3

ILUA II Technical Report Series

Biomass Volume Calculations

By E. N Chidumayo

2016

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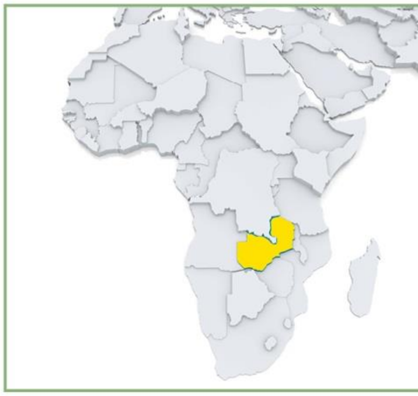
Biomass Volume Calculations

Technical Report No. 3



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Assessment of Existing Models for Biomass Volume Calculations

Technical Paper prepared for the Forestry Department, the Ministry of Lands, Natural Resources and Environmental Protection and the Food Agriculture Organization of the United Nations as a part of the Integrated Land Use Assessment Phase II

by

Emanuel N. Chidumayo[1]

Funding through:
The Ministry for Foreign Affairs, Government of Finland

Implementing agencies:
Forestry Department, Ministry of Lands, Natural Resources and Environmental Protection, Government of the Republic of Zambia

Advisory and technical supervision:
Food and Agriculture Organization of the United Nations

Please cite this paper as:
Forestry Department (2016), Ministry of Lands Natural Resources and Environmental Protection, Integrated Land Use Assessment Phase II - Technical Paper 3, *Assessment of Existing Models for Biomass Volume Calculations*. Food and Agricultural Organization of the United Nations, Ministry of Foreign Affairs Finland. Lusaka, Zambia

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[1] Prof. Emanuel N. Chidumayo, Ecologist and Manager at the Makeni Savanna Research Project in Lusaka, Zambia

FOREWORD

Forest inventories are used as a starting point for estimating biomass and carbon storage in national forests. Biomass equations are normally developed on the basis of data collected in the forest inventory. The Integrated Land-Use Assessment project phase ll (ILUA II) is expected to provide the results of forest stocking that are typically considered within the framework of sustainable forest management and carbon accounting purposes.

It is for these reasons that an assessment of existing models for biomass volume calculations is important in order to explore and provide options of models that are relevant to the ILUA II purposes. It is therefore our belief that this technical paper will highlight the various models for volume and biomass relevant to ILUA II purposes which are also supportive of the Reducing Emissions from Deforestation Forest Degradation (REDD) Mechanisms.

Makumba

Ignatius N. Makumba
DIRECTOR - FORESTRY

Bwalya Chendauka
NATIONAL COORDINATOR - ILUA II

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ACRONYMS

ESP	Environmental Support Programme
FAO	Food and Agriculture Organization of the United Nations
FSP	Forestry Support Programme
GPS	Global Positioning System
GRZ	Government of the Republic of Zambia
ILUA I	Integrated Land-Use Assessment PHASE I
ILUA II	Integrated Land-Use Assessment PHASE II
IPCC	Intergovernmental Panel on Climate Change
JICA	Japan International Cooperation Agency
MENR	Ministry of Environment and Natural Resources
MLNREP	Ministry of Lands, Natural Resources and Environment Protection
MTENR	Ministry of Tourism, Environment and Natural Resources
PFAP	Provincial Forestry Action Programme
REDD+	Reducing Emissions from Deforestation and Forest Degradation, , Conservation, Enhancement of Carbon Stocks and Sustainable Forest Management
RSE	Residual Standard Error
SADCC	Southern Africa Development Coordination Conference
SWD	Specific wood density
UNREDD	United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation
PFAP	Provincial Forestry Action Plan
ZFAP	Zambia Forestry Action

ABSTRACT

Traditionally, wood stocks in Zambian forests have been estimated using tree volumes. From the mid-1980s, there has been a growing interest in estimating wood biomass directly from tree diameter measurements rather than indirectly from volume estimates. The direct estimation of wood biomass has fewer sources of error and therefore tends to give more accurate estimates. The main objective of this study was to test the different volume and biomass models, using an existing Zambian database, to find confidence limits and to determine (a) the accuracy and precision of the models for ILUA II purposes and (b) the need/usefulness to apply more than one model for ILUA II purposes.

The study evaluated four volume models, including the ILUA I model, and compared the prediction performance of the models against volume estimates based on field observations in miombo (*Brachystegia – Julbernardia - Isoberlinia*) woodland. Smalian's model overestimated bole and tree volume while Huber's model, although giving slight underestimates with confidence limits of 2–4%, gave the closest estimates to those based on field observations. However, Huber's method requires the measurement of diameter at stem mid-length, which is not easy to measure in the field. The ILUA I method was the second-best for estimating bole and stem volume, although it overestimates volume by 26–30%.

Using specific wood density values, the volume estimates can be converted to wood biomass. Although the ILUA I method overestimated volume, after conversion to biomass, the method actually underestimated tree biomass by 18–22%, while Huber's method underestimated biomass by 35 – 37%, largely because these methods did not account for the volume and biomass of tree branches and twigs.

Three model types were evaluated for estimating aboveground wood biomass directly from tree diameter measurements: (i) log models based on logarithmically transformed data, (ii) polynomial models and (iii) power models. The last two model types were based on both tree diameter and basal area (BA). The models that gave the most accurate estimates (< 20% deviation from observed values) were the log and power models. The $\text{power}_{\text{dbh}}$ model gave reasonable error terms of <20% for all the data sets except for drier young miombo and munga woodland. The polynomial models only performed well for munga (*Acacia spp.*) and mopane (*Colophospermum mopane*) woodlands while the polynomial models based on dbh and BA were good for the old-growth data set. Log models gave accurate estimates in nearly 80% of the species and species groups in comparison to 50% and 30–35% for power and polynomial models, respectively. Log models gave the most accurate estimates for *Isoberlinia angolensis*, and *Uapaca* species and species-groups of *Acacia*, *Julbernardia* and *Uapaca,* while power models gave the most accurate estimates for *Colophospermum mopane* and *Diplorhynchus condylocarpon*. For *Brachystegia boehmii* and *Julbernardia globiflora,* both log and power models were equally accurate.

For ILUA II the following recommendations are proposed.

1 The biomass data for felled trees that were used in this assessment did not represent trees in the very large dbh classes that were inventoried in the ILUA I survey. Although the error in the biomass estimates did not appear to increase with increasing tree size, consideration should be given in either ILUA II or REDD+ to obtain biomass data for large (>50cm dbh) trees in the country. However, this recommendation should only be considered if resources are available because, in the interim, the models recommended in the paper are adequate for estimating aboveground biomass.

2 It is also recommended that for national estimates, one or a few general models be used to estimate aboveground biomass directly from diameter data. However, although such models can be applied at sub-national level, it is recommended that general models for each main forest type be applied at sub-national levels.

3 For REDD+ requirements, biomass and carbon stocks will be needed for forest types for which volume and/or diameter at breast height measurements may not be appropriate. Thus, diameter measurements at stem/tree base or stump height (0.1–0.3m aboveground ground) may be more suitable. Estimating aboveground wood biomass for such forest types can initially be based on existing models that use diameter or basal area at stem base as predictor variables. Such models can be applied to estimating biomass and carbon stocks in young trees in naturally regenerating and agroforestry stands, in thickets, scrub vegetation and harvested stands with standing stumps.

1. INTRODUCTION

1.1. Integrated Land Use Assessments in Zambia

There have been 17 forest assessments (Table 1.1) and numerous other site specific forest inventories conducted in Zambia. In spite of the many forest assessments that have been done, the databases collected during all these inventories, except the 1952–1967 and 2005–2008 inventories, are difficult to find. Some District Forest Management Books developed from the 1952–1967 country-wide surveys contain data on felled acre (0.405ha) sample plots. The data for each felled acre plot included tree species; stem height; girth at base, breast height, centre, and top from which volume over bark of the stem was calculated; stacked volume of branch wood; and estimated firewood headloads.

The Integrated Land Use Assessment of 2005–2008 (ILUA I) was the most intensive and extensive inventory ever carried out to collect both forestry and socio-economic data in Zambia (Forestry Department and FAO, 2005). The sampling design used in ILUA I was systematic, without stratification. Inventory sample tracts were located at every 30 minutes on the latitude/longitude grid throughout the country. The country was covered by a total of 248 tracts but only 221 were accessible. However, some accessible tracts were located in government restricted areas, while in other cases, landowners refused the inventory teams permission to carry out the survey. A track or cluster is a square area of 1km x 1km within which four rectangular sample plots were demarcated. Each plot was 20m wide and 250m long, with a total area of 0.5ha. Within each plot, three subplots were delineated, one mid-way along the length of the plot and the remaining two at either end of the plot. Each subplot was 10m wide and 20m long, and at the centre of the subplot, a micro-plot of 3.99m radius was established. All trees in the sample plot with a diameter at 1.3m aboveground (diameter at breast height, Dbh, in cm) greater than 20cm were identified by a vernacular or scientific name, or both, and then measured. In the subplots, small diameter trees (7cm ≤ Dbh < 20cm) were measured while micro-plots were used to measure regeneration (Dbh < 7cm).

Equipment used in the inventory included Global Positioning System (GPS) devices for navigation and geographical locations, Suunto Hyposometers for tree height measurements, Suunto Compasses for angles (directions), Suunto diameters for tree diameter measurements, Range finders and rods for calculating distances and ranging out, respectively, and metal pegs for starting each plot in a track.

***Table 1.1** Forest assessments conducted in Zambia. Based on Forestry Department and FAO (2005).*

Period	Inventory
1932–1936	Sample plots established near Ndola to determine the productivity of indigenous *Brachystegia – Julbernardia* (miombo) woodland
1942–1944	Forest inventory to identify and estimate timber volume for Copperbelt Province
1949–1951	Small-scale inventory to identify and estimate timber volume for Western Province concession harvesting
1952–1967	Country-wide forest inventory to develop District Forest Management Books
1972	Timber and woodland survey of Protected Forest Area No. 170 in East Luangwa

Period	**Inventory**
1984–1986	Country-wide wood consumption and supply survey to determine woody biomass resource in the country
1987	Southern Africa Development Coordination Conference (SADCC) wood energy study to determine woody biomass resource in the country
1994–1996	Government of the Republic of Zambia (GRZ) and Japan International Cooperation Agency (JICA) forest resources management study for Zambezi teak forests in south-western Zambia
1996	Provincial Forest Action Plan forest inventory in Mulungushi West Forest reserve in Central Province and Mwewa Forest Reserve in Luapula Province
1996–1998	Provincial Forest Action Plan forest inventories in Copperbelt, Luapula and Southern Provinces (Phase I)
1997	Southern Africa Development Coordination Conference (SADCC) forest area assessment for Zambia
1999–2001	Provincial Forest Action Plan forest inventories in Copperbelt, Luapula and Southern Provinces (Phase II)
2000	Food and Agriculture Organization (FAO) forest area assessment for Zambia
2001	Environmental Support Programme (ESP) local forest inventories in Central Province
2002–2003	Forestry Support Programme (FSP) forest inventories in Central, Copperbelt, Eastern, Luapula, Lusaka, Northern, North-Western, Southern and Western Provinces
2004	Forestry Support Programme (FSP) woody biomass resource assessment
2005–2008	Government of the Republic of Zambia (GRZ) and Food and Agriculture Organization (FAO) country wide Integrated Land Use Assessment (ILUA I)

During ILUA I, 11 different field crews collected inventory data in the different provinces. The crews identified the plot sample points with GPS receivers and placed a metal pole as a permanent marker at each starting point. Three reference features were noted at suitable locations for future identification of the plot starting point. Bias and errors in the measurements and information were due to flaws in the measurements, the methods of selecting samples, the measurement techniques, and the varying capacity and skills in estimating parameters among the field crews. The ILUA I sampling design also resulted in unequal sample representativeness. For example, some important forest types were either not sampled or were poorly represented (Table 1.2).

Table 1.2 *Distribution of fully sampled tracks (four plots per track) during ILUA I. Based on the ILUA I database.*

Forest type		**Number of fully sampled tracks**
Floristic association	**ILUA classification**	
Cryptosepalum evergreen forest	Evergreen forest	1
Baikiaea forest	Deciduous forest	1
Brachystegia – Julbernardia (Miombo) woodland	Semi-evergreen forest	135
Kalahari Sand woodland	Deciduous forest	20
Colophospermum mopane (Mopane)	Deciduous forest	12

Forest type		Number of fully sampled tracks
Floristic association	**ILUA classification**	
woodland		
Acacia (Munga) narrow-leaved woodland	Deciduous forest	2
Undifferentiated broad-leaved woodland	Deciduous forest	27
All forests		198

ILUA II is intended to improve information on sample plot location, marking and tree measurements through the use of better equipment, such as higher resolution GPS devices and Range finders that can also more accurately measure tree heights. In addition, ILUA II will carry out tree re-measurements at selected ILUA I tracks and plots. The ILUA II sampling design will be based on stratified systematic sampling to overcome the problem of unequal sample representativeness among land use and cover types that characterized the systematic sampling design for ILUA I. The long and narrow sample plots used during ILUA I often included more than one land use and cover type which presented problems in classifying tracks and/or plots and their associated data according to land use and cover type. Although the sampling design for ILUA II has not been finalized, the use of circular sample plots has been proposed to replace the rectangular sample plots used in ILUA I.

1.2 Terms of reference for the study

This study to assess existing models for biomass and/or volume estimation consisted of three main parts:

(i) Collection of existing biomass and/or volume models from Zambia and neighbouring countries with similar species and growing conditions.

(ii) Testing the different models on an existing Zambian database to find confidence limits and to determine (a) the accuracy and precision of the models for ILUA II purposes and (b) the need/usefulness to apply more than one model for ILUA II purposes based on, for example, species or species groups.

(iii) Preparation of a proposal on how to proceed in the most practical, cost-efficient way, so as to best serve ILUA II and UNREDD requirements for biomass and/or volume estimations. The proposal should include considerations like working on a species basis, the formation of tree groups based on similarities in growing patterns, zoning of the country based on, for example, rainfall patterns, etc.

The assessment was based on available biomass and volume data of felled trees/stems in Zambia and neighbouring countries with similar vegetation types like Zambia.

1.3 Brief history of volume and biomass estimation for Zambian trees and forests

Forest stocks in Zambia have traditionally been estimated using wood volume (Lees, 1962; Alajärvi, 1996) with the aim of providing planning information for timber harvesting. The Provincial Forestry Action Programme (PFAP) used the Smalian's model to estimate wood volume (Alajärvi, 1996), while the estimates of growing stock given in the Zambia Forestry Action Plan (ZFAP) (MENR, 1998) were based on the PFAP assessments (see Table 1.1). However, Endean (1967), following his work on the Ndola Indigenous Sample Plots, noted that the best indicator of harvestable wood volume in indigenous forests was the Stand Basal Area (BA) and he used this to estimate the productivity of miombo woodland.

The interest in direct biomass estimation in Zambia arose from the need to determine biomass regeneration and burning for ash fertilization under the chitemene shifting cultivation in northern Zambia. Stromgaard (1985a, 1985b) was perhaps the first researcher to apply logarithmic regression models to estimate biomass from tree/stem dbh and height for trees in young fallow regrowth after shifting cultivation. He developed separate equations for six dominant miombo species, for undisturbed miombo and for all trees measured in four 20m x 20m clear-cut sample plots in Kasama District. His approach was later used by Araki (1992) and Oyama (1996) who worked in Mpika District. Araki (1992) measured the above-ground biomass of miombo woodland in a 20m x 20m quadrant of semi-mature woodland (mitanda site) for trees more than 2.5m high following the cutting method of chitemene, and separated the biomass into stumps, trunks, branches and leaves. Oyama (1996) used the regression between log height (dbh^2 x H) and log biomass to estimate biomass in two 10m x 10m plots in regrowth miombo after chitemene and from selected harvested trees in mature woodland.

The work of Chidumayo (1990, 1993a and 2002) was more concerned with estimating biomass for charcoal production and productivity of miombo woodland using both selected harvested trees and clear-cut 20m x 10m sample plots. He used simple linear regression equations based on the diameter, at 0.3m aboveground (dsh) for small stems and dbh for large stems, to estimate different biomass components for mature and regrowth miombo in Central, Copperbelt and Lusaka Provinces (Chidumayo, 1990), and later used power and exponential models to estimate stem wood and twig wood, respectively (Chidumayo, 2002). He also developed a total of 68 biomass equations for estimating different biomass components for individual species and species groups from trees clear cut in 24 plots, 20m x 10m, in the Chakwenga area of Chongwe District (Chidumayo, 1993a). Recently, Kutsch et al. (2011) estimated aboveground wood biomass in Kataba Forest Reserve in Mongu District to assess the impact of charcoal production and greenhouse emissions, although they do not explain how they arrived at the estimates.

More recently, Kaonga and Bayliss-Smith (2010) developed linear, multiple linear and log-linear regression models to estimate stem and total aboveground carbon stocks in two-year-old improved fallows in Eastern Province using a diameter at 0.10m aboveground ground and height. They harvested 222 trees of 12 species and found that logarithmically transformed power functions performed well in estimating aboveground carbon stocks in the fallows.

1.4 Estimating tree volume and biomass

The two approaches for estimating the biomass of woody vegetation types are *the volume method* and *the direct biomass estimate method*. The volume method uses measured volume estimates that are then converted to biomass (tonnes/ha) using a variety of tools. The direct estimates of the biomass method uses biomass allometric equations, i.e. functions that relate oven-dry biomass per tree as a function of a single or a combination of tree dimensions (Brown 1997). Tree biomass equations are very similar to tree volume equations in that both require data on tree diameter at breast height (dbh) as an independent variable, often with tree height (H) and other variables, and both use models of similar types. But, they also differ in a number of ways.

For the volume estimation method, the tree volume must first be estimated before conversion to biomass. Total tree volume (V_{tot}) is calculated as the sum of each component volume of the tree as follows (Segura and Kanninen, 2005):

$$V_{tot} = V_{stem} + V_{L\text{-}branch} + V_{s\text{-}branch} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Equation 1.1}$$

Where V_{stem} is total tree volume, $V_{L\text{-}branch}$ is volume of large branches and $V_{s\text{-}branch}$ is volume of small branches. However, more generally, standard models are used to estimate merchantable or bole volume (up to the point of first branch or defect) and total tree volume. Philip (1994) describes three such models: (i) The Smalian's model, (ii) Huber's model and (iii) Newton's model.

Volume estimates are then multiplied by specific wood density values to derive biomass estimates. Specific wood density (SWD) refers to oven-dry mass per unit of green wood volume (t/m^3 or g/cm^3). Where there is inadequate wood density data, an estimate of a weighted mean wood density can be made from known species by applying the arithmetic mean for known species to unknown species. For Africa, this is 0.58 with a range of 0.50 to 0.79 (Brown, 1997). Biomass estimates are then subjected to biomass expansion factors to account for tree components whose volume or biomass are not measured, such as minor branches and twigs. In general, the expansion factor (*ExpF*) is used to calculate total aboveground volume or biomass where there is partial aboveground volume or biomass data and can be applied to both tree and plot data (Somogyi et al., 2008).

Thus, biomass from volume data can be expressed as:

$$\text{Aboveground biomass} = \text{Estimated volume over bark} \times \text{SWD} \times ExpF \quad \ldots\ldots\ldots\ldots\text{Equation 1.2}$$

Measurements on trees can be directly converted to aboveground biomass using biomass allometric equations developed from trees of many species harvested with a large range of dbh in order to estimate biomass per tree. The equations relate dbh (cm) to biomass (kg/tree) or basal area (cm^2) to biomass (kg/tree). This direct method therefore does not require volume estimates in order to estimate biomass. However, it is important that the biomass of trees with large dbh be estimated as accurately as possible because their contribution to the biomass of a forest stand is much more than their number suggests (Brown, 2002). Similarly, it is important to evaluate several regression equations (linear, non-linear and transformed nonlinear regression equations) and test the behaviour of the equations against observed data before selecting the final equations. Thus, a forest biomass inventory designed to measure forest biomass, in addition to volume, can be conducted to obtain data on additional components of trees and additional forest areas, such as young regrowth consisting of small stems or thickets or agroforestry stands that are not normally included in forest volume inventories. Because of this, biomass data are used for many purposes, such as energy, fodder, medicine, etc. and therefore meet the requirements of more forest users than volume data.

1.5 Main sources of error in volume and biomass estimates

Volume and biomass estimation methods are associated with errors at different stages of the process. However, because estimating biomass from volume estimates involves more steps than direct biomass estimation, there are more sources of error associated with the volume method than the biomass method (Table 1.3). The first potential source of error is the tree measurement process. Errors in trunk diameter, height or specific wood density measurements, all result in errors in estimating the volume stocks and aboveground wood biomass. The second main source of error arises from the construction of the allometric equations. In general, forest allometric models used for aboveground biomass estimation suffer from three important shortcomings: (i) they are constructed from limited samples, (ii) they are sometimes applied beyond their valid diameter range, and (iii) they often do not take into account available information on specific wood density (Chave et al., 2005). It is therefore important to give confidence intervals for the volume and biomass estimates calculated by different models so that meaningful comparisons can be made between the models.

Table 1.3 *Main sources of error in two methods of estimating aboveground wood biomass*

Source of error	**Methodology**	
	Volume estimates (cm^3 or m^3)	**Biomass (g or kg)**
Tree measurements	i. Diameter(s)	i. Diameter
	ii. Height(s)	ii. Mass
	iii. Specific wood density	Only applicable if biomass is derived from volume
Model estimates	iv. Tree height	Optional
	v. Tree volume	iii. Tree biomass
Conversion factors	vi. Conversion to mass	Not applicable
	vii. Conversion to plot estimates	iv. Conversion to plot estimates

There are a number of statistics for evaluating goodness-of-fit, but the Akaike information criterion (Burnham and Anderson, 2002) corrected for small samples (AICc) and residual standard error (RSE) or the standard error of the residuals, when reported together, provide sufficient information on the quality of a statistical fit for mixed-species regression models (Chave et al., 2005). However, a simple way of evaluating the performance of the regression model is by measuring the deviation of the predicted biomass ($\text{Biomass}_{\text{predict}}$) from measured observed biomass ($\text{Biomass}_{\text{measured}}$) for each tree. This error is defined as follows (Chave et al., 2005):

$$\text{Error} = 100(\text{Biomass}_{\text{predict}} - \text{Biomass}_{\text{measured}})/\text{Biomass}_{\text{measured}} \quad \text{……………………Equation 1.3}$$

This means that before selecting a model, the model must first be tested for its accuracy of prediction against the observed data. The majority of the existing biomass models for dry forests in sub-Saharan Africa (see Table 2.1 below) have been selected not on the basis of their accuracy, but on the value of the coefficient of determination (r^2) which is a measure of the explanatory power of the variance in the predicted variable and not necessarily on their accuracy as determined by their mean error of prediction as suggested above. This means that one must first have access to the observed raw data in order to objectively evaluate the accuracy of the model derived from a particular set of observed raw data. Only when this is done and the model meets a threshold level of accuracy can a model be applied to other data. For this reason, it was not possible to evaluate the majority of existing volume and biomass models for forests in Zambia and the neighbouring countries with similar forests, because original raw data that was the basis for model development are not available.

2. METHODOLOGY

2.1 Available models for Zambia and neighbouring countries

Many models have been developed and applied to estimate tree volume and biomass in eastern and southern African countries with forest types similar to Zambia. Henry et al. (2011) present models for Africa that have been published, although the coverage is by no means complete. This assessment is limited to models for trees in natural forests and not in plantations, because plantation trees tend to have a different structure. In fact, Zambia has only about 60,000ha of exotic tropical pine and eucalyptus plantation forest, which constitutes an insignificant proportion (≈ 0.1%) of the forested area in the country. The main focus in this assessment is on the class or type of models, and not the variety of the individual models within each model class or type which could be numbered in the hundreds (for example, see Henry et al., 2011). Power models, for example, belong to one class of models that consists of many individual models that differ in terms of both the predictor variables and other parameters or coefficients. The most commonly used models in sub-Saharan African dry forests are presented in Table 2.1 and these are the models that were evaluated in this assessment. Linear models can be based on logarithmically transformed data (log models) or square-rooted data and/or untransformed data. Others use power models based on either dbh alone, or in combination with other predictors, such as tree height and crown diameter, or basal area, but a few use polynomial models. Very few researchers have used basal area as a predictor in the models. However, Endean (1967) and Frost (1996) indicated that stand basal area provides a good index of both the harvestable volume and the aboveground biomass of miombo woodland stands and recently, a number of publications have shown the importance of basal area as a predictor of biomass in tropical forests (Feeley et al., 2007;).

During the inception workshop for this assignment that was attended by stakeholders, it was proposed to develop and select simple models with a minimum of easy-to-measure critical predictor variables that can be applied at national and sub-national levels. Brown (2002) also noted that for practical purposes, regression equations based on diameter alone are more useful and easy to apply than those that additionally use height, because total tree height measurement is more prone to error than diameter measurement and is not always available in field inventories. In fact, Kamelarczyk (2009) found only slight differences in biomass estimates based on dbh alone and those based on dbh and height.

Table 2.1 *Commonly used model types in estimating aboveground wood biomass in sub-Saharan African dry forests. Where y is the dependent variable (biomass), x is the independent variable (diameter, basal area and/or height), a is an estimate of the intercept of the regression line, b and c are estimates of the slope of the regression line and d is the power coefficient.*

Model type	**Publications that used the model to estimate biomass**
Linear log model: $\ln(y) = \ln(a) + b\ln(x)$	Stromgaard (1985a, 1985b); Okello et al. (2001); Ryan et al. (2010); Mutakela (2009); Oyama (1996); Shackleton and Scholes (2011); Mugasha and Chamshama (2002); Malimbwi and Solberg (1994); Rutherford (1979); Sawadogo et al. (2010).
Power model: $y = ax^d$	Mugasha and Chamshama (2002); Cleemput et al. (2004); Tietema (1993a, 1993b); Guy (1981); Munishi et al. (2010).
Polynomial model: $y = a + b_1x + b_2x^2 + b_3x^3$	Ryan et al. (2010); Mabowe (2006).

2.2 Biomass and volume data

The data used in this assessment were collected at 21 sites in Botswana, Tanzania and Zambia (Figure 2.1 and Table 2.2) in the Zambezian floristic region of White (1983) and included 1,319 stems representing 82 species. The sites represent three woodland types found in Zambia and the neighbouring countries: (i) *Brachystegia-Julbernardia* (miombo) woodland, (ii) *Acacia* (munga) woodland and *Colophospermum mopane* (mopane) woodland.

Table 2.2 *Description of vegetation and felled trees/stems for which biomass measurements were made at study sites in Botswana, Tanzania and Zambia.*

Country/Site	**Woodland type (age in years for young growth)**		**Year of sampling**	**Number of tree species**	**Felled trees/stems**	**Size range (dbh, cm)**[1]
Botswana						
Serowe	*Acacia* (Munga)	Mature	2005	7	61	3 – 21
Serule	Mopane	Mature	2005	1	26	6 – 31
Sexaxa		Mature	2005	1	27	4 – 39
Tamacha		Mature	2005	1	29	4 – 38
Tanzania						
Kitulangalo	Drier miombo	Mature	2002	20	30	1 – 50

Zambia						
Chabesha	Drier miombo	Young (7,9 &12)	1988, 1990/91, 1993	22	336	1 – 9
Chisamba		Mature	1988	7	13	2 – 36
Kamaila		Young (20)	1988	19	47	1 – 11
Kamatupa		Mature	1990/91	23	123	2 – 38
Kankumba		Mature	1988	24	217	2 – 39
Mwambashi		Young (16,18 & 22)	1988, 1990/91, 1993	23	231	2 – 18
Nyati		Mature	2000	2	15	4 – 33
Sanje		Mature	1988	5	11	2 – 39
Soli		Mature & young (17)	1988	20	57	1 – 30
Makeni	*Acacia* (Munga)	Mature	2000	5	56	3 – 32
Lamba	Wetter miombo	Mature	1988	10	16	4 – 31
Luano		Mature & young (22)	1988	14	49	2 – 43
Luanshya		Young (15)	1988	12	32	1 – 11
Maposa		Young (7 & 11)	1988	20	65	1 – 13
Misaka		Mature	1988	12	16	2 – 32
Mwekera		Mature	1988	8	13	5 – 35

[1] dbh is diameter at breast height (1.3 m aboveground ground)

Figure 2.1 *Location of sites from where raw biomass data of felled trees were obtained in Botswana, Tanzania and Zambia.*

Before felling, each tree was identified to species level, while the diameters at stump height (0.1–0.3m aboveground) and breast height (1.3m aboveground) were measured and recorded. Total tree height was measured either before or after felling. Felled sample trees were representative of tree sizes in a plot or community and the species included in the samples are given in Annex 1. Trees were cut at ground level (≤0.3m aboveground ground) and all aboveground parts (i.e., wood and twigs and in some cases leaves) separated and weighed with spring scales immediately after felling. Each stem of a multi-stemmed tree was treated separately. Subsamples of each tissue type were collected and oven-dried to constant mass to correct for moisture content and determine the total aboveground wood dry weight of each tree. In the case of samples collected in 1988 in Zambia, the wood moisture content was measured by an electronic meter and an appropriate factor used to determine dry weight. More details about these methods can be found in the original publications (Chidumayo, 1990; Chidumayo, 1993b; Chidumayo, 2002; Mabowe, 2006; Mugasha and Chamshama, 2002; Mutakela, 2009).

The 1988 data from Zambia also included bole length and, after cross-cutting the main stem into 1.0m long logs from bottom to top, the mid-diameter of each log was also measured and recorded for wetter miombo woodland. Similar data, but without bole length, were also recorded for some samples from drier miombo collected in 1990 and 1991 (Table 2.3). The fresh weight of each 1.0m long log was recorded and converted to oven-dry weight as described above. The data were used to calculate stem volume and specific wood density.

Table 2.3 *Sample stems and 1.0m long logs used for determining volume and specific wood density of miombo woodland trees in Zambia.*

Species	**Wetter miombo**		**Drier miombo**	
	Sample stems	**Sample logs (from base to top of stem)**	**Sample stems**	**Sample logs (from base to top of stem)**
Albizia antunesiana			3	21
Baphia bequaertii	2	15		
Brachystegia boehmii	1	9	38	145
Brachystegia longifolia	3	17		
Brachystegia spiciformis	3	27	8	51
Brachystegia utilis			5	34
Burkea africana			12	42
Dichrostachys cinerea			7	17
Diplorhynchus condylocarpon	3	21	5	24
Faurea saligna	1	9		
Faurea speciosa			3	7
Isoberlinia angolensis	6	54	29	157
Julbernardia globiflora			66	337
Julbernardia paniculata	3	27		
Marquesia macroura	1	9		
Monotes spp.			8	31
Ochna schweinfurthiana			1	6
Parinari curatellifolia	4	27	8	34
Pericopsis angolensis	1	9	2	11
Phyllocosmus lemaireanus			12	46
Protea spp.			5	13
Pseudolachnostylis maprouneifolia	1	8	2	5
Pterocarpus angolensis			1	4
Strychnos innocua			1	5
Swartzia madagascariensis			3	9
Syzygium guineense macrocarpum	1	7	6	14
Terminalia sericea	1	9		
Uapaca kirkiana			38	153
Uapaca nitida	1	7	17	97
Vangueriopsis lanciflora			1	3
Ximenia americana			1	3
All species (31)	32	264	282	1269

2.3 Statistical models for biomass estimation

Because destructive sampling of the entire aboveground mass of trees is a costly, difficult and labour-intensive process, the preferred method for estimating the biomass of individual trees or whole stands is to make use of the strong relationships between the stem diameter and the mass of tree biomass or its components. These relationships vary within and between species, but biomass allometric equations developed from trees of many species harvested with a large range of sizes can be used to estimate biomass per tree. Indeed, for species rich forests and woodlands, mixed species tree biomass regression models have been recommended (Chave et al., 2005). The equations relate dbh (cm) or basal area (cm^2) to biomass (kg/tree). Brown (1997) highlighted the importance of evaluating several regression equations (linear, non-linear and transformed nonlinear regression equations) and testing the behaviour of the equations against observed data before selecting the final equations. Validation of regression equations entails tree felling of a sufficient number (>25) of representative trees (de Gier, 1999) or at least 50 trees (Chave et al., 2004). The evaluation of the performance of the regression model in this study was done by calculating the deviation of the predicted from the measured observed biomass for each tree as given in Equation 1.3

The mean across sample trees is the mean error (or bias, in %), and the standard deviation of error among sample trees is the standard error (also expressed in %) that represents the overall predictive power (accuracy) of the model. The smaller the mean error, the more accurate the allometric model, and the smaller the standard error of the mean error, the more precise is the regression model in estimating the measured biomass. Although the selection of many of the existing models has been based on the coefficient of determination (r^2), there was no clear relationship between r^2 and mean error in this study (Figure 2.2). Thus, higher values of r^2 did not necessarily mean a lower mean error or higher model accuracy.

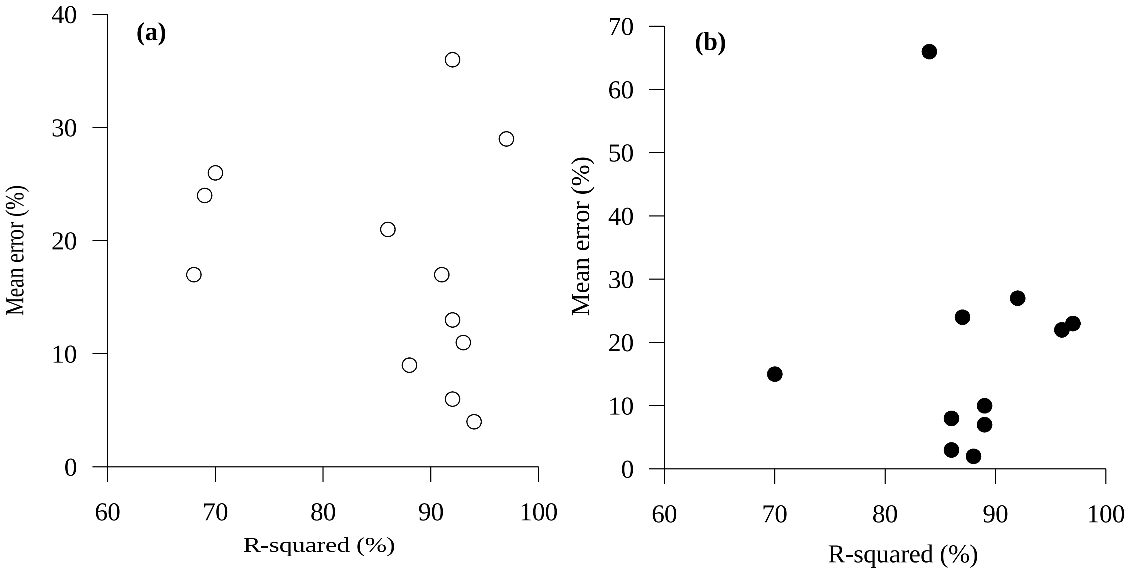

Figure 2.2 *Scatter plots for coefficient of determination (r^2) versus mean error for biomass models: (a) linear log models and (b) power models based on dbh. Models with r^2 <60.00 have been excluded.*

One of the fundamental assumptions of linear regression is that the data is normally distributed and that, where this is not the case, the normality of the data can be improved by log transformation of the original data. The Shapiro-Wilk (W) test (Statistix 9.0©) was used to evaluate whether the data were normally distributed before and after transformation. The test can also be applied to residuals resulting from a linear regression analysis. The W statistic approaches 1.0 for normally distributed data with an associated p-value that is >0.05. The log-transformation of the data may improve the normality of data distribution but also entails a bias in the final biomass estimation after back-transformation and uncorrected biomass estimates are theoretically expected to underestimate the real value. A simple, first order correction for this effect consists of multiplying the estimate by a correction factor (Chave et al. 2005):

$$CF = \exp((RSE^2)/2) \quad \text{………………………………………………………………..Equation 2.1}$$

CF is always >1.0, exp is equal to 2.7183 and RSE is obtained from the model regression procedure. The larger the RSE is, the poorer the regression model and the larger the correction factor (CF).

The estimates based on the model types in Table 2.1 were evaluated against the observed field measurements, the assumption being that biomass values obtained from felled trees/stems represent the best estimate and have the least errors compared to model estimates.

2 .4 Selection of models for volume estimation

Philip (1994) discussed three models that are used to estimate bole, stem and log volume from field measurements of felled trees. These models were evaluated and are given as follows:

(i) The Smalian's model: $V = (\pi L(d_1^2 + d_2^2))/8$

(ii) Huber's model: $V = (\pi L d_m^2)/4$

(iii) Newton's model : $V = (\pi L(d_1^2 + 4d_m^2 + d_2^2))/24$

Where:

d_1 = diameter at base of stem/log (m)

d_m = diameter at mid-length of stem/log (m)

d_2 = diameter at top of stem/log (m)

L = stem/log length (m)

V = volume of stem/log (m^3)

From the field data, d_1 was represented by the diameter at stump height (≈0.3 m above ground), d_m was the mid-length diameter of the 1.0m log half-way along the length of the stem or bole, d_2 was the mid-length diameter of the 1.0m log at the top of the stem or bole and L was the total height of the stem or bole. Stem or bole volume estimates obtained by these models were compared with those estimated by summing the volume estimates of individual 1.0m logs for each stem or bole. Thus, stem or bole volume by this summation method was calculated as

$$\text{Volume } (m^3) = \pi d_1^2/4 + \pi d_2^2/4 + ... + \pi d_n^2/4 \text{ ......Equation 2.2}$$

Where d_1 is mid-diameter of log 1 at the base of the stem, d_2 is mid-diameter of log 2 and so on and d_n is mid-diameter of the last log on top of the stem or bole. As each log was 1.0m long, log length is not explicitly shown in Equation 2.2.

For ILUA I, the following models were used to estimate bole and tree/stem volume:

$$\text{Bole volume } (m^3) = (dbh2/4)\pi Hf_c \text{ ......Equation 2.3}$$

$$\text{Stem volume } (m^3) = (dbh2/4)\pi Hf_g \text{ ......Equation 2.4}$$

Where H is tree height, f_c is a correction (form) factor of 0.74 and f_g is a correction (form) factor of 0.68. Note that in the published ILUA I report these factors are wrongly reversed (see Equation 3.1 for stem volume) and the sources for factors were not given. The mean values of these factors calculated from data of felled stems in miombo woodland in Zambia were 0.81±0.04 for f_c and 0.67±0.01 for f_g. The performance of these ILUA I models was also evaluated in the same way as described above for biomass models.

2.5 Specific wood density

Specific wood density was calculated by dividing the oven-dry weight of the 1.0m long log by the calculated fresh volume of the individual log. A mean specific wood density (SWD) value for each species was calculated using the data for all the stem logs (from bottom to top of stem) of that species (see Table 2.3 for sample sizes). These mean SWD values are given in Table 2.4.

***Table 2.4** The Smalian's model: Specific wood density of trees in drier and wetter miombo woodland in Zambia. Standard error is not shown where values were close to zero.*

Species	**Wetter miombo**	**Drier miombo**
	Kg m^{-3}	**Kg m^{-3}**
Albizia antunesiana		603.0
Baphia bequaertii	644.85	
Brachystegia boehmii	583.54	616.0
Brachystegia longifolia	712.87	
Brachystegia spiciformis	602.66	671.0
Brachystegia utilis		702.0
Burkea africana		543.0
Dichrostachys cinerea		599.0
Diplorhynchus condylocarpon	865.29	586.0
Faurea saligna	600.52	
Faurea speciosa		651.0
Isoberlinia angolensis	544.18	560.0
Julbernardia globiflora		680.0
Julbernardia paniculata	683.22	
Marquesia macroura	640.7	

Species	**Wetter miombo**	**Drier miombo**
	Kg m⁻³	**Kg m⁻³**
Monotes spp.		701.0
Ochna schweinfurthiana		545.0
Parinari curatellifolia	606.62	611.0
Pericopsis angolensis	997.87	654.0
Phyllocosmus lemaireanus		637.0
Protea spp.		508.0
Pseudolachnostylis maprouneifolia	704.94	671.0
Pterocarpus angolensis		537.0
Strychnos innocua		740.0
Swartzia madagascariensis		598.0
Syzygium guineense macrocarpum	524.77	494.0
Terminalia sericea	693.87	
Uapaca kirkiana		505.0
Uapaca nitida	526.92	535.06±9.06
Vangueriopsis lanciflora		399.0
Ximenia americana		463.0
All species (31)	651.45±20.07	602.36±4.15
Combined data	618.55±16.81	

3. ASSESSMENT OF VOLUME MODELS USING INDIVIDUAL TREE DATA

3.1 Evaluation of volume models

The five methods used to estimate bole volume for wetter miombo species gave significantly different results (ANOVA: F = 22.43, P<0.0001). However, multiple pairwise comparisons revealed that the Smalian method gave significantly higher volume estimates than the other methods (Figure 3.1). Stem volume estimates for drier and wetter miombo also showed that estimates by the Smalian method were significantly larger than those by the other four methods (F = 72.58, P <0.0001; Figure 3.1). Philip (1994) also noted that the Smalian's method gave much higher estimates than the other methods and for this reason, the Smalian's method will not be discussed any further in this report. However, it is important to note that the PFAP volume estimates were based on the Smalian's model (Alajärvi, 1996) which may have resulted in higher stem volume estimates.

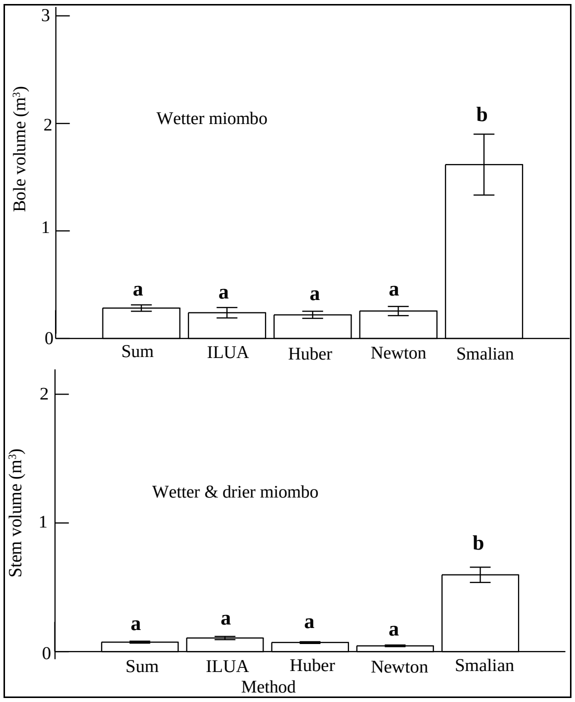

Figure 3.1 *Estimates of bole (top) and stem (bottom) volumes by five different methods: summation (Sum), ILUA 1 (ILUA), Huber's (Huber), Newton's (Newton) and Smalian's (Smalian). Vertical line on each bar indicates standard error of mean and bars with the same letter were not significantly different.*

3.2 Stem volume estimates using ILUA I data

Stem volume estimates using ILUA I data are given in Table 3.1. The volume estimates in the ILUA I report are higher than those calculated using Equation 2.4. It is difficult to explain the source of the differences, unless the reported ILUA I estimates were based on a different formula. The Equation for stem volume estimation reported in the ILUA I report is as follows:

$$\text{Stem volume} = (Dbh^2/4)*\pi*H_{tot} * \pi *0.74 \quad \text{……………………………………………Equation 3.1}$$

Where H_{tot} is tree height and 0.74 is form factor. Discussions with ILUA I Assistant National Coordinator (Mr Jackson Mukosha) and National Consultant (Mr Abel Siampale) over this formula revealed that in reality, the formula used 0.68 as form factor and only a single π value was used. But, even with the use of 0.74 as a form factor, the volume estimates only increase to 42.0±2.77 m^3/ha for miombo woodland and 30.0±3.67 m^3/ha for deciduous forest, which are still much lower than the reported volumes in Table 3.1.

Table 3.1 *Stem volume estimates for adequately sampled forest types using ILUA I data.*

Forest type		**Estimated stem volume (m^3/ha)**	**Volume estimates (m^3/ha) in ILUA report**
Floristic association	**ILUA classification**		
Miombo woodland	Semi-evergreen forest	38.6±2.54	62.4
Kalahari Sand woodland	Deciduous forest	35.2±5.69	40.0
Broad-leaved woodland	Deciduous forest	17.2±3.52	
Mopane	Deciduous forest	44.5±9.82	
All forest types		35.0±2.06	51.2

4. ASSESSMENT OF BIOMASS MODELS USING INDIVIDUAL TREE DATA

4.1 Biomass models for different forest types

Annex 2 gives the details of the models and their outputs using the individual tree biomass data. Using the deviation of the predicted from the measured observed biomass for each tree (mean error, %) the models that gave the most accurate estimates (with narrow confidence intervals) are the log models and power models (Table 4.1). It is also important to note that log transformation of data did not always significantly improve the normality of data distribution (see Annex 2). The power$_{dbh}$ model type gave reasonable error terms of <20% for all the data sets except for drier young miombo, drier miombo in Tanzania and munga woodland (Table 4.1). The polynomial models only performed well for Zambian munga and mopane woodlands, while the polynomial based on dbh and BA were good for the Zambia oldgrowth data set and drier oldgrowth, respectively.

Table 4.1 *Deviations of the predicted from the measured observed biomass by different models using community data. Bold figures indicate regression models with less than 20% mean error that was adopted as the minimum acceptable level of accuracy.*

Data set		**Deviation mean error (%) for each model estimates**				
	Log	**Log$_{CF}$**	**Polymonial (dbh)**	**Polynomial (BA)**	**Power (dbh)**	**Power (BA)**
All Zambia miombo	20.9	21.0	51.5	**14.9**	**7.3**	**7.3**
All Zambia young growth	24.9	25.0	80.6	85.5	46.8	46.8
Drier young miombo	23.7	23.8	69.2	89.5	**15.3**	**15.3**
Wetter young miombo	26.4	27	74.8	65.4	**10.2**	**10.2**
All Zambia oldgrowth miombo	**12.9**	**13.3**	33.7	**1.7**	**2.3**	**2.3**
Drier oldgrowth miombo in Zambia	-35.9	-35.6	**7.0**	-47.0	**-7.8**	**-7.7**
Wetter oldgrowth miombo in Zambia	**10.9**	**14.3**	38.7	21.4	22.3	22.3
Drier oldgrowth miombo in Tanzania	29.1	51.1	1389	30.5	65.6	65.7

Data set			**Deviation mean error (%) for each model estimates**			
	Log	**Log$_{CF}$**	**Polymonial (dbh)**	**Polynomial (BA)**	**Power (dbh)**	**Power (BA)**
Munga in Zambia	**4.1**	**5.4**	**12.9**	**7.8**	23.1	23.1
Munga in Botswana	**9.4**	21.6	24.4	24.1	26.8	26.8
Mopane	**5.6**	**6.5**	**8.5**	**5.9**	**-3.2**	**-3.2**
All the data	**16.6**	**16.9**	134.7	10587	24.4	24.4

Nickless et al. (2011) found confidence intervals of aboveground woody biomass estimates derived from log models for sites in Kruger National Park, South Africa, to range between 24% and 99%, with larger biomass estimates generally having wider intervals. I chose the 20% confidence interval as an acceptable cut-off point for good performance of a regression model. The log and log$_{CF}$ models gave the most accurate estimates for all the data from the three countries but power models gave the most accurate estimates for the miombo data, especially oldgrowth miombo in Zambia. There was little difference between the use of dbh and BA in the power model. Surprisingly, none of the models performed well for the drier oldgrowth miombo data at Kitulangalo in Tanzania, although Mugasha and Chamshama (2002) used log models to estimate biomass of that woodland. The log-transformation correction factor (CF, see Equation 2.1) in the log model increased estimates and mean error slightly (Table 4.1). Polynomial models were generally less accurate than the other models, expect for oldgrowth miombo in Zambia for which the polynomial model based on BA gave the most accurate estimates. Generally, model estimates with the lowest mean error also had the lowest standard error of mean error (see Annex 2).

4.2 Biomass models for species and species-groups

Annex 3 gives the full description of model outputs based on species and species groups. As observed for the different forest types, log models gave accurate estimates in nearly 80% of the species and species groups in comparison to 50% and 30–35% for power and polynomial models, respectively (Table 4.2). Log models gave the most accurate estimates for *Isoberlinia angolensis*, and *Uapaca* species and species-groups of *Acacia*, *Julbernardia* and *Uapaca* while power models gave the most accurate estimates for *Colophospermum mopane* and *Diplorhynchus condylocarpon*. For *Brachystegia boehmii* and *Julbernardia globiflora,* both log and power models were equally accurate. None of the models accurately estimated the biomass of the shrub species, *Dichrostachys cinerea*.

***Table 4.2** Deviations of the predicted from measured biomass for different models using species and/or species-groups. Bold figures indicate regression models with less than 20% mean error that was adopted as the minimum acceptable level of accuracy.*

Species/Group	**Deviation mean error (%) for each model estimates**					
	Log	**Log$_{CF}$**	**Polymonial (dbh)**	**Polynomial (BA)**	**Power (dbh)**	**Power (BA)**
Colophospermum mopane	**5.6**	**6.5**	**8.5**	**5.9**	**-3.2**	**-3.2**
Albizia species	20.6	23.5	33.2	**-18.2**	-39.4	-39.4
Brachystegia boehmii	**12.9**	**13.2**	-32.0	-123.0	**-12.8**	**-12.9**

Species/Group	**Deviation mean error (%) for each model estimates**					
	Log	**Log$_{CF}$**	**Polymonial (dbh)**	**Polynomial (BA)**	**Power (dbh)**	**Power (BA)**
Brachystegia species	**13.1**	**13.6**	-87.0	36.2	-36.0	-36.2
Diplorhynchus condylocarpon	28.0	30.1	51.5	34.8	**8.8**	**8.7**
Isoberlinia angolensis	**5.5**	**7.0**	**14.1**	-32.5	31.6	31.6
Julbernardia globiflora	**9.4**	**10.6**	47.9	37.1	**9.6**	**9.7**
Julbrernardia species	**9.1**	**10.3**	**9.9**	-77.8	**14.2**	**14.2**
Uapaca species	**12.7**	**13.7**	146	30.7	85.1	85.1
Uapaca kirkiana	**13**	**14.3**	108.7	50.3	92.5	92.5
Uapaca nitida	**11.1**	**15.8**	246.9	2689.0	58.2	58.2
Piliostigma thonningii	**2.4**	**3.9**	**5.9**	**11.7**	**8.1**	**8.1**
Acacia species	**4.4**	**8.4**	**18.7**	**16.3**	**10.0**	**10.0**
Dichrostachys cinerea	39.3	40.4	87.9	96.2	62.3	62.3

4.3 Aboveground biomass estimates

4.3.1 Estimating biomass from tree volume data

Specific wood density (SWD) (see Table 2.4) values were used to convert stem volume estimates to biomass estimates using the different stem volume models. Volume estimates were multiplied by SWD to derive biomass estimates (Figure 4.1). Compared to observed stem biomass data, the Newton's method underestimated biomass while the ILUA I (Equation 2.4) method overestimated biomass, but the summation and Huber's methods gave almost similar estimates that were closer to the observed values. However, when all the aboveground wood biomass (excluding leaves) is considered, even the ILUA I method slightly underestimated aboveground wood biomass. Thus, to improve the estimates for all the aboveground wood biomass, the estimates derived from multiplying volume by SWD should be corrected by an expansion factor (*ExpF*) which is calculated as follows:

$$ExpF = OTB/(V \times SWD) \quad \text{......Equation 4.1}$$

Where *ExpF* is biomass expansion factor as in Equation 1.2, OTB is observed total aboveground biomass (kg) and SWD is specific wood density (kg/m^3). The expansion biomass factors for the different methods used in calculating stem volume (V in Equation 4.1) are given in Table 4.3.

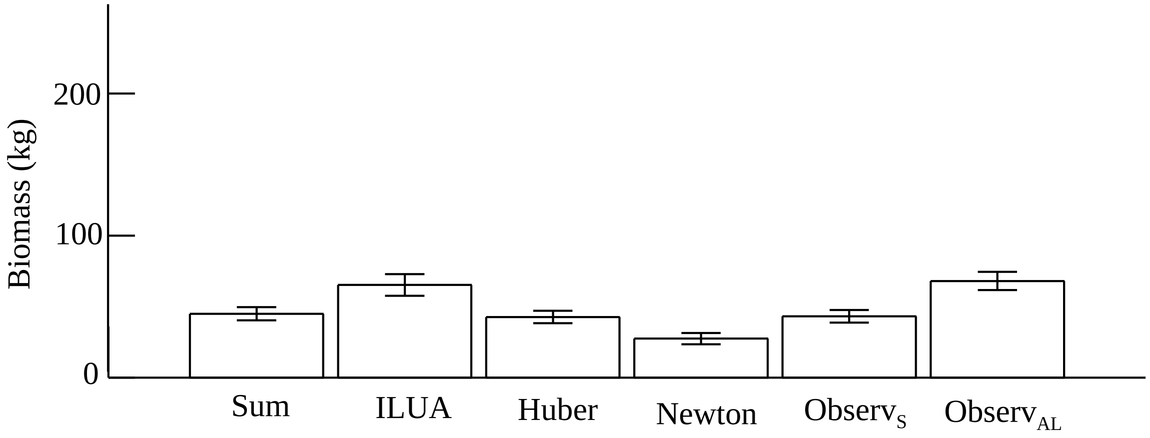

Figure 4.1 *Aboveground wood biomass estimates from volume data and field observations for drier and wetter miombo species in Zambia. Estimates by the summation (Sum), ILUA I (ILUA), Huber's (Huber) and Newton's (Newton) methods and observed biomass data for the stem wood (Observ$_S$) and all wood in stem, branches and twigs (Observ$_{AL}$).*

Table 4.3 *Biomass expansion factors (ExpFs) for biomass estimated by the product of volume and specific wood density using different methods for miombo woodland trees.*

Method of estimating volume	Biomass expansion factor (mean±1SE)
Summation	1.68±0.03
ILUA I	1.38±0.02
Huber's	1.71±0.03
Newton's	4.28±0.09

The biomass estimates published in the ILUA I report were based on the IPCC (2006) methodology using stem volume data (Equation 2.4) and the following Equation to estimate aboveground wood biomass (AGB):

AGB = GS x BCEF ....Equation 4.2

Where GS is growing stock (m^3 over bark) and BCEF is biomass conversion and expansion factor (growing stock in tonnes m^{-3}). Often, BCEFs are applied to plot or stand level data to estimate plot or stand biomass. Kamelarczyk (2009) used low and average BCEF values to derive AGB using ILUA I data after calculating stem volume using the Equation:

Stem volume = (π*dbh^2*H*0.74)/4 ....Equation 4.3

Where H is tree height and 0.74 is a correction (form) factor (f_g) as described in Equation 2.4. This means that Kamelarczyk (2009) used a higher factor value based on the ILUA I report that should have been changed to 0.68. Kamelarczyk (2009) also used two other global models (Brown, 1997; Chave et al. 2005) to estimate biomass from volume data, but these models were not evaluated in this study because they are derived from data of forests not found in Zambia and the neighbouring countries with similar forest types (see Terms of Reference).

4.3.2 Estimating biomass using ILUA I tree diameter data

The majority of sample tracks used to collect forest inventory data during ILUA I were located in miombo and Kalahari Sand woodlands (78%) that share similar tree species, undifferentiated broad-leaved woodland (14%) and mopane woodland (6%). Some tree species in broad-leaved and mopane woodlands are also found in miombo and Kalahari Sand woodlands. The selected best general model for estimating aboveground wood biomass, AGB, for all the ILUA I data is therefore the log model (with a mean error of ± 16%; see Table 4.1):

$\ln AGB = 2.342*\ln(dbh) - 2.059$ ………………………………………………….Equation 4.4

This model was applied to estimate AGB using dbh data. The model was developed using stems with a dbh range of 1–50 cm and should ideally be applied to stems within this range. However, the dbh range of sample stems in ILUA I data was 7–245 cm although 99% were of dbh ≤ 66.00cm. It is therefore difficult to determine the error in estimation of biomass for stems larger than 50.00cm dbh. But, the relationship between error in biomass estimate and dbh appeared to stabilize with an increase in the size of trees (Figure 4.2).

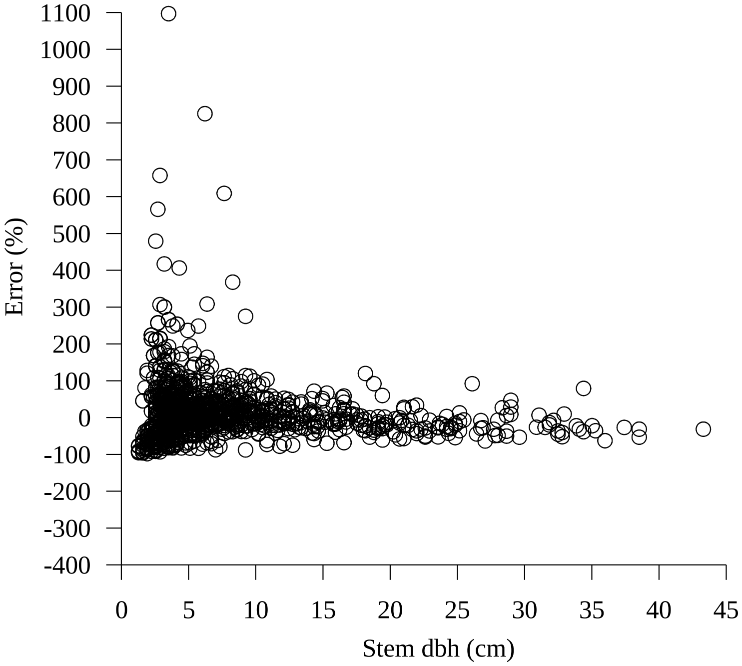

Figure 4.2 *Relationship between stem size and biomass estimation error for miombo woodland trees in Zambia.*

Biomass estimates from stem volume are based on the following equation:

$AGB =((dbh2/4)\pi Hf_g)*0.619$ ……………………………………………………………Equation 4.5

Where 0.619 is mean SWD for all species (Table 2.4).

The results of this analysis are presented in Table 4. 4. The estimates based on the log model using dbh data are very close to those based on stem volume without the biomass expansion factor (*ExpF*). Application of the *ExpF* tended to give higher values than those based on the log model. What is surprising is that all these estimates are much lower than those given in the ILUA I report. It appears that the IPCC BCEF that was used in the biomass estimation using ILUA data greatly overestimated biomass density. Wirth et al. (2004) demonstrated that application of Biomass Expansion Factors (BEFs) to the same forest inventory database using BEFs from the IPCC default database (2003) and from five other sources resulted in biomass estimates that differed by as much as 40%. The differences between estimates using the log allometric equation and *ExpF* ranged from 25–38% in this study. Perhaps a significant proportion of the observed differences in biomass estimates given in the ILUA report can be attributed to the use of the IPCC BCEF. Kamelarczyk (2009) also found that AGB estimated by use of the average BCEF was 2.2 times greater than the estimate made by allometric equations using dbh for miombo woodland, and was similarly 2.24 times greater for deciduous forest.

Table 4.4 *Aboveground wood biomass estimates based on ILUA I forest inventory data.*

Forest type		**Direct biomass method using log model (t/ha)**	**Biomass estimates (t/ha) using stem volume data**		**Biomass (t/ha) in ILUA I report**
Floristic association	**ILUA I classification**		**Uncorrected**	**Corrected using *ExpF* (1.38)**	
Miombo woodland	Semi-evergreen forest	23.7±1.27	23.9±1.57	32.9 ±2.17	93.1
Kalahari Sand woodland	Deciduous forest	23.0±2.78	21.8±3.52	30.1±4.86	61.2
Broad-leaved woodland	Deciduous forest	11.7±2.04	10.6±2.18	14.7±3.01	
Mopane	Deciduous forest	31.7±6.61	27.5±6.07	37.9±8.38	
All forest types		22.1±1.09	21.7±1.27	29.9±1.76	77.2

Compared to other previous inventories, the results in Table 4.4 using the models evaluated in this assessment represent very low biomass for miombo woodland and perhaps other forest types (Figure 4.3). The comparisons reveal that the biomass estimates from ILUA I data are much lower than those based on surveys done in the 1980s and 1990s, possibly indicating a decline in biomass density associated with forest degradation. This is supported by the observation that the majority (≥ 90%) of ILUA I sample tracks were located within 20km of all-weather roads and settlements (Figure 4.4). Very few tracks were located in remote areas where human influence is likely to be low and where forest stands are still relatively undisturbed and, therefore, with higher biomasses.

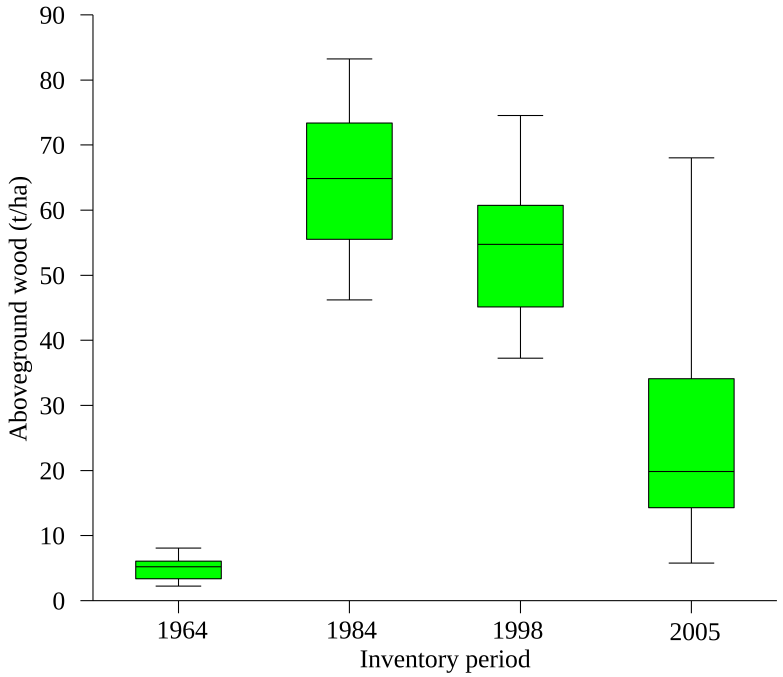

Figure 4.3 *Comparison of aboveground biomass estimates from forest inventories conducted in Central and Lusaka Provinces at different periods using box-and-whiskers. The horizontal line in the box represents the median and the hinges the first and third quartiles, while the vertical bottom and top lines represent minimum and maximum values, respectively. Edmonds (1964) for 1964 data, Chidumayo (unpublished) for the 1984 and 1998 data and ILUA I for 2005 data.*

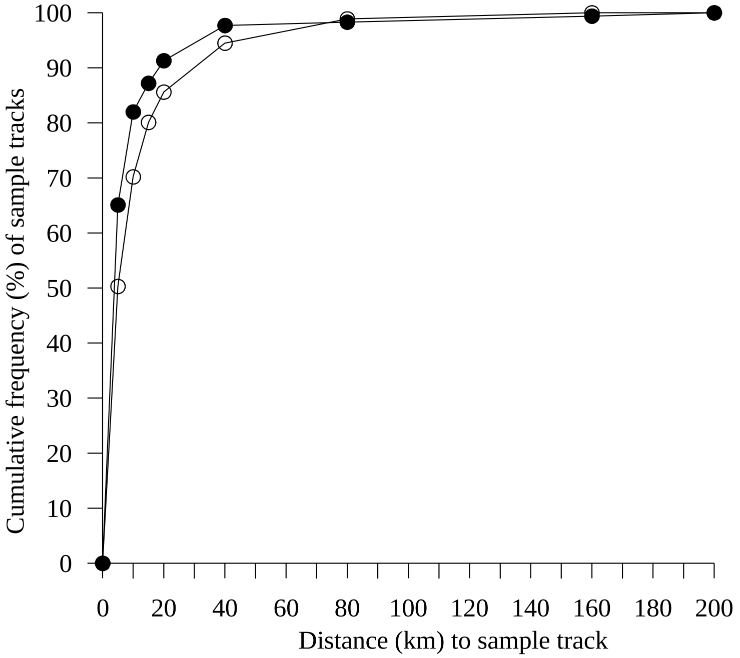

Figure 4.4 *Distribution of ILUA I sample tracks by distance to an all-weather road (○) and settlement (●).*

5. APPLICATION OF RESULTS TO ILUA II AND REDD+ IN ZAMBIA

5.1 Some key observations

The basic field data for estimating volume and biomass to be collected during ILUA II are (i) species, (ii) dbh, (iii) bole length and (iv) tree height. Huber's method is probably the most appropriate for estimating bole and stem volume, but it requires the measurement of diameter at stem mid-length which is not easy to do in the field. The ILUA I method is the second best for estimating bole and stem volume, although it slightly overestimates stem volume. With the specific wood density values given in Table 2.4, accurate estimates of total aboveground wood biomass from stem volume values can be obtained. Care should be exercised when applying biomass expansion factors in estimating aboveground biomass as they have the tendency to overestimate biomass. The IPCC BCEF method used in estimating aboveground wood biomass resulted in significant overestimation of biomass values in the ILUA I initial report. These values are not suitable for REDD+ reporting in Zambia. The sections on Growing stock and Biomass and Carbon Stocks in the ILUA I report should be revised to present a more realistic country situation.

The best models for estimating aboveground wood biomass from dbh data are the log models, but the use of ordinary log models requires log back-transformation of the transformed data. This procedure requires a higher level of statistical knowledge of linear regression analysis. The application of a correction factor, CF, to overcome the underestimation that is usually associated with log data back-transformation of the predicated values does not appear to change the estimates significantly and therefore is not a necessary requirement for the Zambian situation. The second best model type for estimating aboveground wood biomass is the power models based on dbh. This type of model was reasonably accurate and precise for a number of forest types and species and species-groups (see Tables 4.1 and 4.2). The following models are therefore recommended for use in ILUA II and REDD+.

Table 5.1 *Recommended models for estimating aboveground wood biomass (kg) for ILUA II and REDD+ in Zambia.*

Group	Model type	Equation for y (biomass)	Accuracy (%) of estimate
Vegetation type			
All types	Log	2.342*ln(dbh) – 2.059	± 16
Miombo	Power	$0.081*dbh^{2.57}$	± 7
Munga	Log	2.384*ln(dbh) – 2.447	±4
Mopane	Power	$0.056*dbh^{2.634}$	±3
Species/Species group			
Colophospermum mopane	Power	$0.056*dbh^{2.634}$	±3
Brachystegia species group	Log	2.488*ln(dbh) – 2.264	±13
Isoberlinia angolensis	Log	2.613*ln(dbh) – 2.724	±6
Julbernardia species group	Log	2.471*ln(dbh) – 2.107	±9

Group	Model type	Equation for y (biomass)	Accuracy (%) of estimate
Uapaca species group	Log	$2.323*\ln(dbh) – 2.159$	±13
Acacia species group	Log	$2.311*\ln(dbh) – 2.134$	±4
Diplorhynchus condylocarpon	Power	$0.1*dbh^{2.296}$	±9
Piliostigma thonningii	Log	$2.449*\ln(dbh) – 2.711$	±3

Generally, the data collected during ILUA I are adequate for estimating wood volume and biomass in the country. However, it is apparent that the sampling design for ILUA I tended to concentrate sample plots in degraded and/or transformed forest areas which contributed to the estimated low forest volume and biomass values as estimated in this paper.

5.2 Recommendations

Based on the findings of the study, the following recommendations are proposed.

5.1 The biomass data for felled trees that were used in this assessment did not represent trees in the very large dbh classes that were inventoried during the ILUA I. Although the error in the biomass estimates did not appear to increase with increasing tree size, consideration should be given in either ILUA II or REDD+ to obtain biomass data from large (>50cm dbh) trees in the country. However, this option should only be considered if resources are available because, in the interim, the models recommended in the report are adequate for estimating aboveground biomass, especially that the error in the estimates did not increase with tree size.

5.2 It is also recommended that for national estimates, one or a few general models be used to estimate aboveground biomass directly from dbh data. However, although such models can be applied at a sub-national level, it is recommended that general models for each main forest type be applied at sub-national levels.

5.3 For REDD+ requirements, biomass and carbon stocks will be needed for forest types for which volume and/or dbh measurements may not be appropriate. Thus, diameter measurements at stem/tree base or stump height (0.1–0.3m aboveground ground) may be more appropriate. Estimating aboveground wood biomass for such forest types can initially be based on existing models that use diameter or basal area at stem base as predictor variables. Some of these models can be found in the literature cited in Table 2.1. Such models may be applied to estimating biomass and carbon stocks in young trees in naturally regenerating and agroforestry stands, in thickets, scrub vegetation and harvested stands with standing stumps.

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ANNEXES

Annex 1 *Species and samples felled trees/stems used in the assessment of biomass estimation and model validation*

Species	**Drier miombo**		**Wetter miombo**	**Munga**		**Mopane**
	Zambia (11 sites)	**Tanzania (1 site)**	**Zambia (8 sites)**	**Botswana (1 site)**	**Zambia (1 site)**	**Botswana (3 sites)**
Acacia amythethophylla					1	
Acacia fleckii				8		
Acacia gerrardii		1				
Acacia goetzei	1		3		1	
Acacia polyacantha		1			13	
Acacia sieberana					1	
Afzelia quenzensis	1					
Albizia adianthifolia			13			
Albizia antunesiana	15					
Albizia versicolor			5			
Annona senegalensis			3			
Baphia bequaertii			10			
Bauhinia petersiana		1				
Boscia albitrunca				8		
Boscia salicifolia		1				
Brachystegia boehmii	240	5	8			
Brachystegia floribunda			1			
Brachystegia longifolia			5			
Brachystegia manga	16					
Brachystegia microphylla		1				
Brachystegia spiciformis	15		3			
Brachystegia taxofolia	3					
Brachystegia utilis	7					
Bridelia cathartica	4	1				
Burkea africana	21			8		
Cassia abbreviata	3					
Colophospermum mopane						82
Combretum adonogonium		1				
Combretum molle	3	2	8			
Crossopteryx ferbrifuga		1				
Dalbergiella nyassa	2					
Dialiopsis africana	1					
Dichrostachys cinerea	28	1		6		
Diospyros sp.			3			
Diplorhynchus condylocarpon	34	1	11			
Dombeya rotundifolia		1				
Erythrina abyssinica			1			

Species	**Drier miombo**		**Wetter miombo**	**Munga**		**Mopane**
	Zambia (11 sites)	**Tanzania (1 site)**	**Zambia (8 sites)**	**Botswana (1 site)**	**Zambia (1 site)**	**Botswana (3 sites)**
Erythrophleum africanum	1					
Faurea intermedia	1					
Faurea saligna	3		1			
Faurea speciosa	11					
Flacourtia indica	3					
Harungana madagascariensis			1			
Hexalobus monopetalus	6		4			
Hymenocardia acida	2					
Isoberlinia angolensis	84		13			
Julbernardia globiflora	116	3				
Julbernardia paniculata	7		11			
Lannea discolor	8		3			
Lonchocarpus bussei		1				
Lonchocarpus nelsii				10		
Marquesia macroura			14			
Memecylon flavovirens			1			
Monotes spp.	20		4			
Ochna pulchra				9		
Ochna schweinfurthiana	9		4			
Olax abtusifolia	1					
Parinari curatellifolia	17		9			
Pavetta sp.	1					
Pericopsis angolensis	15		4			
Phillipia sp.	2					
Phyllocosmus lemaireanus	18					
Piliostigma thonningii					40	
Protea spp.	16					
Pseudolachnostylis maprouneifolia	17	1	7			
Psorospermum frebrifugum	2					
Pterocarpus angolensis	2	1	1			
Sclerocarya birrea		2				
Securidaca longipedunculata	1					
Strychnos spp.	4		5			
Swartzia madagascariensis	13		7			
Syzygium guineense macrocarpum	13		5			
Terminalia mollis		1				
Terminalia sericea			1	9		
Uapaca kirkiana	80		9			
Uapaca nitida	32		5			

Species	**Drier miombo**		**Wetter miombo**	**Munga**		**Mopane**
	Zambia (11 sites)	**Tanzania (1 site)**	**Zambia (8 sites)**	**Botswana (1 site)**	**Zambia (1 site)**	**Botswana (3 sites)**
Uapaca sansibarica	5					
Vangueriopsis lanciflora	2					
Vitex doniana	1		2			
Ximenia americana	1					
Xeroderris stuhrmannii		2				
Zahna africana		1				
All species (82)	908	30	185	58	56	82

***Annex 2** Descriptive variables for different allometric equations for estimating aboveground live woody biomass for individual trees at sample sites in miombo, mopane and munga woodlands. Dbh id diameter at breast height (cm) and BA is basal area (cm^2) at breast height. W with its associated probability (p) is a measure of the normality in data distribution that is necessary for the application of linear regression analysis. * is mean error after applying a correction factor (CF).*

Forest	Sample	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
Miombo, mopane and munga woodlands in Botswana, Tanzania and Zambia	Oldgrowth and young growth	649	Log	-2.05868	2.34213	-777.77	0.9127	0.29925	16.632±3.4715 16.913±3.4799*	0.9631 (<0.05)
		649	Polynomial (Dbh)	23.9253	-7.29091, 0.69312, 0.00158	5589.3	0.8683	5519.75	134.73±32.574	0.577 (<0.05)
		649	Polynomial (BA)	1.57176	0.27908, 7.473E-04, -2.722E-07	5561.8	0.8737	5290.25	10587±4584.0	0.5807 (<0.05)
		649	Power (Dbh)	0.0975	2.4893	5589.1	0.867466	5535.7	2447.9±1770.6	0.5905 (<0.05)
		649	Power (BA)	0.1317	1.2446	5589.1	0.867466	5535.7	24.389±3.3366	0.5905 (<0.05)

Forest	**Sample**	**Felled stems**	**Model**	**a**	**b, c, d**	**AIC_c**	**R^2**	**MSE**	**Mean error (±se, %)**	**W(p)**
All miombo in Zambia	Old-growth & young growth	1208	Log	-1.88636	2.27889	-1033.4	0.8563	0.42367	20.849±2.4404 20.976±2.4430*	0.9391 (<0.05)
		1208	Polynomial (Dbh)	3.16616	-1.15950, 0.29534, 0.00992	9026.6	0.8896	1749.99	51.467±3.6362	0.3968 (<0.05)
		1208	Polynomial (BA)	-1.51610	0.39845, 5.636E-04, -1.641E-07	9026.6	0.8896	1749.92	14.921±2.3771	0.4055 (<0.05)
		1208	Power (Dbh)	0.0807	2.5699	9023.8	0.889511	1748.8	7.2475±1.9634	0.4011 (<0.05)
		1208	Power (BA)	0.1101	1.2850	9023.8	0.889511	1748.8	7.2928±1.9642	0.4011 (<0.05)
Regrowth miombo in Zambia	All young growth	781	Log	-1.69810	2.11850	-539.56	0.6859	0.49857	23.666±3.6493 23.762±3.6522*	0.9406 (<0.05)
		781	Polynomial (Dbh)	13.1573	-6.35181, 0.99209, -0.01295	4218.9	0.7059	217.106	69.154±6.4582	0.4393 (<0.05)

Forest	Sample	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
		781	Polynomial (BA)	0.47170	0.24159, 0.00246, -3.985E-06	4212.8	0.7082	215.423	89.499±8.0588	0.4083 (<0.05)
		781	Power (Dbh)	0.1496	2.3642	4234.1	0.698495	221.94	15.276±3.1357	0.4083 (<0.05)
		781	Power (BA)	0.1991	1.1821	4234.1	0.698495	221.94	15.301±3.1364	0.4083 (<0.05)
Dry miombo in Zambia	Young growth	647	Log	-1.85553	2.20051	-476.94	0.6812	0.47440	16.632±3.4715 16.913±3.4799	0.9328 (<0.05)
		647	Polynomial (Dbh)	6.03114	-2.49913, 0.38472, 0.01665	3479.1	0.5919	214.394	134.73±32.574	0.3923 (<0.05)
		647	Polynomial (BA)	3.31423	-0.07844, 0.00815, -2.235E-05	3458.9	0.6044	207.818	10587±4584.0	0.4114 (<0.05)
		647	Power (Dbh)	0.0647	2.7492	3477.1	0.590521	214.44	2447.9±1770.6	0.4074 (<0.05)

Forest	**Sample**	**Felled stems**	**Model**	**a**	**b, c, d**	**AIC$_c$**	**R^2**	**MSE**	**Mean error (±se, %)**	**W(p)**
		647	Power (BA)	0.0902	1.3746	3477.1	0.590521	214.44	24.389±3.3366	0.4074 (<0.05)
Wetter miombo in Zambia	Young growth	136	Log	-1.04028	1.82386	-78.202	0.70	0.54572	26.4±7.82 26.95±7.86*	0.96(0.0002)
		136	Polynomial (Dbh)	13.6031	-5.32675, 0.7253,-0.00381	715.79	0.89	184.213	74.8±18.59	0.64(<0.05)
		136	Polynomial (BA)	3.09002	0.12194, 0.00243, -3.332E-06	709.41	0.90	175.765	65.4±12.34	0.62(<0.05)
		136	Power (Dbh)	0.1085	2.4429	715.94	0.89	187.48	10.2±7.05	0.64(<0.05)
		136	Power (BA)	0.1457	1.2215	715.94	0.89	187.48	10.2±7.05	0.64(<0.05)
Oldgrowth miombo in	All oldgrowth	427	Log	-1.78399	2.27691	-567.82	0.9201	0.26203	12.923±2.8432 13.322±2.8532*	0.9568 (<0.05)
		427	Polynomial	6.34188	-	3604.0	0.8787	4563.73	33.688±5.2245	0.5806 (<0.05)

Forest	Sample	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
			(Dbh)		2.01120, 0.33826, 0.00934					
		427	Polynomial (BA)	-2.16471	0.39362, 5.784E-04, -1.725E-07	3603.7	0.8788	4561.22	1.6871±3.0721	0.5855 (<0.05)
		427	Power (Dbh)	0.0742	2.5940	3600.0	0.878684	4543.2	2.2563±2.2933	0.5853 (<0.05)
		427	Power (BA)	0.1015	1.2970	3600.0	0.878684	4543.2	2.2549±2.2933	0.5853 (<0.05)
Drier miombo in Zambia	Oldgrowth	372	Log	-1.72132	2.25522	-497.77	0.9191	0.25950	-35.869±4.7717 -35.615±4.7906*	0.9602 (<0.05)
		372	Polynomial (Dbh)	-3.67016	1.40579, 0.05467, 0.01582	3157.1	0.8580	4770.56	6.9645±3.0045	0.5624 (<0.05)
		372	Polynomial (BA)	-6.24986	0.50554, 1.921E-04, 1.485E-	3154.9	0.8588	4742.39	-46.968±8.7214	0.5830 (<0.05)

Forest	Sample	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
					07					
		372	Power (Dbh)	0.0540	2.6969	3154.4	0.857462	4762.7	-7.7684±2.2731	0.5670 (<0.05)
		372	Power (BA)	0.0747	1.3485	3154.4	0.857462	4762.7	7.7073±2.8094	0.5670 (<0.05)
Wetter miombo	Oldgrowth	55	Log	-2.45366	2.50307	-72.165	0.93	0.2484	10.9±6.69 14.25±6.89*	0.88(<0.05)
		55	Polynomial (Dbh)	8.83304	-2.5058,0.40074,0.00655	431.83	0.97	2259.56	38.7±9.64	0.84(<0.05)
		55	Polynomial (BA)	-3.8239	0.44069, 0.44069, 3.969E-04,-1.018E-07	432.02	0.97	2267.48	21.4±9.6	0.87(<0.05)
		55	Power (Dbh)	0.0951	2.5017	427.05	0.96	2173.3	22.3±7.38	0.85(<0.05)

Forest	**Sample**	**Felled stems**	**Model**	**a**	**b, c, d**	**AIC_c**	**R^2**	**MSE**	**Mean error (±se, %)**	**W(p)**
		55	Power (BA)	0.1287	1.2509	427.05	0.97	2173.3	22.3±7.38	0.85(<0.05)
Drier miombo in Tanzania	Oldgrowth	30	Log	-2.77605	2.55487	-27.934	0.9669	0.33524	29.1±31.2 51.1±36.53*	0.81(<0.05)
		30	Polynomial (Dbh)	29.0735	-10.5881, 0.81662, -5.547E-04	320.23	0.8376	32888	1389±665	0.67 (<0.05)
		30	Polynomial (BA)	28.002	-0.237, 0.0014, -0.0000005	315.26	0.86	27863	3015±1207	0.76 (<0.05)
		30	Power (Dbh)	0.0965	2.4667	314.82	0.837	30703	65.6±43.9	0.67(<0.05)
		30	Power (BA)	0.1301	1.2333	314.82	0.837	30703	65.7±44	0.67(<0.05)
Munga woodland in	Oldgrowth	57	Log	-2.44649	2.38347	-132.75	0.94	0.08633	4.1±3.93 5.38±3.97*	0.97(0.17)
		57	Polynomial	25.3947	-	253.44	0.98	81.4375	12.9±6.67	0.85(<0.05)

Forest	Sample	Felled stems	Model	a	b, c, d	AIC_c	R^2	MSE	Mean error (±se, %)	W(p)
			(Dbh)		8.49972, 0.90111, -0.01015					
		57	Polynomial (BA)	0.33731	0.17621, 0.00114, -1.055E-06	237.79	0.98	61.5761	7.8±3.67	0.83 (<0.05)
		57	Power (Dbh)	0.12	2.309	264.52	0.97	104.02	23.1±4.74	0.77(<0.05)
		57	Power (BA)	0.1586	1.1545	264.52	0.97	104.02	23.1±4.74	0.77(<0.05)
Munga woodland in Botswana	Oldgrowth	58	Log	-2.67555	2.28936	-95.24	0.88	0.1794	9.4±6.64 21.6±7.38*	0.79(<0.05)
		58	Polynomial (Dbh)	13.4018	-5.119, 0.66606, -0.01428	193.53	0.92	24.9236	24.4±11.28	0.93(<0.05)
		58	Polynomial (BA)	1.65128	0.0576, 0.00142, -3.113E-06	186.77	0.93	22.1828	24.1±8.79	0.92(<0.05)
		58	Power (Dbh)	0.1094	2.1358	194.97	0.92	26.725	26.8±8.17	0.93(<0.05)

Forest	**Sample**	**Felled stems**	**Model**	**a**	**b, c, d**	**AIC$_c$**	**R^2**	**MSE**	**Mean error (±se, %)**	**W(p)**
		58	Power (BA)	0.1416	1.0679	194.97	0.92	26.725	26.8±8.17	0.93(<0.05)
Mopane woodland in Botswana	Oldgrowth	77	Log	-1.17349	2.07838	-167.5	0.92	0.10739	5.6± 4.27 6.52±4.31*t	0.97 (0.12)
		77	Polynomial (Dbh)	19.21	-2.349, 0.25343, 0.00947	674.8	0.86	5863.7	8.5±3.89	0.91(<0.05)
		77	Polynomial (BA)	2.37281	0.34055, 4.478E-04	675.01	0.86	5877.69	5.9±4.01	0.90(<0.05)
		77	Power (Dbh)	0.0558	2.6344	670.6	0.86	5729.6	-3.2±4.60	0.93(<0.05)
		77	Power (BA)	0.0767	1.3172	670.6	0.86	5729.6	-3.2±4.60	0.93(<0.05)

Annex 3 *Descriptive variables for different allometric equations for estimating aboveground live woody biomass for individual trees at sample sites in miombo, mopane and munga woodlands. Dbh is diameter at breast height (cm) and BA is basal area (cm^2) at breast height. W with its associated probability (p) is a measure of the normality in data distribution that is necessary for the application of linear regression analysis. * is mean error after applying a correction factor (CF).*

Group	Felled stems	Model	a	b, c, d	AIC_c	R^2	MSE	Mean error (±se, %)	W(p)
Colophospermum mopane	77	Log	-1.17349	2.07838	-167.5	0.92	0.10739	5.6± 4.27 6.52±4.31*	0.97 (0.12)
		Polynomial (Dbh)	19.21	-2.349, 0.25343, 0.00947	674.8	0.86	5863.7	8.5±3.89	0.91(<0.05)
		Polynomial (BA)	2.37281	0.34055, 4.478E-04	675.01	0.86	5877.69	5.9±4.01	0.90(<0.05)
		Power (Dbh)	0.0558	2.6344	670.6	0.86	5729.6	-3.2±4.60	0.93(<0.05)
		Power (BA)	0.0767	1.3172	670.6	0.86	5729.6	-3.2±4.60	0.93(<0.05)
Albizia species	31	Log	-0.16887	1.55630	-16.677	0.7554	0.51125	20.574±12.137 23.490±12.431*	0.95 (0.13)
		Polynomial (Dbh)	14.9685	3.54659, 0.44542, 0.01398	151.37	0.9804	88.1631	33.172±12.299	0.7804 (<0.05)
		Polynomial (BA)	27.3550	0.33872, 8.208E-04, -4.324E-07	151.96	0.9801	89.8057	-18.161±8.8401	0.7285 (<0.05)
		Power (Dbh)	0.0465	2.6853	152.99	0.975577	102.64	-39.422±6.6788	0.8471 (<0.05)
		Power (BA)	0.0643	1.3427	152.99	0.975577	102.64	-39.423±6.6790	0.8471 (<0.05)
Brachystegia boehmii	247	Log	-2.24620	2.44542	-321.55	0.8542	0.26899	12.886 ±3.6851 13.244±3.6968*	0.86 (<0.05)
		Polynomial	-	5.07922, -	1508.9	0.9129	427.997	-31.960±9.2400	0.3172

Group	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
		(Dbh)	13.5245	0.21852, 0.01707					(<0.05)
		Polynomial (BA)	-8.44836	0.88877, -0.00159, 1.476E-06	1428.5	0.9370	309.578	-123.06±16.492	0.4752 (<0.05)
		Power (Dbh)	0.0700	2.5509	1517.9	0.908111	447.75	-12.823±2.7883	0.2876 (<0.05)
		Power (BA)	0.0952	1.2755	1517.9	0.908111	447.75	-12.865±2.7869	0.2876 (<0.05)
Brachystegia species group	297	Log	-2.26392	2.48768	-376.10	0.9044	0.27922	13.125±3.3424 13.626±3.3572*	0.8825 (<0.05)
		Polynomial (Dbh)	-28.1277	10.4785, -0.65057, 0.02950	2298.4	0.8840	2191.07	-87.006±18.125	0.3465 (<0.05)
		Polynomial (BA)	-4.89163	0.66658, -5.780E-04, 7.909E-07	2284.2	0.8895	2088.63	36.236±7.2497	0.3050 (<0.05)
		Power (Dbh)	0.0322	2.8463	2306.8	0.879066	2269.4	-36.029±1.9671	0.3077 (<0.05)
		Power (BA)	0.0453	1.4231	2306.8	0.879066	2269.4	-36.196±1.9618	0.3077 (<0.05)
Diplorhynchus condylocarpon	44	Log	-1.39413	1.82145	-18.627	0.7115	0.59761	28.038±13.183 30.103±13.395*	0.98(0.0.67)
		Polynomial (Dbh)	-0.43078	0.66250, 0.05124, 0.00798	171.20	0.9395	38.1308	51.497±15.697	0.6707 (<0.05)
		Polynomial (BA)	-0.39160	0.29498, -3.929E-04, 1.318E-06	169.01	0.9424	36.3209	34.796±12.166	0.6514 (<0.05)
		Power (Dbh)	0.1001	2.2956	168.05	0.937036	37.845	8.8025±8.7803	0.6745 (<0.05)

Group	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
		Power (BA)	0.1320	1.1478	168.05	0.937036	37.845	8.7334±8.7747	0.6745 (<0.05)
Isoberlinia angolensis	96	Log	-2.72359	2.61271	-192.42	0.9539	0.13167	5.4791±3.2578 6.9555±3.3034*	0.97(0.03)
		Polynomial (Dbh)	8.02624	-3.45811, 0.52494, 0.00390	672.84	0.9719	961.731	14.090±3.7453	0.7171 (<0.05)
		Polynomial (BA)	-11.0171	0.56348, 1.561E-04, 7.154E-09	674.55	0.9714	978.834	-32.522±11.999	0.7872 (<0.05)
		Power (Dbh)	0.1232	2.4296	669.46	0.971612	951.46	31.577±4.5340	0.7295 (<0.05)
		Power (BA)	0.1652	1.2148	669.46	0.971612	951.46	31.563±4.5336	0.7295 (<0.05)
Julbernardia globiflora	115	Log	-2.00972	2.42033	-170.72	0.9188	0.22138	9.4318±4.2267 10.609±4.2722*	0.97 (<0.05)
		Polynomial (Dbh)	22.8098	-7.10081, 0.75658, 0.00436	916.31	0.9126	2548.79	47.917±16.361	0.6369 (<0.05)
		Polynomial (BA)	3.06031	0.23824, 0.00173, -1.164E-06	913.80	0.9144	2494.22	37.104±9.6698	0.6024 (<0.05)
		Power (Dbh)	0.0988	2.5653	912.46	0.912209		9.6160±3.8939	0.6373 (<0.05)
		Power (BA)				0.912209	2514.6	9.6502±3.8949	0.6373 (<0.05)
Julbernardia species group	133	Log	-2.10727	2.47072	-205.44	0.9348	0.20925	9.0522±3.8735 10.269±3.9167*	0.97 (<0.05)
		Polynomial (Dbh)	2.89151	-1.77548, 0.42673,	1096.5	0.9320	3411.65	9.9093±3.6689	0.6993 (<0.05)

Group	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
				0.01008					
		Polynomial (BA)	-14.3662	0.77145	1094.3	0.9331	3355.35	-77.802±22.479	0.7597 (<0.05)
		Power (Dbh)	0.1134	2.5241	1092.5	0.931791	3368.3	14.207±3.8977	0.7124 (<0.05)
		Power (BA)	0.1538	1.2620	1092.5	0.931791	3368.3	14.168±3.8966	0.7124 (<0.05)
Uapaca species group	131	Log	-2.15868	2.32284	-176.87	0.9078	0.25107	12.661±5.7055 13.720±5.7592*	0.97 (<0.05)
		Polynomial (Dbh)	29.4394	-11.5457, 1.31289, -0.02141	715.27	0.9535	223.881	146.02±54.180	0.7688 (<0.05)
		Polynomial (BA)	-0.18322	0.25901, 9.439E-04, -9.793E-07	684.26	0.9633	176.690	30.721±6.5383	0.7131 (<0.05)
		Power (Dbh)	0.3619	1.9649	768.04	0.92805	340.70	85.112±10.735	0.6839 (<0.05)
		Power (BA)	0.4588	0.9825	768.04	0.92805	340.70	85.127±10.735	0.6839 (<0.05)
Uapaca kirkiana	89	Log	-2.12977	2.27644	-123.90	0.9017	0.23693	12.954±7.3691 14.327±7.4587*	0.96 (<0.05)
		Polynomial (Dbh)	27.5960	-11.0471, 1.25770, -0.02024	462.27	0.9519	167.260	108.73±49.216	0.6436 (<0.05)
		Polynomial (BA)	1.87727	0.12925, 0.00153, -1.461E-06	393.89	0.9777	77.5736	50.263±13.396	0.6626 (<0.05)
		Power (Dbh)	0.3621	1.9432	502.84	0.92027	270.96	92.471±13.377	0.7050 (<0.05)
		Power (BA)	0.4579	0.9716	502.84	0.92027	270.96	92.476±13.378	0.7050 (<0.05)
Uapaca nitida	37	Log	-	2.33884	-	0.9123	0.29873	11.124±7.8256	0.96 (0.27)

Group	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
			2.05286		40.032			15.752±8.1515*	
		Polynomial (Dbh)	30.3083	-11.1736, 1.29654, -0.02116	230.32	0.9529	410.170	246.90±160.42	0.8820 (<0.05)
		Polynomial (BA)	5.88408	0.07850, 0.00208, -2.429E-06	217.50	0.9667	290.103	2689.3±552.64	0.8485 (<0.05)
		Power (Dbh)	0.3421	2.0059	230.89	0.944966	452.20	58.206±16.969	0.7876 (<0.05)
		Power (BA)	0.4359	1.0029	230.89	0.944966	452.20	58.184±16.969	0.7876 (<0.05)
Piliostigma thonningii	40	Log	-2.71065	2.44851	-113.72	0.9571	0.05190	2.4039±3.4676 3.8581±3.5168*	0.9669 (0.29)
		Polynomial (Dbh)	7.03867	-2.44665, 0.34904, 0.00149	122.56	0.9944	17.7282	5.8736±3.4551	0.9251 (<0.05)
		Polynomial (BA)	0.41109	0.16593, 8.443E-04, -6.681E-07	117.46	0.9951	15.6087	11.687±4.2111	0.921 (<0.05)
		Power (Dbh)	0.0716	2.4392	119.09	0.994152	17.492	8.1038±3.6656	0.8789 (<0.05)
		Power (BA)	0.0962	1.2196	119.09	0.994152	17.492	8.1819±3.6683	0.8789 (<0.05)
Acacia species group	24	Log	-2.13364	2.31086	-52.692	0.9544	0.08995	4.3812±6.7808 8.3739±7.0402*	0.9189 (0.0553)
		Polynomial (Dbh)	30.0142	-11.1679, 1.19549, -0.01631	105.69	0.9859	56.2895	18.694±17.036	0.9465 (0.2277)
		Polynomial (BA)	3.13679	0.04130, 0.00264, -3.328E-06	93.065	0.9916	33.2637	16.284±8.8428	0.546 (0.3394)

Group	Felled stems	Model	a	b, c, d	AIC$_c$	R^2	MSE	Mean error (±se, %)	W(p)
		Power (Dbh)	0.0996	2.4173	109.40	0.978688	77.133	9.9880±7.1259	0.8444 (<0.05)
		Power (BA)	0.1334	1.2087	109.40	0.978688	77.133	10.035±7.1290	0.8444 (<0.05)
Dichrostachys cinerea	34	Log	-1.13141	1.60429	-8.1051	0.4556	0.68539	39.263±20.839 40.407±21.010*	0.9503 (0.125)
		Polynomial (Dbh)	7.40754	-3.93113, 0.86069, -0.03809	89.835	0.5830	11.1366	87.881±31.203	0.9027 (<0.05)
		Polynomial (BA)	3.68488	-0.26120, 0.01616, -1.458E-04	86.154	0.6258	9.99381	96.181±36.145	0.9193 (<0.05)
		Power (Dbh)	0.3353	1.6869	85.926	0.565011	10.890	62.306±23.733	0.9003 (<0.05)
		Power (BA)	0.4111	0.8434	85.926	0.565011	10.890	62.296±23.732	0.9003 (<0.05)

Technical editing by Gun Mickels-Kokwe
Copy-editing, layout and cover design by Katarina Zeravica

About Integrated Land Use Assessment (ILUA) Phase II

In 2005, the Government of the Republic of Zambia, through the former Ministry of Tourism, Environment and Natural Resources (now Ministry of Lands, Natural Resources and Environmental Protection; MLNRP) and in an effort to reduce poverty, promote economic growth, fill existing human capacity gaps and fulfil its international commitments, requested technical and financial assistance from the Food and Agricultural Organization of the United Nations (FAO) to design and implement an Integrated Land Use Assessment (ILUA). The aim of the project was to establish a permanent forest and tree monitoring system and to obtain baseline national-level data on forest and other related land use resources. This was in order to address the urgent need for knowledge on the state and trends of Zambian forestry resources, given the lack of existing national level surveys and the need to strengthen institutional and financial capacity. In this way, the ILUA served as a pilot to provide data on the national status of land cover, management and use. The ILUA results were seen as vital to supporting national policy processes and planning, but because ILUA was intended as a national-level inventory, the results had limited utility for informing provincial and district level land use planning and decision making due to limited available funds and therefore applied low sampling intensity.

Therefore, based on discussions held with project stakeholders, the continuation of ILUA through an extension was proposed, in March 2009, to the Government of Finland for financing. Since the Environment and Natural Resources Management and Mainstreaming Programme (ENRMMP) has been launched to bring improved coordination and implementation capacity to the environment and natural resource management sector in Zambia, the project is designed to be implemented during 2011-2014 under this programme, with technical assistance from the FAO.

While ILUA I generated baseline data, ILUA II, to be carried out from 2011 to 2016, aimed to enhance the use and development of data and information systems for forest resource monitoring and Sustainable Forest Management, particularly for provincial level land use planning as well as for selected districts. ILUA II aims to provide information on trends in forest change through refined methodologies, re-assessed field plots and a four-fold intensification of sampling density in order to report at the sub-national level. It also aims to cover socio-economic related information needs via the Forest Livelihoods and Economic Survey in order to better understand the drivers of deforestation and to inform policy interventions which support Sustainable Forest Management. Establishing a monitoring system that captures livelihood needs beyond the forests is critical to designing well-targeted and innovative policy solutions that can support and promote sustainable natural resource management. The principal objectives of the ILUA II project are to strengthen forest and land use inventories at the national and sub-national level, and to support the implementation of Sustainable Forest Management and initiatives to Reduce Emissions from Deforestation and forest Degradation (REDD) through better information, capacity building, dissemination of information, and improved multi-sectoral dialogue.

The main stakeholders of the project are: MLNREP and different departments and institutions with which it collaborates, Ministry of Finance and National Planning, Ministry of Agriculture and Livestock, Central Statistical Office, National Remote Sensing Centre (Ministry of Science and Industrial Research), University of Zambia, Copperbelt University, Centre for International Forestry Research, National Institute for Scientific Research, Zambian Agricultural Research Institute, other national and international education and research institutes, smallholder farmers, NGOs and civil society, UN-REDD and other projects, the FAO and other cooperation partners.

The intended beneficiaries of the project can be summarized as follows: policy and decision makers at all levels, forest industries with an interest in timber and non-timber forest products from forest areas, the international community and international organizations requiring reliable information on the natural environment, NGOs, academia and grassroots organizations with interests in forest resource management, environmental protection, timber trade and extension.

In line with the overall policy of the Government of the Republic of Zambia, the impacts of this project are that benefits of Sustainable Forest Management are increased and mainstreamed in the national economy and policies, thereby supporting sustainable development of environment and rural livelihoods and meeting the Millennium Development Goals in a changing climate.

The project's main outcome is ***"strengthened capacity in planning and implementation of Sustainable Forest Management and REDD through better information capacity building, dissemination of information and improved multi-sectoral dialogue"***. The three main outputs of the project are:

Output 1: Effective means of dissemination and utilization of the information for multi-sector dialogue

Output 2: Improved methodological and human capacity in collecting and analyzing forest resource information for Sustainable Forest Management, REDD monitoring and carbon inventory.

Output 3: Implementation of ILUA II Mapping and Field Survey

ILUA II Technical Report Series

Biomass Volume Calculations

By E. N Chidumayo

2016

ILUA II
Integrated Land Use
Assessment Project

Ministry of Lands Natural Resources and
Environmental Protection
Forestry Department
P.O. Box 50042
Lusaka, Zambia
Tel. +260 211 221087

Food and Agriculture Organization
of the United Nations
P.O. Box 30563
Lusaka, ZAMBIA
Tel: +260 211 252277
or +260 211 252558