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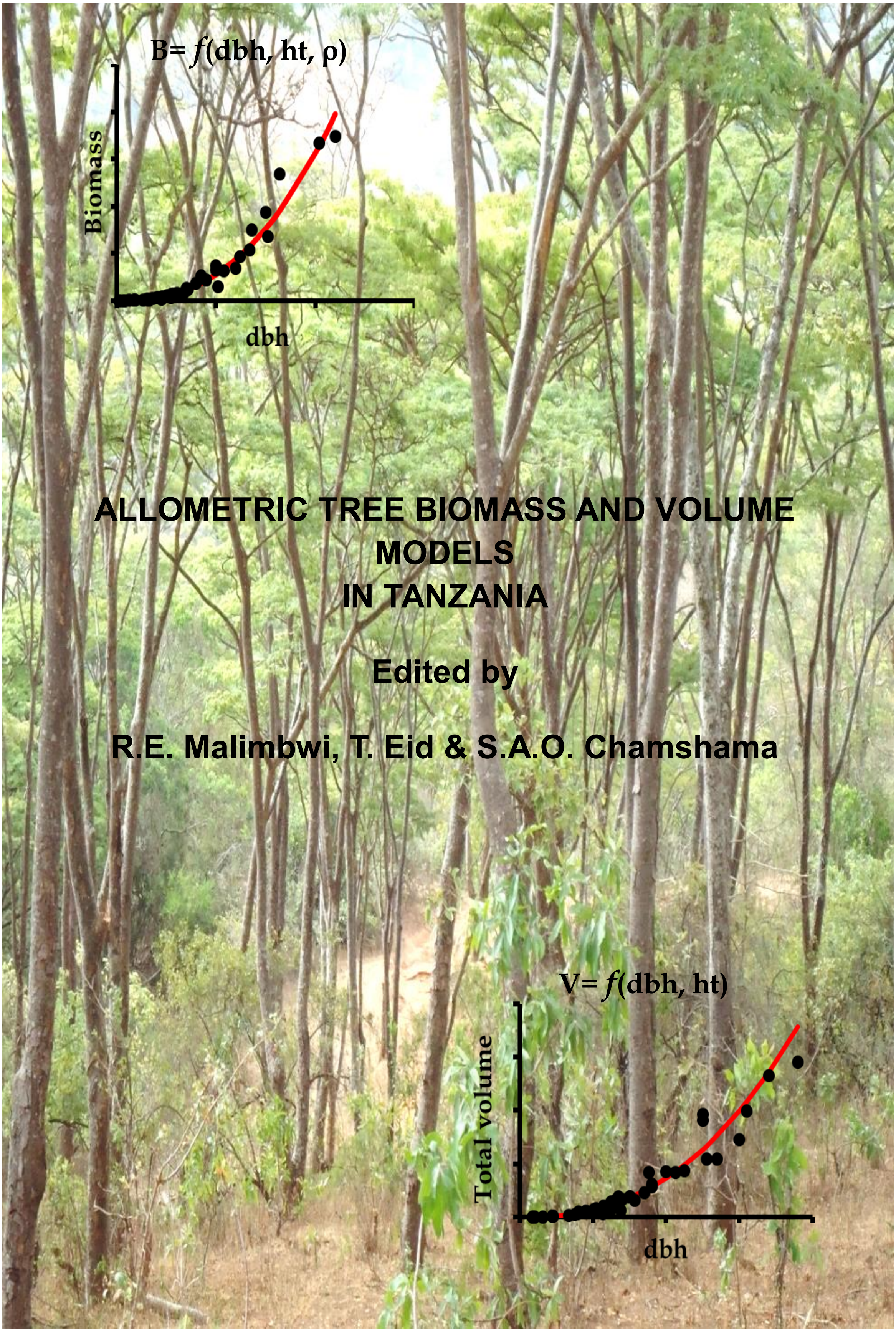

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PREFACE

Under the Norwegian International Climate and Forest Initiative (ICFI), Norway and Tanzania signed a Letter of Intent on a Climate Change Partnership in April 2008. The two countries agreed to cooperate for five years and Norway committed itself to support the cooperation with up to Norwegian Kroner (NOK) 500 million equivalent to United States Dollar (US$) 100 million for the period. As a result of this cooperation, Norway provided support to the government of Tanzania which aimed at improving capacity to manage REDD+ so as to prepare the county for the upcoming REDD+ payments (REDD+ Readiness process).

The Climate Change Impacts, Adaptation and Mitigation (CCIAM) Programme was a 5 year Programme (2009-2014) being supported under the Norwegian ICFI. It was implemented by four local Tanzanian Institutions (Sokoine University of Agriculture, University of Dar es Salaam, Ardhi University and Tanzania Meteorological Agency) in collaboration with four Norwegian Institutions (Norwegian University of life Sciences; Oslo University; Center for International Climate and Environmental Research; and Norwegian Forest and Landscape Institute). The Programme was officially launched on 30th November 2009 and the contract agreement between the Royal Norwegian Embassy (representing the Royal Norwegian Government) and the Ministry of Finance and Economic Affairs (representing the government of Tanzania) was signed on 16th December 2009. Funds for the implementation of the CCIAM Programme were first released on 21st January 2010 and research activities started in February 2011 after holding a harmonization of site selection workshop. Most of the research activities were done through MSc and PhD scholarships.

The Project “Development of biomass estimation models for carbon monitoring in selected vegetation types of Tanzania” was one of several projects implemented under the CCIAM Programme. This project also got additional funding from the research project on Enhancing the Measuring, Reporting and Verification of forests in Tanzania through the application of advanced remote sensing technology (MRV-LiDAR). The main objective of the project was to develop models and methods for assessing and monitoring carbon stocks in Tanzania required for implementation of REDD+ at local as well as national levels. Vegetation types/tree species covered were miombo woodlands, lowland and humid montane forests, mangrove forests, thicket, *Acacia-Commiphora* woodlands, forest plantations (*Pinus patula* and *Tectona grandis*), and coconut, cashewnut and baobab trees.

For some vegetation types, both biomass and volume models were developed while for others only biomass models have been covered. In total 801 tree were sampled for aboveground biomass estimation; 542 for belowground biomass and 551 for volume. The work was implemented through a scholarly process which resulted into 5 PhD and 7 MSc degrees thus contributing to capacity building in the country. Also several papers in peer reviewed journals have been published. This book was written by members of the project as well as students who participated in project research activities. The book may be useful for scholars who wish to engage in tree allometric modelling. The developed models may also be used in REDD+ estimations and other

carbon trade mechanisms. They may as well be useful to the practicing forester for determination of forest stocking levels needed for forest planning.

ACKNOWLEDGEMENT

We are grateful to Norwegian government for funding this research project through the Climate Change Impacts, Adaptation and Mitigation (CCIAM) programme and the project on Enhancing the Measuring, Reporting and Verification of forests in Tanzania through the application of advanced remote sensing technology (MRV-LiDAR) both hosted at Sokoine University of Agriculture (SUA). We thank the Coordinators for ably handling the financial and administrative aspects of the programme/project. We also sincerely thank the CCIAM Coordinator Prof. S.M.S. Maliondo for approving our request for fund to meet the publication costs of this book. The successful implementation of the research activities was enabled by the close collaboration between the partners (SUA and the Norwegian University of Life Sciences). In implementing this project, several forests under different ownerships were involved. We thank Tanzania Forest Services (TFS) Agency, District Councils and Villages for granting access to their forests. In particular, we appreciate the permission given to undertake destructive sampling of valuable tree species. Lastly, we thank all those who assisted with field work which was very involving especially the excavation of belowground tree samples.

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ABBREVIATIONS AND ACRONYMS

AGB	Aboveground biomass
AIC	Akaike information criterion
ANR	Amani Nature Reserve
BA	Basal area per ha
BGB	Belowground biomass
BIC	Bayesian information criterion
C	Carbon
CCIAM	Climate Change Impacts, Adaptation and Mitigation programme
CO_2	Carbon dioxide
dbh	Diameter at breast height
dbh_w	Basal area weighted mean diameter at breast height
DF-ratio	Dry to fresh weight ratio
f	Form factor
FAO	Food and Agriculture Organization
FR	Forest Reserve
g	Tree basal area at breast height
ha	Hectare
ht	Total tree height
ICFI	Norwegian International Climate and Forest Initiative
IPCC	Intergovernmental Panel on Climate Change
IUCN	The World Conservation Union
MNRT	Ministry of Natural Resources and Tourism
MPE (%)	Relative Mean Prediction Error
MRV	Measurement, Reporting and Verification
NAFORMA	National Forest Resources Monitoring and Assessment
NFI	National Forest Inventory
NLIN	Non-linear
NLME	Nonlinear Mixed Effects
NLP	Non Linear Programming
NR	Nature Reserve
NWFPs	Non-wood forest products
PROC	Procedure
R^2	Coefficient of determination
REDD+	Reducing Emissions from Deforestation and forest Degradation, forest conservation, sustainable management of forests, and enhancement of forest carbon stocks
REL	Reference Emission Level
RL	Reference Level
RMSE	Root mean square error
SAS	Statistical Analysis Software
st	Number of stems in thicket clump
SUA	Sokoine University of Agriculture
SUATF	Sokoine University of Agriculture Training Forest
TZS	Tanzania shillings
UNIDO	United Nations Industrial Development Organization

URT	United Republic of Tanzania
WWF	World Wide Fund for Nature
ρ	Wood basic density

MODEL IDENTITY

All biomass and volume models presented in the book have a unique identification where the following four levels of coding were used; 1) Forest type or tree species, 2) Model type, 3) Dependent variable and 4) Independent variables.

Level	**Values**
1 Forest type or tree species	MI (miombo woodlands), LM (lowland and montane forests), MG (mangrove forest), TH (thicket and associate trees), AC (*Acacia-Commiphora* woodlands), PI (*Pinus patula* plantation), TE (*Tectona grandis* plantation), CO (coconut trees), CN (cashewnut trees), BO (baobab trees)
2 Model type	MM (multi-species and multi-site) MS (multi-species and single-site) SM (species-specific and multi-site) SS (species-specific and single-site) Tree species and study sites are numbered respectively
3 Dependent variable	AGB (aboveground biomass), BGB (belowground biomass), TB (twig biomass), TLB (twigs and leaves biomass), BB (branch biomass), SB (stem biomass), MSB (merchantable stem biomass), SBB (stem and branches biomass) TV (total volume), BV (branches volume), SV (stem volume), MSV (merchantable stem volume)
4 Independent variables	1 (dbh), 2 (dbh, ht), 3 (dbh, ρ), 4 (dbh, ht, ρ), 5 (dbh, ht, g), 6 (dbh, st), 7 (dbh, ht, st), 8 (ht)

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1 INTRODUCTION

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1.1 Forests and forest types in Tanzania

Tanzania is endowed with vast forest resources. The total forest area in mainland Tanzania is estimated to be 48.1 million hectares (ha), which is 54.4% of the total land area of 88.3 million ha (MNRT, 2015) (Table 1.1). The main forest and woodland types include miombo woodlands in the western, central and southern parts of the country, *Acacia-Commiphora* woodlands in the northern regions, woodland mosaics in the east, coastal and mangrove forests along the coast of the Indian Ocean, and closed canopy forests on the ancient Precambrian mountains of Eastern Arc, along the Albertine Rift close to Lake Tanganyika in the west, and on the younger volcanic mountains in the north (Burgess et al., 2004). In terms of land cover, woodlands occupy 44.7 million ha or 93.0% of the total forest area or 50.6% of mainland Tanzania while forests (forests here collectively refer to lowland forests, montane forests, mangroves and plantations) occupy 3.5%, bushland and grassland 16.6% and cultivated land 25.2%.

The total wood volume of growing stock is 3.3 billion cubic metres (m^3) (MNRT, 2015). About 97% of the total volume is from trees of natural origin and only 3% is from planted trees. About half of the total volume is found in forestry and wildlife protected areas and is therefore legally inaccessible for harvesting (MNRT, 2015). Table 1.1 shows the areas, volume, biomass and carbon (C) by primary land cover types. Forests account for 11.3% of growing stock while miombo woodlands contain 73.9% of the growing stock. Bushland contain 4.2% of the growing stock while cultivated land contains 7.8% of the growing stock. The rest (2.8%) of the growing stock is in other vegetation types. Total C content in mainland Tanzania is about 1 billion tons (t).

With regard to ownership, forest resources under central government occupy 34.5% of the total forest and woodland areas, local government authority land is 6.5%, village land is 45.7%, private land is 7.3% and general land (i.e. not reserved, not occupied or unused village land) occupy 5.7% (MNRT, 2015).

The forest resources provide a range of benefits, from ecosystem services to wood and non-wood forest products (NWFPs) for livelihoods of people and economy of the country. The wood products include: firewood, charcoal, round wood and sawn wood. The most important use of wood in Tanzania is for fuel and about 92% of the country's energy supply is met by fuelwood (URT, 2001). The NWFPs consist of game meat, medicinal plants, fodder, latex, beverages, dyes, fibres, gums, resins, oils, beeswax and honey, tannins and toxins. Several of these are subsistence products providing nutrition, critical in situations of drought and famine. Traditional medicine is the only affordable alternative available to most rural and urban population.

Ecosystem services include protection of watersheds that are sources of water for power generation and irrigation, soil conservation, conservation of biodiversity, sustaining cultural values, carbon dioxide (CO_2) sequestration, climatic amelioration and eco-tourism. Forest areas also support agriculture and livestock. The forests and woodlands of Tanzania are known for their high biodiversity. There are over 10,000 plant species, hundreds of which are nationally endemic. Among the plant and animal species in Tanzania, 724 are identified as *Threatened* in the World Conservation Union (IUCN) Red List with 276 species classified as *Endangered* (IUCN, 2013). At national level, the forestry sector contributes 2–3.4% of Gross Domestic Product (GDP) per annum (URT, 2001), but this is considered an underestimation because it does not consider the environmental services and other non-wood values.

Despite all the invaluable goods and services provided by forests, there are high rates of deforestation and forest degradation. The National Forest Resources Monitoring and Assessment of Tanzania (NAFORMA) estimated forest cover loss of 372,816 ha per year corresponding to 0.78% of the areas of woodlands and forests (MNRT, 2015). The major direct causes of uncontrolled deforestation and forest degradation are: shifting cultivation and permanent agriculture, development of human settlements, wood for processing (tobacco curing, fish smoking and making burned bricks), overgrazing, firewood and charcoal production, uncontrolled fires, timber extraction, development of infrastructure/industry, refugees and most recently the introduction of large scale agriculture of bio-fuel production. These direct causes of uncontrolled deforestation and forest degradation are driven by market and policy failures, rapid (and uncontrolled) population growth and rural poverty. Deforestation and forest degradation are taking place in both reserved and unreserved forests but more so in the later due to inadequate resources to implement active and sustainable forest management (e.g. Zahabu, 2008). Negative impacts of deforestation and forest degradation include loss of ecological services (such as biodiversity and watershed), the loss of many goods (such as timber, fuel wood, charcoal and NWFPs) (Lamb et al., 2005), and the loss of livelihood sources for more than 80% of rural Tanzanians (URT, 2005). Thus deforestation and forests degradation constitute a huge opportunity cost to Tanzania and her people.

Climate change is also impacting on forests and forest ecosystems and therefore livelihoods of forest dependent communities as well as national economic activities that depend on forest products and services. Due to climate change, forest ecosystems may shift their ranges and loose some of their biodiversity. On the other hand, forests are important sinks for removing CO_2 from the atmosphere and are currently one of the practices that are being used for mitigating climate change.

Table 1.1. Areas, volume, biomass and carbon by land cover type in mainland Tanzania

Primary land cover types	Area		Volume (1000 m^3)	Volume (m^3/ha)	Above-ground biomass (t/ha)	Below-ground biomass (t/ha)	Carbon (t)
	(ha)	(%)					
Forest	3,364,457	3.8	374,962	111.8	59.5	18.2	122,340,057
Woodland	44,726,246	50.6	2,456,252	55.1	27.7	9.5	779,607,827
Bushland	6,445,471	7.3	140,324	21.8	11.0	4.4	46,388,588
Grassland	8,242,245	9.3	46,838	5.7	2.9	1.1	15,115,401
Cultivated land	2,248,092	25.2	260,661	11.8	5.9	2.1	83,293,969
Open land	252,516	0.3	1,439	5.7	2.9	1.1	466,006
Water*	1,162,552	1.3	10,647	9.2	4.6	1.7	3,429,530
Other areas	1,892,720	2.1	31,669	16.8	8.4	3.1	10,192,480
Total/mean	88,334,300	100.0	3,322,791	37.7	19.1	6.5	1,060,833,858

Source: (MNRT, 2015), *Includes Mangroves and other species

1.2 The importance of forest biomass and volume models

A model is a set of mathematically related variables. Tree biomass and volume models comprise of easily measureable tree variables, usually diameter at breast height and height that are correlated to the biomass or volume. Provided that information on individual trees is available, the use of biomass and volume models is the best option to quantify amounts of C and volume of wood.

Quantifying forest biomass and volume may be important for several reasons. Quantification of amounts of biomass, and subsequently C, is presently an important component in the REDD+ initiative. REDD+ is a system of financing mechanisms and incentives aiming at mitigating climate change by reducing deforestation and forest degradation. Participating countries in REDD+ projects are required to produce accurate estimates for their forest C stocks and changes through robust Measurement, Reporting and Verification (MRV) schemes. The assessment of REDD+ is done by comparing current rate of deforestation and forest degradation against established historical rate known as Reference Emission Level (REL)/Reference Levels (RL). The estimation of REL or RL utilises biomass models. Quantification of biomass is also essential for issues related to energy production (fuelwood and charcoal production) in conventional forest management planning.

Tanzania has recently completed her National Forest Inventory (NFI) popularly known as NAFORMA (MNRT, 2015). The major tree variables measured were diameter at breast height (dbh) and total tree height (ht). Using appropriate biomass and volume models, these variables have been used to estimate single tree biomass and volume. The single tree biomass and volume estimates are usually further projected to stand average values in terms of biomass or volume per ha for different biomes. Knowing the extent of the biomes in ha, the total biomass or volume of each biome can be estimated and aggregated into district, regional and finally national estimates. The stand volume estimates are the basis for forest management purposes such as assessment of growing stock, timber valuation, selection of forest areas for harvests, for growth and yield studies and hence achieving sustainable forest management. The biomass is further converted into C and CO_2 and hence enabling the estimation of REDD+.

1.3 The aim of the book

Various methods may be employed to quantify forest C stocks. The most common and accurate approach involve the use of models for prediction of tree dry weight, from which C stock may be derived (e.g. Brown 1997; Chave et al. 2005; 2014). Development of models requires destructive sampling of trees to determine aboveground biomass (AGB) and belowground biomass (BGB).

This book aims to document the various processes involved in developing biomass and volume models for different vegetation types and tree species in Tanzania. Since the ecology of the vegetation types vary, so do the challenges, input requirements and ways to overcome them. Vegetation types and tree species covered are: miombo woodlands, lowland and sub-montane forests, mangrove forests, thicket including associate trees, *Acacia-Commiphora* woodlands, forest plantations (*Pinus patula* and *Tectona grandis*), and coconut, cashewnut and baobab trees. For some vegetation types/tree species, both biomass and volume models were developed while for some only biomass models have been covered (Table 1.2 and Figure 1.1).

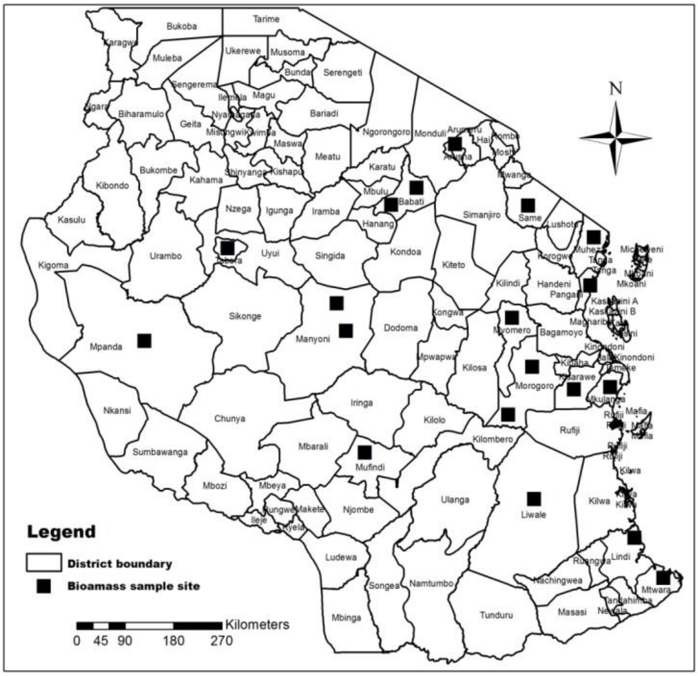

Figure 1.1. Location of study sites

Table 1.2. **Number of sample trees used for model development from different vegetation types/tree species and sites**

Vegetation type/tree species	Site (region)	Number of sample trees used for model development		
		Aboveground biomass	Belowground biomass	Volume
Lowland and sub-montane forests	Tanga	60	29	60
Miombo woodlands	Manyara, Lindi, Katavi, Tabora	167	80	158
Mangroves	Tanga, Pwani, Lindi, Mtwara	119	30	-
Thicket	Singida	60	60	60
Thicket associate trees	Singida	30	30	30
Acacia-Commiphora woodlands	Manyara, Kilimanjaro	110	110	110
Pinus patula plantation	Iringa, Arusha	85	85	-
Tectona grandis plantation	Tanga	44	44	44
Coconut trees	Pwani	46	29	46
Cashewnut trees	Pwani	45	45	43
Baobab	Morogoro	35	-	-
All		801	542	551

1.4 Layout of the book

The rest of the book is structured as follows:

Chapter 2 gives background information on development of biomass and volume models. Specifically the chapter gives some historical background and then dwells in detail on the five basic steps in the development of biomass and volume models.

Chapter 3 is on biomass and volume models for the vast miombo woodlands in Tanzania. Both general and site-specific (AGB, BGB, twigs and branches) biomass models are presented. There are also general and site-specific volume models (total, branches and merchantable).

Chapter 4 provides models for predicting biomass of individual trees in lowland and humid montane forests (AGB, BGB, twigs and leaves, branches and stem). There are also models for predicting individual tree volume (total, branches and stem).

Chapter 5 presents general and species-specific models for AGB and BGB for three main mangrove species (*Avicennia marina*, *Rhizophora mucronata* and *Sonneratia alba*).

Chapter 6 focuses on AGB and BGB biomass models and total volume models for Itigi thickets of central Tanzania dominated by *Pseudoprosopi fischeri* and *Combretum celastroides.* Also models for associate trees species are presented.

Chapter 7 is on *Acacia-Commiphora* woodlands biomass and volume models. Site-specific (AGB and BGB) and general (AGB, BGB and stem) biomass models are presented. There are also general volume (total) and site-specific volume (total, branches and stem) models.

Chapter 8 is on general and site-specific allometric models for estimating biomass of *Pinus patula.* All models are for ABG, BGB, branches and stem components.

Chapter 9 describes models for predicting biomass and volume of *Tectona grandis.* Biomass models are given for AGB, BGB, stem, branches and twigs while volume models are for stem and total tree.

Chapter 10 is on biomass and volume allometric models for coconut trees (*Cocos nucifera*). The biomass models are for the components AGB, BGB and merchantable stem. Also total and merchantable stem volume models are presented.

Chapter 11 presents cashewnut tree (*Anacardium occidentale*) biomass and volume allometric models. Biomass models cover the components AGB, BGB and stem-branches. For volume, total volume models are given.

Chapter 12 is on biomass and volume models of baobab (*Adansonia digitata*). AGB biomass and total volume allometric models are presented.

Chapter 13 compares biomass and volume estimates for different vegetation types and forests obtained by applying models presented in this book with corresponding previously published estimates.

Finally, ***chapter 14*** is on concluding remarks.

1.5 References

Burgess, N.D., Damico H.J., Underwood, E., Dinerstein, E., Olson, D., Itoua, I., Schipper, J., Ricketts, T. and Newman, K. (2004). Terrestrial ecoregions of Africa and Madagascar: a continental assessment. Island Press, Washington DC. 150pp.

Brown, S. (1997). Estimating biomass change of tropical forests: primer. FAO Forestry Paper 134. FAO, Rome. 55pp.

Chave. J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Rie´ra, B. and Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87–99.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G. and Vieilledent, G. (2014). Improved pantropical allometric models to estimate the above ground biomass of tropical forests. Global Change Biology 20: 3177–3190.

IUCN. 2013. IUCN Red list of threatened species. Version 2013.01. IUCN, Gland. http://www.iucnredlist.org/.

Lamb, D., Erskine, P.D. and Parrotta, J.A. (2005). Restoration of degraded tropical landscapes. Science 310: 1628-1632.

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

URT (2001). National Forest Programme in Tanzania 2001 – 2010. Ministry of Natural Resources and Tourism, Dar es Salaam. 133pp.

URT (2005). Tanzania poverty and human development report 2005. Research and Analysis Working Group (R & AWG) of the Poverty Monitoring System. Government Printers, Dar es Salaam, Tanzania. 43pp.

Zahabu, E. (2008). Sinks and sources: A strategy to involve forest communities in Tanzania in global climate policy. University of Twente. 235pp.

2 BACKGROUND ON THE DEVELOPMENT OF BIOMASS AND VOLUME MODELS

Bollandsås, O.M., Zahabu, E. and Katani, J.Z.

2.1 History and approaches on the determination of biomass and volume

There are two main approaches to estimation of tree biomass. One is to obtain biomass as a product of tree volume and wood basic density. However, since most of the volume equations consider only the merchantable part of the tree, a biomass expansion factor that expands merchantable volume directly to total aboveground biomass is usually applied. The second approach is the direct use of biomass models.

The development of both biomass- and volume models have been based on relating easily measurable tree variables, such as diameter at breast height (dbh) and total tree height (ht), to biomass or volume. These variables are considered to be the most efficient input variables for tree level biomass and volume prediction (Brown, 1997; IPCC, 2003; Chave et al., 2014).

Global models have the advantage of being, in principle, applicable anywhere. However, due to great variation in climatic and edaphic factors, such models can yield large error locally. Thus, a model developed on data from a smaller region, will within that region give more accurate estimates. Similarly, a model developed generally for a large number of species is more versatile in the application phase, but will yield estimates with large errors for those species that are atypical relative to the mean relationship between the response and the input variables. A species specific model has a more narrow range of application, but will give better estimates for that particular species. A recent review of biomass and volume models for sub-Saharan African forests done by Henry et al. (2011) revealed that for tropical forests, a large number of species-specific and few general models existed. However, in Tanzania, development of biomass and volume models have been limited in terms of coverage of tree species, tree components, tree sizes and sample sizes (Temu, 1979; Malimbwi and Temu, 1984; Malimbwi, 1987; Malimbwi and Mbwambo, 1990; Malimbwi et al., 1994; Malimbwi et al., 1998; Chamshama et al., 2004; Munishi and Shear, 2004; Malimbwi et al., 2005).

In highly diverse ecosystems such as tropical forests, global models (Brown, 1997; Chave et al., 2005; Chave et al., 2014) have been applied in the absence of general- or species-specific local models. Species-specific models are generally more desirable. However, in a tropical natural forest with a large number of different species, developing species-specific models is almost impossible and consequently general models are the most appropriate

.

2.2 Basic steps in the development of allometric models

Several important issues need to be considered before developing allometric biomass and volume models (see for example Vanclay, 1994). First of all one should decide exactly for what purpose the model is needed for and what kind of results are expect from the model. This is then followed by a decision on what data is needed in order to develop a model that is in accordance with expectations and requirements. A consideration of the available resources for developing the model should also be done to enable planning and assessment of the magnitude of data collection. Already existing datasets could be supplementary to the final pool of data and should therefore be considered. However, it is important that sampling and measurement protocols are harmonized between the existing data and the planned data collection.

Both biomass and volume models are developed from empirical observations of sample trees. The response (biomass or volume) is accurately measured for each sample tree using destructive methods. Easily measurable variables such as dbh and ht are also recorded for each sample tree, and these measurements are later regressed against the response. This results into models that by means of easily measurable variables can predict biomass or volume.

The first consideration that has to be made in the model development process is to know the geographical extent and tree species for which the model will be applied. This is important because tree allometry varies with location, tree sizes and species. Thus, it is important to do the sampling so that the population ranges of these factors are covered when selecting sample trees for biomass and volume modelling. If these guidelines are followed, extrapolations in the model application phase are minimized. This is particularly important to avoid if the model has linear relationship between the response and the input variables.

Selection of sites and sample trees

As indicated above, the selection of sample trees should be carefully planned so that all tree species and size ranges are covered. However, in tropical forests where there are many tree species within small areas, a prioritization of species that are important to be sampled has to be done because of limited resources. Such a decision can either be made on the basis of how frequent different species are or how important different species are for various uses. Either way, information on the frequency and distribution of species is necessary to make this prioritization. A forest inventory of some kind prior to selection of sample trees is therefore required. If no local inventory has been carried out in the area of interest, sample plot information from the national forest inventory (NFI) can be used if it exists. If no prior information is available, a separate sample plot inventory should be carried out with plots systematically distributed throughout the area of interest. Diameter and species registration on each plot enables the establishment of both species and size range for the area of interest. Later, sample trees can be purposely selected for destructive sampling according to the species frequency and size range information. The selection of sample trees can be carried out as single observations over the area of interest. However, it is possible to plan which trees to sample before even going to the field if a plot inventory has already been carried out and the sample trees are selected among these trees. Additional plots can be established in-between the inventory plots for selection of additional sample trees if needed. Furthermore, selecting sample trees from plots where also information on the neighbouring trees is available enables calculation of stand variables, such as stand basal area, that can be included in the model single tree biomass or volume. Even if such variables are not directly included as an input variable in the final model, they can be informative with respect to giving insight to the accuracy assessment of the model, and with respect to learning for which forest conditions the model works particularly well.

The most important aspect when it comes to selection of sample trees is to cover the range of tree sizes, which is approximated from the prior inventory plot information. There will always be trees with more extreme sizes than those measured in sample plots, but extremely big trees will also occur quite rarely when the model later is applied. If there is a concern that the upper tail of the tree size distribution is underrepresented, additional extreme value observations can purposely be selected subsequent to the main sampling effort. The reason for this is that it is important to cover the size range in order to avoid extrapolations in the application phase. Using a model calibrated for small trees to do predictions for larger trees can result in large systematic errors.

Aboveground biomass and volume models

The development of biomass and volume models requires that the biomass or volume of each sample tree be measured accurately through destructive sampling procedures, even though terrestrial laser scanning can be used to build three dimensional models of trees which can be used to calculate volume of the different tree components. If information on wood basic density is also available, for example from a core sample, biomass can also be established. However, destructive sampling where the sample trees are felled and separated into different components (stem, branches, twigs and leaves) and further into billets, have so far been the most common way of establishing the observed biomass or volume. For the determination of aboveground biomass (AGB), each billet is weighed in the field immediately after cutting. The weights of billets from different tree components are summed up for each tree. To estimate the biomass of tree component, samples are then taken from each component of each tree, measured for fresh weight in the field and later taken to the laboratory for oven drying. Thereafter, each sample is once again weighed, followed by calculation of a dry to fresh weight ratio (DF-ratio). The biomass of each tree component is obtained by multiplying component specific DF-ratios with the corresponding fresh weight, while tree biomass is obtained by summing the biomass values of different tree components.

The determination of volume of sample trees is carried out as follows. The sample tree is divided into two main components namely merchantable stem and branches. Subsequently, these components are divided into billets and measured for length and mid diameter. Then, the cross sectional area is calculated and volume determined by multiplying with the length of the billet (Huber’s formula). It can be shown that this formula slightly underestimates the volume and that the under estimation increases with increasing section length. Sections should therefore be kept short, typically less than 1 m.

Belowground biomass models

The determination of belowground biomass (BGB) values basically follows the same procedures as for the AGB with regard to separation into different components (root crown, main roots and side roots) and with regard to determination of DF-ratios. However, there is a huge difference with regard to the resources needed to get the samples available for measurements because of the excavation need. Not only is the excavation work demanding in itself, but it can also be difficult to retrieve all of the root biomass from the ground. Thus, with a limited budged and if the goal is to get as much model accuracy out of that budget as possible, it may be more effective to do sampling of the BGB rather than doing an exhaustive excavation.

The sampling procedure indicated above can be carried out in the following way (see also Mugasha et al., 2013). First, the root crown is excavated and each root that starts from the root crown (main root) is cut at the base and diameter is measured. Three of the main roots, one small, one medium, and one large with respect to basal diameter are selected for excavation in full length. Side roots branching from the excavated main roots are also sampled in the same fashion. Other unexcavated main and side roots are measured for their basal diameters. The excavated root components are further processed in the same way as the aboveground components. First, the roots are weighed fresh in field and then samples are taken to the laboratory for oven drying and are subsequently weighed. Then DF-ratio is calculated for each root and multiplied with the corresponding fresh weight. However, as opposed to the aboveground procedures, models must be developed to predict the biomass of the roots that are not excavated and weighed. Models for the side root biomass are first developed. Such models cannot be made for each tree because the observations are too few, so they must be developed by species and/or within some geographical limits. The root basal diameters are regressed against the observed biomass of corresponding roots. The models are then applied to estimate the biomass of unexcavated roots. These side root biomass predictions are then added to the biomass of their respective main root to adjust for that the entire main roots were not excavated. Having established the total biomass of every main root, main root biomass models are developed. As for the side root model, also these models must be developed by species and/or geographical area. The main root models are then applied to the base diameters measured for non-excavated main roots. A sample is also taken from the root crown itself, and a DF-ratio is calculated and multiplied by fresh weight of the root crown. By summing the partly measured and partly estimated biomass of the different belowground components, BGB is obtained.

The advantage of carrying out this procedure as opposed to excavating every root in full is that more observations can be made available for the final development of the model for BGB. This ensures that more between-tree variation is covered in the data material and that more combinations between tree size and site factors are covered.

However, since the observed biomass values used as response in the modelling partly are results of model predictions, an error is imposed. This is an error that to some degree will draw the observed biomass towards the mean for a given tree size. But, if the modelling is sound, the only effect is that the criteria of model fit will seem a little bit better compared to if the sample were excavated in full.

The procedure described above, was used in several previous studies. Kuyah et al. (2012) for example, did not excavate roots that went deeper than 2 m below the ground surface. Instead diameters were measured and the weight estimated by regression equations. Later the estimated weights were added to the observed biomass and BGB models were developed. Similarly in Niiyama et al. (2010) (Illustration Pg. 275), the stump was pulled from the ground and a lot of roots were broken. The weights of broken roots were estimated using similar approach as described above and finally estimated and observed biomass was added together and a model for BGB was developed.

Model form selection, fitting, selection and evaluation

Model is a general term that means simplification of reality. The allometric models that are the topic of the current book are simplifications in the sense that they yield approximations of the true biomass and volume with the use of measurements of dbh and ht. These are direct, easy to obtain, measurements of tree size, and they correlate quite closely to both biomass and volume. An empirical, statistical relationship between biomass or volume and the input variables, dbh and ht, can then be fitted using regression analysis. This estimates parameter coefficients for the input variables so that the residual errors between fitted values and the corresponding observed response values are minimized. Equation 1 displays a linear model form. This is a simple model where the response (Y) is linearly dependent on the input variables (dbh and ht) through constants β_1 and β_2, and an intercept term, β_0.

$$\mathrm{Y} = \beta_0 + \beta_1 \times \mathrm{dbh} + \beta_2 \times \mathrm{ht} \qquad (1)$$

However, the relationship between dbh and/or ht and biomass and/or volume is not linear. For some tree species, or for parts of a diameter range, the relationship may be close to linear, but in most cases a model need to have the capability to describe non-linear patterns between the response and measurements that are taken in the field. This does not mean that the model form displayed in Equation 1, cannot be used. Linear regression (e.g. Montgomery et al., 2001) is easy to use, and the ordinary least square estimation of the parameter coefficients, always ensures that the best solution is obtained. Thus, if the relationship between the measurements of dbh and ht are non-linear to biomass or volume, transformations of dbh and ht can be carried out. Potential transformations could be for example square, square root or logarithmic. Equation 2 shows an example of a model where the response is linearly dependent on square transformations of dbh and ht. A square transformation of dbh is equivalent to using basal area as input variable.

$$\mathrm{Y} = \beta_0 + \beta_1 \times \mathrm{dbh}^2 + \beta_2 \times \mathrm{ht}^2 \qquad (2)$$

Interaction terms can also be used. Products of dbh and ht or even products of transformations of dbh and ht can sometimes prove to be good input variables. Equation 3 shows an example where the response is linearly dependent to dbh and ht and an interaction term between dbh and ht.

$$Y = \beta_0 + \beta_1 \times \mathrm{dbh} + \beta_2 \times \mathrm{ht} + \beta_3 \times \mathrm{dbh} \times \mathrm{ht} \tag{3}$$

However, in many cases a linear model is not sufficient to represent the relationship between response and the input variables. Non-linear functional forms are more flexible than linear models and there are many that have been used previously. Equation 4 gives an example of a multiplicative model where the parameter coefficient estimates can be determined by a non-linear regression technique. This particular model could actually be fitted on linear form by logarithmic transformation of both response and input variables, but this will introduce the need for correcting bias introduced when transforming the response. However, many non-linear functional forms are not possible to fit linearly through transformation.

$$Y = \beta_0 \times \mathrm{dbh}^{\beta_1} \times \mathrm{ht}^{\beta_2} \tag{4}$$

Fitting of non-linear models requires more knowledge and skills compared to fitting of linear models. The parameter coefficients are estimated through some iteration procedure based on, for example, minimizing of root mean square error (RMSE). Basically non-linear regression procedures start with some values (random or pre-selected) for the parameter coefficients and then they are changed. Subsequent to each change, a goodness-of-fit criterion is evaluated and it is decided if the change made the model better or worse. The changing of parameters is carried out until a marginal change does not improve the goodness of fit criterion any more. However, for some non-linear functional forms, there exist many combinations of parameter coefficients that give local solutions where the goodness-of-fit criterion changes to worse in any direction. Thus, it is therefore important to use a range of different starting values for the parameter coefficients to ensure that the best solution is the global one.

If the modelling data originate from field plots, where several sample trees are selected from each plot, trees within the same plot will tend to be similar in terms of allometry since they have the same growing conditions. This is a challenge to the modelling, since observations that originate from a particular plot will have similar effect on the model. For example, if the number of sample trees varies between plots, those plots where many trees were sampled will have large impact on the model. This means that the growing conditions on plots with many sampled trees will be over represented. In the modelling this can be dealt with by allowing for random effects in the model to account for that the observations were sampled in clusters where observations are correlated. Such models are called mixed effects models and they treat the different hierarchical levels specified by the modeller as different populations. The model parameters are affected by the choice of modelling technique and it may also alter which input variables that are statistically significant.

There are always assumptions related to every modelling technique and if these assumptions are not fulfilled, the resulting model may perform badly in the application phase. Thus a careful check of the assumptions should always be carried out. An example is the assumption that the variance of the residual error should be homoscedastic (equal). In those cases where it is not homoscedastic, a variance function can be applied in the fitting of the model, see for example Mugasha et al. (2013).

In order to select which model form to use, a lot of initial scrutiny of the data should be done. First, graphical plots of the relationship between the response and the input variables should be made. Such plots will easily give the researcher an impression of the relationships investigated. Similar plots with transformed variables should also be made to see if there might be linear relationships on transformed scale. Different alternative models should also be fitted, both linear and non-linear, and assess which form fits best to the data. To be able to compare the models, common criteria for evaluation must be used. One option could be to do a leave-one-out cross validation of all alternative models and compare RMSE and mean prediction error (MPE). Graphical plots of the residuals are also useful, especially related to the selection between a linear and non-linear model. The distribution of the residuals will reveal in many cases quite clearly if a linear model form does not fit the data at hand.

When models for large areas say countries are developed, considerations about stratification have to be made. More specifically, the relationships between response and input variables may change with factors that are known. Forest type, climate and soil type are examples of such factors, and the model developer must consider if stratified models should be chosen over models fitted for the entire dataset. A model fitted on data soundly stratified will fit better to the data compared to a common model because the stratification itself will explain parts of the variation in the response. The downsides are that the model will be based on fewer observations, and that the stratification information must be available also in application phase.

Evaluations of the final models are carried out like the evaluation of alternative models explained above. A cross validation and calculation of RMSE will give an indication of the expected error that will occur when the model is applied. For linear model, it is common to report the coefficient of determination (R^2), which expresses the proportion of variance of the response that is explained by the input variables. For non-linear models, a pseudo-R^2 can be computed from the residuals. Both of these enable comparisons between the goodness-of-fit for different models. For non-linear models, there are many more criteria indicating goodness of fit, such as the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) that enable selection between alternative models. Before models are finally selected, the model behaviour outside the range of the data material should also be tested. In the application phase, there will be certain situations when the models are applied to much larger trees than those sampled in the calibration dataset. It is therefore of interest to push the model beyond this limit by applying it to a diameter range that goes towards values that can be considered as what is maximum.

Documentation of data, model fit and model application

Documentation of both data material and models is important so that the user is able to apply the model within its ranges of validity so that the user also is informed of the expected accuracy of the model. This section will only briefly describe the documentation requirements and for further elaboration and details the reader is referred to Jara et al. (2015) which provides an excellent compilation of guidelines for documentation of allometric equations.

The location from which dataset used for model development is collected, need to be clearly reported since it defines the core area for which the model can be used. A simple way of providing this information is to give the coordinates of the outer edges and/or refer to location names in addition to a map displaying the origin of the data. Further information about the location like elevation, climate (average precipitation, mean temperatures), soil types and landscape characteristics are very useful.

Furthermore, the documentation must include information on definitions of the response values. This means that for each tree component for which biomass or volume is modelled must be clearly defined. For example, does the AGB include the stump or not and what is the cut-off diameter between stem and branches? Moreover, it is essential to report the units of measurement for both the response and input variables (kilogramme vs tonne, cm vs mm, m^3 vs dm^3). If not it will be difficult for the users to interpret the results from the models.

The sampling scheme and the samples themselves must also be described. Which were the criteria for selecting the different sample sites? How were the sample trees selected within sites? Information on the distribution of tree species and tree sizes is also essential, because it enables the user of the model to disclose where the models might be more prone to yield errors. Both scientific and local species names should be reported.

Preparation of the sample trees and subsequent measurements are important to document. For biomass models this includes the cutting into billets and the weighing in field. How large were the billets and what was the accuracy of the scale used in field? The number of samples taken from each tree component for drying in the laboratory must also be disclosed.

Documentation of the modelling is also important to give information on how trustworthy the models are. As a minimum, the model fit as described by R^2, RMSE and MPE should be reported together with the functional form of the model and a table with all parameter coefficients. A leave-one-out cross validation of the model could also add useful documentation of the model accuracy.

Lastly, recommendations on the use of the model should also be included in the model documentation. This will ensure that the models are appropriately applied.

2.3 References

Brown, S. (1997). Estimating biomass change of tropical forests: Primer. FAO Forestry Paper 134, Rome, Italy. 15pp.

Chamshama, S.A.O., Mugasha, A.G. and Zahabu, E. (2004). Biomass and volume estimation for miombo woodlands at Kitulangalo, Morogoro, Tanzania. Southern Forests 200: 49-60.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riera, B. and Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145: 87–99.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G. and Vieilledent, G. (2014). Improved pantropical allometric models to estimate the above ground biomass of tropical forests. Global Change Biology 20: 3177–3190.

Henry, M., Picard, N., Trotta, C., Manlay, R.J., Valentini, R., Bernoux, M. and Saint-André, L. (2011). Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. Silva Fennica 45: 477–569.

IPCC (2003). Good practice guidance for land use, land-use changes and forestry. Institute of Global Environmental Strategies, Kanagawa, Japan. 420pp.

Jara, M.C., Henry, M., Réjou-Méchain, M., Wayson, C., Zapata-Cuartas, M. and Piotto, D. (2015). Guidelines for documenting and reporting tree allometric equations. Annals of Forest Science 72: 763–768.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R. and Neufeldt, H. (2012). Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. Agriculture, Ecosystems & Environment 158: 225–234.

Malimbwi, R.E. and Temu, A.B. (1984). Volume functions for *Pterocarpus angolensis* and *Julbernadia globiflora*. Journal of the Tanzania Association of Foresters 1: 49–53.

Malimbwi, R.E., Solberg, B. and Luoga, E. (1994). Estimation of biomass and volume in miombo woodland at Kitulangalo Forest Reserve, Tanzania. Journal of Tropical Forest Science 7(2): 230–242.

Malimbwi, R.E, Zahabu, E, Madadi, L.M, Monela, G.C., Misana, S. and Jambiya, G.C. (2005). Tree species preference, volume estimation and charcoal kiln efficiencies in eastern Tanzania miombo woodlands. In: Proceedings of the Tanzania Association of Foresters meeting held at Morogoro Hotel, October 2004. pp 27-31.

Malimbwi, R.E. and Mbwambo, Z. (1990). Local volume tables for *Eucalyptus grandis* at Sao Hill Forest Project. Faculty of Forestry, Sokoine University of Agriculture. Record No 45.

Malimbwi, R.E., Mugasha, A.G. and Zahabu, E. (1998). Yield tables for *Pinus patula* at Sao Hill Forest Plantations, Southern Tanzania. FORCONSULT Faculty of Forestry & Nature Conservation, Sokoine University of Agriculture. 41pp.

Mugasha, W.A., Eid, T., Bollandsås, O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J.Z. (2013). Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecology and Management 310: 87–101.

Munishi, P.K.T. and Shear, T.H. (2004). Carbon storage in afro-montane rainforests of the Eastern Arc Mountains of Tanzania: their net contribution to atmospheric carbon. Journal of Tropical Forest Science 16: 78–93.

Niiyama, K., Kajimoto, T., Matsuura, Y., Yamashita, T., Matsuo, N., Yashiro, Y., Ripin, A., Kassim, A.R. and Noor, N.S. (2010). Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. Journal of Tropical Ecology 26: 271–284.

Temu, A.B. (1979). Estimation of millable timber volume in miombo woodlands. University of Dar es Salaam, Division of Forestry Record No. 7. 11pp.

Vanclay, J. (1994). Modelling forest growth and yield: Applications to mixed tropical forests. CABI, Wallingford UK. 312pp.

3 ALLOMETRIC BIOMASS AND VOLUME MODELS FOR MIOMBO WOODLANDS

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3.1 Background

Miombo woodlands cover large areas in south-eastern and central Africa and form the dominant forest type in Angola, Zambia, Zimbabwe, Mozambique, Botswana, Malawi and Tanzania. Miombo woodlands are multi-species and multi-layered and are regenerated both through coppicing and seed dispersal. The distinguishing feature of miombo woodlands from other woodlands is the existence of dominant tree species belonging to main genera like *Brachystegia, Julbernardia* and/or *Isoberlinia* (e.g. Frost, 1996).

The species richness varies significantly with location. In Tanzania, the number of tree species in miombo woodlands exceeds 100 (e.g. Giliba et al., 2011; Mugasha et al., 2013a). The structure of miombo woodlands may also vary significantly. This is attributed to different growing conditions in terms of soil and climate, to wildfires and to wildlife and anthropogenic activities. Often miombo woodlands are found on poor soils, i.e. on acid soils with low nitrogen content. Moreover, many tree species have established specialized survival mechanisms. For example, the most dominant tree species are equipped with ectomycorrhizae, which increase their probability of survival on poor soils. In addition, leaves often shed prior to the dry season to conserve water and some species have thick bark to protect them from fire (Frost, 1996). Miombo woodlands support the livelihood of a large number of people in rural and urban areas through provision of products like charcoal, firewood, poles, timber, medicine, withies, food and carving material. Indirect benefits associated with miombo woodlands include environment services such as water catchment, biodiversity and carbon sequestration.

Recent results from the National Forest Resources Monitoring and Assessment of Tanzania (NAFORMA) show that woodlands, which mostly comprise miombo woodlands, occupy about 44.7 million hectares (ha), which is about 51% of the total land area (MNRT, 2015). This is equivalent to about 93% of the total forest area of the country. Although the average volume is low (55.1 m^3 ha^{-1}), miombo woodlands account for about 74% of the total growing stock (3.3 billion m^3). The rate of deforestation in Tanzania is one of the highest in Africa and has been estimated to be about 373,000 ha annually, corresponding to 0.78% of the areas of woodlands and forests (MNRT, 2015), and miombo woodlands is the most vulnerable vegetation type.

Aboveground biomass (AGB) models developed by Malimbwi et al. (1994) and Chamshama et al. (2004) have previously been applied to miombo woodlands throughout the country. Both these studies used sample trees from only one site in Morogoro region. Given differences regarding climate, soil and topography, their application to other miombo woodlands in Tanzania is questionable. A number of other shortcomings are also pertinent to these models, i.e. they are developed from small samples, narrow diameter ranges and partly they do not include twigs and/or branches. This means that the models often have been applied beyond their valid data ranges. Similar shortcomings are also pertinent to the only previously developed belowground biomass (BGB) model (Malimbwi et al., 1994) and for all the previously developed volume models (Malimbwi and Temu, 1984; Malimbwi et al., 1994; Chamshama et al., 2004).

The aim of this chapter is to describe recently developed biomass and volume models for miombo woodlands in Tanzania. The models comprise general and site-specific models predicting biomass and volume of different components of individual trees. The described models are published by Mugasha et al. (2013b) and Mauya et al. (2014).

3.2 Site description

The data for development of biomass and volume models were collected in Manyara, Lindi, Katavi and Tabora. The four study sites are spatially distributed in order to cover wide ranges of forest conditions within the miombo woodlands of Tanzania. The dominant soil types in Manyara, Lindi, Katavi and Tabora are clay alluvial soils, sandy loam soils, sandy clay soils and sandy clay loam soils respectively. The altitudes ranged between 1,300 and 1,800 m in Manyara, 330 and 600 m in Lindi, 755 and 766 m in Katavi and 1,096 and 1,103 m in Tabora. The sites are characterised by tropical climate with high between-site and temporal within-site variability in temperature and rainfall. Details on locations and climate conditions for the sites are described in Table 3.1.

Table 3.1. Study sites description

Region	**Forest Reserve**	**Location**	**Mean annual temperature (^{0}C)**		**Mean annual rainfall (mm)**
			Min.	**Max.**	
Manyara	Ayasanda and Duru Haitemba	4^0 20’ S, 35^0 47’ E	15	26	854
Lindi	Angai	9^0 47’ S , 37^0 55’ E	20	31	800
Katavi	Mpanda Ndogo	6^0 21’ S, 30^0 57’ E	17	31	881
Tabora	Nyahua	5^0 18’ S, 32^0 58’ E	17	30	771

Source for temperature and rainfall: Tanzania Meteorological Agency, data 1982-2012.

3.3 Data collection and analysis

Selection of sample trees

To obtain information on actual tree species- and size distribution for guiding in the selection of sample trees, advantage was taken of prior systematic sample plot inventories (40 plots with radii of 15 m for each site). Also in the tree selection phase, sample plots of 15 m radius were systematically distributed in each site and in each of these plots, one or two trees were selected for destructive sampling. As tree selection proceeded, the distribution of trees against the target distribution from the prior inventories were evaluated in order to end up with approximately the same distributions with respect to the most frequent tree species and tree sizes.

Before felling, each sample tree was recorded for diameter at breast height (dbh) and total tree height (ht). In addition, tree species were identified. A calliper or a diameter tape (for larger trees) was used to measure dbh, while ht was measured using Suunto- and Vertex hypsometers.

For the AGB models, 40, 47, 40 and 40 trees were selected for Manyara, Lindi, Katavi and Tabora respectively (Table 3.2). Twenty of these trees for each site were selected for excavation of BGB). In total for all sites, 60 different tree species were sampled while the respective numbers for Manyara, Lindi, Katavi and Tabora were 11, 21, 18 and 30.

The same trees were also used to develop volume models, except for eight trees in Lindi with no was no data because the procedure of data collection for volume determination was decided after starting the biomass sampling and one tree in Manyara with inappropriate volume data. A total of 158 trees were therefore included in the development of volume models (Table 3.2).

Destructive sampling and biomass determination

The trees selected for biomass determination were first divided into above- and belowground components. The aboveground component comprised of all biomass above a stump height of 30 cm, except leaves. The aboveground component was further divided into the three components merchantable stem, branches and twigs. The following definitions apply to above- and belowground components when the biomass models were developed:

- Merchantable stem applies only to trees with dbh $\geq$10 cm. No specific minimum diameter was set to distinguish between merchantable stem biomass and branches biomass of trees. Rather, the decision was a subjective judgment based on how much of the stem that could be used to produce timber when considering the length and branching patterns of the stem. For trees with dbh <10 cm, no merchantable stem part was considered and the biomass was allocated to branches and twigs according to the below definitions.

- Branches include all branches (also stems not defined as merchantable) with diameter ≥ 2.5 cm.
- Twigs include those parts of the branches with diameter <2.5 cm. Leaves were excluded from twigs and thus not included in the modelling.
- The belowground component comprised of all biomass in stump (30 cm above ground), root crown and roots with diameter ≥1 cm.

Table 3.2. Summary statistics of sample trees used for developing biomass and volume models

Component	Site	n	dbh (cm)			ht (m)		
			Mean	Min.	Max.	Mean	Min.	Max.
AGB	Manyara	40	35.5	1.7	78.0	11.3	2.7	19.5
	Lindi	47	35.1	1.1	110.0	13.6	1.9	27.5
	Katavi	40	36.2	3.5	79.0	12.9	3.3	26.0
	Tabora	40	32.1	1.2	95.0	12.7	1.9	26.0
	All	167	34.7	1.1	110.0	12.7	1.9	27.5
BGB	Manyara	20	30.1	3.3	78.0	10.8	3.4	18.7
	Lindi	20	32.8	6.4	80.0	13.0	3.5	20.1
	Katavi	20	33.2	8.0	64.0	12.2	5.0	18.8
	Tabora	20	41.7	10.0	95.0	15.3	6.0	26.0
	All	80	34.5	3.3	95.0	12.8	3.4	18.7
Volume	Manyara	39	36.3	3.3	78.0	11.5	2.7	19.5
	Lindi	39	30.6	3.5	76.2	13.0	3.3	24.0
	Katavi	40	36.1	3.5	79.0	12.9	3.3	26.0
	Tabora	40	32.1	1.2	95.0	12.7	1.9	26.0
	All	158	33.8	1.2	95.0	12.5	1.9	26.0

The determination of BGB was based on a root sampling procedure where three main sample roots originating from the root crown and three side sample roots originating from the main root were selected for each tree. Based on these sampled main and side roots, models predicting biomass of main and side roots were developed and subsequently applied on those part of the root system not excavated (for details, see Mugasha et al. 2013b).

All above- and belowground components of the trees were weighed in the field. Sub-samples were taken from all tree components, weighed and then brought to laboratory for drying. Dry weights of all sub-samples were then determined and tree- and component-specific dry to fresh weight ratios (DF-ratios) were computed. Dry weights for the tree components were determined by multiplying tree- and component-specific DF-ratios with the respective fresh weights determined in field. Finally, AGB and BGB of individual trees were found by summing their respective components. Scatter plots of AGB and BGB versus dbh for individual trees are displayed in Figures 3.1 and 3.2.

The trees selected for volume determination were divided into the three components merchantable stem, branches and total volumes according to the following definitions:

- Merchantable stem apply only to trees with dbh ≥15 cm (note that the dbh requirement for merchantable stem volume is different from that of biomass). No specific minimum diameter was set to distinguish between merchantable stem volume and branches volume. Rather, the decision was a subjective judgment based on how much of the stem that could be used to produce timber when considering the length and branching patterns of the stem.
- Branches include all branches (also stems not defined as merchantable) with diameter ≥ 2.5 cm.
- Total volume include both merchantable stem and branches volumes.

The volume of individual logs from the destructive sampling was calculated using Huber's formula. The volume of merchantable stem and branches for a tree was obtained by summing the volumes of the logs of the respective components for that specific tree. Total tree volume was finally obtained by summing merchantable stem and branches volumes. Table 3.3 shows summary statistics of merchantable stem, branches and total volume. Scatter plots of total volume versus dbh for individual trees are displayed in Figure 3.3.

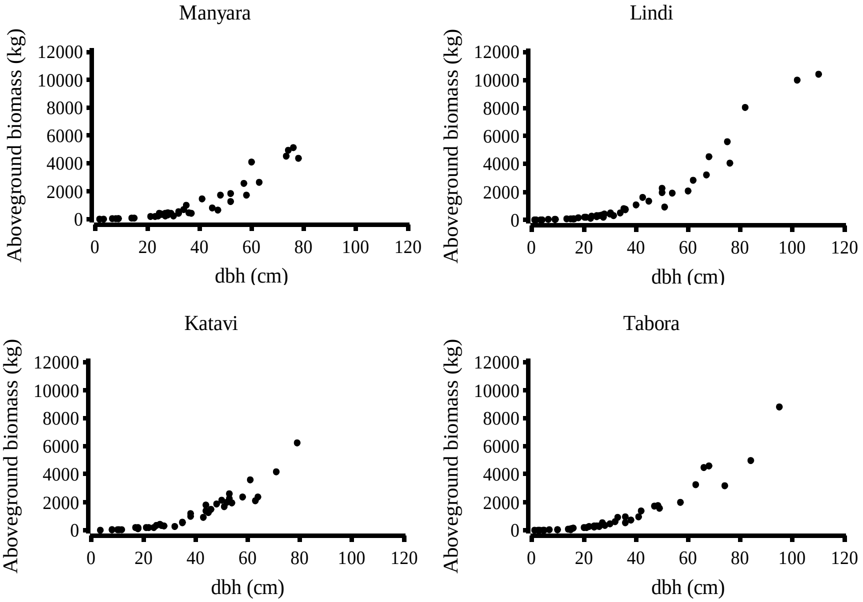

Figure 3.1. Scatter plots of AGB versus dbh for the four sites

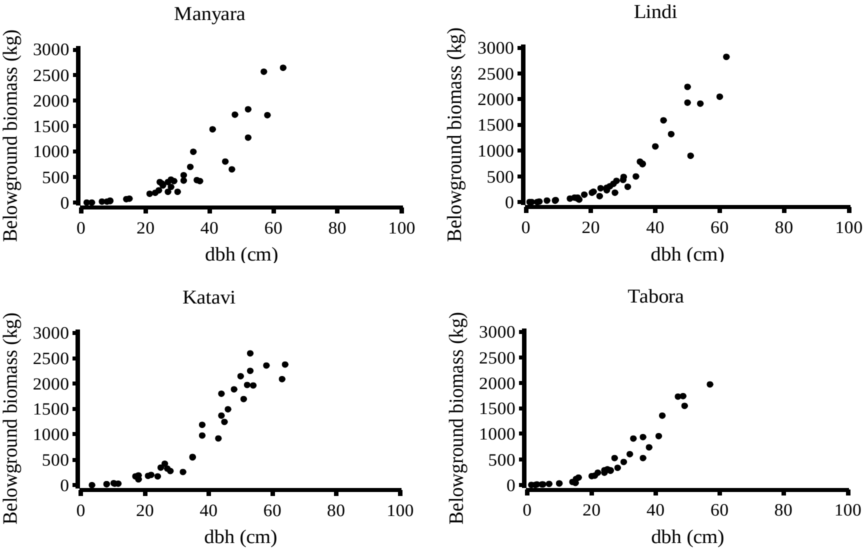

Figure 3.2. Scatter plots of BGB versus dbh for the four sites

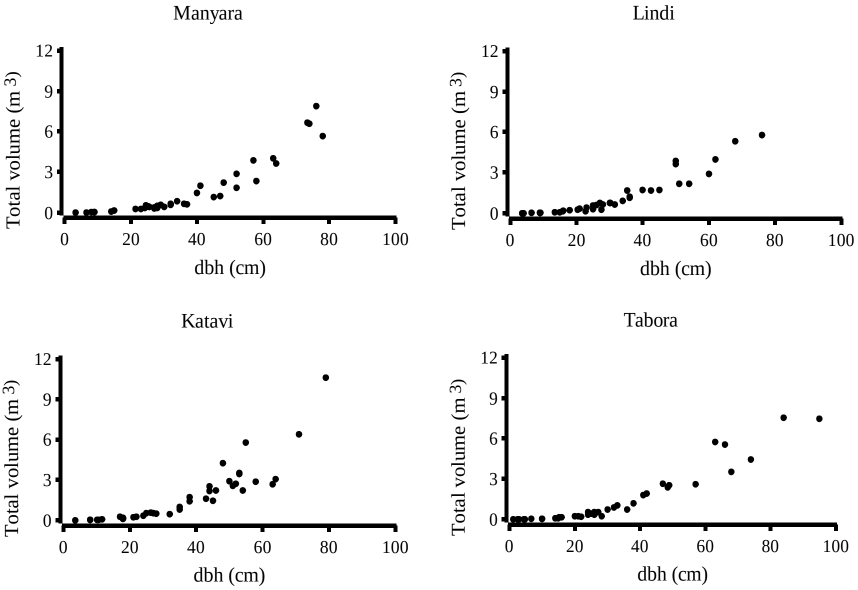

Figure 3.3. Scatter plots of total volume versus dbh for the four sites

Table 3.3. Summary statistics for merchantable stem, branches and total volume (m^3) over sites

Site	Merchantable stem				Branches				Total			
	n	**Mean**	**Min.**	**Max.**	**n**	**Mean**	**Min.**	**Max.**	**n**	**Mean**	**Min.**	**Max.**
Manyara	33	0.378	0.049	1.577	39	1.261	0.002	7.038	39	1.580	0.002	7.872
Lindi	32	0.384	0.040	1.849	39	0.893	0.002	4.210	39	1.208	0.002	5.794
Katavi	34	0.670	0.035	3.080	40	1.233	0.002	7.517	40	1.802	0.002	10.597
Tabora	31	0.571	0.281	2.687	40	1.003	0.000	5.189	40	1.445	0.000	7.531
All	130	0.501	0.028	3.080	158	1.097	0.000	7.517	158	1.511	0.000	10.597

Working conditions and resources required

Working conditions varied from one site to another. Distance and terrain conditions from the road to the working sites in the forest had impact on time consumption, since a significant quantity of different equipment had to be delivered. Terrain conditions also had an impact on the amount of work required at the specific working area. For example, it was very demanding when gathering billets in steep terrain compared to flat terrain. The workload also depended on the size of trees. In dense forest, hang up trees was the main challenge. For the belowground component excavation, variations in soil texture were a major challenge. It was for example easier to excavate the belowground components in the sandy soils of Lindi and Katavi compared to the rocky soils in Manyara and clay loamy soils in Tabora.

The composition of the crew varied with tree sizes and tree components (i.e. belowground and aboveground). To improve efficiency, each tree component had specific crew. Allocation of people to different tasks to some extent depended on their routine work in the village. For example, charcoal makers and those involved in constructing earth roads in the villages were assigned to work for the belowground tree component (excavation). The majority of the work did not require any specific background. However, close supervision by the researchers was mandatory to ensure quality and safety. The crew for the belowground component comprised of a minimum of four persons and up to ten depending on the size of the tree. The number of crews depended on the number of researchers present. For the miombo woodlands, three crews were used most of the time; one for the belowground and two for the aboveground component.

Equipment used during the sampling included callipers for dbh and root diameter measurements and Suunto or Vertex hypsometer for ht measurements. Tapes were used for measuring length of billets, machetes to cut off small branches, a chainsaw to fell trees and cut stems and large branches. Hoes, spades and mattocks were used for excavation while iron brushes were used to remove soils from roots. A spring balance was used to weigh billets and branches while an electronic balance was used to weigh sub-samples.

Table 3.4 shows cost estimates per day and per tree for destructive sampling. For the aboveground component, usually two crews each with six people were involved while for the belowground component one crew with eight people were involved. For processing aboveground components, each crew member was paid TZS 20,000 per day. Number of trees processed per day for the aboveground component ranged between two and four depending on their sizes. In Table 3.4, it is assumed that two trees with a dbh of 40 cm are processed per day. For the belowground component, one to two trees were processed per day depending on their sizes. In Table 3.4 it is assumed that one tree with a dbh of 40 cm are processed per day. The cost per tree for the belowground component was a function of dbh, i.e. TZS 3,000 for one unit in dbh (1 cm), meaning that the total labour cost of a tree with a dbh of 40 cm are TZS 120,000.

The three crews in total consumed one chainsaw chain, five litres of fuel and two litres oil per day. The costs related to these items were split equally between the aboveground and belowground components. The total cost per day for food was TZS 22,000. These costs were split between the aboveground and belowground components according to the number of persons involved in the crews. In total, the costs per tree were TZS 147,350 and TZS 170,300 respectively for the aboveground and the belowground components.

Table 3.4 does not include costs such as per diems for researcher and research assistant, transport and equipment. The costs of equipment used include the following: two spring balances (TZS 200,000), one chainsaw machine (TZS 1,600,000), five hoes (TZS 30,000), five spades (TZS 30,000), four mattocks (TZS 40,000), three iron brushes (TZS 9,000), ropes (TZS 20,000) and three bush knives (TZS 36,000).

Model fitting and evaluation

Four model forms were tested for biomass. Two of the model forms included dbh only and the other two included dbh and ht as independent variables:

$$\mathrm{B} = \beta_0 + \beta_1 \times \mathrm{dbh} + \beta_2 \times \mathrm{dbh}^2 \qquad (1)$$
$$\mathrm{B} = \beta_0 \times \mathrm{dbh}^{\beta_1} \qquad (2)$$
$$\mathrm{B} = \beta_0 \times \mathrm{dbh}^{\beta_1} \times \mathrm{ht}^{\beta_2} \qquad (3)$$
$$\mathrm{B} = \exp[\beta_0 + \beta_1 \times (\mathrm{ht} \times \mathrm{dbh}^2)] \qquad (4)$$

where B is biomass (kg) and β_0, β_1, and β_2 are model parameters.

The NLP procedure (Non Linear Programming) in SAS software (SAS® Institute Inc., 2004) was used to estimate the model parameters (β_0, β_1, and β_2). The procedure produces the least squares estimates of the parameters of a nonlinear model through an iteration process. The procedure fits both model parameters and variance parameters (variance = $(a \times \mathrm{dbh}^b)^2$, where a and b are parameters) simultaneously.

The selection of final models was in general based on the Akaike Information Criterion (AIC). AIC takes into account the number of parameters in the models and penalize them accordingly. However, if a model had insignificant parameter estimates, it was not considered further. The coefficient of determination (R^2) and Root Mean Squared Error (RMSE) were reported for all models. In addition, relative mean prediction error was reported as:

$$\mathrm{MPE}\ (\%) = \frac{100}{\mathrm{MB}} \times \sum\left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass or volume), and MB is mean observed biomass or volume.

Table 3.4. Cost estimates for destructive sampling

Item	Aboveground				Belowground			
	Description	**Units**	**Unit cost (TZS)***	**Total cost (TZS)**	**Description**	**Units**	**Unit cost (TZS)**	**Total cost (TZS)**
Labour	Two crews (12 persons)	12	20,000	240,000	One crew (8 persons)	40	3,000	120,000
Chainsaw chain	Number per day	½	45,000	22,500	Number per day	½	45,000	22,500
Fuel chainsaw	Litres per day	2.5	2,000	5,000	Litres per day	2.5	2,000	5,000
Oil chainsaw chain	Litres per day	1	14,000	14,000	Litres per day	1	14,000	14,000
Food	Persons per day	12	1,100	13,200	Persons per day	8	1,100	8,800
Total cost per day				**294,700**				**170,300**
Cost per tree				**147,350**				**170,300**

* Exchange rate: 1 US$ = TZS 2,100

Four model forms were tested for volume, two forms included dbh only and the other two forms included both dbh and ht as independent variables:

$$V = \beta_0 + \beta_1 \times (dbh)^2 \quad (5)$$
$$V = \beta_0 \times (dbh)^{\beta_1} \quad (6)$$
$$V = \beta_0 \times (dbh)^{\beta_1} \times (h)^{\beta_2} \quad (7)$$
$$V = \beta_0 \times (dbh^2 \times h)^{\beta_1} \quad (8)$$

where V is volume (m^3) and β_0, β_1 and β_2 are model parameters.

Ordinary least square methods were applied when fitting model form 1 while non-linear least square methods using nlstools package in R software (R Development Core Team 2013) were applied when fitting model forms 2-4.

The selection of final models were based on relative Root Mean Square Error (RMSE %) and mean prediction error (MPE %) calculated from a leave-one-out cross validation procedure. Pseudo-R^2 values were reported for all selected models.

3.4 Biomass and volume models

For all general models predicting biomass, i.e. total aboveground, belowground and the aboveground tree components twigs, branches and merchantable stem, there are two options: 1) with dbh only and 2) with both dbh and ht as independent variables (Table 3.5). For all the site-specific models predicting AGB and BGB there are also two options: 1) with dbh only and 2) with both dbh and ht as independent variables (Table 3.6).

For the general models predicting total volume there are two options: 1) with dbh only and 2) with both dbh and ht as independent variables (Table 3.7). General models predicting branches and merchantable stem volumes utilized dbh only as independent variable (Table 3.7).

For the site-specific models predicting total volume there are two options: 1) with dbh only and 2) with both dbh and ht as independent variables (Table 3.8). The site-specific models predicting branches and merchantable stem volume utilized dbh only as independent variable (Table 3.8). The different tree components are defined in Chapter 3.3.

3.5 Application recommendations

The presented models for prediction of biomass and volume in miombo woodlands cover wide ranges of conditions regarding climate, topography and soil, tree sizes (dbh up to 110 cm and 95 cm for the biomass and volume models respectively) and tree species (60). All the general models can therefore be applied for most miombo woodlands in Tanzania with an appropriate accuracy in predictions. It is recommended that site-specific models are applied for local inventories in their respective sites.

Alternative models for predicting biomass and volume are presented: 1) with dbh only and 2) with both dbh and ht as independent variables. Both alternatives can be applied with a reasonable certainty provided that appropriate information on ht is available. However, since including ht only marginally increased the explanation of the biomass and volume variations in the modelling data, care should be taken when obtaining ht information. An adequate sample of trees (number of observations, species- and size ranges) to develop local dbh-ht relationship models is needed and potential challenges in height measurements related to rounded crowns frequently occurring in miombo woodlands and to difficult terrain should carefully be considered. It is also recommended to use models with both dbh and ht in predictions for very large trees (dbh >150 cm) because ht moderates the effect of dbh on biomass and volume predictions as compared to if dbh only is applied.

The recommendations given above also generally apply to the tree component biomass and volume models (twigs, branches and merchantable stem). The definitions of each component described in Chapter 3.3 should be carefully considered when applying these models.

Table 3.5. General biomass models for miombo woodlands

Component	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	MI_MM_AGB_1	$B = 0.1027 \times dbh^{2.4798}$	167	411.5	0.95	1.6
	MI_MM_AGB_2	$B = 0.0763 \times dbh^{2.2046} \times ht^{0.4918}$	167	374.0	0.96	0.9
BGB	MI_MM_BGB_1	$B = 0.2113 \times dbh^{1.9838}$	80	107.5	0.92	2.6
	MI_MM_BGB_2	$B = 0.1766 \times dbh^{1.7844} \times ht^{0.3434}$	80	105.5	0.92	2.4
Twigs	MI_MM_TB_1	$B = 0.1778 \times dbh^{1.8120}$	162	124.9	0.68	-4.8
	MI_MM_TB_2	$B = 0.1540 \times dbh^{1.6688} \times ht^{0.2521}$	162	123.1	0.69	-4.5
Branches	MI_MM_BB_1	$B = 0.0393 \times dbh^{2.6268}$	139	438.3	0.80	1.7
	MI_MM_BB_2	$B = 0.0300 \times dbh^{2.3974} \times ht^{0.4132}$	139	432.7	0.80	1.9
Merchantable stem	MI_MM_MSB_1	$B = 0.0535 \times dbh^{2.3099}$	139	194.1	0.74	1.2
	MI_MM_MSB_2	$B = 0.0291 \times dbh^{1.8384} \times ht^{0.8790}$	139	180.0	0.78	2.0

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 3.6. Site-specific biomass models for miombo woodlands

Component	Site	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	Manyara	MI-MS1_AGB_1	$B = 0.1603 \times dbh^{2.3396}$	40	386.0	0.93	8.8
	Manyara	MI-MS1_AGB_2	$B = 0.1080 \times dbh^{1.9936} \times ht^{0.6628}$	40	328.0	0.95	4.1
	Lindi	MI-MS2_AGB_1	$B = 0.0981 \times dbh^{2.4897}$	47	511.1	0.96	1.9
	Lindi	MI-MS2_AGB_2	$B = 0.0669 \times dbh^{2.2770} \times ht^{0.4253}$	40	475.5	0.96	0.8
	Katavi	MI-MS3_AGB_1	$B = 0.0739 \times dbh^{2.5764}$	40	332.9	0.94	-0.4
	Katavi	MI-MS3_AGB_2	$B = 0.0474 \times dbh^{2.2239} \times ht^{0.6605}$	40	228.4	0.97	-0.6
	Tabora	MI-MS4_AGB_1	$B = 0.1054 \times dbh^{2.4809}$	40	398.0	0.95	-0.8
	Tabora	MI-MS4_AGB_2	$B = 0.0817 \times dbh^{2.1015} \times ht^{0.6021}$	40	378.3	0.96	-0.1
BGB	Manyara	MI-MS1_BGB_1	$B = 0.3789 \times dbh^{1.7904}$	20	59.2	0.89	2.0
	Manyara	MI-MS1_BGB_2	$B = 0.3364 \times dbh^{1.6166} \times ht^{0.2979}$	20	57.5	0.90	1.2
	Lindi	MI-MS2_BGB_1	$B = 29.7026 - 3.6428 \times dbh + 0.2738 \times dbh^2$	20	108.8	0.91	4.9
	Lindi	MI-MS2_BGB_2	$B = \exp(-2.9601 + 0.8692 \times (dbh^2 \times ht))$	20	116.9	0.89	2.9
	Katavi	MI-MS3_BGB_1	$B = 0.1731 \times dbh^{2.0296}$	20	70.4	0.89	0.5
	Katavi	MI-MS3_BGB_2	$B = \exp(-2.3772 + 0.8094 \times (dbh^2 \times ht))$	20	77.2	0.87	4.5
	Tabora	MI-MS4_BGB_1	$B = 0.1849 \times dbh^{2.0318}$	20	153.4	0.94	0.1
	Tabora	MI-MS4_BGB_2	$B = \exp(-1.9534 + 0.7674 \times (dbh^2 \times ht))$	20	158.6	0.93	0.7

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 3.7. General volume models for miombo woodlands

Component	Model ID	Model	n	RMSE (%)	Pseudo-R^2	MPE (%)
Total	MI_MM_V_1	$V = 0.00016 \times dbh^{2.46300}$	158	48.0	0.87	-0.5
	MI_MM_V_2	$V = 0.00011 \times dbh^{2.13300} \times ht^{0.57580}$	158	47.6	0.88	-0.6
Branches	MI_MM_BV_1	$V = 0.00012 \times dbh^{2.44400}$	158	56.5	0.85	-0.4
Merchantable stem	MI_MM_MSV_1	$V = 0.00011 \times dbh^{2.20500}$	130	56.1	0.76	-0.2

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 3.8. Site-specific volume models for miombo woodlands

Component	Site	Model ID	Model	n	RMSE (%)	Pseudo-R^2	MPE (%)
Total	Manyara	MI-MS1_TV_1	$V = 0.00010 \times dbh^{2.62300}$	39	32.7	0.95	0.6
	Manyara	MI-MS1_TV_2	$V = 0.00005 \times (dbh^2 \times ht)^{1.01300}$	39	30.5	0.96	1.1
	Lindi	MI-MS2_TV_1	$V = 0.00016 \times dbh^{2.47200}$	39	39.9	0.91	-2.3
	Lindi	MI-MS2_TV_2	$V = 0.00010 \times (dbh^2 \times ht)^{0.94160}$	39	38.7	0.92	0.2
	Katavi	MI-MS3_TV_1	$V = 0.00009 \times dbh^{2.64200}$	40	47.5	0.86	0.3
	Katavi	MI-MS3_TV_2	$V = 0.00006 \times (dbh^2 \times ht)^{1.01200}$	40	33.3	0.93	-0.2
	Tabora	MI-MS4_TV_1	$V = 0.00042 \times dbh^{2.19786}$	40	48.0	0.92	-1.7
	Tabora	MI-MS4_TV_2	$V = 0.00032 \times (dbh^2 \times ht)^{0.82890}$	40	46.8	0.93	-2.0
Branches	Manyara	MI-MS1_BV_1	$V = 0.00005 \times dbh^{2.66700}$	39	47.6	0.90	0.1
	Lindi	MI-MS2_BV_1	$V = 0.00020 \times dbh^{2.35300}$	39	46.3	0.90	-1.0
	Katavi	MI-MS3_BV_1	$V = 0.00005 \times dbh^{2.64200}$	40	55.5	0.83	0.5
	Tabora	MI-MS4_BV_1	$V = 0.00001 \times dbh^{2.45800}$	40	56.2	0.86	2.2
Merchantable stem	Manyara	MI-MS1_MSV_1	$V = 0.00005 \times dbh^{2.35300}$	33	41.9	0.88	1.6
	Lindi	MI-MS2_MSV_1	$V = 0.00015 \times dbh^{2.13600}$	32	45.4	0.84	1.2
	Katavi	MI-MS3_MSV_1	$V = 0.00005 \times dbh^{2.47800}$	34	51.5	0.76	0.0
	Tabora	MI-MS4_MSV_1	$V = 0.00033 \times dbh^{1.96585}$	31	44.0	0.87	-2.0

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m)

3.6 References

Chamshama, S.A.O, Mugasha, A.G. and Zahabu, E. (2004). Biomass and volume estimation for miombo woodlands at Kitulangalo, Morogoro, Tanzania. South African Forestry Journal 200: 49-60.

Frost P. (1996). Population biology of miombo trees, in: Campbell, B.M. (Ed.), The Miombo in transition: Woodlands and welfare in Africa, pp. 11-57. Center for International Forestry Research. Bogor, Indonesia. 266pp.

Giliba, R.A, Boon, E.K, Kayombo, C.J., Musamba, E.B., Kashindye A.M. and Shayo P.F. (2011). Species composition, richness and diversity in miombo woodland of Bereku Forest Reserve, Tanzania. Journal of Biodiversity 2: 1-7.

Malimbwi, R.E, and Temu, A.B. (1984). Volume functions for *Pterocarpus angolensis* and *Julbernadia globiflora*. Journal of the Tanzania Association of Foresters 1: 49-53.

Malimbwi, R., Solberg, B. and Luoga, E. (1994). Estimation of biomass and volume in miombo woodland at Kitulangalo Forest Reserve, Tanzania. Journal of Tropical Forest Science 7: 230-242.

Mauya, E., Mugasha, W., Zahabu, E., Bollandsås, O.M and Eid, T. (2014). Models for estimation of tree volume in the miombo woodland of Tanzania. Southern Forests 76: 209-219.

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

Mugasha, W.A., Bollandsås, O.M. and Eid, T. (2013a). Relationships between diameter and height of trees for natural tropical forest in Tanzania. Southern Forests 75: 221–237.

Mugasha, W.A., Eid, T., Bollandsås, O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J.Z. (2013b). Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecology and Management 310: 87–101.

R core team. (2013). R: A Language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org (accessed on 12 November 2013).

SAS® Institute Inc. (2004). SAS Institute Inc., Cary, NC, USA. 218pp.

4 ALLOMETRIC BIOMASS AND VOLUME MODELS FOR LOWLAND AND HUMID MONTANE FORESTS

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4.1 Background

Tropical rainforests are found between the Tropic of Cancer (23.5° N Latitude) and the Tropic of Capricorn (23.5° S Latitude) and are considered to constitute one of the largest terrestrial forest biomes in the world (Mayaux et al., 2004; Lewis et al., 2013). Basing on elevation, generally, tropical rainforests are classified into lowland, submontane and montane forests. In Africa, the major rainforests are found in Cameroon, Nigeria, Democratic Republic of Congo, Uganda and Tanzania.

In Tanzania, the term tropical rainforest includes lowland and humid montane forests (MNRT, 2015). They are estimated to occupy about 2.6 million hectares (ha) (5.5%) of forest land with multiple plant species, multi-layered forest structure and potential for water sources. For instance, it has been reported that in Amani Nature Reserve (ANR), there are more than 200 tree species (Frontier Tanzania, 2001) and that tree heights up to 50 m exist (Masota et al., 2014). In addition, lowland and humid montane forests consist of very high growing stocks ranging between 98.3 m^3 ha^{-1} and 171 m^3 ha^{-1} (MNRT, 2015). Because of their potentials, most of these forests are protected for soil and water conservation (Frontier Tanzania, 2001; URT, 2009). In addition, they provide direct and indirect benefits to a large number of people in rural and urban areas as described in Chapter 1. Indirect benefits include carbon (C) sequestration for mitigating climate change. However, the potential of lowland and humid montane forests to sequester C is little known due to lack of appropriate allometric models.

For lowland and humid montane forests, Munishi and Shear (2004) developed volume models without using data from destructive sampling. The volume data used for modelling was computed from basal area (g) and ht using the formula for volume of a cone ($v = g \times ht/3$). Others, for instance Mpanda et al. (2011) and Mgumia (2014) applied general volume equations, multiplying g, ht and a form factor (f) of 0.5. To estimate aboveground biomass (AGB), Munishi and Shear (2004) converted the computed volume to biomass by using wood basic density (ρ). It is quite obvious that uncertainty in volume and AGB estimation is larger based on such computations compared to if models based on destructively sampled data are applied. Estimations of belowground biomass (BGB) are frequently based on root to shoot ratios. Often these root to shoot ratios have been based on data from a different site or from a different vegetation type than the current (Munishi and Shear, 2004; MNRT, 2015). Such procedures may lead to biased estimates.

This chapter describes recently developed set of biomass and volume models for lowland and humid montane forests in Tanzania. The models presented in this chapter are for prediction of biomass and volume of different components of individual trees. The described models are published by Masota et al. (2014) and Masota et al. (2015).

4.2 Site description

Data for development of biomass and volume models were collected in ANR, Muheza district in Tanga region. The ANR is located between 05º05'– 5º14'S and 38º32' – 38º40'E in Usambara Mountains, a part of the Eastern Arc Mountains in Tanzania. It covers 8,380 ha of lowland and humid montane forests, with altitude between 190 and 1,130 m (Frontier Tanzania, 2001). The area receives annual rainfall ranging between 1,800 and 2,200 mm. The mean annual temperature is about 20˚C with a mean daily minimum and maximum temperature of about 16 and 24˚C respectively.

4.3 Data collection and analysis

Selection of sample trees

To obtain information on the tree species and size distribution for guiding the selection of sample trees, previous inventory data of 142 plots (50 m × 20 m) established on a systematic grid over the entire area were used. The selection of trees took cognisance of diameter at breast height (dbh) range, species frequency and varied forest conditions to reflect the structure of the forest shown by the prior inventory.

Each sample tree was recorded for dbh and ht before felling. For trees with buttresses, dbh was measured 30 cm above the buttress. In addition, the tree species were identified and recorded. A calliper or a diameter tape (for larger trees dbh >65 cm) was used to measure dbh, while ht was measured using Vertex hypsometer.

For the AGB models, 60 trees belonging to 34 species were selected. Twenty nine of these trees belonging to 21 species were selected for excavation of roots for BGB determination (Table 4.1). The same trees used for developing AGB models were also used for developing volume models.

Table 4.1. Summary statistics of sample trees used for developing biomass and volume models

Component	**n**	**dbh (cm)**			**ht (m)**		
		Mean	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
Total volume and ABG	60	50.8	6.0	117.0	27.3	6.4	50.0
BGB	29	52.8	6.0	117.0	27.3	8.0	50.0

Destructive sampling and biomass determination

The trees selected for biomass determination were first divided into above- and belowground components. The aboveground component comprised all biomass above 30 cm from the ground. The aboveground component was further divided into three main components, namely stem, branches and twigs and leaves. The following definitions were applied to above- and belowground components when developing the biomass models:

- Stem includes section from the stump to the point where the first large branch occurs.
- Branches include all branches larger than 2.5 cm diameter.
- Twigs and leaves include those parts of the branches with diameter <2.5 cm and leaves.
- The belowground component of sampled tree comprised of all biomass in the stump (cut 30 cm above ground), root crown and roots down to a diameter of 1 cm.

The determination of BGB was based on a root sampling procedure where three main roots originating from the root crown and three side roots originating from the selected main root were selected for each tree. Based on these sampled main and side roots, models predicting green weights of main and side roots were developed and then these models were applied to estimate green weights of unexcavated roots (for details, see Mugasha et al. 2013).

All above- and belowground components of the trees were fresh weighed in the field. At least three sub-samples were taken from each tree component, fresh weighed and then brought to the laboratory for drying at a temperature of 105°C. Biomass of all sub-samples was immediately determined once constant weights were obtained. Tree and component specific dry to fresh weight ratios (DF-ratios) were computed. Biomass for the tree components were determined by multiplying tree- and component-specific DF-ratios with the respective fresh weights determined in the field. Finally, values of AGB and BGB of individual trees were obtained by summing biomass values of the respective components. Scatter plots of AGB and BGB versus dbh for individual trees are displayed in Figure 4.1.

The trees selected for volume determination were divided into two main components, namely stem and branches as defined for biomass. Furthermore, total volume was found by summing stem and branches components.

The volumes of individual stem and branch billets obtained from destructive sampling were calculated using Huber's formula. Then volume of stem and branches for each tree was obtained by summing up individual volumes of billets from respective components for a given tree. Total tree volume was finally obtained by summing up volumes of stem and branches. Ranges of volumes for tree components were 0.004 m^3 to 12.285 m^3 in branches, 0.006 to 17.502 m^3 in stems and 0.017 to 22.372 in total. Scatter plot of total volume versus dbh is displayed in Figure 4.2.

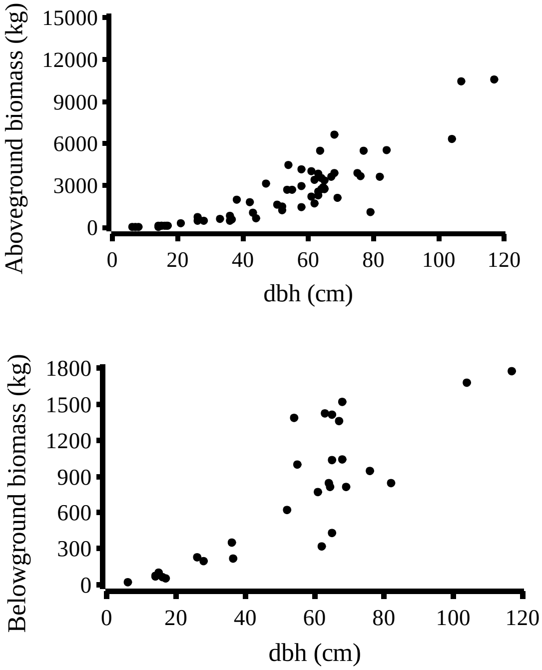


Figure 4.1. Scatter plots of AGB and BGB versus dbh

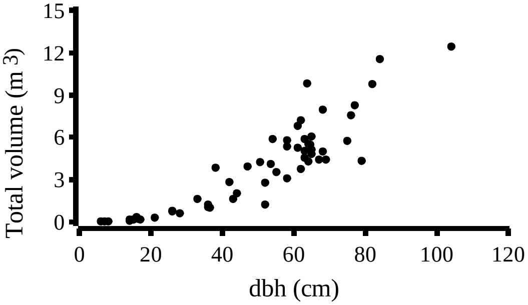


Figure 4.2. Scatter plot of total volume versus dbh

Working conditions and resources required

Generally, working conditions for collecting field data in lowland and humid montane forests are very challenging. The lowland and humid montane forests are characterized by undulating terrains and deep valleys. In addition, these forests are characterized by relatively high number of stems per ha and many understory small trees as well as presence of climbers and lianas. All these aspects make accessibility to these forests difficult. The consequence is reflected by longer time taken in data collection.

Other challenges of working in ANR are related to measuring tree dbh and ht. The presence of large buttresses and steep slopes make dbh measurement difficult such that sometimes it was necessary to use climbing ladders in order to measure accurately the diameter of buttressed trees (Plate 4.1). For ht measurements, the multi-layered structure obstructs the view of tree tops while the steep slopes complicate horizontal distance measurements.

Furthermore, both maximum dbh and ht values are very large for trees in ANR. For instance, Frontier Tanzania (2001) reported maximum dbh of 270 cm and Masota et al. (2014; 2015) observed tree height of 50 m. These large tree sizes pose challenges in felling, crosscutting and collecting stem and branch logs for weighing (Plate 4.2). In addition, high stand density and presence of multi-layered forest structure lead to frequent hang ups and difficult in collecting belowground component data due to high interlocking of roots among trees.

Plate 4.1. A tree with buttress in Amani Nature Reserve (Photo Abel Masota)

The necessary number crew members varied with tree components (i.e. aboveground and belowground). To improve efficiency, each tree component had a specific crew. A total of three crews were formed, two for belowground and one for aboveground component. The crew for above- and belowground components had nine and four members respectively. These crews were closely supervised to ensure quality and safety.

Plate 4.2. Weighing of a stem billet in Amani Natural Reserve (Photo Abel Masota)

Equipment used during the destructive sampling included callipers and diameter tape for dbh and root diameter measurements and Vertex hypsometer for ht measurements. Tapes were used for measuring length of billets, machetes to cut off small branches, a chainsaw for felling trees and crosscutting stem and branches. Also, hoes, iron brushes, axes, spades and mattocks were used for excavation of belowground component and removing soil from roots. A spring balance was used for weighing above- and belowground components while electronic balance was used to weigh sub-samples.

Time and costs for felling, crosscutting, collection and green weighing of aboveground components varied with tree sizes. For example, a tree of 40 cm dbh was processed in a single day by a crew of 8 people. For trees with dbh less than 40 cm at least two trees could be processed in a day, while trees with dbh greater than 40 cm could take 2 - 3 days by one crew. To process trees for BGB, a tree with dbh less than 40 cm could be done in 1 - 2 days while for trees with dbh greater than 40 could take 2 - 3 days. In addition, all members were provided with food, which was served at work site. Workers were paid TZS 5,000 per day while the chainsaw operator was hired at a rate of TZS 30,000 per day. Costs for all activities related to cutting one tree except the costs for acquiring chainsaw and other equipment (hoes, axes, machetes, mattocks, spades and iron brushes) are summarized in Table 4.2.

Table 4.2. Cost estimates for destructive sampling of one tree with dbh 40-50 cm

Tree component	Cost element	Units	Costs (TZS)
Aboveground	Labour costs for collection and weighing	12 man-days	60,000
	Chainsaw operator	1.5 man-days	45,000
	Petrol	5 litres	12,000
	Engine oil	0.5 litres	7,000
	Food	20 rations	30,000
	Transport of crews	2 days	90,000
	Chainsaw chain	1 pc	40,000
	Administrative: Team leader	2 man-days	90,000
	Research assistant	2 man-days	40,000
Belowground	Labour costs for excavation	8 man-days	40,000
	Food	8 rations	12,000
	Chainsaw operator: Crossing	1.5 man-days	45,000
	Collection and weighing	12 man-days	60,000

Model fitting and evaluation

Four model forms were tested for biomass, namely model with dbh only, dbh and ρ, dbh and ht, and lastly dbh, ht and ρ. The values for ρ for different tree species were obtained from Zanne et al. (2009).

$$B = \beta_0 \times dbh^{\beta 1} \quad (1)$$
$$B = \beta_0 \times dbh^{\beta 1} \times \rho^{\beta 2} \quad (2)$$
$$B = \beta_0 \times dbh^{\beta 1} \times ht^{\beta 2} \quad (3)$$
$$B = \beta_0 \times dbh^{\beta 1} \times ht^{\beta 2} \times \rho^{\beta 3} \quad (4)$$

where B is biomass (kg) and β_0, β_1, β_2 and β_3 are model parameters to be estimated.

The PROC MODEL procedure in SAS software (SAS® Institute Inc., 2004) was used to estimate the model parameters (β_0, β_1, β_2 and β_3). The procedure estimates the model parameters of a nonlinear model through an iteration process where the aim is to minimize the residual sum of squares.

The selection of final models was based on the coefficient of determination (R^2) and Root Mean Squared Error (RMSE) and significance of parameter estimates. Models with insignificant parameter estimates were discarded. In addition, relative mean prediction error was reported as:

$$\text{MPE}\ (\%) = \frac{100}{\text{MB}} \times \sum \left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass or volume), and MB is mean observed biomass or volume.

Initially several model forms were tested for volume, but three were finally selected. The selected volume model forms were relating g, ht and f, dbh only, and dbh and ht as independent variables. In model 5, f was substituted with (a + b × ln(dbh)). The model forms are shown below:

$$V = g \times ht \times (a + b \times \ln(dbh)) \quad (5)$$
$$V = \exp(a + b \times \ln(dbh)) \quad (6)$$
$$V = \exp(a + b \times \ln(dbh) + c \times \ln(ht)) \quad (7)$$

where V is volume (m^3) and a, b and c are model parameters to be estimated.

Similar model selection criteria as indicated in biomass models above were used to select volume models.

4.4 Biomass and volume models

Biomass of all tree components can be estimated using the following model options as independent variables: using dbh only, dbh and ht, dbh and ρ, and dbh, ht and ρ (Table 4.3). Volume of total tree and stem can be estimated using the following options as independent variables: 1) g, ht and f and 2) with both dbh and ht. In addition, branch volumes can be estimated using models with dbh only and model with g, ht and dbh as independent variables (Table 4.4). Definitions of different tree components are presented in Chapter 4.3.

4.5 Application recommendations

Models for estimating biomass and volume presented in this chapter were developed based on one of lowland and humid montane forests in the Eastern Arc Mountains of Tanzania. Sample trees were selected to cover wide range of forest conditions, adequate number of observations, species, elevation and tree sizes from both lowland and humid montane forests. It is recommended that the models should be applied in forests with the same allometry as the study area.

Three models for predicting biomass are presented: 1) with dbh only, 2) with both dbh and ht and 3) with dbh, ht and ρ as independent variables. All the models can be applied with acceptable accuracy level provided appropriate information on ρ and ht is available from forest inventory and other reliable sources. It is recommended to use models with both dbh and ht for large trees outside the modelling materials (extrapolation) because of the moderating effects ht has on biomass and volume. However, when ht is included in the model, care must be taken during ht measurement to reduce errors attributed to the difficult terrain, high stand density and tallness of trees.

The recommendations given above also apply to tree component biomass and volume models (stem, branches and twigs and leaves). Definitions for tree components used in this chapter should be taken into account when applying respective models.

Table 4.3. Biomass models for lowland and humid montane forests

Component	**Model ID**	**Model**	**n**	**RMSE (kg)**	**R^2**	**MPE (%)**
AGB	LM_MS1_AGB_1	$B = 0.9635 \times dbh^{1.9440}$	60	1020.3	0.80	0.0
	LM_MS1_AGB_3	$B = 0.9569 \times dbh^{2.0085} \times \rho^{0.4908}$	60	1016.9	0.81	-1.0
	LM_MS1_AGB_2	$B = 0.4020 \times dbh^{1.4365} \times ht^{0.8613}$	60	920.5	0.84	1.0
	LM_MS1_AGB_4	$B = 0.2516 \times dbh^{1.3741} \times ht^{1.1922} \times \rho^{0.7983}$	60	857.7	0.87	-1.0
BGB	LM_MS1_BGB_1	$B = 7.5811 \times dbh^{1.16801}$	29	312.7	0.71	2.0
	LM_MS1_BGB_1	$B = 5.3854 \times dbh^{1.3709} \times \rho^{1.047}$	29	254.4	0.81	-5.0
	LM_MS1_BGB_1	$B = 3.1877 \times dbh^{1.1022} \times ht^{0.4802} \times \rho^{1.0733}$	29	251.2	0.82	-5.0
Twigs and leaves	LM_MS1_TLB_1	$B = 2.0830 \times dbh^{0.9440}$	60	61.2	0.33	-4.5
	LM_MS1_TLB_3	$B = 3.5576 \times dbh^{0.9631} \times \rho^{1.1067}$	60	59.8	0.39	-4.1
Branches	LM_MS1_BB_1	$B = 4.1964 \times dbh^{1.3726}$	60	786.4	0.42	3.4
	LM_MS1_BB_3	$B = 2.6321 \times dbh^{1.8034} \times \rho^{2.6498}$	60	697.8	0.56	3.5
Stem	LM_MS1_SB_1	$B = 0.0450 \times dbh^{2.5272}$	60	658.2	0.82	0.0
	LM_MS1_SB_3	$B = 0.0330 \times dbh^{2.5363} \times \rho^{-0.4384}$	60	615.2	0.84	-1.0
	LM_MS1_SB_2	$B = 0.0089 \times dbh^{1.4802} \times ht^{1.7211}$	60	458.9	0.91	0.5

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m), ρ = wood density (g/cm^3)

Table 4.4. Volume models for lowland and humid montane forests

Component	Model ID	Model	n	RMSE (m^3)	Pseudo-R^2	MPE (%)
Total	LM_MS1_TV_5	$V = g \times ht \times (1.414741 - 0.21174 \times \ln(dbh))$	60	1.343	0.91	-0.9
	LM_MS1_TV_2	$V = \exp(-8.12477 + 1.653497 \times \ln(dbh) + 0.852048 \times \ln(ht))$	60	1.355	0.91	0.0
Branches	LM_MS1_BV_5	$V = g \times ht \times (0.789641 - 0.14111 \times \ln(dbh))$	60	1.508	0.43	6.1
	LM_MS1_BV_1	$V = \exp(-6.88089 + 1.83115 \times \ln(dbh))$	60	1.469	0.46	1.8
Stem	LM_MS1_SV_5	$V = g \times ht \times (0.625100 - 0.07064 \times \ln(dbh))$	60	0.881	0.91	-1.5
	LM_MS1_SV_2	$V = \exp(-10.4281 + 1.434108 \times \ln(dbh) + 1.63197 \times \ln(ht))$	60	0.823	0.93	-0.9

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m), g = basal area at breast height (m^2)

4.6 References

Frontier Tanzania. (2001). Doody, K.Z., Howell, K.M. and Fanning, E. (eds), Amani Nature Reserve: A biodiversity survey. East Usambara Conservation Area Management Programme Technical Paper No. 52.Frontier Tanzania; Forestry and Beekeeping Division and Metsähallitus Consulting, Dar es Salaam, Tanzania and Vantaa, Finland. 117pp.

Lewis, S.L., Sonke, B., Sunderland, T., Begne, S.K., Lopez-Gonzalez, G., van der Heijden, G.M.F., Phillips, O.L., Affum-Baffoe, K., Baker, T.R., Banin, L., Bastin, J.F., Beeckman, H., Boeckx, P., Bogaert, J., De Canniere, C., Chezeaux, E., Clark, C.J., Collins, Murray, Djagbletey, G., Djuikouo, M.N.K., Droissart, V., Doucet, J.L., Ewango, C.E.N., Fauset, S., Feldpausch, T.R., Foli, E.G., Gillet, J.F., Hamilton, A.C., Harris, D.J., Hart, T.B., de Haulleville, T., Hladik, A., Hufkens, K., Huygens, D., Jeanmart, P., Jeffery, K.J., Kearsley, E., Leal, M.E., Lloyd, J., Lovett, J.C., Makana, J.R., Malhi, Y., Marshall, A.R., Ojo, L., Peh, K.S.- H., Pickavance, G., Poulsen, J.R., Reitsma, J.M., Sheil, D., Simo, M., Steppe, K., Taedoumg, H.E., Talbot, J., Taplin, J.R.D., Taylor, D., Thomas, S.C., Toirambe, B., Verbeeck, H., Vleminckx, J., White, L.J.T., Willcock, S., Woell, H. and Zemagho, L. (2013). Above-ground biomass and structure of 260 African tropical forests. Philosophical Transactions of the Royal Society B: Biological Sciences 368: 20120295.

Masota, A.M., Zahabu, E., Malimbwi, R.E., Bollandsås, O.M. and Eid. T. (2014). Volume models for single trees in tropical rainforests in Tanzania. Journal of Energy and Natural Resources 3: 66-76.

Masota, A.M., Zahabu, E., Malimbwi, R.E., Bollandsås, O.M. and Eid, T. (2015). Tree allometric models for predicting above- and belowground biomass of tropical rainforests in Tanzania. XIV World Forestry Congress**,** Durban, South Africa, 7-11 September 2015. 12pp.

Mayaux, P., Bartholome, E., Fritz, S. and Belward, A. (2004). A new land-cover map of Africa for the year 2000. Journal of Biogeography 31: 861–877.

Mgumia, F. (2014). Implications of forestland tenure reforms on forest conditions, forest governance and community livelihoods at Amani Nature Reserve, PhD Thesis, Sokoine University of Agriculture, Tanzania. 280pp.

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

Mpanda, M.M., Luoga, E.J., Kajembe, G.E. and Eid, T. (2011). Impact of forestland tenure changes on forest cover, stocking and tree species diversity in Amani Nature Reserve, Tanzania. Forests, Trees and Livelihoods 20: 215–230.

Mugasha, W.A., Eid, T., Bollandsås, O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J.Z. (2013). Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecology and Management 310: 87–101.

Munishi, P.K.T. and Shear, T.H. (2004). Carbon storage in afromontane rainforests of the Eastern Arc Mountains of Tanzania: their net contribution to atmospheric carbon. Journal of Tropical Forest Science 16: 78–93.

SAS®Instute Inc. (2004). SAS Institute Inc., Cary, NC, USA. 218pp.

URT, (2009). Fourth national report on implementation of Convention on Biological Diversity (CBD). Division of Environment, Vice President’s Office, Dar es Salaam, Tanzania. 81pp.

Zanne, A.E., Lopez-Gonzalez, G., Coomes, D.A., Ilic, J., Jansen, S., Lewis, S.L., Miller, R.B., Swenson, N.G., Wiemann, M.C. and Chave, J. (2009). Global wood density database. Dryad. http://hdl.handle.net/10255/dryad.235.

5 ALLOMETRIC BIOMASS MODELS FOR MANGROVE FORESTS

Njana, A.M., Eid, T., Bollandsås, O.M. and Zahabu, E.

5.1 Background

Mangroves form a unique intertidal forest at the edge between land and sea and are the only forest type capable of thriving in salt water (Massó et al., 2010). About 3.2 million hectares (ha) (21%) out of 15.7 million ha of all mangroves in the world are located in Africa (FAO, 2007). In eastern coast of Africa, there are about 14 mangrove species growing naturally, and among these *Avicennia marina*, *Bruguiera gymnorrhiza* and *Rhizophora mucronata* are abundant.

In Tanzania, mangroves grow naturally along the coastline between the borders to Kenya in north and Mozambique in south. They cover about 158,100 ha (MNRT, 2015) and include 10 different species, namely *A. marina*, *B. gymnorrhiza*, *Ceriops tagal*, *Heritiera littoralis*, *Lumnitzera racemosa*, *R. mucronata*, *Sonneratia alba*, *Xylocarpus granatum*, *Xylocarpus moluccensis* and *Pemphis acidula*.

Mangroves provide a range of goods and services of biological and economic importance. In addition, mangroves store large amounts of carbon per unit area due to high soil carbon content (Donato et al., 2011), and are therefore also important for climate change mitigation (UNEP, 2014). Despite being important, mangroves are threatened by deforestation and forest degradation in Tanzania (e.g. Wang et al., 2003; FAO, 2007) and in other parts of the world (e.g. Valiela et al., 2001; FAO, 2007).

No biomass models have been developed for mangroves in Tanzania, yet numerous models based on data from other regions have been developed (e.g. Komiyama et al., 2008) and some from neighbouring countries (e.g. Kairo et al., 2009; Sitoe et al., 2014). If such models are applied to quantify biomass of mangroves in Tanzania however, they would be used beyond their spatial validity.

This chapter describes recently developed AGB and BGB models for mangrove forests in Tanzania. They comprise both general (i.e. multi-species) and species-specific models. The models are published by Njana et al. (2015a).

5.2 Site description

Data for this study were collected in four study sites namely Pangani, Bagamoyo, Rufiji and Lindi-Mtwara. The four study sites were spatially distributed along the coast of Tanzania mainland in order to cover a wide range of mangrove forest conditions. The sites are characterised by tropical climate with high between-site and temporal within-site variability in temperature and rainfall. Details on locations and conditions regarding the sites are described in Table 5.1.

Table 5.1. Study sites description

Site	Location	Dominant soil type	Mean annual temperature (°C)	Mean annual rainfall (mm)
Pangani	05° 38' S - 05° 40' S, 38° 53' E - 38° 54' E	Alluvial, clay and sandy soils	26.6	1,240
Bagamoyo	06° 20' S - 06° 33' S, 38° 50' E - 39° 06' E	Alluvial and sandy soils	26.1	940
Rufiji	07° 38' S - 07° 55' S, 39° 16' E - 39° 24' E	Alluvial, silt and clay soils	27.0	879
Lindi-Mtwara	10° 02' S - 10° 15' S, 39° 39' E - 40° 10' E	Alluvial and sandy soils	25.7	1,072

Source of rainfall and temperature data: Tanzania Meteorological Agency, rainfall and temperature data; Pangani and Lindi–Mtwara (1970–2012); Bagamoyo (1964–2013) and Rufiji (2005–2012)

5.3 Data collection and analysis

Selection of sample trees

Data for this study were collected from sample plots laid along transect lines. Generally, site conditions in mangroves vary transversely with reference to the sea or river (e.g. Dahdouh-Guebas et al., 2004; Lovelock et al., 2005). Therefore, transects were established perpendicular to the sea and or river. A total of 120 plots were established: 15 in Pangani, 45 in Bagamoyo, 45 in Rufiji and 15 in Lindi–Mtwara. A nested plot design with 2 and 10 m radius concentric plots were applied. In each plot, dbh (1.3 m above soil surface for all species except for *R. mucronata* where dbh was measured at 0.3 m above the highest stilt root) were measured for all trees with dbh $\geq$ 1 and $\geq$ 5 cm within the 2 and 10 m radius plots, respectively. All trees were identified for species names.

In each plot, one tree was selected for destructive sampling. A total of 120 trees (one tree was later excluded because the stem was hollow) were measured for AGB and 30 out of these were excavated and measured for BGB. In addition to allocation of equal number of trees to each of the three tree species (40), the selection of trees was based on strata defined by five dbh classes: 1–10, 10.1–20, 20.1–30, 30.1–40 and > 40 cm. The dbh classes were established based on previous studies on mangrove structure in the country (Mattia, 1997; Luoga et al., 2004; Nshare et al., 2007). Before destructive sampling, sample trees were measured for dbh using a calliper and ht using a Suunto hypsometer. Table 5.2 shows summary statistics of sample trees for developing biomass models of mangroves.

Table 5.2. Summary statistics of sample trees used for developing biomass models

Species	Component	n	dbh (cm)			ht (m)		
			Mean	Min.	Max.	Mean	Min.	Max.
A. marina	AGB	40	22.7	1.1	70.5	12.6	3.1	30.6
	BGB	10	17.6	3.0	38.6	9.6	3.1	21.5
S. alba	AGB	39	18.2	1.1	47.5	11.8	3.1	28.1
	BGB	10	17.1	6.5	33.8	9.5	4.0	20.9
R. mucronata	AGB	40	19.2	1.4	41.5	10.2	0.8	32.2
	BGB	10	17.5	1.4	32.6	7.4	0.8	18.7

Destructive sampling and biomass determination

The trees selected for biomass determination were first divided into AGB and BGB. The AGB comprised of stem, branches, twigs and leaves while BGB included roots, root crown and stump with height of 15 cm from the ground (Figure 5.1).

The determination of BGB was based on a root sampling procedure where one or two main sample roots originating from the root crown and one or two side roots originating from the main root were selected for each tree. Based on sampled main and side roots, models predicting biomass of main and side roots were developed, and subsequently applied for prediction of dry weights for roots not excavated (for details, see Njana et al., 2015b).

All above- and belowground components of the trees were weighed for fresh weight in the field. At least three sub-samples were taken from all tree components, weighed for fresh weight and then taken to the laboratory for oven-dry weight determination. Dry weights of all sub-samples were then determined, and tree- and component-specific dry to fresh weight ratios (DF-ratios) were then computed. Dry weights for the tree components were determined by multiplying tree- and component-specific DF-ratios with the respective fresh weights determined in the field. Finally, AGB and BGB of individual trees were determined by summation of dry weights of tree components. Scatter plots of AGB and BGB versus dbh for individual trees are displayed in Figure 5.2.

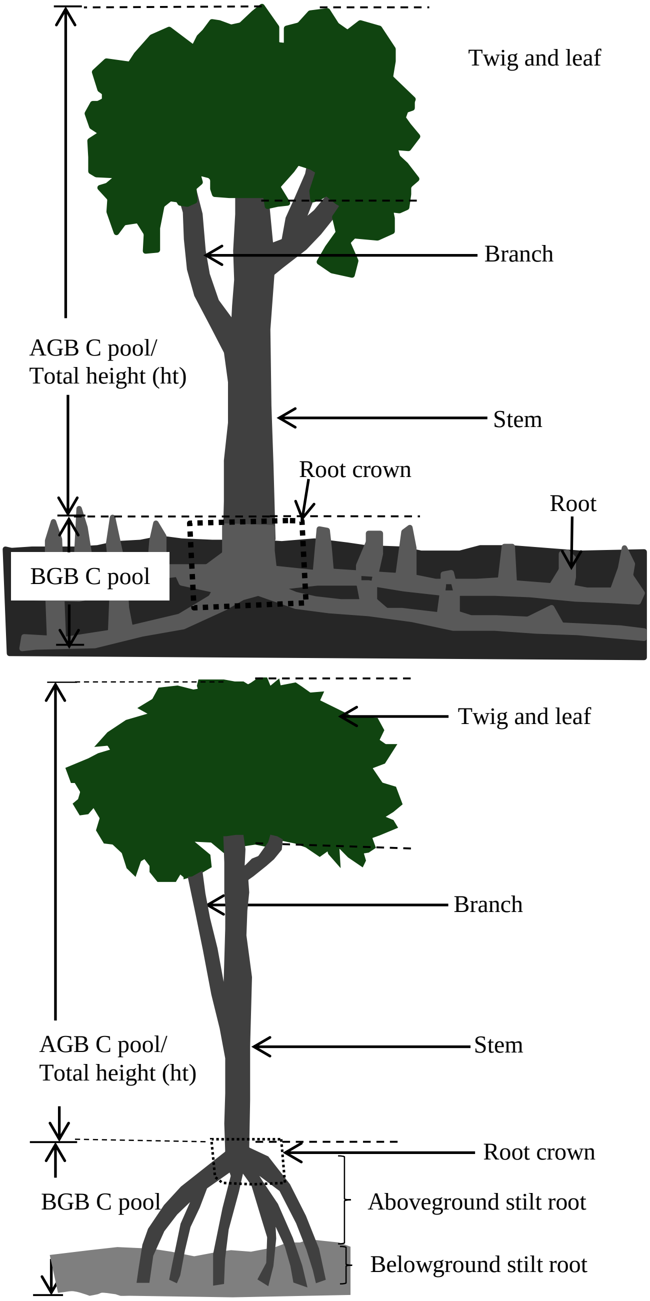


Figure 5.1. Sketch of *A. marina* and *S. alba* trees (upper) and *R. mucronata* trees (lower) showing different tree components and variables

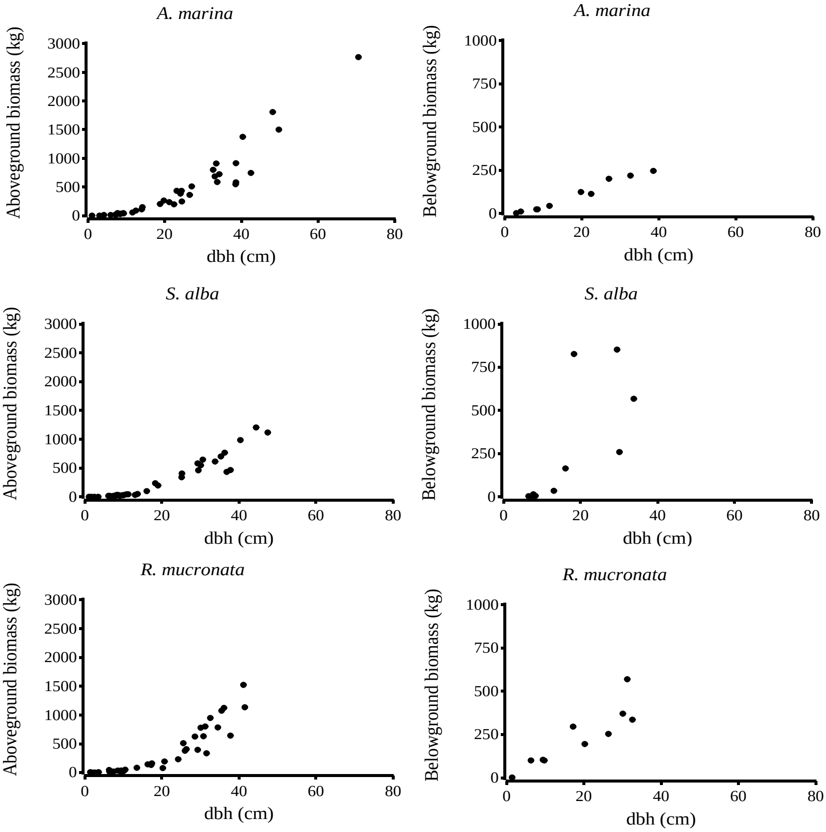


Figure 5.2. Scatter plots of AGB and BGB versus dbh for *A. marina, S. alba* and *R. mucronata*

Working conditions and resources required

Working conditions varied between sites. Distance and sea conditions (waves, tides, mud) had direct impact on time consumption and transport cost. Before working in mangrove forests, it is important to use tide tables in the planning since it is necessary to complete the work on each tree before high tides. In dense mangrove forests, tree hang up during felling was another challenge. Related to excavation of belowground components, some soil types were more challenging than others. It was for example easier to excavate the belowground components in the sandy soils in parts of Bagamoyo compared to the muddy and sticky soils in Rufiji.

The crew comprised of a minimum of six persons and up to ten depending on working conditions. The composition of the crew did not vary with tree sizes and components. To improve efficiency, each individual crew member had specific tasks. The majority of the activities did not require experience. However, close supervision by the researcher was necessary to ensure quality of the data and safety of the crew.

Equipment used during the sampling included diameter tape and Vernier calliper for dbh and root diameter measurements respectively. Suunto hypsometer was used for ht measurements. Tape measure was used for measuring length of billets; machetes and axe for cutting off small branches; a chainsaw to fell trees and crosscut stems, large branches and roots. Hoes, spades and mattocks were used for excavating and exposing roots while iron brushes were used to remove soils from roots. A spring balance was used to weigh billets while an electronic balance was used to weigh sub-samples or small tree parts.

The crew consisted of four to eight field assistants, one boat driver and one assistant to boat driver. Assuming the crew accomplishes one tree per day, the total cost per tree was TZS 190,000 (Table 5.3). However, this estimate excludes cost of the researcher, land transport, equipment, meals and boat hiring.

Table 5.3. Cost estimates for destructive sampling

Item	**Cost per tree (TZS)**
Boat driver	30,000
Assistant boat driver	15,000
Fuel	25,500
Casual labour	120,000
Total	190,000

Model fitting and evaluation

Various model forms were initially tested on raw data, where power model forms were found to be the best. Power model forms have been widely used in biomass modelling for mangrove trees (e.g. Tamai et al., 1986; Komiyama et al., 2005; Kairo et al., 2009). The models were:

$$B = \beta_0 \times \mathrm{dbh}^{\beta_1} \qquad (1)$$

$$B = \beta_0 \times \mathrm{dbh}^{\beta_1} \times \mathrm{ht}^{\beta_2} \qquad (2)$$

where B is AGB or BGB (kg) and β_0, β_1, and β_2 are model parameters.

Three important assumptions for regression modelling are normality, homoscedasticity and independency of residuals. Results and conclusions based on regression analysis are only reliable if these assumptions are met (Ritz and Streibig, 2008; Zuur et al., 2009). For biological data, however, such assumptions may be difficult to meet.

Nonlinear mixed-effects (NLME) modelling is one way of confronting challenges encountered in conventional regression approaches since it relaxes regression assumptions and takes into account the complex nature of biological data (Pinheiro and Bates, 2000; Zuur et al., 2009). Within the NLME model framework, parameters may also be allowed to vary by grouping variables (i.e. random variables) (Ritz and Streibig, 2008). Since the data used in this study is hierarchical (correlation within sites and species) and the scatter plot (Figure 5.2) shows that the biomass-dbh relationship was nonlinear, tree biomass was modelled using the NLME approach. The use of NLME also ensured that the original scale of data was preserved.

Model fitting was carried out using the NLME function in the NLME package in R software (Pinheiro et al., 2015). Random-effects variables included species and site. Both tree AGB and BGB models were developed. In all cases, the power model form was applied. For AGB models, independent variables included dbh and ht while for the rest only dbh was used as independent variable due to limited number of observations for BGB (n = 30). Relative root mean square error and relative mean prediction error, reported as:

$$\text{MPE (\%)} = \frac{100}{\text{MB}} \times \sum \left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass), and MB is mean observed biomass, were used as indicators of goodness of fit.

5.4 Biomass models

Site and species as random-effects variables improved model fit and species resulted into significant random-effects parameters. Therefore general and species-specific models are reported (Tables 5.4 and 5.5). For the AGB models, there are two options; 1) dbh only and 2) dbh and ht as independent variables while for BGB models, there is only one option with dbh only as independent variable.

5.5 Application recommendations

Both general and species-specific AGB and BGB models for *A. marina*, *S. alba* and *R. mucronata* were developed. The species-specific models performed better than the general models, therefore the use of species-specific models is recommended. The models provide two options: 1) models with dbh only and 2) models with dbh and ht as independent variables. Both model options may be applied with appropriate accuracy. However, the inclusion of ht in addition to dbh slightly improved the model fit. Therefore, if information on ht is available from a forest inventory or predicted using reliable ht-dbh models, it is recommended to use models with both dbh and ht.

The biomass models reported in this chapter may be applied to forest inventory data such as NAFORMA. The use of these models beyond species considered may be uncertain. However, assuming the three species considered represent average population characteristics of mangrove species, the developed general models may be applied to unrepresented mangrove species in Tanzania.

Table 5.4. General biomass models for mangrove forests

Component	Model ID	Model	n	RMSE (%)	MPE (%)
AGB	MG_MM_ AGB_1	$B = 0.25128 \times dbh^{2.24034}$	119	42.6	-0.6
	MG_MM_ AGB_2	$B = 0.19633 \times dbh^{2.07919} \times ht^{0.29654}$	119	38.4	-1.0
BGB	MG_MM_ BGB_1	$B = 1.42040 \times dbh^{1.59666}$	30	89.6	-18.2

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 5.5. Species-specific biomass models for mangrove forests

Component	Species	Model ID	Model	n	RMSE (%)	MPE (%)
AGB	*A. marina*	MG_S1M_AGB_1	$B = 0.25128 \times dbh^{2.24351}$	40	41.3	2.8
	A. marina	MG_S1M_AGB_2	$B = 0.19633 \times dbh^{2.08791} \times ht^{0.29654}$	40	31.4	1.6
	S. alba	MG_S2M_AGB_1	$B = 0.25128 \times dbh^{2.21727}$	39	34.2	2.8
	S. alba	MG_S2M_AGB_2	$B = 0.19633 \times dbh^{2.04113} \times ht^{0.29654}$	39	23.1	2.0
	R. mucronata	MG_S3M_AGB_1	$B = 0.25128 \times dbh^{2.26026}$	40	40.5	-6.6
	R. mucronata	MG_S3M_AGB_2	$B = 0.19633 \times dbh^{2.10853} \times ht^{0.29654}$	40	42.5	-4.6
BGB	*A. marina*	MG_S1M_BGB_1	$B = 1.42040 \times dbh^{1.44260}$	10	16.8	1.5
	S. alba	MG_S2M_BGB_1	$B = 1.42040 \times dbh^{1.65760}$	10	95.1	-32.1
	R. mucronata	MG_S3M_BGB_1	$B = 1.42040 \times dbh^{1.68979}$	10	38.7	1.6

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

5.6 References

Dahdouh-Guebas, F., De Bondt, R., Abeysinghe, P.D., Kairo, J.G., Cannicci, S., Triest, L. and Koedam, N. (2004). Comparative study of the disjunct zonation pattern of the grey mangrove *Avicennia Marina* (Forsk.) Vierh. In Gazi Bay (Kenya). Bulletin of Marine Science 74: 237–252.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto. S., Stidham, M. and Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience 4: 293–297.

FAO. (2007). The World's mangroves 1980-2005. FAO Forestry Paper 153. FAO, Rome. 77pp.

Kairo, J.G., Bosire, J., Langat, J., Kirui, B. and Koedam, N. (2009). Allometry and biomass distribution in replanted mangrove plantations at Gazi Bay, Kenya. Aquatic Conservation 19: S63–S69.

Komiyama, A., Poungparn, S. and Kato, S. (2005). Common allometric equations for estimating the tree weight of mangroves. Journal of Tropical Ecology 21: 471–477.

Komiyama, A., Ong, J.E. and Poungparn, S. (2008). Allometry, biomass, and productivity of mangrove forests: a review. Aquatic Botany 89:128–137.

Lovelock, C.E., Feller, I.C., McKee, K.L. and Thompson, R. (2005). Variation in mangrove forest structure and sediment characteristics in Bocas del Toro, Panama. Caribbean Journal of Science 41: 456–464.

Luoga, E.J., Malimbwi, R.E., Kajembe, G.C., Zahabu, E., Shemwetta, D.T.K., Lyimo-Macha, J., Mtakwa, P. and Mwaipopo, C.S. (2004). Tree species composition and structures of Jasini-Mkwajuni Mangrove forest at Pangani, Tanzania. Journal Tanzania Association of Foresters 10: 42–47.

Massó, I., Alemán, S.C., Bourgeois, W., Appeltans, B.,Vanhoorne, N., De Hauwere, P., Stoffelen, A., Heaghebaert, F. and Dahdouh-Guebas. (2010). The 'Mangrove Reference Database and Herbarium'. Plant Ecology Evolution 143: 225–232.

Mattia, S.B. (1997). Species and structural composition of natural mangrove forests: a case study of the Rufiji delta, Tanzania. Dissertation for award of MSc. Degree at Sokoine University of Agriculture, Morogoro, Tanzania. 125pp.

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

Njana, M.A., Bollandsås, O.M., Eid, T., Zahabu, E. and Malimbwi, R.E. (2015a). Above- and belowground tree biomass models for three mangrove species in Tanzania: a non-linear mixed-effects modelling approach. Annals of Forest Science. DOI 10.1007/s13595-015-0524-3.

Njana, M.A., Eid, T., Zahabu, E. and Malimbwi, R.E. (2015b). Procedures for quantification of belowground biomass of three mangrove tree species. Wetlands Ecology and Management 23: 749–764.

Nshare, J.S., Chitiki, A., Malimbwi, R.E., Kinana, B.M. and Zahabu, E. (2007). The current status of the mangrove forest along seashore at Salenda bridge, Dar es Salaam, Tanzania. Journal Tanzania Association of Foresters 11: 172–179.

Ritz, C. and Streibig, J.C. (2008). Nonlinear regression with R. Springer, New York. 151pp.

Sitoe, A.A., Mandlate, L.J.C. and Guedes, B.S. (2014). Biomass and carbon stocks of Sofala bay mangrove forests. Forests 5:1967–1981.

UNEP. (2014). The importance of mangroves to people: a call to action. Van Bochove, J., Sullivan, E., Nakamura, T. (Eds). United Nations Environment Programme World Conservation Monitoring Centre, Cambridge. 128pp.

Valiela, I., Bowen, J.L. and York, J.K. (2001). Mangrove forests: one of the world's threatened major tropical environments. Bioscience 51: 807–815.

Wang, Y., Bonynge, G., Nugranad, J., Traber, M., Ngusaru, A., Tobey, J, Hale, L., Bowen, R. and Makota, V. (2003). Remote sensing of mangrove change along the Tanzania coast. Marine Geodesy 26: 1–14.

Zuur, A., Ieno, E.N., Walker, N.J., Saveliev, A.A. and Smith, G.M. (2009). Mixed effects models and extensions in ecology with R. Springer, New York. 574pp.

6 ALLOMETRIC BIOMASS AND VOLUME MODELS FOR ITIGI THICKET

Makero, J.S., Malimbwi, R.E., Eid, T. and Zahabu, E.

6.1 Background

Thicket is a dense formation of evergreen and weakly deciduous shrubs and low trees (2–5 m), often thorny and festooned with vines (Vlok et al., 2003). Thicket is generally influenced by soil type and structure, and is found in Africa, Asia, Australia and central and southern America (FAO, 2000). In eastern Africa, thicket extends from central Tanzania to the lowlands of the Somalia-Masai region all the way to Eritrea (Kindt et al., 2011; Cowling et al., 2005). Plant families and genera in thicket include Brassicaceae (*Boscia* spp, *Maerua* spp), Loganiaceae (*Strychnos* spp), Malvaceae (*Grewia* spp), Ochnaceae (*Ochna* spp), Rubiaceae (*Canthium* spp, *Psydrax* spp, *Xeromphis* spp), Rutaceae (*Clausena* spp, *Zanthoxylum* spp) and Euphorbiaceae (*Euphorbia* spp) (Cowling et al., 2005). Thicket supports a diverse fauna, including species like African elephant (*Loxodonta africana*), African buffalo (*Syncerus caffer*), Burchell's zebra (*Equus burchelli*), kudu (*Tragelaphus strepsiceros*) and eland (*Taurotragus oryx*) (Cowling et al., 2005; WWF, 2008).

The biomass of trees and shrubs can be estimated by either the product of stem volume, wood basic density and biomass expansion factors, or by applying allometric biomass models. Biomass and volume models are relevant in estimating biomass using remote sensing techniques and ground inventories related to conventional forest management planning. No biomass and volume models presently exist for thicket in Tanzania. Given the differences regarding climate, soils, topography and morphology of thicket species, the application of the models from elsewhere may result in unreliable estimates of biomass. Thus, developing models that suit Itigi thicket was necessary. This chapter presents recently developed biomass and volume models for Itigi thicket and associate trees in Tanzania.

6.2 Site description

Data for this study were collected in Itigi thicket located in the northern part of Manyoni district, Singida region (5° 31' to 5° 50'S and 34° 31' to 34° 49'E). The altitude ranges between 1,244 and 1,300 m above sea level. The area has unimodal rainfall distribution with annual mean rainfall of 624 mm. The minimum temperature in July is 19°C while the maximum temperature in November is 24.4°C. Geologically, the area is underlain by a basement floor of granite. The soils are silk clay loams and favour the root systems of thicket species to penetrate easily (MNRT, 2008).

6.3 Data collection and analysis

Selection of sample trees

A total of 60 clumps of dominant thicket species (30 clumps of *Pseudoprosopi fischeri* and 30 clumps of *Combretum celastroides*) and 30 associate trees were selected for destructive sampling. A thicket clump here refers to a group of stems originating from the same root crown. Associate trees refer to small trees (usually with a dbh below 20 cm and height below 8 m) found scattered in thicket stands.

To obtain information on the actual thicket and associate tree species and size distribution for guiding the selection of sample trees, randomly located sample plots (30 plots with radii of 7 m) were established. In each plot, two clumps of thicket species with more than five stems and one associate tree were selected for destructive sampling. The closest thicket clumps for each species and closest associate tree to the plot centre were selected. If an associate tree was not found inside the plot, the closest tree to the plot centre outside the plot was selected.

Before felling, each thicket sample was identified by its scientific name. Subsequently, the number of stems in the clump (*st*) was recorded and all stems measured for diameter at breast height (dbh) using a Vernier calliper. In addition, the total height of tallest stem (ht) in a clump was measured. For each clump, a basal area weighted mean $\mathrm{dbh_w}$ was computed in the following way:

$$\mathrm{dbh_w} = \sqrt{\frac{\sum \mathrm{BA_i} \times 4}{st \times \pi}}$$

where $\mathrm{BA_i}$ is basal area of the $\mathrm{i^{th}}$ stem.

Similarly, the selected associate tree was identified and measured for dbh and ht. Tables 6.1 and 6.2 show statistical summaries of selected thicket clumps and associate trees.

Destructive sampling for biomass and volume determination

The thicket clumps selected for biomass determination were excavated and divided into above- and belowground parts. The aboveground part comprised of all components 10 cm above ground level, except leaves as they were shed during sampling. The aboveground part was further divided into three components i.e. stem, branches and twigs. The belowground part comprised of root crown and roots (Plate 6.1).

Table 6.1. Summary statistics of sample thicket clumps used for developing biomass and volume models

Species	**n**	**dbh_w (cm)**			**ht (m)**			**st**		
		Mean	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
Combretum celastroides	30	2.4	1.5	3.2	4.5	3.5	6.5	15	6	29
Pseudoprosopis fischeri	30	2.2	1.2	3.0	4.1	3.0	6.0	22	9	57

Table 6.2. Summary statistics of sample associate trees used for developing biomass and volume models

Species	**n**	**dbh (cm)**			**ht (m)**		
		Mean	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
Canthium burtii	2	7.4	7.3	7.5	5.5	5.0	6.0
Cassipourea mollis	2	10.2	9.9	10.4	7.2	6.9	7.5
Haplocoelum foliolosum	8	10.7	6.1	18.0	5.9	5.0	7.0
Lannea fulva	6	10.8	10.1	11.7	5.3	5.0	6.0
Vangueria madagascariensis	12	10.0	7.0	15.2	6.2	5.0	7.2
All	30	10.0	6.1	18.0	6.0	5.0	7.5

The following definitions were used for above- and belowground components of thicket clumps during biomass models development:

- Stem applies to thicket stem with diameter > 2 cm.
- Branches include all branches and stems with diameter ≤ 2 cm and ≥ 1 cm.
- Twigs include those parts of the branches with diameter < 1 cm.

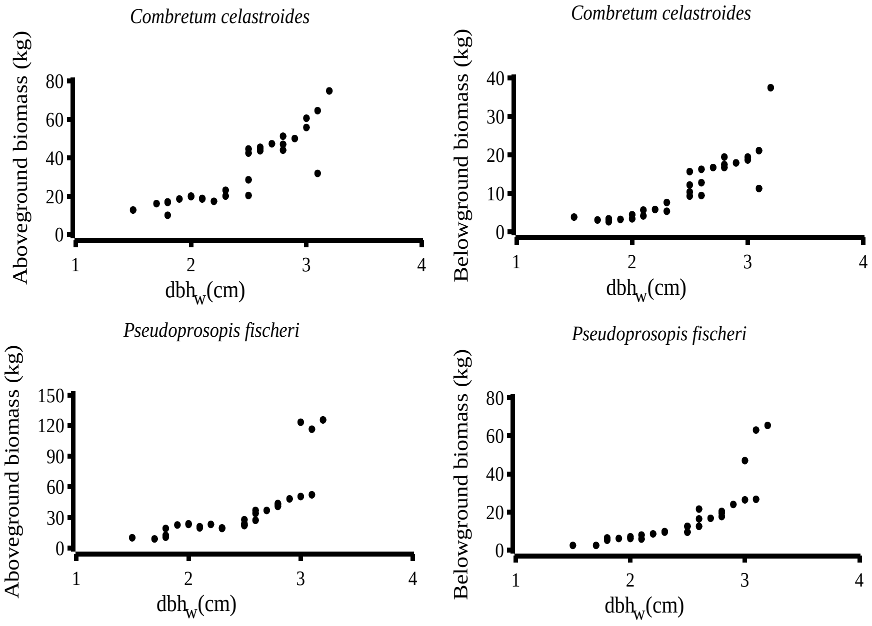
Plate 6.1. Root crown and roots of thicket (Photo Tron Eid)

Associate trees were first felled and aboveground components were separated into:

- Stem with diameter > 5 cm.
- Branches with diameter ≤ 5.0 cm and ≥ 2.5 cm.
- Twigs with diameter < 2.5 cm.

The belowground component was excavated as described in Chapter 3. Procedures for determination of components biomass are also described in Chapter 3. Figures 6.1 and 6.2 show the scatter plots of AGB and BGB versus dbh for individual thicket clumps and associate trees.

The thicket clumps and associate trees selected for volume determination were divided into two components i.e. stem and branches. The procedures for determination of stem and branch volumes are as described in Chapter 3. Total volume was determined by summing stem and branches volumes.



Combretum celastroides

Combretum celastroides

Pseudoprosopis fischeri

Pseudoprosopis fischeri

Figure 6.1. Scatter plots of AGB, BGB versus dbh$_w$ for thicket clumps

Working conditions and resources required

Itigi thicket is characterized by densely interlaced bushes, often thorny and festooned with vines. The dense bushes restricted access to some thicket areas and prolonged time for data collection. A game scout was included in the field crew due to the presence of dangerous wild animals and this had an impact on the field cost and interfered with programme of work. Large number of stems in a clump was another challenge when measuring dbh and counting stems which could be as many as 60. When dealing with belowground component, sorting of roots was also a challenge due to interlocked roots from different clumps.

Compared with other vegetation types, destructive sampling of thicket clumps for the belowground component was easy (Plate 6.2). In addition to game scout and local guide, the crew for the above- and belowground components for both thicket and associate trees comprised of two persons regardless of the size of clump/tree. Equipment used during the sampling included Vernier callipers for dbh and root diameter measurements and Suunto hypsometer for ht measurements. Tape was used for measuring billets (logs) length, machetes to cut off thicket stems, a chainsaw to fell and crosscut associate trees. To remove soils from roots and for excavating, tools like hoe, spade and mattock were used. Spring balance was used to weigh billets while an electronic balance was used to weigh sub-samples.

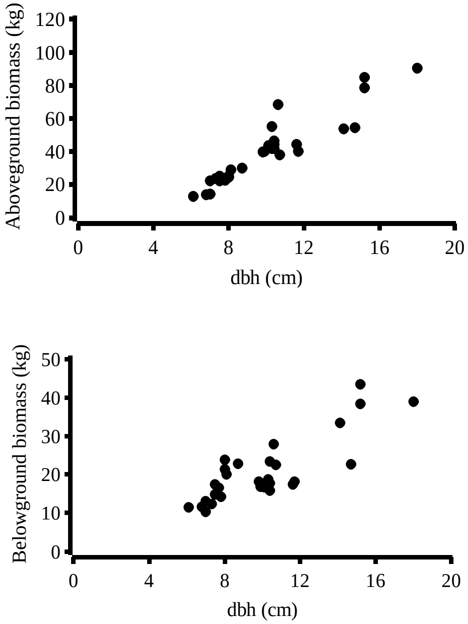


Figure 6.2. Scatter plots of AGB, BGB versus dbh for associate trees

Plate 6.2. Excavation of thicket clump (Photo Joseph Makero)

The cost estimates for destructive sampling of thicket are shown in Table 6.3. The costs are based on a daily task which targeted to accomplish (felling, excavating and measuring) four to six clumps and two to three associate trees.

Table 6.3. Cost estimates for destructive sampling

Item	Unit	Quantity	Unit Cost (TZS)
Labour cost for felling, excavating and measuring	day	4 clumps and 2 trees	90,000
Cost of game scout	day	1	30,000
Cost of local guide	day	1	30,000
Cost of hiring vehicle	day	1	60,000
Daily subsistence allowance	day	1	30,000
Lunch for crew	day	1	30,000
Total cost per day			**270,000**

Model fitting and evaluation

Biomass model forms 1 and 2 were tested for thicket and model forms 3 and 4 were tested for associate trees. Model forms 1 and 2 include dbh_w, ht and stem count (st) while model forms 3 and 4 include dbh and ht as independent variables:

$$B = \beta_0 \times dbh_w^{\beta 1} \times st^{\beta 2} \quad (1)$$
$$B = \beta_0 \times dbh_w^{\beta 1} \times ht^{\beta 2} \times st^{\beta 3} \quad (2)$$
$$B = \beta_0 \times dbh^{\beta 1} \quad (3)$$
$$B = \beta_0 \times dbh^{\beta 1} \times ht^{\beta 2} \quad (4)$$

where B is biomass (kg), β_0, β_1, β_2, β_3 are model parameters to be estimated.

The PROC NLN procedure in SAS software (SAS® Institute Inc., 2004) was used to estimate the model parameters (β_0, β_1, β_2, and β_3). The procedure produces the least squares estimates of the parameters of a nonlinear model through an iteration process.

The selection of final models was in general based on the Akaike Information Criterion (AIC). AIC takes into account the number of parameters in the models and penalize them accordingly. However, if a model had insignificant parameter estimates, it was not considered further. The coefficient of determination (R^2) and Root Mean Squared Error (RMSE) were reported for all models. In addition, relative mean prediction error was reported as:

$$\text{MPE (\%)} = \frac{100}{\text{MB}} \times \sum \left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass), and MB is mean observed biomass.

For volume, model forms 1 and 2 were used for thicket and model forms 4 and 5 were used for associate trees:

$$V = \beta_0 \times dbh_w{}^{\beta 1} \times st^{\beta 2} \qquad (5)$$
$$V = \beta_0 \times dbh_w{}^{\beta 1} \times ht^{\beta 2} \times st^{\beta 3} \qquad (6)$$
$$V = \beta_0 \times dbh^{\beta 1} \times ht^{\beta 2} \qquad (7)$$
$$V = \beta_0 + \beta_1 \times dbh^2 \qquad (8)$$

where V is volume (m^3) and other symbols are as defined for biomass models. Volume modelling and model selection procedures were as for the biomass models.

6.4 Biomass and volume models

Models for prediction of AGB, BGB and volume for the thicket clumps and associate trees are presented in Tables 6.4 and 6.5. For thicket clumps, the models utilise dbh, st and ht or dbh and st while for associate trees, the models use dbh only.

6.5 Application recommendations

The models for prediction of biomass and volume in Itigi thicket cover a wide range of thicket clump and tree sizes (i.e. dbh up to 3.2 cm, ht up to 6.5 m and st up to 57 for thicket clumps and dbh up to 18 cm and ht 7.2 m for associate trees). The models may be applied for all Itigi thicket vegetation in Tanzania. They may also be applied for other thicket species with similar morphology. The models for associate trees should only be applied in Itigi thicket stands.

Table 6.4. Biomass models for thicket and associate trees

Component	Species	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	*Combretum celastroides*	TH_S1S1_AGB_7	$B = 0.7269 \times dbh^{2.6710} \times ht^{0.5737} \times st^{0.2039}$	30	6.03	0.90	-0.2
	Pseudoprosopis fischeri	TH_S2S1_AGB_6	$B = 0.4276 \times dbh^{2.4053} \times st^{0.5290}$	30	9.14	0.90	0.1
	Associate trees	TH_MS1_AGB_1	$B = 1.2013 \times dbh^{1.5076}$	30	8.09	0.85	-0.5
BGB	*Combretum celastroides*	TH_S1S1_BGB_6	$B = 0.1006 \times dbh^{4.0062} \times st^{0.3499}$	30	3.53	0.82	-0.2
	Pseudoprosopis fischeri	TH_S2S1_BGB_6	$B = 0.1442 \times dbh^{4.1534} \times st^{0.4117}$	30	3.85	0.95	1.1
	Associate trees	TH_MS1_BGB_1	$B = 1.3803 \times dbh^{1.1671}$	30	4.73	0.69	0.2

Note: B = biomass (kg). For ticket clumps: dbh = basal area weighted mean dbh (cm) of all stems in clump, ht = height of tallest stem in clump (m), st = number of stems in clump. For associate trees: dbh = diameter at breast height (cm), ht = total tree height (m)

Table 6.5. Volume models for thicket and associate trees

Component	Species	Model ID	Model	n	RMSE (%)	R^2	MPE (%)
Total	*Combretum celastroides*	TH_S1S1_TV_7	$V = 0.00023 \times dbh^{2.4615} \times ht^{0.9089} \times st^{0.4534}$	30	31.8	0.69	1.2
	Pseudoprosopis fischeri	TH_S2S1_TV_7	$V = 0.00017 \times dbh^{2.2177} \times ht^{0.5468} \times st^{0.7903}$	30	23.3	0.93	0.5
	Associate trees	TH_MS1_TV_2	$V = 0.00042 \times dbh^{1.5009} \times ht^{0.6419}$	30	14.3	0.93	-0.1

Note: V = volume (m^3). For ticket clumps: dbh = basal area weighted mean dbh (cm) of all stems in clump, ht = height of tallest stem in clump (m), st = number of stems in clump. For associate trees: dbh = diameter at breast height (cm), ht = total tree height (m)

6.6 References

Cowling, R.M., Proches, S. and Vlok, J.H.J. (2005). On the origin of southern African subtropical thicket vegetation. South African Journal of Botany 7(1): 1 - 23.

FAO (2000). State of forest genetic resources in dry zone southern African development. Forest department. In: the SADC regional workshop on forest and tree genetic resources held in Nairobi, Kenya in December, 1999 and Arusha in June, 2000. 56pp. http://www.fao.org/docrep/005 > Retrieved on October 2012.

Kindt, R., Van Breugel, P., Lillesø, J.P.B., Bingham, M., De Missew, S., Dudley, C., Friis, I., Gachathi, F., Kalema, J., Mbago, F., Minani, V., Moshi, H.N., Mulumba, J., Namaganda, M., Ndangalasi, H.J., Ruffo, C., Jamnadass, R. and Graudal, L. (2011). Potential natural vegetation of eastern Africa. Volume 4: Description and tree species composition for bushland and thicket potential natural vegetation types. Forest and Landscape Working Paper 64-2011. 111pp.

MNRT (2008). Management plan of Agondi National Bee Reserve for 2008- 2013. Forestry and Beekeeping Division, MNRT. 27pp.

SAS Institute Inc. (2004). SAS Institute Inc., Cary, NC, USA. 218pp.

Vlok, J.H.J., Euston-Brown, D.I.W. and Cowling, R.M. (2003). Acocks' valley bush veld 50 years on: new perspectives on the delimitation, characterisation and origin of subtropical thicket vegetation. South African Journal of Botany 69: 27 - 51.

WWF (2008). Itigi-Sumbu thicket. In: Encyclopedia of Earth. Eds. Cleveland, C.J. (Washington, D.C.: Environmental information coalition, National Council for Science and the Environment). http://www.eoearth.org/article/Itigi-Sumbu_thicket > Retrieved on May 2012. (Online document)

7 ALLOMETRIC BIOMASS AND VOLUME MODELS FOR *ACACIA-COMMIPHORA* WOODLANDS

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7.1 Background

Acacia-Commiphora woodlands are dominated by mainly two thorn-bush genera of *Acacia* and *Commiphora*. The genus for *Acacia* is made up of mainly evergreen trees and shrubs in the family Fabaceae (Ross, 1981). The genus for *Commiphora* species is composed of most flowering plants in the family Burseraceae. They are native to tropical and subtropical regions of the world, particularly Australia and Africa (Hayward, 2004) where they dominate different ecological regions as they can sustain growth in semi-arid and arid dry areas with mean annual rainfall of up to 800 mm (Marshall et al., 2012). In Tanzania, *Acacia-Commiphora* woodlands are widely distributed in the central and northern dry lowlands and fall mostly within the Somali-Masai phytochorion (URT, 2001; URT, 2003; Marshall et al., 2012).

Despite of high distribution of *Acacia-Commiphora* woodlands in Tanzania, their potential to sequester carbon dioxide and hence their contribution to climate change mitigation is not known. In order to get reliable estimates of carbon stocks, forest type specific biomass and volume allometric models are needed. However, such models are currently lacking.

Therefore, this chapter describes the newly developed aboveground biomass (AGB), belowground biomass (BGB) and volume models for *Acacia-Commiphora* woodlands based on sample trees from Kiteto and Same districts in Manyara and Kilimanjaro regions respectively. The set of models comprises general and site-specific models for predicting biomass and volume of different components of individual trees.

7.2 Site description

In Same district, this study was carried out at Mkonga forest reserve. The forest is located in the semi-arid plains of the western Pare lowlands with mean annual rainfall ranging approximately from 400 to 600 mm. Mkonga forest reserve is located 8 km away from Same district town centre along Moshi to Dar es Salaam road. The forest has a total area of 520 ha and was gazetted in 1986.

In Kiteto district, this study was carried out in Kimana village which covers an area of 55,194.76 hectares (ha). Traditionally, a greater portion of the district is designated as a game controlled area and it forms the eastern corridor of Maasai Steppe (Olekao, 2011). In this vegetation, an estimated area of more than 2000 ha has been allocated for pastoral activities in Kimana village. Out of this, about 1500 ha was delineated for this study, excluding grassland area with no trees. The area falls under Southern *Acacia-Commiphora* bushland and thicket ecoregion (Burgess et al., 2004). Description of both study sites is presented in Table 7.1.

Table 7.1. Study sites description

Region	**District**	**Location**	**Dominant soil type**	**Altitude (m)**	**Mean annual temperature (°C)**
Kilimanjaro	Same	04° 02’ - 04°37’ S 37° 48’ - 38° 04’ E	Loamy soils	2133	16 -32
Manyara	Kiteto	04° 31’ - 06° 03’ S 36° 15’ - 37°25’ E	Black cotton soils and clay sandy soils	1325	22

7.3 Data collection and analysis

Selection of sample trees

To get information on tree species composition and sizes, forest inventory was carried out in both sites. The National Forest Resource Monitoring and Assessment (NAFORMA) concentric plot design was applied in this study (URT, 2010). The information collected from forest inventory guided the selection of trees for destructive sampling. Trees were selected randomly within the plots in order to capture different tree sizes and species. Selected trees were measured for both diameter at breast height (dbh) and total height (ht) using calliper and Suunto hypsometer respectively. The numbers of tree species were 15 and 12 in Same and Kiteto respectively and overall the number was 22. Summary statistics of tree parameters are presented in Table 7.2.

Table 7.2. Summary statistics of sample trees used for developing biomass and volume models

Component	**Site**	**n**	**dbh (cm)**			**ht (m)**		
			Mean	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
ABG	Same	60	14.0	2.5	30.3	6.1	1.5	10.5
	Kiteto	50	22.2	5.9	79.2	7.7	3.9	14.9
	All	110	17.8	2.5	79.2	6.8	1.5	14.9
BGB	Same	60	14.0	2.5	30.3	6.1	1.5	10.5
	Kiteto	50	22.2	5.9	79.2	7.7	3.9	14.9
	All	110	17.8	2.5	79.2	6.8	1.5	14.9
Volume	Same	60	14.0	2.5	30.3	6.1	1.5	10.5
	Kiteto	50	22.6	5.9	79.2	7.8	3.9	14.9
	All	110	18.6	4.5	79.2	7.1	2.5	14.9

Destructive sampling and biomass determination

Trees selected for biomass determination were first divided into above- and belowground components. The aboveground component comprised of all biomass above a stump height of 15 cm above ground. Descriptions of field procedure for above-and belowground components (both data for volume and biomass) are as described in Chapter 3. Similarly, procedures for determination of component's volume, BGB and AGB are as described in Chapter 3. Scatter plots of AGB, BGB and total volume versus dbh for individual trees are displayed in Figure 7.1.

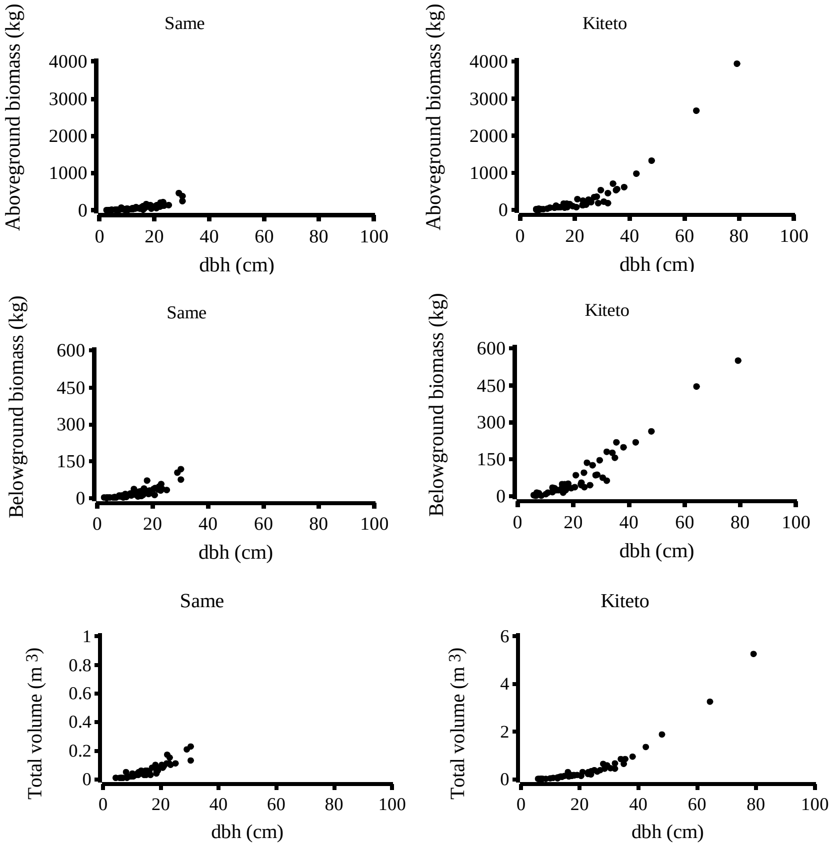

Figure 7.1. Scatter plots of ABG, BGB and total volume versus dbh

Working conditions and resources required

Working conditions within Mkonga forest reserve varied from plot to plot and transect to transect. There was a slight variation in terrain and soil conditions with regard to different plots and transects. Terrain conditions also had an impact on the amount of work required at the specific working area.

The field team comprised a total of ten people. These included the researcher, research assistant (1), chainsaw operator (1), casual labourers (6), local tree identifier (1) and a cook. For casual labourers, the mode of payment was by piece of work, where 60 sample trees were excavated, separated from branches and twigs and cut into convenient lengths for green weight determination. Each casual labourer was paid a total of TZS 350,000 after completion of the field work. The labourers were closely supervised to ensure quality of data and safety. The chainsaw operator and local tree identifier were paid TZS 200,000 and 300,000 respectively. The research assistant was paid TZS 650,000 after completion of the field work. Other costs included chainsaw maintenance, fuel for chainsaw, chainsaw chains, transport fare for researcher and research assistant, food, and other equipment, i.e. one digital balance, two weigh scale, four hoes, five machetes, four spades, five mattocks, two iron brushes, envelopes and ropes (Table 7.3). It should be noted that the cost estimates in Table 7.3 do not include per diem for researcher and research assistant and cost for forest inventory equipment.

The field work was accomplished in 21 days. Lunch was provided during the field work. The number of trees destructively sampled per day varied depending on working conditions that included topography, presence and distribution of thorny shrubs and trees and the size of the trees to be sampled.

Equipment used during the sampling included callipers for measuring dbh, stump, billet mid-diameter and root base diameter; and Suunto hypsometer for measuring ht. Tape was used for measuring length of billets, machetes to cut off small branches, a chainsaw to fell and crosscut a tree. Hoes, spades, iron brushes and mattocks were used for excavation and removal of soils from roots. Spring balance was used to weigh billets of tree stem and branches while electronic balance was used to weigh sub-samples for laboratory analysis.

Table 7.3. Cost estimates for destructive sampling

Item	**Cost (TZS)**
Total cost for 60 sample trees (allowances for casual labourers)	2,100,000
Cost of fuel for Chainsaw for the total sampled trees	156,000
Food per day per person TZS 3,500 for 21 days	735,000
Cost per chainsaw chain	120,000
Other cost (e.g. chainsaw maintenance, spades, spring balance, hoes, iron brushes, machetes)	434,000
Total cost	**3,545,000**
Cost per tree	**59,080**

Model fitting and evaluation

Model forms commonly reported in literature (Zianis et al., 2005; Mugasha et al., 2013; Masota et al., 2014; Mauya et al., 2014) which use either dbh only or both dbh and ht as independent variables were applied to fit biomass and volume component models. Mixed effect modelling approach was used to fit general models to accommodate the variation among sites using PROC NLMIXED, a procedure in SAS while site specific models were fitted by non-linear procedure in SAS (PROC NLP) (SAS®, 2008).

Evaluation of models performance to achieve candidate allometric models was based on significance of parameter estimates, high value of R^2, low values for RMSE and relative mean prediction error, logical behaviour of the models and simplicity of the models. Relative mean prediction error was reported as:

$$\mathrm{MPE}\ (\%) = \frac{100}{\mathrm{MB}} \times \sum \left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass or volume), and MB is mean observed biomass or volume.

During evaluation, candidate models with insignificant parameter estimates were omitted. Finally, the selection of the best models was based on lower Akaike's Information Criterion (AIC) (e.g. Chave et al., 2005). AIC was computed as follows:

$$\mathrm{AIC} = -2\ln(\mathrm{l}) + 2\mathrm{p}$$

where l is the likelihood of the fitted model, ln is natural logarithm and p is the total number of parameters in the model.

7.4 Biomass and volume models

For all the general models predicting biomass, i.e. AGB, BGB, stem biomass, there are two options: 1) with dbh only and 2) with both dbh and ht as independent variables (Table 7.4). For all the site-specific AGB and BGB models, there are also two options i.e. with dbh only and with both dbh and ht as independent variables (Table 7.5).

For the general total volume models, two options of models are presented, i.e. a model with dbh only and a model with both dbh and ht (Table 7.6). For the site specific total volume, branches and stem there are two optional models i.e. with dbh only and with both dbh and ht as independent variables (Table 7.7).

7.5 Application recommendations

In this study, two sites were sampled to represent the central and northern *Acacia-Commiphora* woodlands. Because of this, the presented models cover wide ranges of conditions regarding climate, topography and soils and tree sizes (dbh up 79 cm). All the general models can therefore be applied to most *Acacia-Commiphora* woodlands in Tanzania with an appropriate accuracy in predictions. It is recommended that the site-specific models are applied to local inventories in their respective sites.

Alternative models for predicting biomass and volume are presented: 1) with dbh only and 2) with both dbh and ht as independent variables. Both alternatives can be applied with a reasonable certainty, provided that appropriate information on ht is available. Since including ht only marginally increased the explanation of the biomass and volume variations in the modelling data, it is recommended that models with dbh only be used. However, it is recommended to use models with both dbh and ht in predictions for larger trees (dbh > 100 cm) because ht moderates the effect of dbh on biomass and volume predictions as compared to if dbh only is applied.

The recommendations given above also generally apply to the tree component biomass and volume models (branches and merchantable stem). The definitions of each component as described in Chapter 3.3 should be carefully considered when applying these models.

Table 7.4. General biomass models for *Acacia-Commiphora* woodlands

Component	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	AC_MM_AGB_1	$B = 0.3154 \times dbh^{2.3189}$	110	72.4	0.97	-5.4
	AC_MM_AGB_2	$B = 0.0292 \times dbh^{2.0647} \times ht^{1.0146}$	110	59.5	0.98	-3.9
BGB	AC_MM_BGB_1	$B = 0.0915 \times dbh^{1.9820}$	110	23.2	0.92	10.9
	AC_MM_BGB_2	$B = 0.0593 \times dbh^{1.4481} \times ht^{1.0210}$	110	19.2	0.94	9.0
Merchantable stem	AC_MM_MSB_1	$B = 0.0311 \times dbh^{2.6176}$	110	62.2	0.98	0.3
	AC_MM_MSB_2	$B = 0.0223 \times dbh^{2.0926} \times ht^{0.9586}$	110	55.6	0.98	0.9

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 7.5. Site-specific biomass models for *Acacia-Commiphora* woodlands

Component	Site	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	Same	AC_MS1_AGB_1	$B = 0.1068 \times dbh^{2.3213}$	60	40.7	0.82	3.8
		AC_MS1_ABG_2	$B = 0.0292 \times dbh^{2.0476} \times ht^{1.0146}$	60	39.5	0.83	1.3
	Kiteto	AC_MS2_ABG_1	$B = 0.1879 \times dbh^{2.2904}$	50	95.0	0.98	-0.1
		AC_MS2_ABG_2	$B = 0.1050 \times dbh^{2.0423} \times ht^{0.6205}$	50	83.7	0.98	1.8
BGB	Same	AC_MS1_BGB_1	$B = 0.0811 \times dbh^{1.9946}$	60	8.7	0.78	10.1
		AC_MS1_BGB_2	$B = 0.0766 \times (dbh^2 \times ht)^{0.7630}$	60	5.6	0.85	10.1
	Kiteto	AC_MS2_BGB_1	$B = 0.3867 \times dbh^{1.6749}$	50	26.3	0.94	-3.4
		AC_MS2_BGB_2	$B = 0.2504 \times (ht \times dbh^2)^{0.6775}$	50	21.5	0.96	-2.7

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 7.6. General volume models for *Acacia-Commiphora* woodlands

Component	Model ID	Model	n	RMSE (m^3)	R^2	MPE (%)
Total	AC_MM_TV_1	$V = 0.000142 \times dbh^{2.3008}$	110	0.1	0.98	8.0
	AC_MM_TV_2	$V = 0.00009 \times dbh^{2.0993} \times ht^{0.4914}$	110	0.1	0.98	2.1

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 7.7. Site-specific volume models for *Acacia-Commiphora* woodlands

Component	Site	Model ID	Model	n	RMSE (m^3)	R^2	MPE (%)
Total	Same	AC_MS1_TV_1	$V = 0.0005 \times dbh^{1.7091}$	55	0.18	0.84	6.0
		AC_MS1_TV_2	$V = 0.00022 \times dbh^{1.823} \times ht^{0.494}$	55	0.14	0.85	2.8
	Kiteto	AC_MS2_TV_1	$V = 0.0002 \times dbh^{2.3269}$	49	0.13	0.99	-1.4
		AC_MS2_TV_2	$V = 0.00013 \times dbh^{2.1555} \times ht^{0.4352}$	49	0.15	0.99	0.2
Branches	Same	AC_MS1_BV_1	$V = 0.0002 \times dbh^{1.8123}$	55	0.07	0.48	9.9
		AC_MS1_BV_2	$V = 0.00004 \times (dbh^2 \times ht)^{0.887}$	55	0.06	0.56	8.82
	Kiteto	AC_MS2_BV_1	$V = 0.0205 + 0.000015 \times dbh^2$	49	0.05	0.19	0.01
		AC_MS2_BV_2	$V = 0.0018 \times (ht \times dbh^2)^{0.3486}$	49	0.06	0.27	-1.6
Merchantable stem	Same	AC_MS1_MSV_1	$V = 0.00009 \times dbh^{2.0115}$	55	0.12	0.31	-6.9
		AC_MS1_MSV_2	$V = 0.0002 \times (dbh^2 \times ht)^{0.760}$	55	0.11	0.93	2.3
	Kiteto	AC_MS2_MSV_1	$V = -0.1308 + 0.000807 \times dbh^2$	49	0.11	0.98	-0.01
		AC_MS2_MSV_2	$V = 0.000089 \times dbh^{2.2036} \times ht^{0.5039}$	49	0.13	0.99	0.2

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m).

7.6 References

Burgess, N., Hales, J.D., Underwood, E., Dinerstein, E., Olson, D., Houa, I., Schipper, J., Ricketts, T. and Newman, K. (2004). Terrestrial ecoregions of Africa and Madagascar: A Conservation Assessment. Island Press, Washington, Covelo, London.

Chave. J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Rie´ra, B. and Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145: 87–99.

Hayward, B. (2004). The Acacia tree: A sustainable resource for Africa. An overview of research conducted by the Oxford Forestry Institute, the Natural Research Councils (NERC) Centre for Ecology and Hydrology (formerly the NERC Institute of Terrestrial Ecology) and the University of Dundee with partners in Finland, Kenya, Senegal, South Africa, Sudan, the UK and Zimbabwe. 48pp.

Marshall, A.R., Platts, P.J., Gereau, R.E., Kindeketa, W., Kangethe, S. and Marchant, R. (2012). Genus Acacia (Fabaceae) in East Africa: Distribution, diversity and the protected area network. Plant Ecology and Evolution 145: 289–301.

Masota, A.M., Zahabu, E., Malimbwi, R.E., Bollandsås, O.M., and Eid, T. (2014). Volume models for single trees in tropical rainforests in Tanzania. Journal of Energy and Natural Resources 3: 66-76.

Mauya, E., Mugasha, W.A, Zahabu, E., Bollandsås, O.M and Eid, T. (2014). Models for estimation of tree volume in the miombo woodland of Tanzania. Southern Forests 76: 209-219.

Mugasha, W.A., Eid, T., Bollandsås O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J. (2013). Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecology and Management 310: 87–101.

Olekao, S.K. (2011). A profile of KINNAPA development programme.14 pp.

Ross, J.H. (1981). Analysis of the African Acacia species: their distribution, possible origins and relationships. Bothalia 13: 389–413.

SAS® Institute Inc. (2008). SAS/ETS user's guide, version 9.2. Cary, NC: SAS Institute Inc.218pp.

URT (2001). National report on the implementation of the Convention on Biological Diversity. Division of Environment. Vice President's Office. 79pp.

URT (2003). Initial national communication under the United Nations Framework Convention on Climate Change (UNFCCC). The Vice President's Office. 40pp.

URT (2010). Field manual biophysical survey. Ministry of Natural Resources and Tourism. 108pp.

Zianis, D., Muukkonen, P., Mäkipää, R. and Mencuccini, M. (2005). Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs 4. 63pp.

8 ALLOMETRIC BIOMASS MODELS FOR *PINUS PATULA* PLANTATIONS

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8.1 Background

Large scale establishment of forest plantations in Tanzania started in the 1950s after some years of species and provenance trials. To date, forest plantation area in Tanzania is estimated to be about 554,500 hectares (ha) of which 95,000 ha is owned by government, 40,000 ha is privately owned and about 419,500 ha of woodlots are owned by small farmers (MNRT, 2015). Among the six planted tree species (*Pinus patula, P. elliottii, P. caribaea*, Cypress, *Eucalyptus* and *Tectona grandis*), pines are the most abundant with about 78% of the total area while the remaining 22% is shared among hardwoods and other softwood tree species (Ngaga, 2011).

Tree plantations were established mainly to fulfil the increasing demand for wood while at the same time reducing communities' dependence on the natural forests (Ngaga, 2011). For small woodlots holders, tree planting serves as a major income generating activity in some areas of Tanzania (see e.g. Malimbwi et al., 2010). While the motivation of plantation establishment were solely based on the direct benefits, i.e. poles and timber, forest plantations also have the potential to qualify for the Clean Development Mechanism (CDM) and Reducing Emission from Deforestation and forest Degradation (REDD+) schemes (Kongsager et al., 2013) because of their ability to store carbon (C).

However, the implementation of C market schemes require reliable ground-based monitoring, reporting and verification tools of C storage including allometric biomass models (Asner et al., 2010). A number of *Pinus patula* aboveground biomass (AGB) models have been developed elsewhere (e.g. Henry et al., 2009). Accurate estimation of tree biomass requires the use of local allometric models. Due to growth conditions variability, application of models developed elsewhere may result in unreliable estimates (e.g. Mugasha et al., 2013; Chave et al., 2014). In addition, developing local allometric biomass models comprehends with the higher level of Tiers for C reporting proposed by the Intergovernmental Panel for Climate Change (IPCC) (IPCC, 2003).

It is against this background that this chapter presents AGB and belowground biomass (BGB) models for *Pinus patula* plantations in Tanzania. The set of models comprise general and site-specific models predicting biomass of different components of individual trees.

8.2 Site description

This study was carried out in two locations namely Sokoine University of Agriculture training forest (SUATF) in Arusha and Sao Hill government forest plantation in Iringa. SUATF covers a total area of about 840 ha. It is bordered by Meru forest plantation to the east and west, Arusha national park to the north and villages to the south. Most parts of the training forest are mountainous with slopes ranging from gentle to steep. The planted area of Sao Hill forest plantation is estimated to be about 45,000 ha out of total gazetted area of 95,000 ha (Ngaga, 2011). Details of locations and conditions regarding the sites are described in Table 8.1.

Table 8.1. Study sites description

Forest	Location	Soil type	Altitude (m)	Mean annual temperature (°C)		Mean annual rainfall (mm)
				Min.	Max.	
SUATF	03° 15' - 03° 18' S 36° 41' - 36° 42' E	Volcanic soil	1,740-2,320	8	24	1,040
Sao Hill	08° 18'- 08° 33' S 35° 06'- 35° 20' E	Dystric nitisols	1,700-2,000	10	20	900

8.3 Data collection and analysis

Selection of sample trees

To appropriately represent biomass variation among trees, six compartments representing different tree sizes and ages were selected. The ages ranged between four and 31 years (4, 7, 13, 16, 28 and 31) and between five and 31 years (5, 9, 15, 21, 26 and 31) in SUATF and Sao Hill forest plantations respectively. In each selected compartment, forest inventories were carried out where at least 20 plots of 15 m radius were laid out depending on the compartment size. In each plot, all trees were measured for diameter at breast height (dbh) and three trees (smallest, medium and largest) were selected and measured for total tree height (ht). Forest inventory information guided the selection of sample trees for destructive sampling. At least seven trees, representing wide range in terms of dbh were selected for destructive sampling in each age class. The total number of sample trees were 35 and 50 in Sao Hill and SUATF forest plantations respectively. Summary statistics of the selected sample trees are presented in Table 8.2.

Destructive sampling and biomass determination

A sample tree was divided into two main sections i.e. above- and belowground. AGB was considered to be all biomass above the ground level and it was further divided into three sections:

- Stem (trunk section of tree with minimum trunk top diameter of 15 cm).
- Branches (non-stem section) including top (up to diameter of 1 cm).
- Twigs (with diameter less than 1 cm).

Table 8.2. Summary statistics of sample trees used for developing biomass models

Component	Site	n	dbh (cm)			ht (m)		
			Mean	Min.	Max.	Mean	Min.	Max.
AGB	SUATF	50	31.1	4.3	65.0	20.6	4.0	33.0
	Sao Hill	35	19.9	1.0	46.0	16.9	2.0	31.0
BGB	SUATF	50	31.1	4.3	65.0	20.6	4.0	33.0
	Sao Hill	35	19.9	1.0	46.0	16.9	2.0	31.0
	All	85	26.5	1.0	65.0	19.1	2.0	33.0

Stem and branches were cross-cut to manageable billets and weighed for fresh weight. Twigs were collected in bundles and weighed. From each section, a total of three samples were collected, weighed and labelled for laboratory analysis to determine dry to fresh weight ratio (DF-ratio).

For BGB, the root sampling procedure which considers main roots (root initiating from root crown), side roots (roots initiating from main root) and root crown developed by Mugasha et al. (2013) was implemented. In this procedure, three main roots (small, medium and largest) were measured for basal diameter and excavated. Other unexcavated main roots were only measured for basal diameter. Three sample side roots initiating from main roots were also measured for basal diameter and fully excavated. Other side roots were only measured for basal diameter. Excavated roots and root crown were cleaned from soils and measured for fresh weight and at least two samples were collected from each section for laboratory work (for details, see Mugasha et al., 2013).

In the laboratory, the collected samples were oven dried at 105 ± 2^{o}C for at least 72 hours until they retained a constant weight. Thereafter, average DF-ratios were computed for each component of individual trees.

Tree component biomass was obtained as the product of fresh weight and DF-ratio. Total AGB was obtained by summation of biomass of all aboveground components i.e. branch, stem and twigs. Total BGB was obtained by summation of biomass of root crown and roots. Scatter plots of AGB and BGB versus dbh for individual trees are displayed in Figure 8.1.

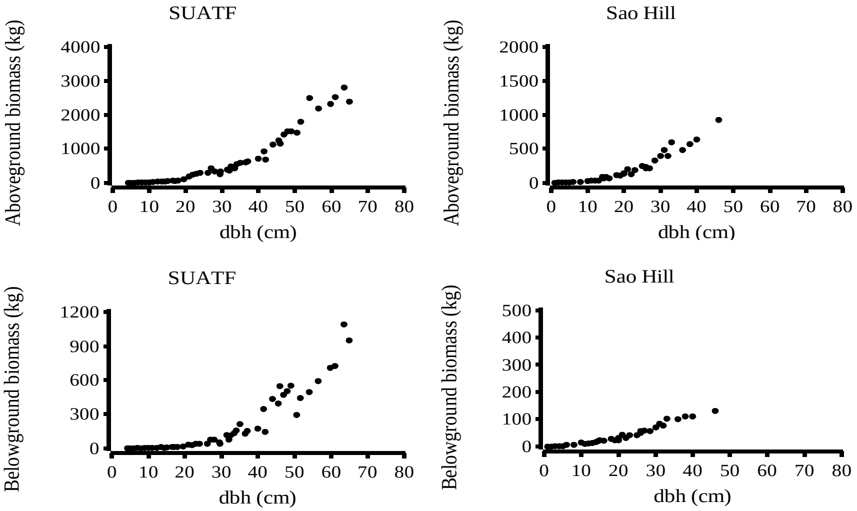

Figure 8.1. Scatter plots of ABG and BGB versus dbh

Working conditions and required resources

Working conditions between the study sites varied. The slope of the terrain at SUATF was higher compared to the flat terrain at Sao Hill. The main challenge was related to the forest density where hang up trees was the main challenge in both sites. This also affected processing of belowground component. Despite the fact that soils were easy to excavate in both sites, the close spacing between trees made excavation difficult due to interlocking roots.

Equipment used during the sampling included callipers for dbh and root diameter measurements and Suunto or Vertex hypsometer for ht measurements. Tapes were used for measuring length of billets, machetes to cut off small branches, a chainsaw to fell a tree and crosscut the stem and large branches. Hoes, spades and mattocks were used for excavation while iron brush was used to remove soils from roots. A spring balance was used to weigh billets and branches while an electronic balance was used to weigh sub-samples.

Generally, processing aboveground tree components was easier than belowground components. Likewise, processing large trees (dbh > 30 cm) was more challenging compared to small trees (dbh < 30 cm). Working with trees with dbh larger than 35 cm required one day to process both above- and belowground tree components. Each component, i.e. above- and belowground, had one crew each with five members. Each crew member was paid TZS 15,000 per day. This work took 52 days to process 85 trees. In addition, there were one researcher, one research assistant and one chainsaw operator. Cost estimates for destructive sampling are presented in Table 8.3. It should be noted that allowances to researcher and research assistant were not included.

Table 8.3. Cost estimates for destructive sampling

Item	Units/ days/litres	Unit Cost (TZS)	Total cost (TZS)
Labourer (10 local labourer for 52 days)	520	15,000	7,800,000
Chainsaw operator for 52 days)	52	25,000	1,300,000
Chainsaw chains	15	45,000	675,000
Hiring a chainsaw (per day)	52	20,000	1,040,000
4 litres of fuel for chainsaw per day for 52 days	210	7,500	1,575,000
Other equipment	Lump sum	250,000	250,000
Total cost			**12,640,000**
Cost per tree			**148,706**

Model fitting and evaluation

To fit biomass, four model forms were tested. One of the model forms included dbh only, one model form included ht in addition, and two model forms included dbh, ht and age as follows:

$$\mathrm{B} = \beta_1 \times \mathrm{dbh}^{\alpha} \qquad (1)$$
$$\mathrm{B} = \beta_1 \times \mathrm{dbh}^{\alpha} \times \mathrm{ht}^{\beta_3} \qquad (2)$$
$$\mathrm{B} = \exp[\beta_1 + \alpha \times \ln(\mathrm{dbh}) + \beta_3 \times \ln(\mathrm{age})] \qquad (3)$$
$$\mathrm{B} = \exp[\beta_1 + \alpha \times \ln(\mathrm{dbh}) + \beta_3 \times \ln(\mathrm{ht}) + \beta_4 \times \ln(\mathrm{age})] \qquad (4)$$

where β's are parameter estimates, exp: exponent, ln: natural logarithm and B: dependent variable i.e. AGB and BGB, stem and branches biomass, α is a parameter set to vary with sites as follows: $\alpha = \beta_2 + \mu$ where μ is random site effect.

Parameter estimates of the resulting general (combining data from both sites) non-linear mixed effect models were estimated by maximum likelihood method using the PROC NLINMIX procedure in SAS (SAS Institute Inc., 2008) while for site-specific models, parameter estimates of non-linear models were estimated by maximum likelihood approach using PROC NLP procedure in SAS (SAS Institute Inc., 2003). To select among alternative models, significant parameters and AIC were considered. This was also applied to selected site-specific models. Relative mean prediction error was reported as:

$$\mathrm{MPE}\ (\%) = \frac{100}{\mathrm{MB}} \times \sum \left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass), and MB is mean observed biomass.

8.4 Biomass models

For all the general models predicting biomass, i.e. AGB and branches, there are two options; 1) with dbh only and 2) with both dbh and ht as independent variables (Table 8.4). For BGB, and stem biomass, models with only dbh are presented. Site-specific models with different combinations of independent variables are presented in Table 8.5.

8.5 Application recommendations

The presented models for prediction of biomass of *Pinus patula* in Tanzania were developed based on data from one plantation in northern highlands (SUATF) and one plantation in southern highlands (Sao Hill). They cover wide ranges of conditions regarding climate, topography, soils and tree sizes (dbh up to 65 cm). All the general models can therefore be applied to predict biomass of *P. patula* plantations in Tanzania with an appropriate accuracy. It is however recommended that the site-specific models be applied for local inventories in their respective sites.

There are two models for predicting biomass: 1) with dbh only and 2) with both dbh and ht as independent variables. Both models may be applied with reasonable certainty, provided that appropriate information on ht is available from forest inventory. It should be noted that the inclusion of ht improves prediction of AGB (both general and site specific) and stem component (site-specific models). This is reflected with higher MPE% in most cases when using dbh alone (Tables 8.4 and 8.5) .

Table 8.4. General biomass models for *Pinus patula* plantations

Component	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	PI_S1M_AGB_1	$B = 0.0550 \times dbh^{2.5968}$	85	113.6	0.97	5.5
	PI_S1M_AGB_2	$B = 0.0357 \times dbh^{2.4679} \times ht^{0.2809}$	85	11.2	0.97	1.5
BGB	PI_S1M_BGB_1	$B = 0.0027 \times dbh^{3.0579}$	85	59.2	0.93	0.7
Stem	PI_S1M_SB_1	$B = 0.0385 \times dbh^{2.6449}$	72	91.3	0.97	5.2
Branches	PI_S1M_BB_1	$B = 0.6227 \times dbh^{0.9692}$	82	86.7	0.61	24.1
	PI_S1M_BB_2	$B = 0.0357 \times dbh^{2.4679} \times ht^{0.2809}$	82	88.7	0.59	20.1

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 8.5. Site-specific biomass models for *Pinus patula* plantations

Component	Site	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	SUATF	PI_S1S1_AGB_1	$B = 0.0304 \times dbh^{2.7590}$	50	143.7	0.97	7.4
	SUATF	PI_S1S1_AGB_2	$B = 0.0124 \times dbh^{2.1643} \times ht^{0.9574}$	50	139.2	0.97	2.9
	Sao Hill	PI_S1S2_AGB_1	$B = 0.1564 \times dbh^{2.2711}$	35	41.7	0.97	-1.8
	Sao Hill	PI_S1S2_AGB_2	$B = 0.1298 \times dbh^{2.0096} \times ht^{0.3390}$	35	41.8	0.97	-4.1
BGB	SUATF	PI_S1S1_BGB_1	$B = 0.0018 \times dbh^{3.1697}$	50	68.1	0.94	7.8
	Sao Hill	PI_S1S2_BGB_1	$B = 0.1551 \times dbh^{1.7915}$	35	6.4	0.97	5.2
	Sao Hill	PI_S1S2_BGB_2	$B = 0.1405 \times dbh^{1.6111} \times ht^{0.2248}$	35	5.7	0.98	6.3
Stem	SUATF	PI_S1S1_SB_1	$B = 0.0327 \times dbh^{2.6879}$	44	119.8	0.97	10.0
	SUATF	PI_S1S1_SB_2	$B = 0.0055 \times dbh^{2.1518} \times ht^{1.1617}$	44	117.9	0.98	3.2
	Sao Hill	PI_S1S2_SB_1	$B = 0.0587 \times dbh^{2.5181}$	28	55.9	0.93	11.3
	Sao Hill	PI_S1S2_SB_2	$B = 0.0327 \times dbh^{1.5634} \times ht^{1.1884}$	28	51.9	0.94	2.0
Branches	SUATF	PI_S1S1_BB_1	$B = 0.0005 \times dbh^{3.3553}$	47	77.7	0.80	-3.1
	Sao Hill	PI_S1S2_BB_1	$B = 0.0099 \times dbh^{2.3679}$	35	14.6	0.70	1.8

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

8.6 References

Asner, G.P., Powell, G.V., Mascaro, J., Knapp, D.E., Clark, J.K., Jacobson, J., Kennedy-Bowdoin, T., Balaji, A., Paez-Acosta, G. and Victoria, E. (2010). High-resolution forest carbon stocks and emissions in the Amazon. Proceedings of the National Academy of Sciences 107: 16738-16742.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G. and Vieilledent, G. (2014). Improved pantropical allometric models to estimate the above ground biomass of tropical forests. Global Change Biology 20: 3177–3190.

Henry, M., Tittonell, P., Manlay, R., 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 & environment 129: 238-252.

IPCC (2003). Good practice guidance for land use, land-use changes and forestry. Institute of Global Environmental Strategies, Kanagawa, Japan. 420pp.

Kongsager, R., Napier, J. and Mertz, O. (2013). The carbon sequestration potential of tree crop plantations. Mitigation and Adaptation Strategies for Global Change 18: 1197-1213.

Malimbwi, R.E., Zahabu, E., Katani, J.Z., Mugasha, W.A. and Mwembe, U. (2010). Woodlot management guidelines for smallholder farmers in Makete District. ISBN 978-9987-640-55-3. 17pp

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

Mugasha, W.A., Eid, T., Bollandsås, O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J.Z. (2013). Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecology and Management 310: 87-101.

Ngaga, Y.M. (2011). Forest plantation and woodlots in Tanzania. African Forest Forum Working Paper Series 1:16. 30pp.

SAS. 2003. STAT User’s Guide Version 9.1. SAS Institute Inc., Cary, NC. 218pp.

SAS® Institute Inc. 2008. SAS/ETS User’s Guide, Version 9.2. Cary, NC: SAS Institute Inc. 4086pp.

9 ALLOMETRIC BIOMASS AND VOLUME MODELS FOR *TECTONA GRANDIS* PLANTATIONS

Zahabu, E., Mugasha, W.A., Katani, J.Z., Malimbwi, R.E., Mwangi, J.R. and Chamshama, S.A.O.

9.1 Background

Large scale establishment of forest plantations in Tanzania started in the 1950s after a series of species and provenance trials. The gross area of forest plantations in year 2015 was estimated to be 554,500 hectares (ha). Out of this, the total area of industrial plantations (private and government) is 135,000 ha while that of woodlots is 419,000 ha (MNRT, 2015). The main planted species in government plantations include *Pinus patula, P. elliottii* and *P. caribaea*), cypress (mainly *Cupressus lusitanica*), *Eucalyptus* (several species), and teak (*Tectona grandis*). The Government owns two teak plantations, i.e. Mtibwa (1,410 ha) and Longuza (2,450 ha) (Ngaga, 2011).

The objectives of establishing forest plantations in Tanzania were to ensure sustainable supply of forest products and services. Teak has excellent properties with wide range of uses, including flooring, decking, framing, cladding and barge boards. In the decorative line, it can be used for lining, panelling, carving, furniture (both indoor and outdoor) and parquetry (Cacho et al., 2003). As such it is an excellent alternative to the dwindling fine hardwood species such as *Pterocarpus angolensis* and *Milicia excelsa.*

Forest plantations play a significant role to sequester atmospheric carbon dioxide (Kongsager et al., 2013). However, estimation of forest carbon requires allometric biomass models. In addition, tree volume models are required for general forest management purposes including timber licensing and pricing. Previous efforts in plantation forests were geared to quantifying tree growth and volume towards obtaining merchantable volume (Malimbwi, 1987; Malimbwi et al., 1998). For teak, data for quantifying tree growth and volume was obtained from government plantations. Furthermore, a biomass model for teak in Mtibwa plantation forest has been developed (Okting'ati et al., 1998). There are no biomass models developed for Longuza teak plantation.

The aim of this chapter is to describe recently developed biomass and volume models for the teak plantation in Longuza, Tanzania. The models developed in this study are for predicting biomass and volume of different tree components. Although there are existing volume models for Longuza (Malimbwi et al., 1998), the data collected for biomass in this study were used to develop new volume models for comparison with the existing models.

9.2 Site description

Data for development of biomass and volume models were collected from Longuza forest plantation (4°55'- 5°10'S and 38°40'- 39°00' E), Muheza district, Tanga region. The altitude ranges from 160 to 560 m. The mean annual rainfall is 1,500 mm with annual temperature range of 27 to 32 °C. The soils are loamy sandy.

9.3 Data collection and analysis

Selection of sample trees

In order to obtain representative data for tree sizes and ages, six strata were established based on age. These strata were 1-5 years, 6-10 years, 11-15 years, 16 -20 years, 21-25 years and greater than 25 years. Circular plots of 8.92 m radius (area of 0.025 ha) were laid out along transects. Distance between plots and between transects ranged from 60 m to 140 m, depending on the area of the stratum. In each plot, all trees were measured for diameter at breast height (dbh) and three trees (large, medium and small) were sampled for measurement of total tree height (ht). This information was necessary for selection of trees for destructive sampling.

Eight dbh classes from 1-10 cm to 60.1-70 cm and > 70 cm were established from the forest inventory data. Selection of trees for destructive sampling were determined based on the distribution of tree numbers within each diameter class, while for dbh > 70 cm, at least four to five trees were selected. Summary statistics of the sample trees are presented in Table 9.1.

Table 9.1. Summary statistics of sample trees used for developing biomass and volume models

Component	**n**	**dbh (cm)**			**ht (m)**		
		Mean	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
AGB, BGB and volume	44	42.5	6.0	84.4	28.6	6.5	37.5
BGB	44	42.5	6.0	84.4	28.6	6.5	37.5
Volume	44	42.5	6.0	84.4	28.6	6.5	37.5

Destructive sampling and biomass and volume determination

The trees were first divided into above- and belowground components. The aboveground component comprised of all biomass above a stump height of 15 cm except leaves. The aboveground component was further divided into three components namely stem, branches and twigs. The following definitions apply to above- and belowground components when the biomass models were developed:

- Stem - tree trunk that can produce timber.
- Branches - branches (including cone) with diameter ≥ 2.5 cm.

- Twigs - small branches with diameter < 2.5 cm. Leaves were excluded from twigs and thus not included in the modelling.
- The belowground component comprised of all biomass of stump, root crown and roots down to a diameter of 1 cm.

Total volume included stem and branches up to 2.5 cm minimum diameter while merchantable volume included stem up to the minimum diameter of 10 cm. Merchantable stem was divided into billets (1.5 m length) and measured for length and mid diameter. AGB, BGB and volume were determined as described in Chapter 3. Scatter plots of AGB, BGB, and total volume versus dbh are presented in Figure 9.1. Figure 9.2 shows a scatter plot of ht versus age of teak trees. The scatter plot shows that teak seems to attain maximum ht at an early age.

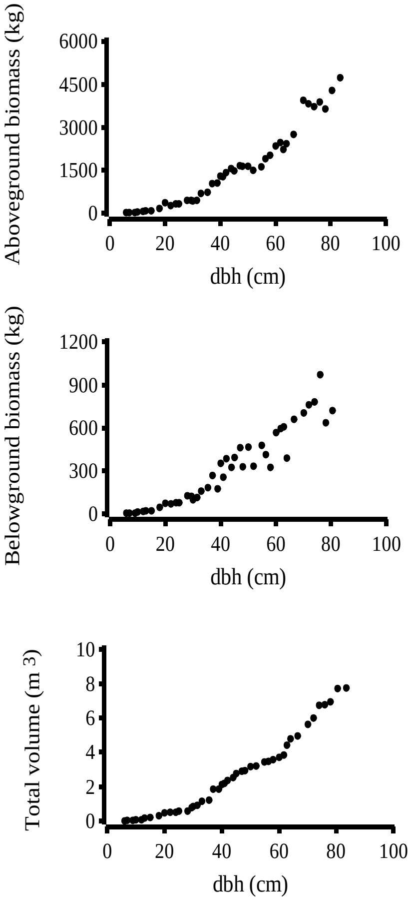

Figure 9.1. Scatter plots of AGB, BGB and total volume versus dbh

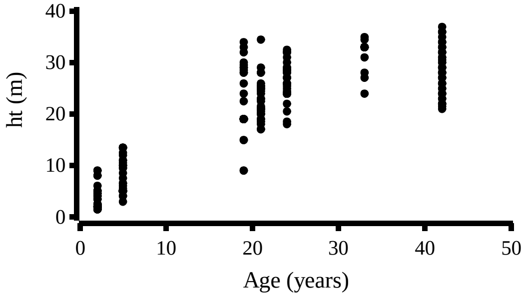

Figure 9.2. Scatter plot of ht versus age

Working conditions and resources required

Longuza plantation is situated at the foot of Eastern Arc Mountain located at the north-eastern coast of Tanzania. Most of the forest plantation area is flat dominated by loamy sandy soils. This nature of soils made the excavation exercise easy. However, the major challenge was the close spacing between trees (above 700 trees per ha) which affected processing of both above- and belowground components. For example, tree hang ups were very common which increased working time and reduced the number of trees processed per day. The high wood basic density of the tree heartwood led to frequent replacement of chainsaw chains and consequently affected the costs. Due to high stand density, tree roots were interlocked consequently making it difficult to collect below ground components of the sample trees.

Cost incurred included local labourers and researcher allowances, hiring chainsaw machine and vehicle, fuel for chainsaw, cost for equipment such as bush knives (3), spades (3), mattocks (2), chainsaw chains (15), machetes (2), ropes (3), umbrellas (2), electronic balance (1), spring balances (2), iron brushes (3) and field sample bags (400). The total cost of all these equipment was TZS 440,000.

One crew with five members was involved to process above- and belowground components and they were paid on piece work basis. The cost for processing one tree into above- and belowground components ranged between TZS 30,000 and 80,000 with an average of TZS 50,000. On average, two trees were processed per day. Chainsaw and vehicle were hired at TZS 30,000 and TZS 50,000 respectively per day. The cost for food was TZS 20,000 per day. The cost estimates for destructive sampling are presented in Table 9.2. It should be noted that allowance for researcher and research assistant; and cost for other equipment such as callipers, Suunto hypsometer and tapes are not included.

Table 9.2. Cost estimates for destructive sampling

Item	Units	Unit Cost (TZS)	Total cost (TZS)
Crew (two trees per day)	2	50,000	100,000
Chainsaw machine hiring cost	1	30,000	30,000
Cost for hiring vehicle	1	50,000	50,000
Equipment	Lump sum	440,000	440,000
Food	Lump sum	20,000	20,000

Model fitting and evaluation

Four model forms were fitted to biomass and volume. Two model forms included dbh only and two included dbh and ht as follows:

$$Y = \beta_o + \beta_1 \times dbh^2 \qquad (1)$$
$$Y = \beta_o \times dbh^{\beta_1} \qquad (2)$$
$$Y = \beta_0 \times dbh^{\beta_1} \times ht^{\beta_2} \qquad (3)$$
$$Y = \beta_0 \times (dbh^2 \times ht)^{\beta_1} \qquad (4)$$

where Y is biomass (kg) or volume (m^3), β_0, β_1 and β_2 are model parameters to be estimated.

The NLP procedure (Non Linear Programming) in SAS software (SAS® Institute Inc., 2004) was applied when fitting models. The procedure fits both model parameters and variance parameters (variance = a^2dbh^{2b}, where a and b are parameters) simultaneously.

The selection of final models was based on the Akaike Information Criterion (AIC). AIC takes into account the number of parameters in the model and penalizes them accordingly. However, if a model had insignificant parameter estimates, it was not considered further. The coefficient of determination (R^2) and Root Mean Squared Error (RMSE) were reported for all models. In addition, relative mean prediction error was reported as:

$$\text{MPE (\%)} = \frac{100}{\text{MB}} \times \sum \left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass or volume), and MB is mean observed biomass or volume.

9.4 Biomass and volume models

Models for predicting AGB, BGB and stem were of two options which included either dbh only or both dbh and ht as independent variables. The model for predicting branches and twigs biomass used dbh only (Table 9.3). Models for predicting total and stem volume were of two options: with dbh only and with both dbh and ht as independent variables (Table 9.4).

Table 9.3. Biomass models for *Tectona grandis* plantations

Component	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	TE_S1S1_AGB_1	$B = 0.3356 \times dbh^{2.1651}$	44	208.1	0.97	0.3
	TE_S1S1_AGB_2	$B = 0.1711 \times dbh^{2.0047} ht^{0.3767}$	44	224.8	0.97	8.5
BGB	TE_S1S1_BGB_1	$B = 0.0636 \times dbh^{2.2182}$	44	91.6	0.91	5.7
	TE_S1S1_BGB_2	$B = 0.0279 \times dbh^{1.7430} ht^{0.7689}$	44	90.9	0.91	6.7
Merchantable stem	TE_S1S1_MSB_1	$B = 0.4179 \times dbh^{2.0455}$	41	209.3	0.96	6.7
	TE_S1S1_MSB_2	$B = 0.05196 \times (ht \times dbh^2)^{0.8943}$	41	218.3	0.95	5.0
Branches	TE_S1S1_BB_2	$B = 0.0170 \times dbh^{3.0573}$	41	140.7	0.87	25.1
Twigs	TE_S1S1_TB_1	$B = 0.1745 \times dbh^{1.5093}$	44	28.3	0.63	10.2

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 9.4. Volume models for *Tectona grandis* plantations

Component	Model ID	Model	n	RMSE (m^3)	R^2	MPE (%)
Total	TE_S1S1_TV_1	$V = 0.0012 \times dbh^{1.9912}$	44	0.05	0.99	2.2
	TE_S1S1_TV_2	$V = 0.00014 \times (ht \times dbh^2)^{0.8793}$	44	0.05	0.98	0.1
Merchantable stem	TE_S1S1_MSV_1	$V = 0.00058 \times dbh^{2.1219}$	41	0.36	0.96	3.7
	TE_S1S1_MSV_2	$V = 0.0001 \times dbh^{1.7240} \times ht^{0.9060}$	41	0.41	0.95	7.4

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m)

9.5 Application recommendations

Models presented in this chapter were developed with data covering wide ranges of ages and tree sizes (dbh 6.0 to 84.4 cm). The developed models can be used for predicting AGB, BGB, total and stem volume in the study area. All the models can be applied with a reasonable certainty, provided that appropriate information on ht is available from the inventory. As observed in Tables 9.3 and 9.4, including ht does not improve the model fit. This is because teak seems to attain maximum ht at an early age in the study site (see Figure 9.2). Therefore, it is generally recommended to apply the models with dbh only. However, it is also recommended to use models with both dbh and ht in predictions for very large trees (dbh > 100 cm) because ht moderates the effect of dbh on biomass and volume predictions as compared to if dbh only is applied.

The recommendations given above also generally apply to the tree component biomass (twigs, branches and stem).The definitions of each component described in Chapter 9.3 should be carefully considered when applying these models.

9.6 References

Kongsager, R., Napier, J. and Mertz, O. (2013). The carbon sequestration potential of tree crop plantations. Mitigation and Adaptation Strategies for Global Change 18: 1197-1213.

Malimbwi, R.E. (1987). A growth and yield model for *Pinus patula* at Sao Hill. A thesis submitted for PhD at Aberdeen University. 145pp.

Malimbwi, R.E., Mugasha, A.G. and Zahabu, E. (1998). Yield tables for *Pinus patula* at Sao Hill Forest Plantations, Southern Tanzania. Faculty of Forestry and Nature Conservation, Sokoine University of Agriculture. 41pp.

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

Ngaga, Y.M. (2011). Forest plantation and woodlots in Tanzania. African Forest Forum Working Paper Series 1:16. 30pp.

O’Ktinga’ati, A., Monela, G. and Dale, T. (1998). The potential of *Tectona grandis* at Mtibwa to act as a carbon sink. Faculty of Forestry Record No. 67. Special issue for the First Annual Forestry Workshop in Tanzania, held at Olmotonyi, Arusha, 24 - 26 March 1997. pp 156 – 167.

Cacho, O.J., Marshall, G.R. and Milne, M. (2003). Smallholder agroforestry projects: potential for carbon sequestration and poverty alleviation. Rome, Italy: The Food and Agriculture Organization of the United Nations (FAO). 81pp.

SAS® Institute Inc. 2008. SAS/ETS user’s guide, version 9.2. Cary, NC: SAS Institute Inc. 218pp.

10 ALLOMETRIC BIOMASS AND VOLUME MODELS FOR COCONUT TREES

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10.1 Background

Coconut tree (*Cocos nucifera*) is among the four major palm species of economic importance among nearly 2400 palm species in the world. The other three are *Elaeis oleifera, Borassus flabellifer* and *Phoenix dactylifera* (Arancon, 1997; Govaerts and Dransfield, 2005; Goodman et al., 2013). Majority of coconut trees are found in higher rainfall coastal areas characterized by saline soils (Kant, 2010). In Tanzania mainland, coconut trees are dominantly found in regions located in the eastern coast and quite few in patches in non-coastal regions like Morogoro, Manyara and Tabora (Mwinjaka et al., 1999). In Zanzibar, coconut trees are the most dominant tree species (Revolutionary Government of Zanzibar, 2013). In the end of 1990s, the number of coconut trees in Tanzania was estimated to be about 22.6 million, growing on 240,000 hectares (ha) where about 95% of the coconut acreage was grown by smallholder farmers (Mwinjaka et al., 1999).

Coconut trees have high economic and environmental importance. Fruits, fronds and wood provide thousands of smallholders throughout the tropics with a cash income and with many of the basic necessities of life such as food, drink, fuel and shelter. The coconut fruit is by far the most important nut in the world (DebMandal and Mandal, 2011). The mature trunk of coconut tree may be used for timber and charcoal (Arancon, 1997; Durst et al., 2004).

Nevertheless, there is unexploited opportunity in which smallholder farmers of coconut trees may benefit. This is their potential to sequester atmospheric carbon dioxide and therefore qualify for carbon (C) trading mechanisms such as Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests and enhancement of carbon stocks (REDD+). An added advantage of coconut trees to the farmers is that quite few other woody vegetation types grow in coastal saline lands. Therefore, coconut trees provide outstanding opportunity to community residing in these lands to benefit from C market projects. However in Tanzania, biomass models which are necessary tools for estimation of C stored in coconut trees are missing. Similarly, models for estimating timber volume from coconut trees are lacking. Much of the efforts in developing these tools were focused on dicotyledonous trees (e.g. Mugasha et al., 2013; Mauya et al., 2014). The aim of this chapter is therefore to describe recently developed biomass and volume models for coconut trees in Tanzania.

10.2 Site description

Data for development of biomass and volume models were collected from Mkuranga and Kisarawe districts, Pwani region. Mkuranga district is located 50 km south of Dar es Salaam city adjacent to the coastal shores of Indian Ocean while Kisarawe district is located about 78 km from coastal shore. Study sites description is presented in Table 10.1.

Table 10.1. Study sites description

District	Location	Dominant soil type	Altitude (m)	Mean annual rainfall (mm)	Mean annual temperature (^{0}C)
Mkuranga	39^o 09” 16’ E 07^o 17” 23’ S	Sandy soils (Arenosals)	< 400	1,090	28.0
Kisarawe	38^o 44” 12’ E 07^o 15” 44’ S	Sandy soils and fluvisols	< 400	1,090	26.1

10.3 Data collection and analyses

Selection of sample trees

Mixed age farms of coconut trees were selected for data collection. Farms are often small and fragmented. This limits systematic layout of sample plots. Therefore, purposive sampling was carried out in few farms to represent wide range of coconut tree sizes. For each study site, a total of 23 coconut trees were selected for destructive sampling. Prior to destructive sampling, the coconut trees were measured for diameter at breast height (dbh) using calliper and total height (ht) excluding rachis using Suunto hypsometer. The ht was measured at the bottom of the oldest rachis. Summary statistics of sampled coconut trees are presented in Table 10.2. It was not possible to include young coconut trees whose trunks were still occupied by rachis below 1.3 m from the ground. Consequently, the minimum dbh encountered was 19.0 cm.

Table 10.2. Summary statistics of sample tree used for developing biomass and volume models

Component	Site	n	dbh (cm)			ht (m)		
			Mean	Min.	Max.	Mean	Min.	Max.
AGB and volume	Mkuranga	23	29.4	21.0	40.0	8.1	1.6	14.4
	Kisarawe	23	29.5	19.0	39.0	12.7	5.9	21.0
	All	46	29.5	19.0	40.0	9.9	1.6	21.0
BGB	Mkuranga	14	29.7	21.0	37.0	8.4	1.6	14.4
	Kisarawe	15	29.3	22.5	38.0	12.2	9.6	15.3
	All	29	29.5	21.0	38.0	9.5	1.6	15.3

Destructive sampling and determination of biomass and volume

The aboveground component consists of stem (other uses including charcoal and merchantable component), rachis and leaflets (Figure 10.1). Characterisation of the stem components was based on local knowledge as well as observable wood properties during crosscutting. Consequently, the merchantable component is the entire stem excluding the top part which is normally softer than the rest (Figure 10.1). The stem components were crosscut into billets with length of 1 m at most. Each billet was weighed, measured for length and mid diameter. Leaflets were removed from rachis, bundled and their fresh weight determined separately. Three samples from stem components of about 2.5 cm width from the bark to the pith were extracted and weighed using electronic balance. Similarly, at least two samples from rachis and leaflets were collected and fresh weighed ready for laboratory analysis.

Due to fibrous nature of coconut tree roots, BGB was determined by excavating an area of 1 m radius from the coconut tree to the depth of 1.5 m. This is because most of the coconut tree roots are within this radius and depth (Thampan, 1981). The coconut trees were excavated while standing for them to fall on their own weight and consequently uproot any roots beyond the prescribed excavation dimensions. Roots were removed from the root crown and then both root crown and roots were cleaned for soil and measured for fresh weight. For each of the two belowground components, at least three sub-samples were collected and fresh weighed for laboratory analysis. In the laboratory, the collected sub-samples were oven dried at 105 ± 2 ^{o}C for at least 72 hours to constant weight. Thereafter, average dry to fresh weight ratios (DF-ratio) were computed for each component.

Tree biomass was determined as a product of respective component fresh weight and DF-ratio. AGB and BGB were computed by summing the biomass of all above- and belowground components respectively (Figure 10.1). Billet volume was computed by using Huber’s formula. Scatter plots of AGB, BGB and volume versus ht and are shown in Figure 10.2.

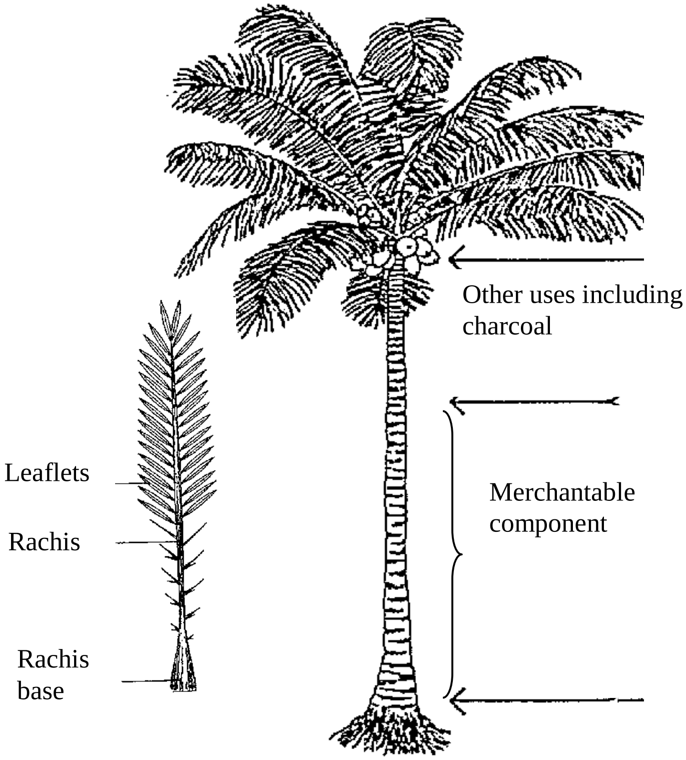

Figure 10.1. Components of coconut tree

Working conditions and resources required

Working conditions in the coconut trees farms were conducive. Distance and terrain conditions from the road to the working sites had no impact on time consumption, since most of the farms are accessible by road. Terrain conditions were also favourable. The soils are sandy which can easily be excavated.

In contrast to other vegetation types studied where sample trees were provided free of charge by relevant authorities, coconut trees for this study were purchased at an average price of TZS 50,000 per tree. During the field work, the owners of the trees and neighbours were members of the crew to facilitate understanding with local communities and avoid conflicts.

On average it was possible to accomplish three trees of 40 cm dbh per day for both above- and belowground components with a crew of 10 people. Table 10.3 summarizes the cost estimates used for the destructive sampling of coconut trees. Note that the estimates excluded the cost of researchers, transport and equipment.

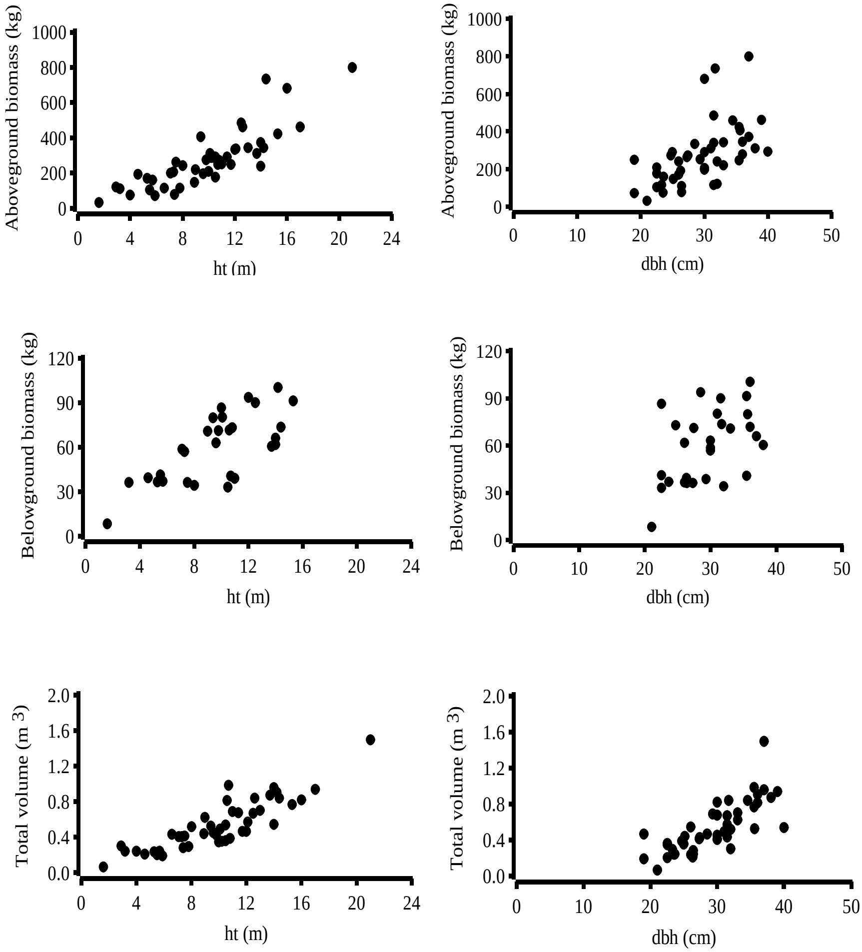

Figure 10.2. Scatter plots of AGB, BGB and volume versus ht and dbh

Equipment used during the sampling included diameter tape and calliper for dbh measurements. Suunto hypsometer was used for ht measurements. Tape measure was used for measuring length of billets; machetes and axe for cutting off small branches; a chainsaw to fell trees and crosscut stems, large branches and roots. Hoes, spades and mattock were used for excavating and exposing roots while iron brush was used to remove soils from roots. A spring balance was used to weigh logs and branches while an electronic balance was used to weigh sub-samples or small tree parts.

Table 10.3. Cost estimates for destructive sampling

Item	Number of units	Unit cost (TZS)	Total cost (TZS)
Crew size (10 persons)	Labour cost per day per person	20,000	200,000
Petrol	5 litres per day	2,000	10,000
Engine oil	0.5 litres per day	7,000	3,500
Chainsaw replaceable	1 pc per day	45,000	45,000
Research assistant	1 person	65,000	65,000
Total cost per day			**323,500**
Number of trees per day (3)	Average cost one coconut tree		**107,833**

Model fitting and evaluation

Biomass and volume data were fitted to non-linear functions (1-4) which are common and widely documented in literature (e.g. Zianis et al., 2005; Chave et al., 2014). Mixed effect modelling approach was applied to accommodate the variation among sites using PROC NLMIXED, a procedure in SAS (SAS®, 2008). To account for random effects, parameter b varied with sites in such a way that $b = \beta + \varrho$, where ϱ is a random parameter varying with sites.

$$Y = a \times dbh^b \quad (1)$$
$$Y = a \times dbh^2 + b \quad (2)$$
$$Y = a \times ht^b \quad (3)$$
$$Y = a \times ht^b \times dbh^c \quad (4)$$

where Y is dependent variable i.e. biomass (kg) or volume (m^3), a, b and c are unknown parameters to be estimated. Total tree height (ht) and dbh are in m and cm respectively.

Selection of best performing models was based on low Akaike Information Criterion (AIC) and relative mean prediction error. Other model performance criteria such as Root Mean Square Error (RMSE) and coefficient of determination (R^2) were presented. Relative mean prediction error was computed as:

$$\text{MPE (\%)} = \frac{100}{\text{MB}} \times \sum \left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass or volume), and MB is mean observed biomass or volume.

10.4 Biomass and volume models

This study developed allometric models for predicting total AGB, BGB and merchantable stem biomass for coconut trees. Total and merchantable volume models were also developed. For all the models predicting biomass, i.e. AGB, BGB, merchantable stem, there is one option i.e. models with ht only as independent variable (Table 10.4).

For all the models predicting volume i.e. total volume and merchantable volume, there are two options: 1) with ht only as independent variable and 2) with both dbh and ht as independent variables (Table 10.5).

10.5 Application recommendations

Models presented in this chapter were developed with data collected from two sites located in Pwani region which covered tree sizes ranging from dbh of 19.0 - 40 cm and ht of 1.6 - 21 m. These models can only be applied elsewhere after they are tested.

For coconut trees, ht explained majority of variation in biomass and volume, which contrasts with most models developed for dicotyledonous tree species where dbh explained much of the variation. This implies that for accurate estimation of biomass and volume, ht should be measured with care, e.g. for leaning and curved coconut trees. In addition, ht should be measured from stump to the bottom of the oldest rachis.

Table 10.4. Biomass models for coconut trees

Component	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	CO_S1M_AGB_8	$B = 3.7964 \times ht^{1.8130}$	46	77.9	0.78	-4.5
BGB	CO_S1M_BGB_8	$B = 13.5961 \times ht^{0.6635}$	29	16.2	0.53	9.9
Merchantable stem	CO_S1M_MSB_8	$B = 6.0344 \times ht^{1.4191}$	22	84.3	0.75	16.1

Note: B = biomass (kg), ht = total tree height (m)

Table 10.5. Volume models for coconut trees

Component	Model ID	Model	n	RMSE (m^3)	R^2	MPE (%)
Total	CO_S1M_TV_8	$V = 0.03470 \times ht^{1.1873}$	46	0.12	0.80	4.9
	CO_S1M_TV_2	$V = 0.00134 \times ht^{0.7841} \times dbh^{1.2295}$	46	0.09	0.88	2.6
Merchantable stem	CO_S1M_MSV_8	$V = 0.0043 \times ht^{1.7780}$	22	0.11	0.75	8.1
	CO_S1M_MSV_2	$V = 0.0015 \times ht^{1.6400} \times dbh^{0.4138}$	22	0.11	0.77	9.2

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m)

10.6 References

Arancon, R.N. (1997). Asia Pacific forestry sector outlook: focus on coconut wood. Asia-Pacific Forestry Towards 2010. Asia-Pacific Forestry Sector Outlook Study Working Paper Series (FAO). 42pp.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G. and Vieilledent, G. (2014). Improved pantropical allometric models to estimate the above ground biomass of tropical forests. Global Change Biology 20: 3177–3190.

DebMandal, M. and Mandal, S. (2011). Coconut (*Cocos nucifera* L.: Arecaceae): in health promotion and disease prevention. Asian Pacific Journal of Tropical Medicine 4: 241-247.

Durst, P.B., Killmann, W. and Brown, C. (2004). Asia's new woods. Journal of Forestry 102: 46-53.

Goodman, R.C., Phillips, O.L., del Castillo Torres, D., Freitas, L., Cortese, S.T., Monteagudo, A. and Baker, T.R. (2013). Amazon palm biomass and allometry. Forest Ecology and Management 310: 994-1004.

Govaerts, R. and Dransfield, J. (2005). World checklist of palms. Royal Botanic Gardens. 223pp.

Kant, P. 2010. Should bamboos and palms be included in CDM forestry projects? (IGREC Working Paper No. IGREC07:2010). New Delhi: Institute of Green Economy. Web Publication No.07/2010. 5pp.

Mauya E.W, Mugasha W.A, Zahabu E, Bollandsås O.M. and Eid T. (2014). Models for estimation of tree volume in the miombo woodlands of Tanzania. Southern Forests 76: 209-219.

Mugasha, W.A., Eid, T., Bollandsås, O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J.Z. (2013). Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecology and Management 310: 87-101.

Mwinjaka, S., Chiduza, C., Temu, A., Sukume, C. and Diehl, L. (1999). Cocunut palm replacement model for Tanzanian farming systems. Journal of Agricultural Economics & Development 3: 61-70.

Revolutionary Government of Zanzibar (2013). Zanzibar wood biomass survey, biophysical inventory report, Department of Forestry and Non-Renewable Natural Resources, Ministry of Agriculture and Natural Resources. Zanzibar. 104pp.

SAS® Institute Inc. (2008). SAS/ETS user’s guide, version *9.2*. Cary, NC: SAS Institute Inc. 218pp.

Thampan P.K. (1981). Handbook on coconut palm. Report No. 8120402146. 311pp.

Zianis, D., Muukkonen, P., Mäkipää, R. and Mencuccini, M. (2005). Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs 4. 63pp.

11 ALLOMETRIC BIOMASS AND VOLUME MODELS FOR CASHEWNUT TREES

Zahabu, E., Mlagalila, H. and Katani, J.Z.

11.1 Background

Cashewnut trees (*Anacardium occidentale*) are tropical nut crop trees that belongs to the family Anacardiaceae, which is known for having resinous bark and often, caustic oils in leaves, barks and fruits. Cashewnut trees are native of South America, very likely the centre of origin is Brazil (Mitchell and Mori, 1987). They are thought to have been brought to East Africa and India by the Portuguese in the sixteenth century (Johnson, 1973; Ohler, 1979; Behrens, 1998).

Cashewnut trees consist of about 73 genera and 600 species (Nakosone and Paull, 1998). The tree is evergreen, fast growing and reaches a height of 10 - 15 m and often has irregularly shaped trunk. Farm management practices consist of weeding, pruning and spraying pesticides and fungicides. Cashewnut trees are planted at a spacing of 12 × 12 m making a total of 70 trees per hectare (ha) (UNIDO, 2011). This species has ability to grow on poor soils and can be intercropped with food crops such as maize, cassava and groundnuts. Cashewnuts are consumed as food as well as marketed for export. The crop prefers deep, well drained, light textured soils which facilitate extensive lateral root extension (Martin et al., 1997; Mitchel, 2004). It grows well from sea level to 1,200 m where the temperature does not fall below 20^0C. The optimum monthly temperature for cashewnut tree growth is 27^0C. The cashewnut tree is grown in areas with rainfall ranging from 800 – 1600 mm per annum. The crop is best adapted to the coastal areas (Shomari, 2000, 1990; Orwa et al., 2009).

The area under cashewnut trees cultivation in Tanzania has been estimated to be about 400,000 ha either in mono or mixed crop production systems. It is estimated that over 80% of the crop comes from Mtwara, Lindi and Ruvuma regions (Shomari, 1990; Topper et al., 1998; Ngatunga et al., 2003; Masawe, 2006). This estimate might be underestimated since the area occupied by wooded crops which include cashewnut trees in Mtwara, Lindi and Ruvuma is about 724,000 ha and that of Pwani region are 88,000 ha (MNRT, 2015).

While other uses of cashewnut trees are widely documented, information about carbon (C) storage potential is scant or not available in Tanzania. Many studies were focused on natural forests and plantations of timber trees (Mugasha et al., 2013; Alvarez et al., 2012; Abbot et al., 1997). Studies on C storage potential of other agroforestry systems have been carried out in Tanzania (e.g. Kimaro et al., 2011), but none has presented C sequestration potential of agro-forestry systems with cashewnut trees.

The aim of this chapter is to describe recently developed biomass and volume models for cashewnut trees in Tanzania.

11.2 Site description

Data for development of biomass and volume models were collected from Kisarawe district (38º 44” 12’ E; 7º 15” 44’ S), Pwani region. Altitude is about 400 m. The district is located about 78 km from coastal shore. The district receives mean annual rainfall of 1090 mm and experience mean annual temperature of 26.1°C. The soils are sandy and fluvisols.

11.3 Data collection and analysis

Selection of sample trees

A total of 45 trees were purchased from farmers for destructive sampling. These trees were used for biomass modelling while 43 trees among them were used for volume modelling. Each sample tree was measured for dbh and ht before felling. A calliper or a diameter tape (for larger trees) was used to measure dbh, while ht was measured using Suunto hypsometer. The diameter at breast height (dbh) of selected trees ranged from 6.0 to 89.8 cm with an average of 35.8 cm. Total height (ht) ranged from 2.5 to 15.5 m with an average of 8.8 m.

Destructive sampling and biomass determination

The determination of tree biomass considered above- and belowground components. Sample trees were felled at 30 cm above ground level. Aboveground component consisted of stem, branches and twigs. Stem and branches consist all aboveground components with diameter >5 cm while twigs are those with diameter ≤5 cm. Cashewnut trees branch very near to the ground (often <1.3 m), for this reason, stem and branches components were combined since it was not possible to model stem and branches separately. The belowground component consisted of stump, root crown and roots.

Stems and branches were trimmed and crosscut into billets that were convenient to weigh. Each billet was measured for length and mid diameter for volume model development and fresh weight was measured for biomass model development. All 45 trees selected for destructive sampling were excavated for belowground biomass (BGB) determination. The determination of BGB was based on a root sampling procedure as described by Mugasha et al. (2013) where three main sample roots originating from the root crown and three side sample roots originating from the main root were selected for each tree. Based on these sampled main and side roots, models predicting biomass of main and side roots were developed, and subsequently applied to estimate biomass of unexcavated roots.

For each tree component, at least three wood sub-samples with thickness of about 2 cm were cut (from bark to pith) and measured for fresh weight and taken to the laboratory for dry weight determination. The oven dry weight was used to calculate dry to fresh weight ratio (DF-ratio). The DF-ratio was multiplied by respective tree component fresh weight to get biomass. Scatter plots of AGB and BGB versus dbh of individual trees are shown in Figure 11.1.

Volume of individual billets was calculated using Huber's formula. The billets considered for total tree volume were those of the main stem and branches to 5 cm diameter. During modelling, two observations for tree volume were removed due to their unrealistic values.

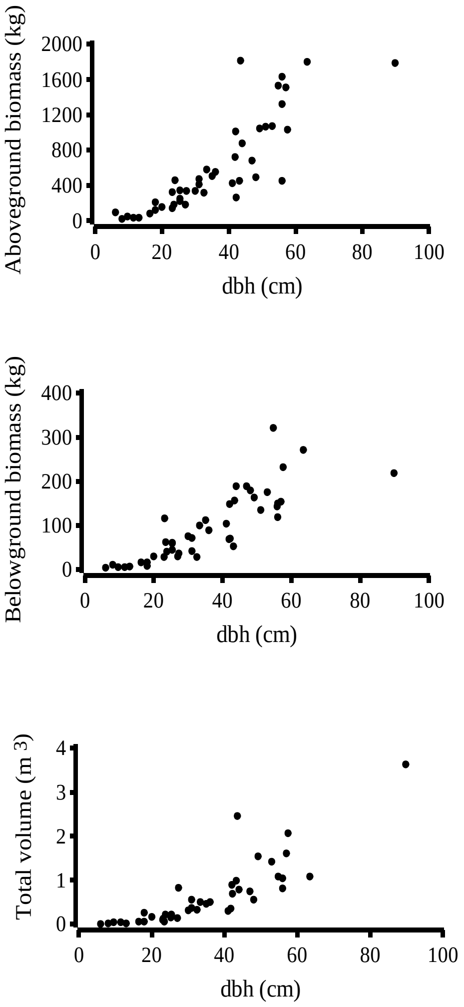

Figure 11.1. Scatter plots of AGB, BGB and total volume versus dbh

Working conditions and resources required

Working conditions in the cashewnut tree stands were conducive. Distance and terrain conditions from the road to the working sites had no impact on time consumption, since most of the farms are accessible by road. Terrain conditions were also favourable.

In contrast to other vegetation types studied where sample trees were provided free of charge by relevant authorities, cashewnut trees for this study were purchased at average price of TZS 200,000. During the field work, the owners of the trees and neighbours were members of the crew to facilitate understanding with local communities and avoid conflicts.

It was possible to accomplish two trees of average of 40 cm dbh per day for both above- and belowground component with a crew of 12 people. Table 11.1 summarizes the cost estimates used for the cashewnut trees destructive sampling. Note that these estimates excluded the cost of researchers, transport and equipment.

Equipment used during the sampling included diameter tape, calliper, Suunto hypsometer, machetes, axes, chainsaw, hoes, spades, mattock, iron brushes, spring and electronic balances.

Table 11.1. Cost estimates for destructive sampling

Item	Above- and belowground
Crew size (persons)	12
Local labour cost per day per person (TZS)	20,000.00
Average price of the tree (TZS)	200,000.00
Costs per day (TZS)	640,000.00
Trees per day	2
Costs per tree (TZS)	320,000.00

Model fitting and evaluation

Three model forms for biomass and volume were tested. One of the model forms included dbh only and two included both dbh and ht:

$$Y = \beta_0 \times dbh^{\beta_1} \qquad (1)$$
$$Y = \beta_{0\times} dbh^{\beta_1} \times ht^{\beta_2} \qquad (2)$$
$$Y = \beta_0 \times (ht \times dbh^2)^{\beta_1} \qquad (3)$$

where Y is biomass (kg) or volume (m^3) and β_0, β_1, and β_2 are model parameters.

Non Linear Programming (NLP) procedure in SAS software (SAS® Institute Inc., 2004) was used to estimate the model parameters (β_0, β_1, and β_2). The procedure produces the least squares estimates of the parameters of a nonlinear model through an iteration process. The procedure fits both model parameters and variance parameters (variance = a^2dbh^{2b}, where a and b are parameters) simultaneously.

The selection of final models was based on the Akaike Information Criterion (AIC). AIC takes into account the number of parameters in the models and penalizes them accordingly. However, if a model had insignificant parameter estimates, it was not considered further. The coefficient of determination (R^2) and Root Mean Squared Error (RMSE) were reported for all models. In addition, relative mean prediction error was reported as:

$$\text{MPE (\%)} = \frac{100}{\text{MB}} \times \sum\left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass or volume), and MB is mean observed biomass or volume.

11.4 Biomass and volume models

For models predicting AGB and stem-branches components biomass, there are two options; 1) model with dbh only and 2) model with both dbh and ht as independent variables. For model predicting BGB component biomass, there is only one option i.e. model with dbh only as independent variable (Table 11.3). The different tree components are defined in Chapter 11.3.

For the models predicting total volume there is only one options i.e. model with dbh only as independent variable (Table 11.4).

11.5 Application recommendations

The presented models for prediction of biomass and volume of cashewnut trees cover relatively narrow ranges of conditions regarding climate, topography and soil, but tree sizes considered were adequate (dbh ranged from 6.0 to 89.8 cm). The models can therefore be applied to most of the cashewnut trees along the coastal zone of Tanzania. It is however recommended that the use of these models beyond this zone need testing.

Table 11.3. Biomass models for cashewnut trees

Component	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
AGB	CN_S1S1_AGB_1	$B = 0.8450 \times (dbh^2)^{0.8873}$	45	160.6	0.79	-7.6
	CN_S1S1_AGB_2	$B = 0.3152 \times dbh^{1.7722} \times ht^{0.5003}$	45	196.2	0.83	-9.8
BGB	CN_S1S1_BGB_1	$B = 0.09287 \times (dbh^2)^{0.9394}$	45	31.7	0.78	-13.2
Stem-branches	CN_S1S1_SBB_1	$B = 0.0951 \times dbh^{2.2622}$	45	130.9	0.83	-4.0
	CN_S1S1_SBB_1	$B = 0.0659 \times (ht \times dbh^2)^{0.9163}$	45	133.1	0.87	-12.7

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 11.4. Volume models for cashewnut trees

Component	Model ID	Model	n	RMSE (m^3)	R^2	MPE (%)
Stem-branches	CN_S1S1_SBV_1	$V = 0.0000001 \times dbh^{2.6044}$	43	0.22	0.79	-9.8

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m)

11.6 References

Abbot, P.J. and Werren, M. (1997). Models for the estimation of single tree volume in four Miombo wood lands types. Forest Ecology and Management 97: 25 – 37.

Alvarez, E., Duque, A., Saldarriga, J., Cabrera, K., Salas, G., Valle, I., Lema, A., Moreno, F., Orrego, S. and Roddriguez, L. (2012). Tree above ground biomass allometries for carbon stocks estimation in the natural forests of Columbia. Forest Ecology Management 267: 297 – 308.

Behrens, R. (1998). Cashew as an agroforestry crop: Prospects and potential. Tropical Agriculture Weikersheim, Margraf. 19pp.

Johnson, D. (1973). The botany, origin and spread of the cashew *Anacardium occidentale* L. Journal of Plantation Crops 1: l – 7.

Kimaro, A.A., Isaak, M.E. and Chamshama, S.A.O. (2011). Carbon pools in tree biomass and soils under rotational woodlot systems in eastern Tanzania. In: B.M. Kumar and P.K.R. Nair (eds.), Carbon sequestration potential of agroforestry systems: Opportunities and challenges, Advances in Agroforestry 8: 129-143.

Martin, P.J., Topper, C.P., Bashiru, R.A., Boma, F., Waal, D. De, Harries, H.C. and Kasuga, L.J. (1997). Cashew nut production in Tanzania: Constraints and progress through integrated crop management. Crop Protection 16: 5–14.

Massawe, P.A.L. (2006). Tanzanian Cashew cultivars - selected clones hand book. Cashew Research Programme, Naliendele Agricultural Research Institute, Colour Print (T) Ltd, Dar es Salaam, Tanzania. 43pp.

Mitchell, D. (2004). Tanzania's cashew sector: Constraints and challenges in a global environment. World Bank Africa Region Working Paper Series No. 70, Washington DC. 30pp.

Mitchell, J.D. and Mori, S.A. (1987). The cashew and its relatives *(Anacardium;* Anacardiaceae). Memours of New York Botanic Gardens 42: l – 76.

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

Mugasha, W.A., Eid, T., Bollandsås, O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J.Z. (2013). Allometric models for prediction of above and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecology and Management 310: 87–101.

Nakosone, H.Y. and Paull, R.E. (1998). Tropical fruits. Commonwealth for Agriculture Bureau International, UK. 432pp.

Ngatunga, E.L., Dondeyne, S. and Deckers, J.A. (2003). Is sulphur acidifying cashew soils of south-eastern Tanzania? Agriculture, Ecosysytems and Environment 95: 179–184.

Ohler, J.G. (1979). Cashew communication. Working Paper No. 71. Department of Agricultural Research of the Royal Topical Institute, Amsterdam, the Netherlands. 22pp.

Orwa, C.A., Mutua, K.R. and Jamnadass, R.S.A. (2009). Agroforestry tree data base: A tree reference and selection. [http://www.worldagroforestry.org/sites/treedbs/treedatabases.asp] site visited on 5/8.2015 (Online data base)

SAS® Institute Inc. 2004, SAS Institute Inc., Cary NC, USA. 218pp.

Shomari, S.H. (1990). A review on cashew research in Tanzania. A paper presented to Tanzania agricultural research master plan conference, Arusha, 12 - 15 December, 1990. 35pp.

Shomari, S.H. (2000). Cashewnut production hand book. Naliendele Agricultural Research Institute, Mtwara, Tanzania.20pp.

Topper, C.P., Martin, P.J., Katinila, N., Kikoka, L.P., Lamboll, R., Masawe, P.A.L. and Shomari, S.H. (1998). The historical and institutional back grounding of the Tanzanian cashew industry. In: Proceedings of the international cashew and coconut conference trees for life: The key to development. (Topper C.P., Caligari, P.D.S., Kullaya, A. K., Shomari, S.H., Kasuga L.J., Masawe, P.A.L. and Mpunami, A.A.), Biohybrids International Ltd, Reading, UK. pp.76 – 83.

UNIDO (2011). Tanzania’s cashew value chain: A diagnostic. United Nations Industrial Development Organization, Vienna, Austria. 54pp.

12 ALLOMETRIC BIOMASS AND VOLUME MODELS FOR BAOBAB TREES

Masota, A.M., Zahabu, E. and Malimbwi, R.E.

12.1 Background

Baobab (*Adansonia digitata*) is a deciduous tree occurring in seasonally dry regions of Africa and Australia (Chapotin et al., 2006). In Africa, baobab trees are found among others in Zambia, Tanzania, Kenya, Sudan and Mali (Johansson, 1999). These trees are adapted to arid environments by having swollen stems to store water (Chapotin et al., 2006) and to adapt to fires which are common in dry areas (Johansson, 1999). Often the tree has one trunk. It produces fruits with acidic, floury pulp and coarse fibres around the hard seeds, rich in vitamin C. The timber is very soft and spongy and its use is yet to be established. In Tanzania, baobab is found in Dodoma, Iringa, Lindi, Morogoro, Singida, Manyara, Simiyu and Shinyanga.

Baobab provides both socio-economic and environmental services. The socio-economic services include medicine, fibres, fruits, vegetable, worshiping as well as source of income through fruits and fibres (Romero et al., 2001; Johansson, 1999). The environmental services include environmental protection, support of bat biodiversity and carbon sequestration.

According to NAFORMA (MNRT, 2015), out of the total wood volume of 3.3 billion m^3 in Tanzania, baobab trees constitute 4%. However, the biomass is considered to be negligible due high water content. Despite the high deforestation rate in Tanzania, empirical evidence shows that baobab trees are rarely cut due to their socio-economic values, environmental factors and their poor timber quality (Johansson, 1999).

Much work in modelling has been done in biomass and volume for different vegetation types in Tanzania as reported by Malimbwi et al. (1994), Chamshama et al. (2004), Mugasha et al. (2013) and Mauya et al. (2014). These models did not include baobab trees despite their high contribution to the total volume in the country. A further literature search in Africa also showed inexistence of baobab tree biomass and volume models. Lack of such models and adequate information about baobab trees in Africa, Tanzania inclusive, was one of the main reasons for NAFORMA to employ crude methods in estimating volume and biomass which may have resulted in unreliable estimates.

This chapter describes recently developed biomass and volume models for baobab trees in Tanzania. An attempt to collect belowground data was made but failed due to rooting complications and high costs of excavation.

12.2 Site description

The data for development of the biomass and volume models were collected in Ruaha Mbuyuni and Malolo villages (30° 30’ 06” E; 7° 27’ 02” S), Kilosa district in Morogoro region. To the south, the district borders River Ruaha. This river also forms a regional boundary between Morogoro and Iringa regions. The district borders Kilolo district in Iringa region to the south. The area is dominated with *Acacia-Commiphora* and scattered bushes which are characteristics of dry areas.

12.3 Data collection and analysis

Selection of sample trees

To obtain information of diameter at breast height (dbh) distribution of baobab trees for guiding in the selection of sample trees, NAFORMA data which were collected for the whole country was accessed and used (MNRT, 2015). These data showed that dbh of baobab trees ranged between 1 cm and 350.3 cm. Also, previous studies have shown skewed dbh distribution of baobab population, with few individuals in smaller sizes and its solitaire occurrence (Johannsson, 1999; Romero et al., 2001). In this context, sampling of baobab trees was not plot based, but ensured coverage of dbh distribution reflected in NAFORMA data. In total 35 baobab trees for destructive sampling were selected to cover the possible dbh sizes.

Each sample tree was measured for dbh and total tree height (ht) before felling. A diameter tape was used to measure dbh, while ht was measured using Suunto hypsometer. For trees with buttresses, dbh was measured at 30 cm above the buttress. The dbh of the sampled trees ranged from 31 to 318 cm while the ht ranged from 6.5 to 14.4 m.

Destructive sampling and biomass determination

Baobab trees selected for AGB determination were felled at 30 cm above the ground level. Then the aboveground component was divided into three components, namely stem, branches, and twigs and leaves. The stem and branches were cut into billets or slices that were convenient to measure. The stem was defined as aboveground component of the tree from the stump to the first large branch, while branches were the remaining parts of the aboveground component up to a diameter of 2.5 cm. Twigs were defined as branches with diameter below 2.5 cm.

All aboveground parts of baobab trees were weighed for fresh weight in the field. At least three sub-samples were taken from all tree components, fresh weighed using electronic balance and taken to laboratory for dry weight determination. Tree- and component-specific dry to fresh weight ratios (DF-ratios) were computed. Biomass for the components was determined by multiplying component-specific mean DF-ratios with the respective fresh weight determined in the field. Finally, AGB of individual trees was found by summing up their respective components (stem, branches and twigs and leaves). Figure 12.1 shows the scatter plot for AGB versus dbh for individual baobab trees.

Before cross cutting, tree stem and branch sections of approximately equal bottom and upper diameters were marked and their lengths and mid diameters measured. Their volumes (m^3) were computed using Huber's formula. The volume of stem and branches components was obtained by summing up the volumes of the sections. Finally, total tree volume was obtained by summing up stem and branch volumes. The scatter plot of total volume versus dbh is shown in Figure 12.2.

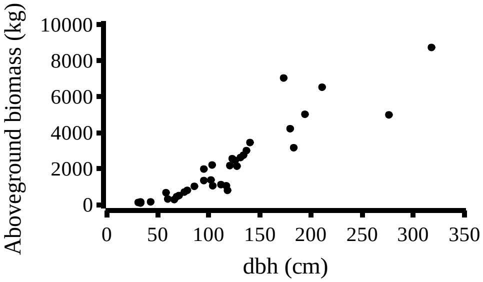

Figure 12.1. Scatter plot of ABG versus dbh

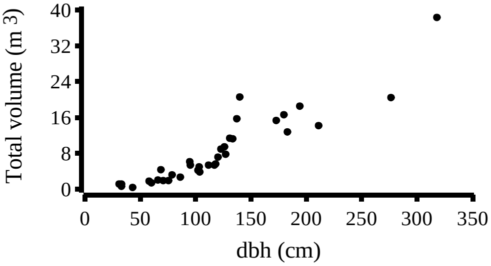

Figure 12.2. Scatter plot of total volume versus dbh

Working conditions and resources required

The working conditions in arid and semi-arid areas, where baobab trees are found, are challenging due to relatively high temperatures during day time, which reduced the speed of working crew. Another challenge of working with baobab trees is related to their large sizes, which prolonged cutting time (Plate 12.1). Apart from their large sizes, baobab trees consist of spongy fibres which are difficult to cut by chainsaw or axes. This caused frequent jams during felling and crosscutting. Generally, all these factors had impact on time consumption and costs of doing destructive sampling procedures in baobab trees.

The crew consisted of 13 persons and the members were involved in measuring, collecting weighing and supervising. The crew was closely supervised by the researcher to ensure consistence of measuring, recording of tree data and general safety. Roles of crew members and their respective costs are shown in Table 12.1.

Plate 12.1. Felling of baobab sample tree (Photo Abel Masota)

Table 12.1. Cost estimates for destructive sampling of one tree with dbh of 60 cm

Cost element	Units	Costs (TZS)
Labour costs for collection and weighing	18 man-days	180,000
Chainsaw operator	2 man-days	60,000
Petrol	8 litres	20,000
Engine oil	0.5 litres	7,000
Food	13 rations	30,000
Transport of crews to and back from work	2 days	90,000
Chainsaw replaceable	1 pc	40,000
Administrative: Team leader	2 man-days	130,000
Research assistant	2 man-days	90,000

Equipment used during destructive sampling procedures included diameter tape, callipers for measuring mid diameters of small billets <65 cm and Suunto hypsometer for ht measurements. Others equipment included tape (30 m) for measuring length of billets, machetes to cut off small branches and twigs, a chainsaw to fell sample trees and crosscut stems and large branches. Also, a spring balance was used for weighing logs and branches, and an electronic balance was used for measuring weight of sub-samples.

Model fitting and evaluation

For biomass, different model forms were initially tested. Finally, two models using dbh only as predictor variable and the two using both dbh and ht as predictor variables were selected:

$$Y = \beta_0 \times dbh^{\beta_1} \quad (1)$$
$$Y = \beta_0 + \beta_1 \times dbh + \beta_2 \times dbh^2 \quad (2)$$
$$Y = \beta_0 \times dbh^{\beta_1} \times ht^{\beta_2} \quad (3)$$
$$Y = \beta_0 \times (ht \times dbh^2)^{\beta_1} \quad (4)$$

where B is biomass (kg) and β_0, β_1, and β_2 are model parameters to be estimated.

The PROC NLIN procedure in SAS software (SAS® Institute Inc., 2004) was used to estimate the model parameters. The procedure produces the least squares estimates of the parameters of a nonlinear model through an iteration process.

The selection of final models was based on significance of parameter estimates, Root Mean Squared Error (RMSE), and coefficient of determination (pseudo-R^2). Models with insignificant parameter estimates were not considered further for evaluation. In addition, relative mean prediction error was reported as:

$$\text{MPE (\%)} = \frac{100}{\text{MB}} \times \sum \left(\frac{e}{n}\right)$$

where e is model residuals (difference between observed and predicted biomass or volume), and MB is mean observed biomass or volume.

For volume five different model forms were also tested, three of them included dbh only as independent variables while two model forms included both dbh and ht:

$$V = \beta_0 \times dbh^2 \quad (5)$$
$$V = \beta_0 + \beta_1 \times dbh + \beta_2 \times dbh^2 \quad (6)$$
$$V = \beta_0 + \beta_1 \times dbh^2 \quad (7)$$
$$V = \beta_0 \times dbh^{\beta_1} \times ht^{\beta_2} \quad (8)$$
$$V = \beta_0 \times (dbh^2 \times ht)^{\beta_1} \quad (9)$$

where V is volume (m^3) and β_0, β_1, and β_2 are model parameters to be estimated.

Similar procedures for determining model parameters and models selection criteria for biomass models were used for volume modelling.

12.4 Biomass and volume models

Models for estimating AGB and total volume of baobab trees are shown in Tables 12.2 and 12.3 respectively. These models have two options: 1) with dbh only as independent variable and 2) with both dbh and ht as independent variables.

Table 12.2. Biomass models for baobab trees

Component	Model ID	Model	n	RMSE (kg)	R^2	MPE (%)
ABG	BO_S1S1_AGB_1	$B = 2.234966 \times dbh^{1.43543}$	35	916.7	0.82	3.7
	BO_S1S1_AGB_2	$B = 0.192416 \times dbh^{1.204898} \times ht^{1.4954}$	35	754.4	0.88	2.4

Note: B = biomass (kg), dbh = diameter at breast height (cm), ht = total tree height (m)

Table 12.3. Volume models for baobab trees

Component	Model ID	Model	n	RMSE (m^3)	R^2	MPE (%)
Total	BO_S1S1_TV_1	$V = 0.005804 \times dbh^{1.507423}$	35	3.071	0.8559	1.9
	BO_S1S1_TV_2	$V = 0.001175 \times dbh^{1.338395} \times ht^{1.016581}$	35	2.792	0.8844	1.4

Note: V = volume (m^3), dbh = diameter at breast height (cm), ht = total tree height (m)

12.5 Application recommendations

The presented models in this chapter for prediction of biomass and volume of baobab trees cover wide ranges of tree sizes (dbh up to 318 cm). The developed models can generally be applied to predict biomass and volume of baobab trees which are found in dry areas of Tanzania.

Models for predicting biomass and volume are presented: 1) with dbh only and 2) with both dbh and ht as independent variables. Both models may be applied to estimate biomass and volume of baobab trees. Challenges related to ht measurements due to rounded crowns frequently occurring in baobab trees will probably imply that the models with dbh only in many cases will be the best for biomass estimation.

12.6 References

Chamshama, S.A.O., Mugasha, A.G. and Zahabu, E. (2004). Biomass and volume estimation for miombo woodlands at Kitulangalo, Morogoro, Tanzania. Southern Forests 200: 49-60.

Chapotin, S.M., Razanameharizaka, J.H. and Holbrook, N.M. (2006). A biomechanical perspective on the role of large stem volume and high water content in baobab trees (Adansonia spp.; Bombacaceae). American Journal of Botany 93(9): 1251–1264.

Johansson, M. (1999). The baobab tree in Kondoa Irangi Hills, Tanzania. Swedish University of Agricultural Sciences. Minor Field Studies No. 74: 1-41.

Malimbwi, R., Solberg, B. and Luoga, E. (1994). Estimation of biomass and volume in miombo woodland at Kitulangalo Forest Reserve, Tanzania. Journal of Tropical Forest Science 7: 230-242.

Mauya, E., Mugasha, W.A., Zahabu, E., Bollandsås, O.M. and Eid, T. (2014). Models for estimation of tree volume in the miombo woodland of Tanzania. Southern Forests 76: 209-219.

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

Mugasha, W.A., Eid, T., Bollandsås, O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J.Z. (2013). Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecology and Management 310: 87–101.

Romero, C., Dovie, D., Gambiza, J., Luoga, E., Schmitt, S. and Grundy, I. (2001). Effects of commercial bark harvesting on *Adansonia digitata* (Baobab) in the Save Odzi-Valley, Zimbabwe with considerations for its management. Hot Springs Working Group. IES Working Paper 18, 28-50.

SAS® Institute Inc. (2004). SAS Institute Inc., Cary, NC, USA. 218pp.

13 STOCKING ESTIMATES OF BIOMASS AND VOLUME USING DEVELOPED MODELS

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13.1 Background

The basic challenge in estimating forest carbon (C) emission is the requirement of information about changes in biomass and C stock of the forests at national and regional as well as local levels. Information on such changes will be based on inventories relying on field plots only or on field plots combined with remote sensing methods. Ground inventories involve the estimation of C from the five Intergovernmental Panel on Climate Change (IPCC) biomass pools; aboveground biomass (AGB) and belowground biomass (BGB) from trees, and deadwood, litter and soil organic biomass. In order to accurately estimate AGB and BGB, allometric models are imperative. Country specific allometric models enable the country and forest managers to report on C estimates at high IPCC tiers. IPCC identifies three reporting tier levels whereby tier 1 utilizes global models while tiers 2 and 3 require site-specific models and information. Volume and C estimates also provide important information as basis for implementing sustainable forest management.

Tree biomass and volume models utilize easily measureable tree variables, usually diameter at breast height (dbh) and height (ht) that are correlated to the biomass or volume. Provided that information on individual trees is available, the use of biomass and volume models is the best option to quantify amounts of biomass and C, and volume of wood. Quantification of biomass is also essential for issues related to energy production (fuelwood and charcoal) in conventional forest management planning. Tree volumes are imperative for forest management purposes such as assessment of growing stock, timber valuation, selection of forest areas for harvesting, and for growth and yield studies.

Tanzania has recently completed her first National Forest Inventory popularly known as NAFORMA (National Forest Resources Monitoring and Assessments) (MNRT, 2015). The inventory was based on tree measurements in field plots. The tree measurements could only be converted to biomass and volume estimates using rather simple and deficient allometric models. Before the implementation of NAFORMA, tree allometric models that existed in Tanzania were deficient in terms of narrow tree species coverage, tree size range and spatial representation respectively (Malimbwi et al., 1994, Chamshama et al., 2004).

This chapter presents forest stocking levels for different vegetation types in Tanzania. The stocking estimates are based on sample plot inventories where the allometric volume and biomass models described in this book have been applied. A review of previous stocking levels, based on allometric models existing prior to those described in this book, are also given.

13.2 Estimated biomass and volume

Most of the sample trees used for the development of the allometric models in this book came from systematically laid out sample plots where tree variables (dbh and ht) were measured. From these data, several forest stocking values can be estimated, including biomass and volume using the developed models. The calculated forest stocking values are presented in Tables 13.1 and 13.2 as a demonstration of the performance of the models for the desired stand parameters.

In natural forests (Table 13.1), forest stocking values are arranged in descending order with the generally highest values in lowland and humid montane forests and lowest in Itigi thicket. Basal area and AGB, for example, were 47.8 m^2 ha^{-1} and 470.0 tons ha^{-1} in lowland and humid montane forests and 5.3 m^2 ha^{-1} and 17.9 tons ha^{-1} in Itigi thicket.

In plantation forests (Table 13.2), number of trees ha^{-1} was generally high at low age and then decreased with increasing age due to for example thinning and natural mortality. However, high numbers of trees ha^{-1} were observed in compartments of 15 and 21 years in the Sao Hill plantation. This may be due to lack of thinning operation in these compartments. Generally, stocking levels in terms of volume and biomass were increasing with increasing age as expected.

The root to shoot ratios (RS-ratios) based on the biomass estimates in Tables 13.1 and 13.2 were mainly higher than 0.4 for natural forests while they ranged between 0.15 and 0.25 for forest plantations. These differences are partly due to the fact that natural forests have to invest more in root biomass as a strategy to survive from competition, poor soils, fire and drought as compared to plantation forest. The RS-ratio, however, is also depending on the size distribution of the trees measured in the sample plot inventories. This is illustrated in Figure 13.1 with an example based on the sample trees used for modelling biomass of lowland and humid montane forests (see Chapter 4) where the RS-ratio clearly decrease with increasing tree size.

This pattern seen in Figure 13.1 is also suggesting that application of a mean RS-ratio for estimating BGB from AGB in a forest area may lead to biased estimates. The results seen in Table 13.1 for mangrove forests are illustrating this problem. Based on the biomass estimates using BGB models (see chapter 5), the RS-ratio for Pangani, Bagamoyo, Rufiji and Lindi-Mtwara were 0.71, 1.08, 0.64 and 0.87 respectively. The differences between the sites in RS-ratio seen here are due to differences both in size- and species distributions between the sites. Applying a mean RS-ratio over all the mangrove sites here would obviously lead to biased estimates for BGB for the individual sites. Mean RS- ratios have frequently been used to estimate BGB (e.g. Munishi and Shear, 2004). However, when BGB models are available, this practice should be avoided, and if they are not available, application of mean RS-ratios should be done with caution.

Table 13.1. Forest stocking values for different vegetation types

Vegetation types	Location	No. of plots	Basal area (m^2 ha^{-1})			Volume (m^3 ha^{-1})	Biomass (tons ha^{-1})	
			Mean	STD	CV (%)		AGB	BGB
Lowland and humid montane forests	Amani	67	47.8	24.2	50.6	790.4	470.0	215.1
Miombo woodlands	Manyara	40	15.3	5.0	32.9	149.1	101.4	39.0
	Lindi	30	11.2	3.9	34.7	103.2	70.1	28.6
	Tabora	40	7.4	3.4	45.8	69.6	47.3	19.0
Mangrove forests	Pangani	15	15.0	6.6	44.0	-	103.1	72.7
	Bagamoyo	45	8.9	5.8	65.2	-	53.4	57.5
	Rufiji	45	18.7	9.8	52.4	-	127.3	81.9
	Lindi-Mtwara	15	10.7	5.0	46.7	-	69.0	60.3
Acacia-Commiphora woodlands	Same	58	5.7	3.0	52.4	38.0	17.4	5.8
	Kiteto	109	8.9	5.1	56.9	21.9	48.8	18.6
Itigi thicket	Manyoni	59	5.3	2.6	49.3	20.1	17.9	12.9

Table 13.2. Forest stocking values for *Pinus patula* and *Tectona grandis* grown in plantations

Vegetation type	Location	Age (yr)	No. of plots	Trees ha^{-1}	Mean dbh (cm)	Basal area (m^2 ha^{-1})			Volume (m^3 ha^{-1})	Biomass (tons ha^{-1})	
						Mean	STD	CV (%)		AGB	BGB
Pinus patula	Sao Hill	5	10	1332	8.7	8.3	0.8	9.7	37.8	18.0	2.7
		9	10	608	16.1	13.3	2.2	16.8	94.8	45.4	8.9
		15	10	1088	18.6	32.3	5.3	16.3	269.3	129.2	27.5
		21	10	1048	21.1	40.1	7.6	19.0	368.5	176.9	39.7
		26	10	620	25.4	33.2	4.5	13.5	336.7	161.9	38.2
		31	10	600	29.5	43.5	9.3	21.3	494.0	237.8	59.7
	SUATF	1-5	18	1198	9.7	9.4	2.3	24.3	46.4	22.1	3.5
		6-10	15	1083	15.3	21.1	5.3	25.0	146.1	69.9	13.4
		11-15	15	765	22.6	32.1	3.7	11.6	293.6	141.0	31.4
		16-20	15	421	26.3	23.8	5.3	22.1	242.7	116.7	27.5
		>20	21	324	33.8	31.3	9.7	30.8	405.6	195.6	53.0
Tectona grandis	Longuza	1-5	15	493	3.0	0.4	0.3	70.1	6.1	2.4	1.1
		6-10	15	1571	9.3	11.6	4.4	37.9	174.5	99.4	32.8
		11-15	10	576	23.2	27.3	5.7	20.9	405.2	314.8	81.0
		16-20	15	739	24.3	36.1	14.7	40.8	431.1	365.6	87.7
		21-25	17	320	33.3	29.1	9.2	31.5	535.9	412.2	106.9
		>25	23	193	44.3	31.1	12.4	38.9	471.8	445.6	98.1

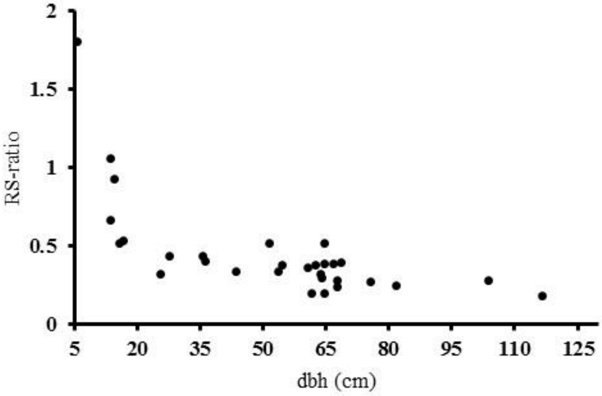

Figure 13.1. Scatter plot of root-shoot ratio versus dbh in Amani Nature Reserve

13.3 Review and comparison with previous volume and biomass estimates

Forest stocking levels from previous studies of different vegetation types in Tanzania are presented in Tables 13.3 and 13.4. Tree volumes in these studies were mainly determined as a product of tree basal area (g), tree height (ht) and a form factor (*f*) of 0.5 (e.g. Zahabu, 2008; Mpanda et al., 2011; Mbwambo et al., 2012; Mgumia, 2014) or 0.33 (e.g. Munishi and Shear, 2004) while biomass were obtained by converting volume (based on such simple computation methods) to biomass through expansion factors or wood basic density (e.g. Munishi and Shear, 2004; Mbwambo et al., 2012; Shirima et al., 2011).

It is therefore obvious that the computational methods used to determine volume and biomass in the previous studies were more likely to produce biased forest stocking levels (Tables 13.3 and 13.4) as compared to forest stocking levels obtained from the models presented in this book (Table 13.1). Other factors that could explain the observed differences in stocking levels could of course also be related to differences in anthropogenic activities and climatic and edaphic variations.

Table 13.3. Forest stocking levels from previous studies for miombo woodlands in Tanzania

Vegetation type	**Author**	**Forest**	**Basal area (m^2ha^{-1})**	**Volume (m^3ha^{-1})**	**Aboveground biomass (tons ha^{-1})**
Miombo woodlands	Zahabu (2001)	Kitulangalo FR	10.2	78.0	-
	Malimbwi et al. (2002)	Handeni Hill FR	11.2	108.9	-
	Malimbwi (2003)	Duru Haitemba FR	12.4	97.3	-
	Chamshama et al. (2004)	Kitulangalo FR (Government)	9.0	76.0	43.6
	Chamshama et al. (2004)	Kitulangalo FR (SUA)	9.0	76.0	41.4
	Zahabu (2008)	Kitulangalo FR	7.9 - 9.9	55.3 - 74.8	35.2 - 45.9
	Zahabu (2008)	Kimunyu FR	7.9 - 8.8	72.4 - 88.2	39.7 – 45.0
	Zahabu (2008)	Haitemba FR	13.4	155.9	74.7
	Zahabu (2008)	Warib FR	8.4	47.5	32.9
	Njana (2008)	Urumwa FR	8.5	58.4	-
	Nuru et al. (2009)	Urumwa FR	8.7	59.7	-
	Shirima et al. (2011)	Kitonga and Nyanganye FR	11.0	-	24.2
	Mbwambo et al. (2012)	Mgori FR	15.1	90.8	59.1
	Mongo et al. (2014)	Riroda FR	11.3	89.9	-
	Mongo et al. (2014)	Bubu FR	10.5	78.0	-
	Katani et al. (2015)	Angai FR	9.2-11.6	67.0-85.2	-

FR= Forest Reserve, NR= Nature Reserve

Table 13.4. Forest stocking levels from previous studies for lowland and humid montane forests and mangrove forests in Tanzania

Vegetation type	Author	Forest	Basal area (m^2ha^{-1})	Volume (m^3ha^{-1})	Aboveground biomass (tons ha^{-1})
Lowland and humid montane forests	Mgumia (2014)	Amani NR	47.9	1000.5	579.0
	Mbwambo et al. (2012)	Shagayu FR	37.5	506.4	293.7
	Mbwambo et al. (2012)	Shume FR	17.4	171.0	99.2
	Mbwambo et al. (2012)	Sagara FR	37.6	572.0	331.8
	Mpanda et al. (2011)	Amani NR	46.8	965.3	-
	Hansen et al. (2015)	Amani NR	-	-	463.0
	Munishi and Shear (2004)	Mazumbai FR	52.0	-	1055.0
	Munishi and Shear (2004)	Uluguru NR	42.0	-	790.0
	Zahabu and Malimbwi (1998)	Kwamkoro FR	59.0	655.0	-
	Kajembe et al. (2004)	Kwizu FR	17.2	196.3	-
	Zahabu (2008)	Mangala FR	25.0	306.7	177.9
	Zahabu (2008)	Handei FR	24.6	299.2	173.0
Mangrove forests	Mattia (1997)	Rufiji FR	28.0	268.0	-
	Luoga et al. (2004)	Pangani FR	5.0	20.7	-
	Nshare et al. (2007)	Salenda-bridge FR	35.0	167.0	-

FR= Forest Reserve, NR= Nature Reserve

13.4 References

Chamshama, S.A.O., Mugasha, A.G. and Zahabu, E. (2004). Biomass and volume estimation for miombo woodlands at Kitulangalo, Morogoro, Tanzania. Southern Forests 200: 49-60.

Hansen, E. H., Gobakken, T., Bollandsås, O.M., Zahabu, E. and Næsset, E. (2015). Modeling aboveground biomass in dense tropical submontane rainforest using airborne laser scanner data. Remote Sensing 7: 788-807.

Kajembe, G.C., Namubiru, E.L., Shemwetta, D.T.K., Luoga, E.J. and Mwaipopo, C.S. (2004). The impact of rules in forest conservation in Tanzania: Case of Kwizu Forest Reserve, Same District, Kilimanjaro. In: Institutions incentives and conflicts in forest management: A perspective, Proceedings of the IFRI East African Regional Conference. (Edited by Shemwetta, D.T.K, Luoga, E.J., Kajembe, G.C. and Madoffe, S.S.) 12 – 13 January 2004, Moshi, Tanzania. pp. 92 – 107.

Katani, E., Mustalahti, I., Mukama, K. and Zahabu, E. (2015). Participatory forest carbon assessment in south-eastern Tanzania: Experiences, costs and implications for REDD+. Oryx, 1-10. http://dx.doi.org/10.1017/S0030605315000174.

Luoga, E.J., Malimbwi, R.E., Kajembe, G.C., Zahabu, E., Shemwetta, D.T.K., Lyimo-Macha, J., Mtakwa, P. and Mwaipopo, C.S. (2004). Tree species composition and structures of Jasini Mwajuni Mangrove forest at Pangani, Tanzania. Journal of Tanzania Association of Foresters 10: 42–47.

Malimbwi, R.E. (2003). Inventory reports of Ayasanda, Bubu, Duru, Endagwe, Gidas Endanachan, Hoshan and Riroda Village Forest Reserves in Babati Manyara, Tanzania. Manyara, Tanzania: Land Management Programme, Babati District Council. 20pp.

Malimbwi, R., Solberg, B. and Luoga, E. (1994). Estimation of biomass and volume in miombo woodland at Kitulangalo Forest Reserve, Tanzania. Journal of Tropical Forest Science 7: 230-242.

Malimbwi, R.E. and Mugasha, A.G. (2002). Reconnaissance timber inventory report for Handeni Hill Forest Reserve in Handeni District, Tanzania for the Tanga Catchment Forest Project. FORCONSULT, Faculty of Forestry and Nature Conservation, Sokoine University of Agriculture, Morogoro, Tanzania. 34pp.

Mattia, S. B. (1997). Species and structural composition of natural mangrove forests: a case study of the Rufiji delta, Tanzania. Dissertation for award of MSc. Degree at Sokoine University of Agriculture, Morogoro, Tanzania.

Mbwambo, L., Eid, T., Malimbwi, R.E., Zahabu, E., Kajembe, G.C. and Luoga, E.J. (2012). Impact of decentralised forest management on forest resource condition in Tanzania. Forests, Trees and Livelihoods 21:97-113.

Mgumia, F. (2014). Implications of forestland tenure reforms on forest conditions, forest governance and community livelihoods at Amani Nature Reserve, PhD Thesis, Sokoine University of Agriculture, Tanzania. 280pp.

MNRT (2015). National Forest Resources Monitoring and Assessment (NAFORMA) main results. Tanzania Forest Services, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania. 106pp.

Mongo, C., Eid, T., Kashaigili, J.J., Malimbwi, R., Kajembe, G. and Katani, J. (2014). Forest cover changes, stocking and removals under different decentralised forest management regimes in Tanzania. Journal of Tropical Forest Science 26: 484–494.

Mpanda, M.M., Luoga, E.J., Kajembe, G.E. and Eid, T. (2011). Impact of forestland tenure changes on forest cover, stocking and tree species diversity in Amani Nature Reserve, Tanzania. Forests, Trees and Livelihoods 20: 215–230.

Munishi, P.K.T. and Shear, T.H. (2004). Carbon storage in afromontane rainforests of the Eastern Arc Mountains of Tanzania: their net contribution to atmospheric carbon. Journal of Tropical Forest Science 16: 78–93.

Njana, M.A. (2008). Arborescent species diversity and stocking in the Miombo woodland of Urumwa Forest Reserve and their contribution to livelihoods, Tabora, Tanzania. Dissertation for award of MSc Degree at Sokoine University of Agriculture, Morogoro, Tanzania. 99pp.

Nshare, J.S., Chitiki, A., Malimbwi, R.E., Kinana, B.M. and Zahabu, E. (2007). The current status of the mangrove forest along seashore at Salenda bridge, Dar es Salaam, Tanzania. Journal of Tanzania Association of Foresters 11:172-179.

Nuru, H., Rubanza, C.D.K. and Nezia, C.B. (2009). Governance of key players at district and village levels on health improvement of Urumwa Forest Reserve, Tabora: Ten years of Joint Forest Management. In Nshubemuki et al. (Editors). Proceedings of the First Participatory Forest Management (PFM) Research Workshop: Participatory Forest Management for Improved Forest Quality, Livelihood and Governance. June 2009. 1: 111- 122.

Shirima, D.D., Munishi, P.K.T., Lewis, S.L., Burgess, N.D., Mashall, A.R., Balmford, A., Swetnam, R.D. and Zahabu, E. (2011). Carbon storage, structure and composition of miombo woodlands in Tanzania’s Eastern Arc Mountains. African Journal of Ecology 49, 332–342.

Zahabu E. and R.E. Malimbwi 1998. Structure and composition of tree species in Amani Nature Reserve. Faculty of Forestry, Sokoine University of Agriculture. Record No. 67: 259-266.

Zahabu, E. (2001). Impact of charcoal extraction on the miombo woodlands: The case of Kitulangalo Area, Tanzania. Unpublished Dissertation for Award of MSc Degree at Sokoine University of Agriculture, Morogoro, Tanzania, 106pp.

Zahabu, E. (2008). Sinks and sources: A strategy to involve forest community in Tanzania in global climate policy. PhD-Thesis, University of Twente, Enschede, the Netherlands. 235pp.

14 CONCLUDING REMARKS

Eid, T., Malimbwi, R.E. and Chamshama, S.A.O.

This book documents a large number of allometric volume and biomass models covering many vegetation types and tree species in Tanzania. The developed models were based on comprehensive data sets, unique for Africa with respect to number of observations and number of tree species included. In total about 800 trees were destructively sampled for aboveground biomass (AGB) and among these more than 500 for belowground biomass (BGB) and volume. All together more than 125 different tree species were sampled, of which 60 were found in miombo woodlands, 34 in lowland and humid montane forests, 22 in *Acacia-Commiphora* woodlands, and seven in tickets. The selection of trees was also mostly based on prior sample plot inventories in the respective study sites in order to collect as representative data as possible regarding tree species- and tree size distributions.

The destructive sampling applied to prepare the data material for model development was challenging. Especially, the work related to baobab trees and lowland and humid montane trees were demanding because the upper tail of the tree size distribution comprises very large trees (up to almost 120 cm in dbh and 50 m in ht for lowland and humid montane forests and almost 320 cm in dbh for baobab). High costs in destructive sampling also apply to the BGB determination, especially for mangrove forests where excavations of roots were very demanding.

The models were developed using well documented statistical methods, and they were evaluated and tested in different ways to secure appropriate performance. For most vegetation types, optional models with different independent variables were developed. This allows the user to choose model(s) according to which input variables that are available from the existing forest inventory. The developed models cover the most important vegetation types, plantation tree species and cash crop tree species in Tanzania regarding biomass quantities, and only a few gaps are left where biomass models based on data from outside Tanzania or simpler quantification methods have to be applied.

The development of all these models has therefore taken Tanzania a large step in the direction of preparing the country for REDD+ and other carbon trade mechanisms. The developed models will in addition be important tools that can be applied by forest managers throughout the country in their search for optimal and sustainable management options.

The development of the models was carried out through a scholarly process and in close cooperation between researchers in Tanzania and Norway (south and north cooperation). This resulted in five PhD degrees, seven MSc degrees and several publications in international peer reviewed journals. Hopefully this book will inspire and engage scholars who wish to continue the efforts and progress in tree allometric modelling.