

Estimation of Tree Biomass, Carbon Stocks, and Error Propagation in Mecrusse Woodlands

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Abstract

We performed a biomass inventory using two-phase sampling to estimate biomass and carbon stocks for mecrusse woodlands and to quantify errors in the estimates. The first sampling phase involved measurement of auxiliary variables of living *Androstachys johnsonii* trees; in the second phase, we performed destructive biomass measurements on a randomly selected subset of trees from the first phase. The second-phase data were used to fit regression models to estimate below and aboveground biomass. These models were then applied to the first-phase data to estimate biomass stock. The estimated forest biomass and carbon stocks were 167.05 and 82.73 Mg·ha⁻¹, respectively. The percent error resulting from plot selection and allometric equations for whole tree biomass stock was 4.55% and 1.53%, respectively, yielding a total error of 4.80%. Among individual variables in the first sampling phase, diameter at breast height (DBH) measurement was the largest source of error, and tree-height estimates contributed substantially to the error. Almost none of the error was attributable to plot variability. For the second sampling phase, DBH measurements were the largest source of error, followed by height measurements and stem-wood density estimates. Of the total error (as total variance) of the sampling process, 90% was attributed to plot selection and 10% to the allometric biomass model. The total error of our measurements was very low, which indicated that the two-phase sampling approach and sample size were effective for capturing and predicting biomass of this forest type.

Keywords

Aboveground Production, Additivity, *Androstachys johnsonii* Prain, Belowground Carbon Allocation, Error Margins, Root Growth

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1. Introduction

Mecrusse is a forest type dominated by *Androstachys johnsonii* Prain, which generally occupies between 80% and 100% of the canopy (Mantilla & Timane, 2005). *A. johnsonii* (family Euphorbiaceae) is native to Africa and Madagascar and is the sole member of genus *Androstachys*; today, mecrusse forest is primarily found in Mozambique (Cardoso, 1963).

Mecrusse is an important woodland. Besides being restricted to Mozambique (Cardoso, 1963), it has important socio-economic value to local communities, which use stakes of *A. johnsonii* in the construction of homes, shelters, and furniture. At the global scale, mecrusse forest forms part of the woodland belt that stretches over large portions of southern Africa and is reported to be a tipping point in regional ecological and socio-economic development (Leadley et al., 2010). Carbon sequestration in tree biomass is a key ecosystem service provided by woodlands. However, to date, no estimates of biomass or carbon stocks are available for these woodlands despite the relevance of this vegetation type in Mozambique.

Estimates of biomass stock are important for predicting carbon fluxes and stocks, assessing nutrient cycling and fluxes, determining potential wood energy, and for policy making. The errors associated with biomass estimates must be known for the derived predictions and policies to be reliable. However, the error is rarely evaluated carefully in biomass studies (Chave et al., 2004). Many studies that estimate biomass stock employ a two-phase sampling design; most of these studies found that the error due to second phase (error due to allometric equations) to be larger than that of the first phase (error due to plot selection) (Samalka, 2007; Chave et al., 2004; Molto et al., 2012). The error of estimates from two-phase sampling has two main components, one associated with each phase (Cunia, 1986a; Cunia, 1990). Moreover, each variable measured in each sampling phase contributes to the error of that phase. The objective of this study was to estimate the above and belowground biomass and carbon stocks of mecrusse woodlands and to quantify the errors in those estimates.

2. Material and Methods

2.1. Study Area

In Mozambique, mecrusse woodlands are mainly found in Inhanbane and Gaza provinces, in Massangena, Chicualacuala, Mabalane, Chigubo, Guijá, Mabote, Funhalouro, Panda, Mandlakaze, and Chibuto districts. The easternmost mecrusse forest patches, located in Mabote, Funhalouro, Panda, Mandlakaze, and Chibuto districts, were defined as the study area. The study area comprised 4,502,828 ha (Dinageca, 1997), of which 226,013 ha (5%) were mecrusse woodlands. The physical and natural conditions for each district of the study area are summarized in Table 1.

Table 1. Physical and natural conditions of the study area.

District	Description	Relief, topography and altitude	Soils (FAO classification)
Mabote	Climate: dry tropical; Mean annual temperature: 24°C; Mean annual precipitation: 600 mm; Hydrology: no rivers, temporary lakes.	Relief and topography: flat. Altitude: 100 to 200 m a.s.l.	Ferralic Arenosols (>90%).
Funhalouro	Climate: dry tropical; Mean annual temperature: >24°C; Mean annual precipitation: from 500 to 800 mm; Hydrology: not crossed by any river.	Relief and topography: flat. Altitude: 100 to 200 m a.s.l.	Ferralic Arenosols (>85%) and Arenosols (>10%).
Panda	Climate: dry and humid tropical; Mean annual temperature: from 18°C to 35°C; Mean annual precipitation: 750 mm; Hydrology: crossed by Nhatócue river.	Relief and topography: flat. Altitude: 50 to 200 m a.s.l.	Arenosols (>50%) and Stagnic soils (<50%).
Mandlakaze	Climate: dry and humid tropical; Mean annual temperature: >24°C; Mean annual precipitation: from 400 to 950 mm; Hydrology: 63 lakes and 2 rivers (Changane and Mangonhane).	Relief and topography: flat. Altitude: 100 to 200 m a.s.l.	Ferralic Arenosols (>40%), Umbric Fluvisols (<20%) and Arenosols (>20%).
Chibuto	Climate: dry tropical; Mean annual temperature: >24°C; Mean annual precipitation: from 400 to 600 mm; Hydrology: 4 rivers (Limpopo, Changane, Chégua and Jatinguá).	Relief and topography: flat. Altitude: 50 to 200 m a.s.l.	Stagnic soils (60%) and Ferralic Arenosols (40%).

Sources: Dinageca (1997), Mae (2005a-e), and FAO (2003).

2.2. Sampling and Data Collection

The first sampling phase involved the selection of a large number of trees (3574 trees) in randomly located plots for measurement of diameter at breast height (DBH) and total tree height, which were expected to be correlated with component and whole tree biomass. The second phase involved the selection of a subset of trees from the first phase for destructive measurement of biomass, along with the variables of the first phase. Simple random sampling was used in both phases.

2.2.1. First Phase: Plot-Level Sampling and Measurements

We established 23 randomly located circular plots (20-m radius) in the study area; randomness was achieved using Hawth's Tools in ArcGIS 9.3 (ESRI, 2009). The plots were located using a GPS and maps and were demarcated on the ground using a Vertex IV hypsometer and a 360° transponder. DBH and total height were measured for all trees with DBH \geq 5 cm in each plot.

2.2.2. Second Phase: Tree-Level Sampling and Measurements

Within each of the 23 plots, 2 to 6 trees ($n = 93$ total) were selected in proportion to the frequency of five diameter classes for destructive biomass sampling; diameter classes with >5 trees were included. Each tree was felled and divided into the following components: 1) root system, 2) stem wood, 3) stem bark, and 4) crown. The root system was completely excavated, including the fine roots. Tree components were sampled and the dry weights estimated as follows.

1) Root System

The stump height was predefined as being 20 cm for all trees and considered as part of the taproot, as recommended by Parresol (2001) and because in larger *A. johnsonii* trees this height (20 cm) is affected by root buttress; thus, the root collar was also considered part of the taproot. The root system was divided into 3 sub-components: fine lateral roots, coarse lateral roots and taproot. Lateral roots with diameters at the insertion point on the taproot < 5 cm were considered as fine roots and those with diameters ≥ 5 cm were considered as coarse roots.

First, the root system was partially excavated to the first node, using hoes, shovels, and picks, to expose the primary lateral roots (Figure 1(a) and Figure 1(b)). The primary lateral roots were numbered and separated from the taproot with a chainsaw (Figures 1(a)-(c)) and removed from the soil, one by one. This procedure was repeated in the subsequent nodes until all primary roots were removed from the taproot and from the soil. Finally, the taproot was excavated and removed (Figure 1(c) and Figure 1(d)). The complete removal of the root system was relatively easy because 90% of the lateral roots of *A. johnsonii* are located in the first node, which is

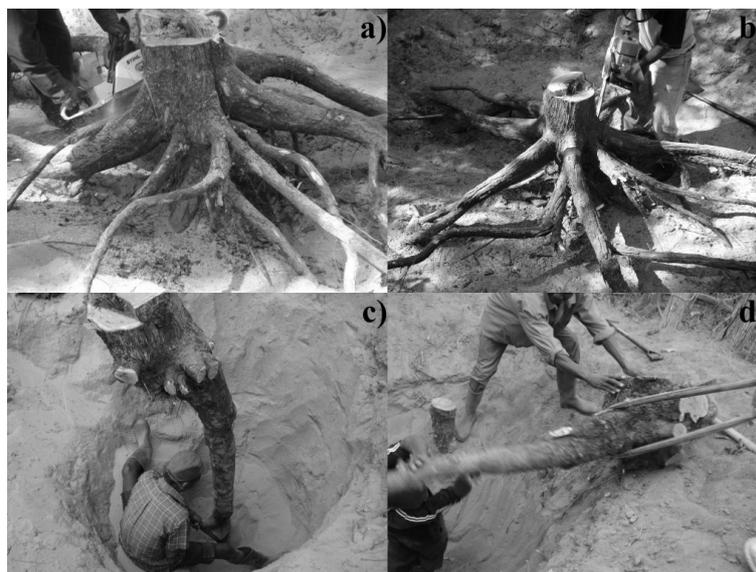


Figure 1. Separation of lateral roots from the taproot ((a), (b)), and removal of the taproot including the root collar and the stump ((c), (d)).

located close to ground level (**Figures 1(a)-(c)**); the lateral roots grow horizontally to the ground level, do not grow downwards; and because the taproots had, at most, only 4 nodes and at least 1 node (at ground level).

Fresh weight was obtained for the taproot, each coarse lateral root and for all fine lateral roots. A sample was taken from each sub-component, fresh weighed, marked, packed in a bag, and taken to the laboratory for oven drying. For the taproot, the samples were two discs, one taken immediately below the ground level and another from the middle of the taproot. For the coarse lateral roots, two discs were also taken, one from the insertion point on the taproot and another from the middle of it. For fine roots the sample was 5% to 10% of the fresh weight of all fine lateral roots. Oven drying of all samples was done at 105°C to constant weight, hereafter, referred to as dry weight.

2) Stem Wood and Stem Bark

Felled trees were scaled up to a 2.5 cm top diameter. The stem was defined as the length of the trunk from the stump to the height that corresponded to 2.5 cm diameter. The remainder (from the height corresponding to 2.5 cm diameter to the tip of the tree) was considered a fine branch. The stem was divided into sections, the first with 1.1 m length, the second with 1.7 m, and the remaining with 3 m, except the last, which length depended on the length of the stem. Discs were removed at the bottom and top of the first section, and on the top of the remaining sections; i.e.: discs were removed at heights of 0.2 m (stump height), 1.3 m (breast height), 3 m, and the successive discs were removed at intervals of 3 m to the top of the stem, and their fresh weights measured using a digital scale.

Diameters over and under bark were taken from the discs in the North-South direction (previously marked on the standing tree) with the help of a ruler. The volumes over and under the bark of the stem were obtained by summing up the volumes of each section calculated using Smalian's formula (de Gier, 1992; Husch et al., 2003). Bark volume was obtained from the difference between volume over bark and volume under bark.

The discs were dipped in drums filled with water for its saturation (3 to 4 months) and subsequent determination of the saturated volume and basic density. The saturated volume of the discs was obtained based on the water displacement method (Brasil et al., 1994) using Archimedes' principle. This procedure was done twice: before and after debarking; hence, we obtained saturated volume under and over the bark.

Wood discs and respective barks were oven dried at 105°C to constant weight. Basic density was obtained by dividing the oven dry weight of the discs (with and without bark) by the relevant saturated wood volume (de Gier, 1992; Bunster, 2006). Therefore, two distinct basic densities were calculated: 1) basic density of the discs with bark and 2) basic density of the discs without bark.

We estimated the basic density at point of geometric centroid of each section using the regression function of density over height (Seifert & Seifert, 2014). This density value was taken as representative of each section (Seifert & Seifert, 2014).

3) Crown

The crown was divided into two sub-components: branches and foliage. Primary branches, originating from the stem, were classified in two categories: primary branches with diameters at the insertion point on the stem ≥ 2.5 cm were classified as large branches, and those with diameters < 2.5 cm were classified as fine branches.

Large branches were sampled similarly to coarse roots, and fine branches and foliage were sampled similarly to fine roots. All the leaves from each tree were collected and fresh weighed together and a sample taken for oven drying. The sub-components branches and foliage were not treated as separated components because in the preliminary analysis the weight of the foliage did not show significant variation with *DBH*, total tree height (*H*), and live crown length (LCL); exhibiting, therefore, poor fits.

4) Tree Component Dry Weights, and Carbon Concentration

Dry weights of coarse and fine roots, large and fine branches, and foliage were obtained from the "fresh weight/oven dry weight" ratio of the respective samples by multiplying it by the relevant sub-component total fresh weight. Dry weights of the root system and crown were obtained by summing up the relevant sub-components' dry weights. Dry weights of each stem (with and without bark) were obtained by multiplying respective average densities by relevant stem volumes. The dry weight of the stem bark was obtained from the difference between the dry weights of stem and stem wood. Finally, the total tree biomass was obtained by adding the component dry weights.

A subsample ($n = 17$ trees) was randomly selected from the 93 harvested trees (one to two trees per diameter class and location) for carbon analysis. Five samples were randomly selected from each of these 17 trees, from each of the components: roots, leaves, branches, bark, and stem. The samples were pooled and milled together by component to form a composite sample. Carbon concentration in the composite samples was measured using

a TruSpec Micro analyser (LECO Corp) at the Central Analytical Facilities, Stellenbosch University (Stellenbosch, South Africa). The average carbon content of the crown was obtained from the average values for branches and foliage. Carbon concentrations for each tree component, with standard deviation (*SD*) and coefficient of variation (*CV*, in percentage), are presented in **Table 2**.

2.3. Biomass Models

Biomass estimation typically requires estimation of tree components and total tree biomass (Seifert & Seifert, 2014). To ensure the additivity of component biomass estimates into total tree biomass, component and total biomass models were fitted using the same regressors (Parresol, 1999; Goicoa et al., 2011) (conventional method of enforcing additivity). For this, first the best tree component and total tree biomass equations were selected by running various possible linear regressions on combinations of the independent variables (*DBH*, *H*, and *LCL*) and evaluating them using the following goodness of fit statistics: coefficient of determination (R^2), standard deviation of the residuals ($S_{y,x}$) and *CV* of the residuals, mean residual (*MR*), and graphical analysis of the residuals. The computation and interpretation of these fit statistics were previously described by Meyer (1941); Gadow & Hui (1999), Ruiz-Peinado et al. (2011), and Goicoa et al. (2011).

Among the different model forms tested, the model form $\hat{Y} = b_0 + b_1 D^2 H$ was the best for three components (root system, stem wood, and stem bark) and for the total tree biomass, and the second best for crown biomass. Therefore, to allow all three components and total tree models to have the same regressors, and thus achieve additivity, this model form was generalized for all tree component and total tree models.

Linear weighted least squares were used to address heteroscedasticity. The weight functions were obtained by iteratively finding the optimal weight that homogenised the residuals and improved other fit statistics. Among the tested weight functions ($1/D$, $1/D^2$, $1/DH$, $1/DLCL$, $1/D^2H$, $1/D^2LCL$), the best weight function was found to be $1/D^2H$, for all tree components and total tree models. Although, the selected weight function might not be the best one among all possible weights, it is the best approximation found.

Linear models were preferred over nonlinear models because the conventional method of enforcing additivity is only applicable for linear models (Parresol, 1999; Goicoa et al., 2011) and because the procedure of combining the error of the first and second sampling phases (Cunia, 1986a) is limited to biomass regressions estimated by linear weighted least squares (Cunia, 1986a). **Table 3** shows the regression models and their statistics for each tree component and for total biomass.

The graphs of the residuals against predicted values for the models in the **Table 3** are presented in the **Figure 2** and did not show any particular trend or heteroscedasticity.

Table 2. Carbon concentration (%) in each tree component.

	Roots	Stem wood	Stem bark	Crown
Average	53.14	49.04	45.15	48.67
<i>SD</i>	1.71	1.54	3.93	0.78
<i>CV</i>	3.21	3.15	8.70	1.60

Table 3. Parameters ($\pm SE$) and fit statistics for the selected models.

Tree component	Model form	Weight function	b_0 ($\pm SE$)	b_1 ($\pm SE$)	R^2 (%)	$S_{y,x}$ (kg)	<i>CV</i> (%)	<i>MR</i> (kg)
Roots	$\hat{Y} = b_0 + b_1 D^2 H$	$1/D^2 H$	0.2522 (± 0.6334)	0.0097 (± 0.0002)*	95.00	9.59	20.10	-2.05E-14
Stem wood	$\hat{Y} = b_0 + b_1 D^2 H$	$1/D^2 H$	0.6616 (± 1.1451)	0.0251 (± 0.0004)*	97.52	19.66	15.84	-7.96E-16
Stem bark	$\hat{Y} = b_0 + b_1 D^2 H$	$1/D^2 H$	0.1895 (± 0.3503)	0.0028 (± 0.0001)*	84.41	4.97	34.97	-1.96E-16
Crown	$\hat{Y} = b_0 + b_1 D^2 H$	$1/D^2 H$	0.3033 (± 1.5640)	0.0118 (± 0.0006)*	82.36	25.11	43.01	1.71E-15
Total tree	$\hat{Y} = b_0 + b_1 D^2 H$	$1/D^2 H$	1.4066 (± 2.1984)	0.0494 (± 0.0008)*	97.64	34.92	14.29	-1.24E-15

\hat{Y} = tree component biomass (kg); *D* = diameter at breast height (cm); *H* = tree height (m); b_0 and b_1 = regression parameters; *SE* = standard error of the regression parameters; "*" = significant at $\alpha \geq 5\%$; "" = not significant at any probability level.

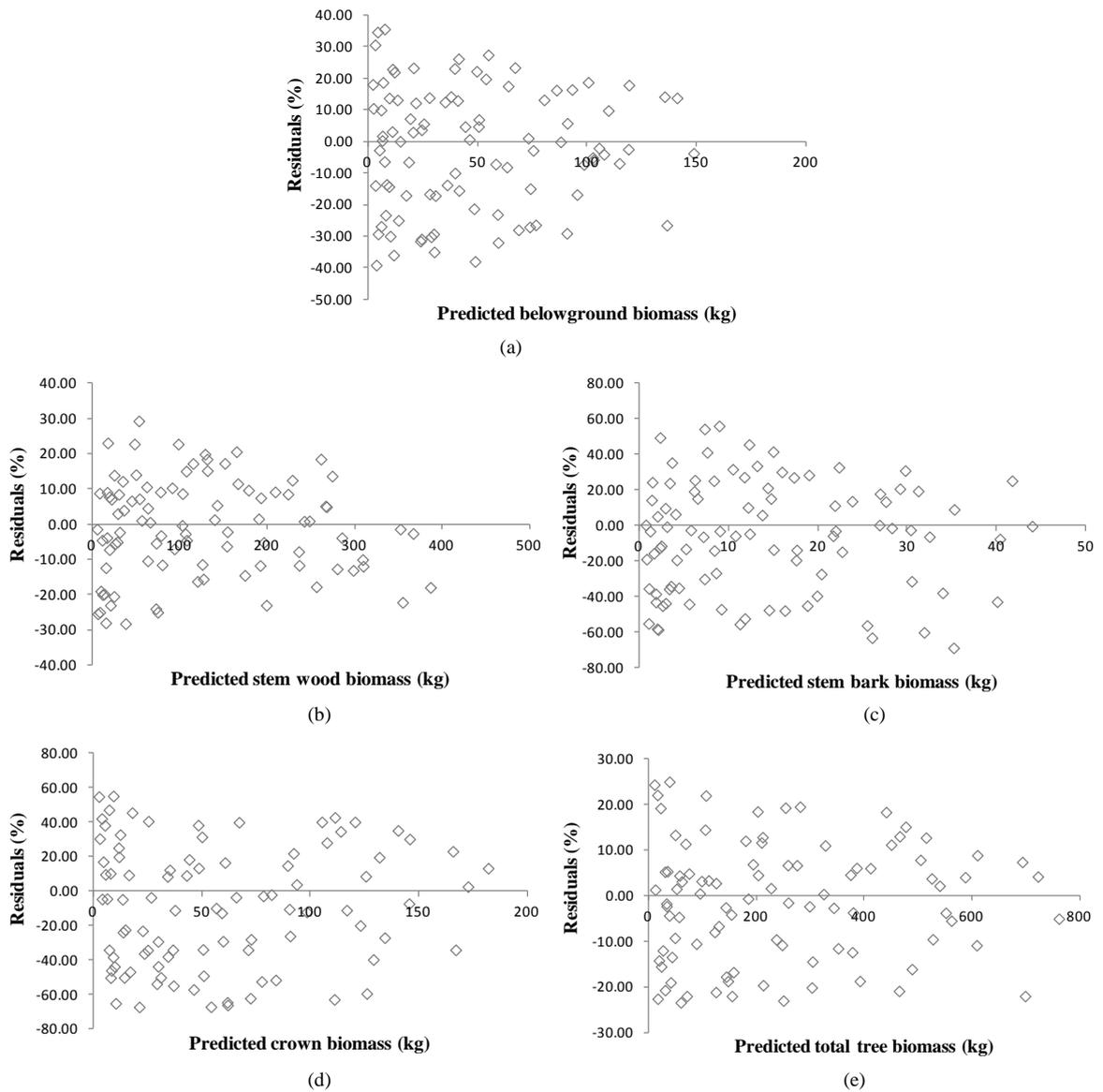


Figure 2. Residuals against predicted biomass for the models in the **Table 1**.

2.4. Estimation of Biomass and Carbon Stocks

The model equation for component and total tree biomass (\hat{Y}) was as follows:

$$\hat{Y} = b_0 + b_1 D^2 H \tag{1}$$

where D represents *DBH* and H represents tree height. The biomass of the k^{th} tree in the h^{th} plot (\hat{Y}_{hk}) estimated by Equation (1) is determined by Equation (2):

$$\hat{Y}_{hk} = b_0 + b_1 D_{hk}^2 H_{hk} \tag{2}$$

The biomass of plot h (\hat{Y}_h) is estimated by summing the individual biomass (\hat{Y}_{hk}) values of the n_h trees in plot h as follows:

$$\hat{Y}_h = \sum_{k=1}^{n_h} \hat{Y}_{hk} = b_0 n_h + b_1 \sum_{k=1}^{n_h} D_{hk}^2 H_{hk} \tag{3}$$

where $k = 1, 2, \dots, n_h$, and $h = 1, 2, \dots, n_p$, n_p = number of plots in the sample, and n_h = number of trees in the h^{th}

plot. Then, dividing Equation (3) by plot size a gives biomass \hat{Y} on an area basis:

$$\hat{Y} = \frac{\hat{Y}_h}{a} = \frac{b_0 n_h}{a} + \frac{b_1 \sum_{k=1}^{n_h} D_{hk}^2 H_{nh}}{a} \quad (4)$$

Denoting $S_{h0} = \frac{n_h}{a}$ and $S_{h1} = \frac{\sum_{k=1}^{n_h} D_{hk}^2 H_{nh}}{a}$, Equation (4) can be rewritten as:

$$\hat{Y} = b_0 S_{h0} + b_1 S_{h1} \quad (5)$$

The biomass stock \bar{Y} (average biomass per hectare) is estimated by summing the biomass \hat{Y} of each plot (area basis) and dividing it by the number of plots n_p :

$$\bar{Y} = \frac{\sum_{h=1}^{n_p} \hat{Y}}{n_p} = \frac{b_0 \sum_{h=1}^{n_p} S_{h0}}{n_p} + \frac{b_1 \sum_{h=1}^{n_p} S_{h1}}{n_p} \quad (6)$$

Now, denoting $Z_0 = \frac{\sum_{h=1}^{n_p} S_{h0}}{n_p}$ and $Z_1 = \frac{\sum_{h=1}^{n_p} S_{h1}}{n_p}$, Equation (6) can be rewritten as follows:

$$\bar{Y} = b_0 Z_0 + b_1 Z_1 = [b]^\top [Z] \quad (7)$$

where $[b]^\top = [b_0 \ b_1]$ is the row vector of the regression coefficient of Equation (2) (also referred to as the row vector of the estimates from the second sampling phase), and $[Z] = \begin{bmatrix} Z_0 \\ Z_1 \end{bmatrix}$ is the column vector of the estimates from the first phase. As seen in Equation (7), biomass stock is obtained by combining the estimates from the first and second phases.

Equations (2)-(7) were applied to estimate biomass stock of each tree component, whole tree, and diameter class. The carbon stock of each tree component was estimated by multiplying the relevant carbon concentration by biomass stock.

2.5. Error Propagation

Biomass stock (Equation (7)) was estimated by combining the estimates of the first and second phases ($[Z]$ and $[b]^\top$, respectively). Two main sources of error must be accounted for in this calculation, that resulting from plot-level variability (first sampling phase) and that from the allometric equations (second phase).

Cunia (1965, 1986a, 1986b, 1990) demonstrated that the total variance of the estimated \bar{Y} (mean biomass per hectare) is given by Equation (8):

$$VAR_t = VAR_1 + VAR_2 = [b]^\top [S_{zz}] [b] + [Z]^\top [S_{bb}] [Z] \quad (8)$$

where VAR_1 and VAR_2 are variance components from the first and second sampling phases, respectively; $[b]^\top$ and $[b]$ are row and column vectors, respectively, of the regression coefficients; $[Z]^\top$ and $[Z]$ are row and column vectors, respectively, of the estimates from the first phase; $[S_{zz}]$ represents the variance-covariance matrix of vector $[Z]$; and $[S_{bb}]$ represents the variance-covariance matrix of vector $[b]^\top$ or of the regression coefficients. In this specific case, $[S_{bb}]$ and $[S_{zz}]$ are calculated from Equations (9) and (10):

$$[S_{bb}] = \begin{bmatrix} S_{b_0 b_0} & S_{b_0 b_1} \\ S_{b_0 b_1} & S_{b_1 b_1} \end{bmatrix} \quad (9)$$

$$[S_{zz}] = \begin{bmatrix} S_{z_0z_0} & S_{z_0z_1} \\ S_{z_0z_1} & S_{z_1z_1} \end{bmatrix} \quad (10)$$

where $S_{b_i b_j}$ = covariance of b_i and b_j , and $S_{z_i z_j} = \frac{\sum_{h=1}^{n_p} (S_{hi} - \bar{S}_i)(S_{hj} - \bar{S}_j)}{(n_p - 1)n_p}$.

The square root of Equation (8) is the total standard error (SE) of \bar{Y} ; the square root of the first component of Equation (8) $\sqrt{[b]' [S_{zz}] [b]}$ is the standard error of the first phase; and the square root of the second component $\sqrt{[Z]' [S_{bb}] [Z]}$ is the standard error of the second phase.

In this study, the error of \bar{Y} is expressed as the percent SE of the first sampling phase (Equation (11)), the second sampling phase (Equation (12)), and both phases combined (Equation (13)):

$$SE_1 (\%) = \frac{\sqrt{[b]' [S_{zz}] [b]}}{\bar{Y}} \times 100 \quad (11)$$

$$SE_2 (\%) = \frac{\sqrt{[Z]' [S_{bb}] [Z]}}{\bar{Y}} \times 100 \quad (12)$$

$$SE_t (\%) = \frac{\sqrt{[b]' [S_{zz}] [b] + [Z]' [S_{bb}] [Z]}}{\bar{Y}} \times 100 \quad (13)$$

However, in some cases, the error is expressed as the variance of \bar{Y} , especially where the proportional influence of a particular source of error needs to be known.

Because carbon stocks are determined by multiplying the carbon concentration by biomass stock, variance of the estimated carbon stock is determined by multiplying the variance of biomass stock by the square of the carbon concentration.

The Monte Carlo error propagation approach was applied to estimate the percent contribution of each variable measurement error to the error of each sampling phase. We determined the contribution of DBH measurement error, height measurement error, and plot variability in the first sampling phase. Plot variability was defined as error resulting from variation in the number of trees per hectare (S_{h0}). There were numerous sources of error from the second sampling phase; these sources are described below.

Belowground dry weight was determined by summing the dry weights of lateral roots (coarse and fine) and the taproot (Equation (14)). The sources of error in this calculation are the fresh-weight (FW) and moisture content (MC) determinations:

$$LRFW - LRFW \times LRMC + TRFW - TRFW \times TRMC \quad (14)$$

where LR = lateral roots; TR = taproot; $LRFW \times LRMC$ = water weight of lateral roots; and $TRFW \times TRMC$ = water weight of the taproot. Note that MC is a ratio and varies from 0 to 1.

Equation (14) can be rearranged as:

$$LRFW(1 - LRMC) + TRFW(1 - TRMC) \quad (15)$$

Dry weight of stem wood was determined by multiplying the estimated mean stem wood basic density (ρ_{sw}) by its estimated volume (Equation (16)):

$$\frac{\Pi}{4} DBH^2 \times H \times ff \times \rho_{sw} \quad (16)$$

Because the form factor ff and the value $\frac{\Pi}{4}$ are constants, they do not contribute to error and can be removed

to form Equation (17):

$$DBH^2 \times H \times \rho_{sw} \quad (17)$$

Thus, the sources of error in the calculation of stem-wood dry weight are the DBH and height measurements and estimated mean density.

The stem volume obtained by summing the volumes of the constituent stem sections was assumed equal to the volume obtained using form factor; in fact, the mean difference between those two estimates was only 2.3%.

Dry weight of stem bark was calculated as the difference between total stem dry weight (including bark) and dry weight of stem wood (Equation (18)), where ρ_s is stem basic density (specific gravity):

$$DBH^2 \times H \times \rho_s - DBH^2 \times H \times \rho_{sw} \quad (18)$$

The sources of errors in Equation (18) include the DBH and height measurements and the estimated mean stem and stem wood basic densities.

Crown dry weight was determined by summing the dry weights of branches and foliage (Eq. 19), with error due to FW and MC determination:

$$BFW - BFW \times BMC + LFW - LFW \times LMC \quad (19)$$

where B = branches; L = leaves; $BFW \times BMC$ = water weight of the branches; and $LFW \times LMC$ = water weight of the foliage.

Equation (19) can be rearranged as:

$$BFW(1 - BMC) + LFW(1 - LMC) \quad (20)$$

Whole tree dry weight and total error were calculated from the sum of Equations (15), (17), (18) and (20).

The contribution of each phase-1 variable measurement error (DBH, total height, and plot variability) to total phase-1 error was determined using Equation (7) and the phase-1 data; the contribution of error from the second phase was determined from Equations (15), (17), (18) and (20). These calculations were performed using the “propagate” package (Spiess, 2013) in R (R Core Team, 2013). All statistical analyses were performed at the 95% probability level.

The sources of error accounted for in this study are DBH measurement, total tree height estimation and plot variability for phase-1; and DBH and total tree height measurements, stem and stem wood basic density estimation, determination of moisture content (of foliage, branches, and roots), and measurement of fresh weights (of foliage, branches, and roots) for phase-2. Further research is needed to account for other sources of errors not included here, such as the slope of the terrain, distance between the tree and the hypsometer, diameters at successive heights on the stem, etc.

3. Results

3.1. Biomass and Carbon Stocks

Biomass stock (from Equation (7)) and the corresponding carbon stock ($\text{Mg} \cdot \text{ha}^{-1}$), are presented in **Table 4** and **Table 5**, respectively. The whole tree and aboveground biomass stocks were 167 and 134 $\text{Mg} \cdot \text{ha}^{-1}$, respectively. Stem wood formed the largest share of biomass for all diameter classes, followed by the crown. The proportional distribution of biomass at the forest scale was as follows: stem wood, 51%; crown, 24%; belowground biomass, 19%; and stem bark, 6%.

The 15 - 20 and 20 - 25 cm diameter classes represented >50% of the total forest biomass stock (**Figure 3(a)**); however, only ~30% of all trees were in these size classes (**Figure 3(b)**).

Note that the DBH of *A. johnsonii* rarely exceeds 35 cm (here, <1% of trees during the first sampling phase); therefore, trees encountered in diameter classes larger than the highest class in **Figure 3(b)** ($25 \leq DBH < 30$) were considered as belonging to this diameter class.

3.2. Error Propagation

Low variance in the estimates of biomass stock indicated that there was a high level of precision in the estimates (**Table 6**). The largest error was observed for stem bark and crown; the goodness of fit for these components was poorer in the models (smaller R^2 and higher CV of the residuals; **Table 3**), which explained the higher error.

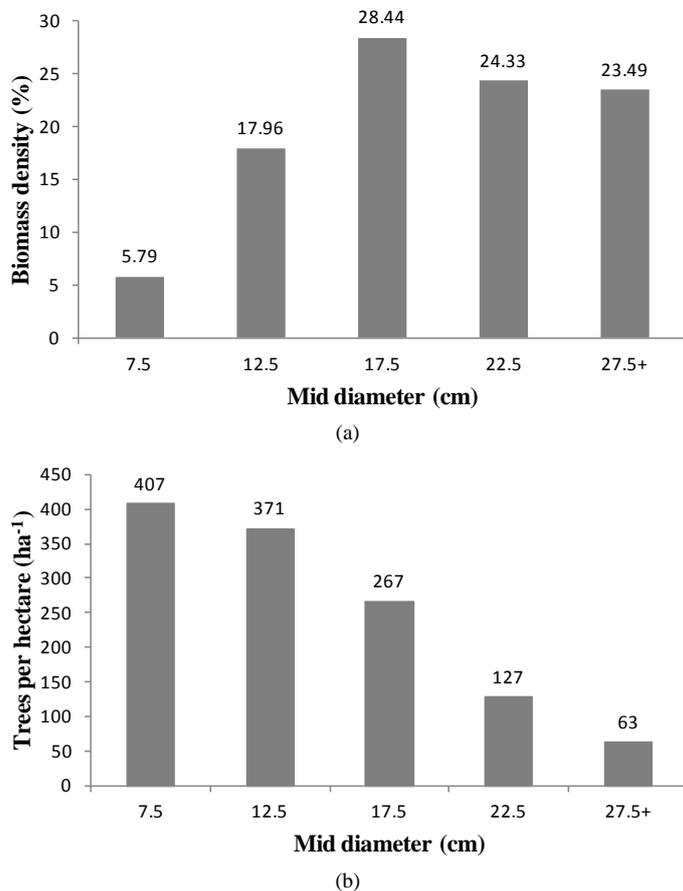


Figure 3. Proportion of total forest biomass stock (a) and diameter distribution (b) (obtained using phase-1 data) for each diameter class in mecrusse woodlands in the study area.

Table 4. Biomass stock (Mg·ha⁻¹) for each tree component and diameter class.

Tree component	Diameter class (cm)					Total
	[5 - 10[[10 - 15[[15 - 20[[20 - 25[[25 - 30+]	
Belowground	1.88	5.85	9.27	7.93	4.20	32.60
Stem wood	4.89	15.22	24.12	20.64	10.93	84.79
Stem bark	0.60	1.77	2.77	2.36	1.25	9.77
Crown	2.30	7.16	11.35	9.71	5.14	39.90
Whole tree	9.67	29.99	47.51	40.64	21.52	167.05
Harvested trees	18.00	18.00	18.00	17.00	22.00	93.00

Table 5. Carbon stock (Mg·ha⁻¹) for each tree component and diameter class.

Tree component	Diameter class (cm)					Total
	[5 - 10[[10 - 15[[15 - 20[[20 - 25[[25 - 30+]	
Belowground	1.00	3.11	4.93	4.22	2.23	17.32
Stem wood	2.40	7.46	11.83	10.12	5.36	41.58
Stem bark	0.27	0.80	1.25	1.06	0.56	4.41
Crown	1.12	3.48	5.52	4.73	2.50	19.42
Whole tree	4.79	14.85	23.53	20.13	10.66	82.73
Harvested trees	18.00	18.00	18.00	17.00	22.00	93.00

Table 6. Variance $[(\text{Mg}\cdot\text{ha}^{-1})^2]$, absolute standard error $(\text{Mg}\cdot\text{ha}^{-1})$, and percent standard errors of the estimates of biomass stock for each tree component and sampling phase.

Tree component	VAR_1	VAR_2	VAR_t	SE_1	SE_2	SE_t	SE_1 (%)	SE_2 (%)	SE_t (%)
Belowground	2.20	0.54	2.74	1.48	0.74	1.66	4.55	2.26	5.08
Stem wood	14.89	1.77	16.66	3.86	1.33	4.08	4.55	1.57	4.81
Stem bark	0.19	0.17	0.36	0.44	0.41	0.60	4.50	4.17	6.13
Crown	3.30	3.30	6.60	1.82	1.82	2.57	4.55	4.55	6.44
Whole tree	57.74	6.52	64.26	7.60	2.55	8.02	4.55	1.53	4.80

For the crown, the error in the allometric equations (second sampling phase) was equal to the error of plot-level variability (differences in the number of trees per plot in the first sampling phase). In contrast, more of the variance for belowground, stem wood, stem bark, and total biomass was attributable to plot-level variability than to the allometric equations (Table 7).

Subscripts 1 and 2 indicate the first and second sampling phases, respectively; subscript t indicates the total variance or standard error for a given component.

Actual whole tree biomass stock (from 95% CI) was between 151 and 183 $\text{Mg}\cdot\text{ha}^{-1}$ (Table 8). Carbon stock ($\text{Mg}\cdot\text{ha}^{-1}$) varied from approximately 75 - 91 $\text{Mg}\cdot\text{ha}^{-1}$ (Table 9). DBH measurement error contributed close to two-thirds of the error from the first sampling phase, while the tree height measurement error contributed more than one third. Plot-level variability contributes negligibly to the uncertainty (Table 10).

In the second sampling phase (using allometric equations), fresh-weight measurement error accounted for >90% of the total error in biomass calculations. The majority of errors in stem bark and stem wood calculations arose from the errors of basic density estimation and DBH measurements, respectively, while DBH measurement error accounted for most of the error in whole tree biomass calculations (Table 11).

Note that the stem wood basic density estimation is not included as a source of error for the whole tree. The whole tree biomass is obtained by summing Equations (15), (17), (18) and (20); as for the errors. However, by summing Equations (17) and (18) the result is $DBH^2 \times H \times \rho_s$, which excludes stem wood basic density (ρ_{sw}). In fact, the stem biomass ($DBH^2 \times H \times \rho_s$) includes both stem wood (Equation (17)) and stem bark biomass (Equation (18)); as for stem density (ρ_s).

4. Discussion

4.1. Biomass and Carbon Stocks

Our finding that approximately half of total tree biomass and carbon stocks were attributable to stem wood was consistent with the results of Paladinic et al. (2009) for fir-beech and oak forests and Wang et al. (2011) for *Abies nephrolepis* (Maxim). In Mozambique, *A. johnsonii* is classified as a first-class commercial species with minimum harvestable diameter of 30 cm (DNFFB, 2002). Stakes of *A. johnsonii* used by local communities for construction purposes are generally from trees that are 10 - 15 cm in diameter (Mantilla & Timane, 2005). This diameter class comprised <20% of the total biomass.

Biomass stock is a function of stem density and DBH, and thus of basal area (see Figure 4, where the diameter classes with the largest proportion of basal area are the same as those with the largest proportion of biomass stock). Biomass stock has been correlated with basal area by many authors (Rai, 1981; Brunig, 1983; Cannell, 1984; Rai & Proctor 1986; Slik et al. 2010).

In Mozambique, most studies of tree biomass and carbon stocks focus on miombo (*Brachystegia* spp.) woodlands, which represent 75% of the forest in this country (Siteo & Ribeiro, 1995). Existing estimates of biomass and carbon stocks for miombo woodlands are much lower than the estimates obtained here for mcrusse woodlands. Ribeiro et al. (2013) found that the tree biomass and carbon stocks in miombo woodlands of Niassa National Reserve were approximately 59 and 30 $\text{Mg}\cdot\text{ha}^{-1}$, respectively. Miombo carbon stocks in Nhambita, Gorongozo District, in Mozambique were estimated as 21.2 $\text{Mg}\cdot\text{ha}^{-1}$ for stems and 8.5 $\text{Mg}\cdot\text{ha}^{-1}$ for coarse roots (Ryan et al., 2010).

Low stem density (380 - 400 ha^{-1}) and basal area (7 - 19 $\text{m}^2\cdot\text{ha}^{-1}$) in miombo (Ribeiro et al., 2002) can explain

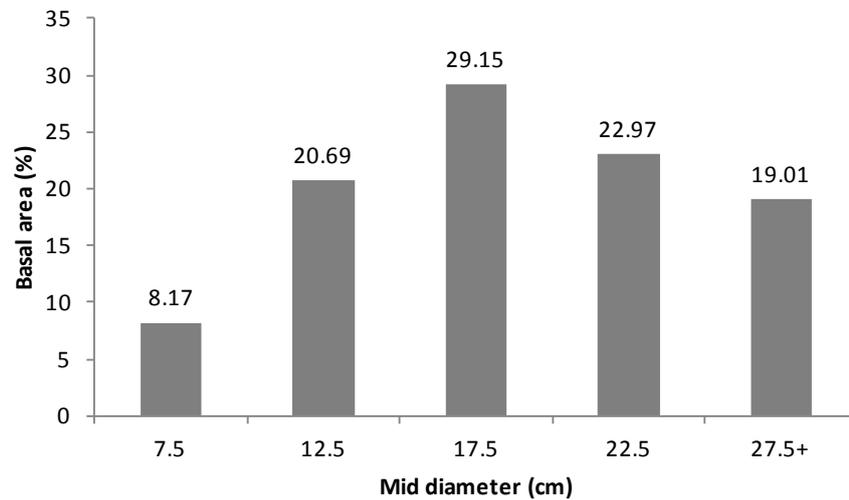


Figure 4. Percent basal area distribution for each diameter class in mecrusse woodlands in the study area.

Table 7. Percentage of total error (as variance) attributed to each sampling phase.

Tree component	Percentage of total variance attributed to the first phase	Percentage of total variance attributed to the second phase
Belowground	80	20
Stem wood	89	11
Stem bark	54	46
Crown	50	50
Total tree	90	10

Table 8. Biomass stocks and 95% confidence limits.

Tree component	Biomass stock (Mg·ha ⁻¹)	95% Confidence limit (Mg·ha ⁻¹)	95% Confidence limit (%)
Belowground	32.60	±3.31	±10.16
Stem wood	84.79	±8.16	±9.63
Stem bark	9.77	±1.20	±12.26
Crown	39.90	±5.14	±12.88
Total tree	167.05	±16.03	±9.60

Table 9. Carbon stocks and 95% confidence limits.

Tree component	Carbon stock (Mg·ha ⁻¹)	95% Confidence limit (Mg·ha ⁻¹)	95% Confidence limit (%)
Belowground	17.32	±1.76	±10.16
Stem wood	41.58	±4.00	±9.63
Stem bark	4.41	±0.54	±12.26
Crown	19.42	±2.50	±12.88
Total tree	82.73	±7.94	±9.60

Table 10. Percent contribution of the error of each variable to error of the first sampling phase.

Source of error	Percent contribution to the error
DBH measurement	62.1
Total tree height estimation	37.88
Plot variability	0.02

Table 11. Percent contribution of the error of each variable to the error of the second sampling phase.

Tree component	Source of error	Contribution to the total error (%)
Belowground	Measurement of the fresh weight of the lateral roots	41.40
	Measurement of the fresh weight of the taproot	56.02
	Determination of MC of the lateral roots	0.99
	Determination of MC of the taproot	1.58
Stem wood	DBH measurement	66.27
	Total height measurement	20.04
	Stem wood basic density estimation	13.70
Stem bark	DBH measurement	12.92
	Total height measurement	3.91
	Stem basic density estimation	40.58
	Stem wood basic density estimation	42.59
Crown	Measurement of the fresh weight of the branches	81.87
	Measurement of the fresh weight of the foliage	10.46
	Determination of MC of the branches	5.10
	Determination of MC of the foliage	2.57
Whole tree	Measurement of the fresh weight of the lateral roots	8.3E-04
	Measurement of the fresh weight of the taproot	1.1E-03
	Determination of MC of lateral roots	2.0E-05
	Determination of MC of taproot	3.2E-05
	DBH measurement	66.11
	Total height measurement	19.99
	Stem basic density estimation	13.89
	Measurement of the fresh weight of the branches	1.8E-03
	Measurement of the fresh weight of the foliage	2.3E-04
	Determination of MC of branches	1.1E-04
	Determination of MC of foliage	5.6E-05

the lower estimates for biomass and carbon compared to our estimates for mecrusse woodlands (1237 ha⁻¹ and 22 m²·ha⁻¹, respectively). Aboveground biomass estimates by [Brown \(1997\)](#) at the national scale indicated actual and potential biomass stock of 56 and 96 Mg·ha⁻¹, respectively. However, [Saatchi et al. \(2011\)](#) estimated aboveground biomass densities from 51 to 75 Mg·ha⁻¹ for the region in which our study was located. This lower estimate is presumably a result of consideration of other vegetation types (e.g. savannah and thicket) associated

with mecrusse woodlands by Saatchi et al. (2011). Lower values for biomass and carbon stock than those estimated here were also reported in neighbouring countries (Malimbwi et al., 1994; Munishi et al., 2010).

The default value for carbon content used by the Intergovernmental Panel on Climate Change is 50% (IPCC, 2003). We compared our measured values with those calculated with this default value and found only slight differences in the estimates (Table 12). However, although the differences were small, these errors would propagate as estimates are scaled up, for example to the stand or forest level.

4.2. Error Propagation

The high level of precision in our biomass estimates was a result of the homogeneity of the tree species and site characteristics (*A. johnsonii* is the only canopy species in mecrusse forest). Stellingwerf (1994) suggested that the 95% CI should not exceed $\pm 20\%$ of the mean. Brown et al. (1995) reported a total error of 20% for above-ground biomass estimates for Amazonian forests, and this level of precision was considered acceptable. Our 95% CI for estimates of whole tree biomass stock was $\pm 9.6\%$, which was well within these accepted limits.

We showed that the relatively higher error for stem bark and crown biomass stocks was largely a result of the error in the allometric equations, which were relatively poor models for estimating biomass. These models were poor, presumably because of variation in crown weight among trees with the same DBH and height, which might have been caused by differences in stand density, crown shape, and density of branch wood (Pardé, 1980; Carvalho & Parresol, 2003), and by variation in stem bark density within and between trees.

Because the overall error was largely attributed to plot selection, the total error could be reduced by increasing the number of sampling plots.

In contrast to our findings, we expected the error due to allometric equations to be larger than that due to sample plot selection, because destructive measurement (phase two) is labour demanding and time consuming and, therefore, more susceptible to errors. However, according to the definition of large sample size suggested by Husch et al. (2003), Stellingwerf (1994), Freese (1962, 1984) and Stauffer (1983), in which the number of replicates should be >30 , our sample for the phase-two measurements ($n = 93$) was large, which led to lower variance. In contrast, our phase-one sample size ($n = 23$) might be considered small, yielding relatively large variance values.

Field studies that estimate biomass generally perform destructive sampling on a relatively small number of trees (even in multi-species tropical forests), especially when the roots are included, which leads to higher variance (error) of the second phase. Salis et al. (2006) destructively sampled 10 trees per species to estimate aboveground biomass and obtained wider confidence intervals than the suggested by Stellingwerf (1994). Wang (2006) and Dias et al. (2006) used sample sizes of 10 and 15 trees per species, respectively, which might not have been sufficient to represent all sources of variation. Malimbwi et al. (1994) performed destructive sampling of 17 trees from 15 species in 10 sample plots in miombo woodland at Kitulungalo Forest Reserve, Tanzania, and obtained a total percent error of 36% for biomass stock. That study examined approximately one tree per species, which (combined with the small number of plots) might have contributed strongly to the large total error.

Samalca (2007) estimated aboveground biomass for a multi-species forest in Indonesia using 143 plots (0.05 ha each, first phase) and destructive sampling of 40 trees (second phase), and found that $>60\%$ of total error was

Table 12. Comparison of carbon stock estimates using values estimated with TruSpec Micro analyser (this study) and the IPCC default value (carbon content = 50% of biomass) (IPCC, 2003).

Tree component	Carbon stock (Mg·ha ⁻¹)		
	This study	IPCC default	Difference (%)
Belowground	17.32	16.30	-6.28
Stem wood	41.58	42.39	1.92
Stem bark	4.41	4.88	9.70
Crown	19.42	19.95	2.66
Whole tree	82.73	83.52	0.95

attributed to allometric equations (second phase). The total variance was attributed to the second phase, where the sample size was relatively small considering the multi-species forest (Samalca 2007). Chave et al. (2004) and Molto et al. (2012), using Monte Carlo and Bayesian error propagation approaches, respectively, also found that the most important source of error in biomass estimates for tropical forest was related to allometric equations, in contrast to our findings.

We expected the contribution of DBH measurement error, in both the first and second phase, to be smaller than that of total tree height measurement/estimation as found by some authors (Schmid-Haas et al., 1981; Gertner & Köhl, 1992; Berger et al., 2014), since DBH is easily and directly measured and thus less susceptible to measurement error than tree height (Loetsch et al., 1973; Machado & Filho 2006; Sanquetta et al., 2006). The largest contribution of DBH measurement error to the total error of both phases is explained by the higher variability of DBHs compared to total tree height (Table 13). Table 13 shows that the variability (CV) of DBH is, approximately, twice as large as the variability of the total tree height in both phases. Moreover, the quadratic term for DBH in Equations (2), (17), and (18) caused its error to propagate disproportionately (quadratically) to that of the height.

The larger error in height measurements for the first sampling phase compared to the second phase occurred because tree height was measured directly using a tape in the second phase, while height was estimated using a Vertex IV hypsometer in the first phase. In the first phase, the measurements were more susceptible to instrument error, error inherent to the trees, and error caused by the distance between the instrument and the tree.

The relatively higher total percent error for stem bark and crown biomass stock originating in the allometric equations might have been a result of variation in crown weight among trees with the same DBH and height. When the contribution of branches and foliage to error are removed (Table 11), variation in crown weight was seen to be influenced by error in fresh weight of branches, which in turn was a result of variation in branch weight within and between trees. This finding is consistent with findings of Pardé (1980). The higher error for stem bark in the allometric equations was caused by variations in density.

5. Conclusion

The total tree biomass stock was 167 Mg·ha⁻¹ of which, approximately, 134 Mg·ha⁻¹ was aboveground biomass. Our measurements showed that more than half of the forest biomass and carbon stocks in mecrusse woodlands were contained in stem wood of trees that were 15 - 25 cm in diameter. The total error of our total tree biomass estimate was very low (<5%), which indicated that the two-phase sampling approach and sample size were effective for capturing and predicting biomass of this forest type. Sources of measurement error included the sample plot selection (first phase) and the allometric models (second phase). Measurement errors of DBH and errors in estimates of total height and mean stem density contributed strongly to the total error.

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Table 13. Descriptive statistics of DBH and total tree height for both phases.

Statistics	Phase-1		Phase-2	
	DBH (cm)	Tree height (cm)	DBH (cm)	Tree height (m)
Average	13.41	10.56	17.59	12.32
Minimum	5.00	1.80	5.00	5.69
Maximum	50.00	22.50	32.00	16.00
Variance	39.54	7.64	56.43	4.57
SD	6.29	2.76	7.51	2.14
CV (%)	46.89	26.17	42.72	17.35

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