Lessons and Implications for REDD+

Implementation Experiences from Tanzania

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Climate Change Impact, Adaptation and Mitigation
The 5 year CCIAM programme which ended in December 2015, focused on promoting natural forest conservation, afforestation, reforestation and better agricultural practices for improved livelihoods related to the "Reduced Emissions from Deforestations and Forest Degradation (REDD)" initiative.

Chapter 5

Biomass and volume models for different vegetation types of Tanzania

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Abstract

Climate change and high rates of global carbon dioxide (CO_2) emissions have increased the attention paid to the need for high-quality monitoring systems to assess how much carbon (C) is present in terrestrial systems and how these change over time. The choice of a system to adopt relies heavily on the accuracy of the

method for quantifying biomass and volume as important primary variables for computing C stock and changes over time. Methods based on ground forest inventory and remote sensing data have commonly been applied in the recent decade to estimate biomass and volume in the tropical forests. However, regardless of the method, accurate tree level biomass and volume models are needed to translate field or remotely sensed data into estimates of forest biomass and volume. Therefore, the main goal of this study was to develop biomass and volume models for the forests, woodlands, thickets, agroforestry systems and some selected tree species in Tanzania. Data from destructively sampled trees were used to develop volume and above- and below-ground biomass models. Different statistical criteria, including coefficient of determination (R^2), relative root mean square error (RMSE %) and Akaike Information Criterion (AIC), were used to assess the quality of the model fits. The models selected showed good prediction accuracy and, therefore, are recommended not only to support the ongoing initiatives on forest C Measurement, Reporting and Verification (MRV) processes but also for general forest management in Tanzania.

1.0 Introduction

Tanzania is endowed with vast forest resources. The total forest area on mainland Tanzania is estimated at 48.1 million hectares (ha), which is 55 percent of the total land area of 88.3 million ha (MNRT, 2015). The main vegetation types include forests and woodlands. Forests include montane and lowland forests, mangroves and plantations of mainly *Pinus patula, Tectona grandis* and *Eucalyptus* spp. The woodlands are either closed or open but can also be distinguished in terms of species composition into, for example, Miombo woodlands, *Acacia-Commiphora* and Thickets. Woodlands occupy 44.7 million ha or 92 percent of the total forest area or 50.4 percent of mainland Tanzania whereas forests[1] occupy 4.2 percent, bushland and grassland 17.2 percent and cultivated land 24.4 percent (MNRT, 2015). The cultivated land includes Agroforestry systems such as coconut and cashewnut trees-rich plantations. The total wood volume of growing stock is 3.3 billion cubic metres (m^3) (MNRT, 2015). About 97 percent of the total volume is from trees of natural origin and only three percent is from planted exotic tree species. About half of the total volume is found in forestry and wildlife protected areas and, therefore, legally inaccessible for harvesting (MNRT, 2015). Forests account for 11.3 percent of growing stock whereas Miombo woodlands contain 73.9 percent of the growing stock. Total forest Carbon(C) content in the country is about one billion tonnes (t).

1 Forests here collectively refer to Low= land forests, Montane forests, Mangroves and Plantations

The importance of forests in climate change mitigation have prompted negotiations towards a post-Kyoto agreement to include Reducing Emissions from Deforestation and forest Degradation (REDD). Subsequently, REDD+ started in the context of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol annual meeting of 2005 held in Montreal, Canada (UNFCCC, 2005). The submissions also considered whether and how incentives to reduce tropical deforestation could be included in future climate regimes. Furthermore, this has led to the discussion of how to address REDD+ in developing countries. In fact, recent policy advances include drawing lessons and experiences drawn from pilot projects at the country level that addressed REDD+.

At the core of the discussion on REDD+ is the creation of an incentive mechanism (payment) for those responsible for reducing deforestation and degradation. Establishing a REDD+ mechanism along these lines leads to numerous challenges. The basic challenge, however, is the requirement of information on changes in biomass and Carbon (C) stock of the forests at the national and regional as well as local levels. Information on such changes can be based on inventories relying on field plots only or on field plots combined with remote sensing methods. Field plots inventories for REDD+ involve the estimation of C in five Intergovernmental Panels on Climate Change (IPCC) pools of above-ground biomass (AGB), below-ground biomass (BGB), deadwood, foliage and soil organic C. Out of these, AGB and BGB are the most important pools as they are vulnerable to changes. To estimate accurately AGB and BGB, allometric models are imperative. Country-specific allometric models enable the country and forest managers to report on C estimates at higher IPCC tiers. IPCC identifies three reporting tier levels whereby tier 1 utilises global models whereas tiers 2 and 3 utilise site-specific models and information. Volume and C estimates also provide important information as a basis for implementing sustainable forest management.

Tree biomass and volume models comprise easily measureable tree variables, usually diameter at breast height (dbh) and total 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 quantifying amounts of C and volume of wood. Quantification of biomass is also essential for issues related to energy production (fuelwood and charcoal production) in conventional forest management planning. Tree volumes are also important for forest management purposes such as the assessment of growing stock, timber valuation, selection of forest areas for harvesting, and for growth and yield studies.

Tanzania has recently completed its National Forest Inventory popularly known as the National Forest Resources Monitoring and Assessment (NAFORMA) (MNRT, 2015). The inventory was based on tree measurements in field plots. The tree measurements could only be converted to biomass/C and volume estimates using appropriate allometic models. Before the implementation of this project, tree allometric models that existed in Tanzania were deficient in terms of narrow tree species coverage, narrow tree size range and narrow spatial representation (Malimbwi *et al.*, 1994, Chamshama *et al.*, 2004). NAFORMA was, therefore, bound to utilise these models and other general models regardless of their deficiencies.

2.0 Objectives of the study

The main objective of the study was to develop models and methods for assessing and monitoring C stocks in Tanzania required for the implementation of REDD+ initiatives at the local as well as national levels. The study developed individual tree biomass and volume models for all major vegetation types such as Miombo woodlands, montane and lowland forests, mangroves, *Acacia-Commiphora*, thicket and plantations of mainly *Pinus patula,* and *Tectona grandis*. Species-specific models for baobab trees and agroforestry system trees composed of mainly coconut and cashewnut were also developed. Baobab was picked from the woodlands due to its significant contributions to volume (4% of total volume in the country) (MNRT, 2015) whereas its biomass is believed to be low due to high water content.

3.0 Methodology

3.1 Study sites

The study sites were spatially distributed across the country to cover different vegetation types that exist in the country (Table 5.1; Figure 5.1).

Vegetation types	Site and Location	Elevation (m)	Soil type
Mangrove	Pangani(5^{0}24′S, 38^0 59′ E)		Alluvial, clay and sandy soils
	Bagamoyo (6^0 26′S, 38^{0}54′ E)		Alluvial and sandy soils
	Rufiji (7^{0}49 ′S,39^{0}15′ E)		Alluvial, silt and clay soils
	Lindi (10^{0}2 ′S, 39^{0}39′ E)		Alluvial and sandy soils
	Mtwara (10 ^{0} 15′ S, 40^{0}10′ E)		Alluvial and sandy soils
Miombo	Manyara (4^0 20’ S, 35^0 47′ E)	1300-1800	Clay and alluvial soils
	Lindi (9^0 47′S, 37^0 55′ E)	330-600	Sand and loam soils
	Katavi (6^0 21′ S, 30^0 57′ E)	755-766	Sand and clay soils
	Tabora (6^0 21′ S, 30^0 57′ E)	1096-1103	Sand, clay and loam soils
Lowland and Sub-Montane	Amani (5^0 05′ S, 38^0 40′ E)	190-1130	Red loam soils
Thicket	Manyoni, Itigi (5^0 31’ – 34^0 31’E)	1244-1300	Granite soils
Acacia	Kiteto(4° 31′ S, 36° 03′ E)	1325	Sand and clay soils
	Same (4° 02′ S, 37° 48′ E)	2133	Loamy soils
Boabab	Kilosa, Ruaha Mbuyuni		
Forest Plantation			
Pinus patula	Sao Hill	1740-2000	Dystric nitisols
	Meru	1700-2320	Volcanic soils
Tectona grandis	Mtibwa	640	Clay loamy soils
	Longuza	160-560	Loamy soils
Agroforestry			
Cashew nut	Kisarawe	<400	Sandy soils
Coconut	Kisarawe and Mkuranga	<400	Mbuga and fluvisols soils

Table 5.1: Studied vegetation types and description of the study sites in Tanzania

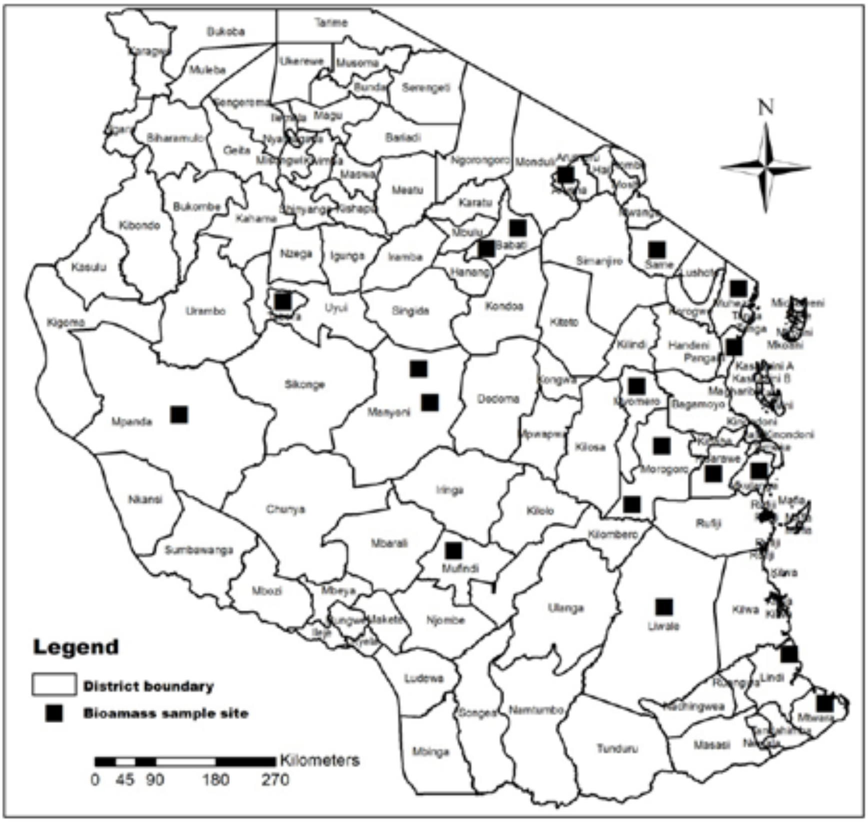

Figure 5.1: Location of study sites

3.2 Sampling procedures

Destructive sampling procedures (see, for example, Snowdon *et al.*, 2002; Mugasha *et al.*, 2013;Mauya *et al.,* 2014) were adopted to collect data used for the development of AGB, BGB and tree volume models for all major vegetation types and selected species. Destructive sampling was conducted following steps described in 3.3.

3.3 Selection of the sample trees

For all study sites, the selection of sample trees was done to ensure representation of tree size and species distribution of respective sites. This selection was based on published and unpublished information from previous forest inventories. Prior to tree felling, the entire sample trees were identified for species name (local and scientific name) and tree variables such diameter at breast height (dbh), and total height (ht) were measured. Callipers and diameter tapes were used to measure dbh whereas ht was measured with Suunto and Vertex hypsometers.

3.4 Data collection and laboratory procedures for biomass determination

To obtain the relevant dataset to achieve the objectives of the study, each of the sample trees was divided into above- and below-ground parts. The above-ground part was considered as all biomass above stump height of 30cm, was further divided into three sections, namely, the stem, branches including tops (up to a minimum diameter of 2.5 cm) and twigs (with diameter less than 2.5 cm). Stems and branches were trimmed and cross cut into billets ranging from 1 to 2.5 m in length and then weighed for green weight (see, for example, Mugasha *et al.*, 2013, Njana *et al.*, 2015). Two or three small samples (depending on the stem length) from stem and branches, respectively, were extracted and weighed green and finally oven-dried in laboratory to obtain the dry weight. Twigs were collected in separate bundles and the green weight of each was determined. Small disk samples from each bundle were collected, labelled, measured for green weight and finally oven-dried.

For BGB, the excavation of the below-ground part of the individual tree was firstly done to ensure that all main roots initiating from the root crown were clearly visible. Then three main roots from the root crown (largest, medium and smallest in diameter) were selected and excavated (see, for example, Mugasha *et al.*, 2013, Njana *et al.*, 2015). These main roots were measured for diameter at the branching point from the root crown and then weighed. Three side roots were also selected from the excavated main roots and measured for diameter at the branching points from the main root and then weighed. The remaining side roots from the excavated main roots were measured for diameter at the branching point. All the main roots that were not excavated were measured for diameter at the branching point of the root crown. Then the root crown was also recorded for green weight. To obtain estimates of the dry weights of the belowground components, a minimum of two samples was taken from all main and side roots and two from the root crown. They were all weighted for green weight, labelled and oven-dried.

3.5 Computations of above- and below-ground biomass of the sample trees

For the above-ground part of the trees, we computed all the mean dry to green weight ratio (DG-ratio) for each tree section (stem, branches and twigs). The dry weight of each section was obtained as a product of mean DG-ratio and the green weight of the respective tree section. Total AGB was computed as the sum of stem, branches and twigs. For the below-ground parts of the excavated trees, we first converted all green weights from different parts to dry weight biomass as the product of the DG-ratio and their green weights. Models developed from the excavated main and side-roots were applied to predict biomass of those parts of the root system not excavated (see, for example, Mugasha *et al.*, 2013, Njana *et al.*, 2015).

3.6 Data collection for tree volume

The data used for the development of AGB models was also used to develop tree volume models. This started with the computation of the volume of the individual logs obtained from the destructive sampling. The volume of each log-section (i.e. stem and branches) was calculated by multiplying the cross-sectional area at the midpoint of each log with its length. Then the total tree volume was obtained as a sum of stem and branches volumes. A detailed description is provided by Mauya *et al.* (2014).

3.7 Characterisation of the biomass and volume models data

The data used for developing tree biomass and volume models covered a wide range of conditions in terms of vegetation types and geographical locations. The statistical summary of the data is presented in Table 5.2:

		AGB			BGB		
			dbh (cm)			dbh (cm)	
Vegetation type/species	**Location**	**n**	**Min**	**Max**	**n**	**Min**	**Max**
Mangroves							
A. marina	Tanzania	40	1.1	70.5	10	3.0	38.6
S. alba	Tanzania	39	1.1	47.5	10	6.5	33.8
R. Mucronata	Tanzania	40	1.4	41.5	10	1.4	32.6
Miombo	Manyara	40	1.7	78.0	20	3.3	78.0
	Tabora	47	1.2	95.0	20	10.0	95.0
	Katavi	40	3.5	79.0	20	8.0	64.0
	Lindi	47	1.1	110.0	20	6.4	80.0
Lowland and Sub-Montane	Amani	60	6.0	117.0	29	6.0	117.0
Thicket	Manyoni						
Combretumcelastroides		30	1.5[a]	3.2	30	1.5	3.2
*Pseudoprosopis*fischeri		30	1.2	3.0	30	1.2	3.0
Associate tress		30	6.1	18.0	30	6.1	18.0
Acaciacommiphora	Kiteto	50	5.9	79.2	50	5.9	79.2
	Same	60	2.5	30.0	60	2.5	30.0
Boabab	Kilosa	35	31.0	318.0	-	-	-
Forest Plantations							
Pinuspatula	Meru	50	4.3	65.0	50	4.3	65.0
	Sao Hill	35	1.0	46.0	35	1.0	46.0
Tectonagrandis	Longuza	50	1.0	83.4	50	1.0	83.4
Agroforestry							
Cashewnut	Kisarawe	45	6.0	89.8	45	6.0	89.8
Coconut	KisaraweMkuranga	18	19.0	39.0	9	22.5	38.0
		28	21.0	40.0	20	21.0	37.0

Table 5.2: Statistics for dbh and number (n) of sample trees used in model development

[a]*Basal area weighted mean diameter of thicket clump*

3.8 Statistical analyses

Ordinary least square regression, non-linear regression, weighted non-linear regression and nonlinear mixed effects modelling techniques were applied to develop AGB, BGB and tree volume models (see, for example, Mugasha *et al.*, 2013; Mauya *et al.*, 2014; Njana *et al.*, 2015). R software (R Development Core Team 2013) and SAS software (SAS® Institute Inc., 2004) were applied during data analyses. The model development procedure started with the selection of appropriate model forms commonly used in previous studies. Similarly, forest mensuration literature was used to suggest appropriate model forms (Philip, 1983; Köhl *et al.*, 2006;). Different model forms were tested for each forest type and study site with the aim of getting models with dbh only and models with both dbh and ht as input variables.

Regression assumptions on homoscedasticity and normal distribution of residuals were examined by means of graphical plots. In cases where these assumptions were not met, weighted regression procedures were used to account for heteroscedasticity (i.e. non constant variance). Likewise, in other studies logarithmic transformation of both response and predictor variables were applied.

Different statistical criteria were used to assess the quality of the models and to guide the selection of the best models. The criteria used included coefficient of determination (R^2), pseudo-R^2, Akaike information criterion (AIC), relative root mean square error (RMSE) and mean prediction error (MPE%). Details on how the model selection criteria were applied are available in individual studies (see, for example, Mugasha *et al.*, 2013; Mauya *et al.*, 2014; Njana *et al.*, 2015).

4.0 Results and discussion

4.1 AGB models

AGB models covering different vegetation types and some species in Tanzania were developed. General site and species-specific models were developed as presented in Table 5.3. Different criteria for the assessment of model fits were used in individual studies (see, for example, Mugasha *et al.*, 2013; Njana *et al.*, 2015). For the Miombo woodlands, lowland and sub-montane forests, thickets and *Acacia-Commiphora*, the R^2 ranged from 0.80 to 0.97 (Mugasha *et al.*, 2013; Masota *et al.*, 2015; Mathias, 2015). RMSE% was used for assessing the model quality for mangroves, where the values ranged from 23.1 percent to 42.6 percent (Njana *et al.*, 2015). The R^2 for the species specific models were all above 0.80, indicating that the majority of AGB variations were explained by the models. All the models developed were further evaluated over sites and diameter classes. None of the selected models produced MPE% values that were statistically significantly different from zero ($p > 0.05$). Additional tests for model evaluations are given in the individual studies (see Table 3). Therefore, based on the aforementioned model performance statistical criteria, which are comparable to results from previous studies in tropical forests (see, for example, Malimbwi *et al*., 1994; Chamshama *et al*., 2004; Ryan *et al*., 2011; Chave *et al*., 2014; Mwakalukwa *et al*., 2014), the developed models can be used to estimate tree AGB with reliable precision. In addition, the developed models do not only cover a wider geographical range, but also wider ranges of tree sizes and species as than the previously reported models in Tanzania (for example, Malimbwi *et al*., 1994; Chamshama *et al*., 2004). This indicates that the models can be used over a wide range of tree sizes and sites in Tanzania.

4.2 BGB models

Models for predicting BGB were developed for all vegetation types mentioned above (see Table 5.3). The model fits for BGB were generally not as good as for the AGB models. R^2 for the Miombo woodlands and lowland and sub-montane forests ranged from 0.71 to 0.93 (Mugasha *et al*., 2013; Masota *et al*., 2015;). RMSE values for Mangrove tree species for the below-ground biomass models ranged from 16.8 percent to 95.1 percent (Njana *et al*., 2015). The BGB models were also evaluated over sites and tree sizes, and the MPE% values were not significantly different from zero ($p > 0.05$). Generally, the poor performance of the models can be attributed to methodological approaches to data collection. As not all roots were excavated and measured, the use of regression analysis in estimating the unmeasured roots might have resulted into accumulated errors (Mugasha *et al*., 2013; Malimbwi *et al*., 2016). Nonetheless, this weakness could not be avoided due to the high cost associated with total tree roots excavation. Despite the shortcomings related to the methodology applied, the models are far better than the use of biomass default values (IPCC, 2003).

Vegetation/ species	Location	Model[a] AGB (kg)	Model[a] BGB (kg)	Source
Mangrove				
A. marina	Tanzania	$=0.25128\times dbh^{2.24351}$	$=1.42040\times dbh^{1.44260}$	Njana *et al.*(2015)
		$=0.19633\times dbh^{2.08791}\times ht^{0.29654}$		
S. alba	Tanzania	$=0.25128\times dbh^{2.21727}$	$=1.42040\times dbh^{1.65760}$	
		$=0.19633\times dbh^{2.04113}\times ht^{0.29654}$		
R. mucronata	Tanzania	$=0.25128\times dbh^{2.26026}$	$=1.42040\times dbh^{1.68979}$	
		$=0.19633\times dbh^{2.10853}\times ht^{0.29654}$		
Miombo woodlands	Tanzania	$=0.1027\times dbh^{2.4798}$	$=0.2113\times dbh^{1.9838}$	Mugasha *et al.* (2013)
		$=0.0763\times dbh^{2.2046}\times ht^{0.4918}$	$=0.1766\times dbh^{1.7844}ht^{0.3434}$	
	Manyara	$=0.1603\times dbh^{2.3396}$	$=0.3789\times dbh^{1.7904}$	
		$=0.1080\times dbh^{1.9936}\times ht^{0.6628}$	$=0.3364\times dbh^{1.6166}ht^{0.2979}$	
	Tabora	$=0.1054\times dbh^{2.4809}$	$=0.1849\times dbh^{2.0318}$	
		$=0.0817\times dbh^{2.1015}\times ht^{0.6021}$	$=\exp[-1.9534+0.7674\times \ln(ht\times dbh^{2})]$	
	Katavi	$=0.0739\times dbh^{2.5764}$	$=0.1731\times dbh^{2.0296}$	
		$=0.0474\times dbh^{2.2239}\times ht^{0.6605}$	$=\exp[-2.3772+0.8094\times \ln(ht\times dbh^{2})]$	
	Lindi	$=0.0981\times dbh^{2.4897}$	$=29.7026-3.6428\times dbh^{-}+0.2738\times dbh^{2}$	
		$=0.0669\times dbh^{2.2770}\times ht^{0.4253}$	$=\exp[-2.9601+0.8692\times \ln(ht\times dbh^{2})]$	
Lowland and Sub-Montane	Amani-Tanga	$=0.9635\times dbh^{1.9440}$	$=7.5811\times dbh^{1.16801}$	Masota *et al.* (2015)
		$=0.4020\times dbh^{1.4365}\times ht^{0.8613}$		

Thicket	Manyoni			Makero *et al.* (in press)
Combretum celastroides		$=0.7269 \times dbh^{2.6710} \times ht^{0.5737} \times st^{0.2039}$	$=0.1006 \times dbh^{4.0062} \times st^{0.3499}$	
Pseudoprosopis fischeri		$=0.4276 \times dbh^{2.4053} \times st^{0.5290}$	$=0.1442 \times dbh^{4.1534} \times st^{0.4117}$	
Associate trees		$=1.2013 \times dbh^{1.5076}$	$=1.3803 \times dbh^{1.1671}$	
Acacia -Commiphora	Same-	$=0.33285 \times (dbh^2 \times ht)^{0.778}$	$=0.07655 \times (dbh^2 \times ht)^{0.763}$	Mathias A. (2015)
	Kiteto	$=0.1879 \times dbh^{2.2904}$	$=0.3867 \times dbh^{1.6749}$	
		$=0.1050 \times dbh^{2.0423} \times ht^{0.6205}$	$=\exp(-1.3847+0.6775 \times \ln(ht \times dbh^2))$	
Baobab	Kilosa	$=2.2349 \times dbh^{1.4354}$	NA	Masota et al. (in press)
		$=0.1924 \times dbh^{1.2049} \times ht^{1.4954}$		
		$=0.6991 \times (dbh^2 \times ht)^{0.6726}$		
Plantations				
Pinus patula	Tanzania	$=0.0550 \times dbh^{2.5968}$	$=0.0027 \times dbh^{3.0579}$	Mugasha et al. (in press)
	Sao Hill	$=0.1564 \times dbh^{2.2711}$	$=0.1551 \times dbh^{1.7915}$	Mugasha et al. (in press)
	Meru	$=0.0304 \times dbh^{2.7590}$	$=0.0018 \times dbh^{3.1697}$	Mugasha et al. (in press)

Tectona grandis	Longuza	$=0.3356\times dbh^{2.1651}$	$=0.0636\times dbh^{2.2182}$	Mugasha et al. (in press)
		$=0.1711\times dbh^{2.0047}\times ht^{0.3767}$	$=0.0279\times dbh^{1.7430}\times ht^{0.7689}$	
Agroforestry				
Coconut	Tanzania	$=3.7964\times ht^{1.8130}$	$=13.5961\times ht^{0.6635}$	Mugasha et al.(in press)
		$=5.2988\times dbh^{-0.1829}\times ht^{1.9297}$	$=8.4628\times dbh^{0.1689}\times ht^{0.6214}$	
Cashewnut	Kisarawe	$=\exp(-0.1684+0.8873\times \ln(dbh^2))$	$=\exp(-2.3765+0.9394\times \ln(dbh^2))$	Zahabu *et al.*(in press)

Table 5.3: Above- and below-ground biomass models for different vegetation types in Tanzania

[a]*AGB = Above ground biomass (kg); BGB = Below ground biomass; dbh = Diameter at breast height (cm); ht = Total tree height (m); st = Number of stems in thicket clup;   = Wood density*

4.3 Tree volume models

Tree volume models were developed for Miombo woodlands, lowland and sub-montane forests, thickets and *Acacia-Commiphora* (see Table 4). General and some species-specific volume models were also developed for different sites (see Table 5.4). The pseudo-R^2 of the models ranged from 0.69 to 0.96 (Masota *et al.*, 2014; Mauya *et al.*, 2014; Makero *et al.*, in press; Mathias, 2015).The models were evaluated by testing their performance over different sites and tree sizes, which resulted into MPE% that were not significantly different from zero ($p > 0.05$), thus indicating that the developed models were unbiased. The models are considered to be unique in terms of wider geographical and species coverage. For example, the models which were developed for Miombo woodland (see, for example, Malimbwi *et al.*, 1994; Chamshama *et al.*, 2004) covered only one site in eastern Tanzania, but the newly-developed models cover four regions endowed with abundant and diverse Miombo tree species (MNRT, 2015). Moreover, previously there were no tree volume models available for *Acacia-Commiphora* and mountain forests.

Vegetation/ species	Location	Model	Source
Miombo woodlands	Tanzania	$= 0.00016\times dbh^{2.463}$ $= 0.00011\times dbh^{2.133}ht^{0.5758}$	Mauya *et al.* (2014)
	Manyara	$= 0.00005\times (dbh^2ht)^{1.013}$	
	Tabora	$= 0.00042\times dbh^{2.19786}$	
	Katavi	$= 0.00009\times dbh^{2.642}$ $= 0.00006\times (dbh^2ht)^{1.012}$	
	Lindi	$= 0.00016\times dbh^{2.472}$ $= 0.0001\times (dbh^2ht)^{0.9416}$	
Lowland and Sub-Montane	Amani-Tanga	$=g\times ht\times(1.414-0.211\times \ln(dbh))$ $= \exp(-7.41201 +2.1901527\times \ln(dbh))$ $=\exp(-8.12477+1.653497\times \ln(dbh) + 0.852048\times \ln(ht))$	Masota *et al.* (2014)
Thicket	Manyoni		Makero *et al.* (in press)
Combretum celastroides		=0.0002×dbh2.4615×ht×0.9089×st0.4534	
Pseudoprosopis fischeri		=0.0002×dbh2.2177×ht0.5468×st0.7903	
Associate trees		=0.0004×dbh1.5009×ht0.6419	
Acacia -Commiphora	Same-Kilimanjaro	$= \exp(-8.46+ 1.82\times \ln(dbh) + 0.49\times \ln(ht))$	Mathias (2015)
	Kiteto	$=0.0002\times dbh^{2.3269}$ $=0.00013\times dbh^{2.1555}\times ht^{0.4352}$	Luganga (2015)

Baobab	Kilosa	$=0.005187\times dbh^{1.5726}$ $=-1.04601+0.56162\times dbh+0.000279\times dbh^2$ $=2.62312+0.000444\times dbh^2$ $=0.001904\times(dbh^2\times ht)^{0.714836}$	Masota *et al.* (in press)
Plantations			
Pinus patula	Meru	$=0.0004\times dbh^{2.2923}$ $=\exp(-9.6383+0.9991\times \ln(ht\times dbh^2))$	Msalika (2014)
Tectona grandis	Longuza	$=0.0012\times dbh^{1.9912}$ $=0.00014\times(dbh^2ht)^{0.8793}$	Mugasha et al.(in press) Mwangi (2015)
Agroforestry			
Coconut	Kisarawe and Mkuranga	$=0.0347\times ht^{1.1873}$ $=0.00134\times dbh^{1.2295}\times ht^{0.7841}$	Mugasha et al.(in press)
Cashewnut	Kisarawe	$=\exp(-9.4111+2.6044\times \ln(dbh))$	Zahabu et al.(in press)

Table 5.4: Tree volume models covering different vegetation types in Tanzania

[a]*g = Basal area; dbh = Diameter at breast height (cm); ht = Total tree height (m); st = Number of stems in thicket clup;* **ρ**= *Wood density*

4.4 Key lessons learnt

Normally, the development of species and site-specific models are preferred in bid to boost accuracy. However, this can hardly be achieved for the entire country such as Tanzania with not only a large geographical coverage but also with more than 800 tree species. In this study, general models that aggregate species and sites were developed and their prediction accuracy were within acceptable ranges. This implies that general models can be used in the absence of species and site-specific models.

It was further learnt that, utilising students in research projects is an effective way of facilitating capacity-building and sustaining research. In fact, the developed models reported in this chapter are based on dissertations and theses of seven MSc and five PhD students. In addition, a total of ten scientific papers have been published in peer-reviewed journals. Moreover, a book detailing the procedures and findings on allometric models has been published (Malimbwi *et al.*, 2016). It should, however, be noted that these studies on the construction of AGB and BGB allometric models through destructive sampling procedures are limited since they are tedious and costly and, therefore, not easily repeatable. In this regard, the support rendered by the Government of Kingdom of Norway was invaluable and the documented results will ensure their long-term and wide application.

5.0 Implications of the lessons learnt for REDD+ and climate change mitigation and adaptation in general

REDD+ involves the estimation of C in five IPCC pools of AGB, BGB, deadwood, litter and soil organic C. Out of these, AGB and BGB are the most important pools since they are vulnerable to changes. To estimate accurately AGB and BGB, allometric models are imperative. This study has developed biomass and volume models for major vegetation cover types identified in Tanzania by NAFORMA (MNRT, 2015). The developed models can facilitate accurate estimation of C stocks for the AGB and BGB. This will enable the country to report on C estimates at higher tiers, in particular tier 3[2]. Volume and C estimates also provide important information for sustainable forest management.

2 IPCC identified three reporting tier levels where by tier 1 utilizes global models while tiers 2 and 3 utilize site specific models and information.

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