13          7     11.447     4.072            (-----*------)
14          9     11.570     9.796             (----*-----)
15          4      9.433     2.138       (--------*-------)
16          5     14.276     5.124              (-------*-------)
17         10     15.999    13.596                   (----*----)
18          5      9.612     5.579         (------*------)
19          9     14.968     6.893                 (-----*----)
20          4      8.630     4.631      (---------*-------)
21          8      9.994     5.827           (----*-----)
22         10     10.968     7.026            (-----*----)
23          9     10.482     5.657            (----*-----)
24          6     13.053     4.939              (-----*------)
25          8     12.128     5.442             (-----*-----)
26          8      7.340     2.387       (-----*-----)
27          5      4.346     1.433  (------*-------)
28          7     15.137     9.961                 (-----*-----)
29          5      7.924     5.763      (-------*------)
30          9      7.851     4.424        (-----*----)
31          5      5.164     3.007   (------*-------)
32          9     14.793     8.224                 (----*-----)
33          9      9.130     7.210          (----*-----)
34          6      8.348     2.043        (-----*------)
35          8     12.469     3.572              (-----*----)
36          8     12.794     7.464              (-----*-----)
37         10     11.675     8.739             (-----*----)
38         11     12.865     5.908               (----*----)
39          8     13.159    10.103               (----*-----)
40          3     10.603     4.480        (---------*---------)
41         10     12.041    11.980              (----*----)
42         10      5.941     2.257      (----*-----)
43          8     12.958     6.894              (-----*-----)
44          9     11.892     6.682             (-----*----)
45          7     13.999     5.436               (-----*------)
46         10     13.664    10.052                (----*----)
47          6      8.357     6.308        (-----*------)
48          5      5.266     4.196   (-------*------)
49          9      8.929     5.847          (----*-----)
50          9     11.298     9.245             (----*-----)
51          5     13.658     8.826              (------*-------)
52          8      9.424     7.413          (-----*-----)
53          9     10.047     7.527           (-----*----)
54         10     10.946     5.343            (-----*----)
55         10      7.865     4.436         (----*----)
56          7     12.927     6.015              (-----*-----)
57          5     11.132     3.044          (-------*------)
58          8     10.205     3.171           (-----*-----)
```

```
59          6    12.807     3.813              (------*------)
60          9     5.877     2.500       (----*-----)
61          9    11.966    10.042              (-----*-----)
62          9     8.679     5.401          (-----*----)
63         11    10.613     4.624             (----*----)
64          4    11.890     6.185            (-------*-------)
65          8    10.786     5.982             (----*-----)
66          7    10.751     4.682            (-----*------)
67          6    13.100     7.485               (-----*------)
68          6    20.765    12.264                        (------*------)
69          7    11.206     7.353             (-----*-----)
70          9     6.760     2.895        (----*-----)
71         11     7.029     4.791         (----*----)
72          7     8.547     7.356         (------*-----)
73          4     8.983     1.428        (-------*--------)
74          4    13.888     7.594              (-------*--------)
75          8     6.266     3.165       (-----*-----)
76         10    11.064     8.859              (----*----)
77          8    12.184    10.635              (-----*-----)
78         10     9.719     5.098            (----*----)
79          6    10.407     4.160           (------*------)
80         12    10.022     4.959             (----*---)
81          6    12.027     7.702             (------*------)
82         11    10.172     6.119             (----*----)
83          7    11.926     7.880              (-----*-----)
84          9    12.356    11.673               (----*-----)
85         10    13.180     4.327                (----*-----)
86          5    14.028    11.201               (-------*------)
87         10    10.051     3.747            (-----*----)
88          9     7.356     4.874         (----*-----)
89         11     5.586     2.659       (----*----)
90         11     8.667     5.018           (----*----)
91          5     7.396     2.658       (------*-------)
92          5    13.526    16.379              (-------*------)
93          7    15.954     7.606                   (-----*-----)
94          8     6.884     3.567        (-----*-----)
95          9    10.739     6.591             (----*-----)
96          5     7.468     6.105       (------*-------)
                                   ---+---------+---------+---------+---
Pooled StDev =    6.803             0.0       8.0      16.0      24.0
```

Appendix 7: Selected photos from the study

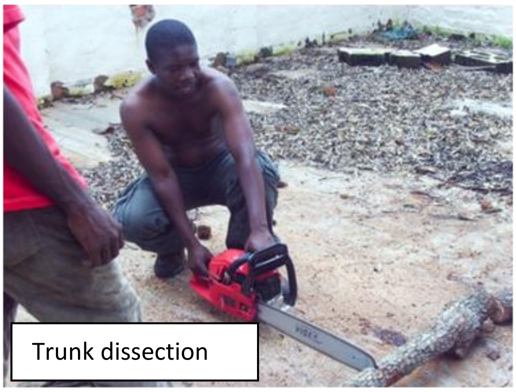

Collection of foliage


Samples await transportation


Separation into component parts


Pile of branches


Some root samples


Trunk dissection

Photos incorporated with consent of those in view.


Samples on way to ovens for drying


Oven for drying


Drying of leaves


Dry trunks


Dry roots


Dry branches

Photos incorporated with consent of those in view.