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Original Research Article

Allometric models for managing lowland miombo woodlands of the Beira corridor in Mozambique

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ABSTRACT

Appropriate allometric models are urgently needed to assess the status and changes in biomass and carbon of the trees in miombo woodlands occupying large geographical areas in Mozambique. This study developed two new and interchangeable allometric models for estimating total above-ground biomass (AGB) of lowland miombo woodlands in the Beira corridor, central Mozambique, based on stem diameter at breast height (DBH) and stump diameter (SDI). The Beira corridor study area covers approximately 29,000 km^2, of which about three-quarters is lowland miombo woodland. The SDI-based model is proposed principally for estimating total AGB (stem, branches, foliage) of harvested trees/shrubs when diameter cannot be measured at breast height, and thus to reconstruct the former biomass in forests subjected to logging, or clear-cutting for agriculture.

The DBH-based model and SDI-based model were fitted using data on a destructive sample of 155 trees, which were representative of tree sizes (diameter and height) and tree species in the Beira corridor area. The following allometric models were developed: DBH-based model [$tDW\ (kg\ tree^{-1}) = 0.1754 * (DBH)^{2.3238}$], with prediction performance, *i.e.* adjusted R-squared 98–99%; and SDI-based model [$tDW\ (kg\ tree^{-1}) = 0.08495 * (SDI)^{2.3987}$], with prediction performance 86–96%. Carbon comprises 50% of biomass. Both the DBH- and SDI-based models can be used for estimating total AGB of lowland miombo woodlands with a high degree of reliability, based on field inventory within the Beira corridor region. Evaluation of the mathematical and statistical credibility of these models, which was carried out on the construction dataset (verification procedure) and independent dataset (validation procedure), gave satisfactory results. Moreover, when applied on our data, these models were more appropriate for the Beira corridor than allometric models found in the literature. However, application of both models should be restricted to the lowland miombo type in the Beira corridor, not mountain miombo.

1. Introduction

There is a strong need for appropriate allometric models to assess the status and changes in biomass and carbon of trees in the miombo woodlands that cover large geographical areas in Mozambique. Allometric models are needed for many applications, including to assess the impacts of forest restoration initiatives or wood exploitation on total above-ground biomass

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(AGB) stocks. Total AGB here includes stem, branches and foliage of trees and shrubs. Estimating total AGB is the most critical step in quantifying total above-ground carbon stocks and carbon changes in forests (Gibbs et al., 2007). Moreover, AGB is a critical carbon pool in implementation of emerging carbon credit market mechanisms such as Reducing Emissions from Deforestation and Forest Degradation (Mugasha et al., 2013). Appropriate allometric models are also needed to improve the reliability of estimations of total AGB by remote sensing and to allow mapping, monitoring, reporting, and verification of forest biomass in a rapid, consistent, and accurate way (Vashum and Jayakumar, 2012, Barbosa et al., 2014; Gofc-Gold, 2015; Scott et al., 2015).

Miombo is the most extensive seasonal deciduous tropical woodland and dry forest formation in Africa (Campbell et al., 1996; Kutsch et al., 2011; Chidumayo, 2013; Jew et al., 2016). Miombo is also the most widespread forest type in the Beira corridor region (study area) and in Mozambique in general (Wild and Grandvaux Barbosa, 1967; Marzoli, 2007). In the Beira corridor, in central Mozambique, miombo woodland comprises around 75% of the total forest cover. Despite its significant importance in ecological and socioeconomic terms (*e.g.,* habitat for wildlife, climate regulation, ecotourism, and provisioning of timber and non-timber forest products), in recent decades overexploitation of miombo in Mozambique and similar Africa countries has caused deforestation or forest degradation (DFD) and loss of ecosystem services at high rates (Campbell et al., 2007; Ciais et al., 2011; Sitoe et al., 2012; Jew et al., 2016).

According to Ceagre & Winrock-International (2016), between 2000 and 2012 about 138,000 ha of forest were lost annually in Mozambique. According to that study, DFD was responsible for approximately 4.4 million tons of carbon being released per year to the atmosphere, of which nearly 80% came from miombo woodlands. A large proportion (>75%) of the DFD in Mozambique is directly caused by agricultural practises and expansion (mainly shifting cultivation), wood fuel production (charcoal), and logging (especially illegal activities), often acting in combination (Ceagre & Winrock-International, 2016).

The Beira corridor region, otherwise known as Beira development corridor, is more strongly threatened by DFD than other development corridors within Mozambique. As defined by the Mozambique Development Strategy (RdM, 2014), development corridors are large geographical areas where integrated activities are carried out to promote local development. Four development corridors (Beira, Nacala, Limpopo, and Maputo) have been defined at national level. Development activities include forestry, agriculture, tourism, fisheries, and mining, among others, to achieve social, economic, and environmental goals. The rate of DFD in the Beira corridor region (0.36% per year) is 57% higher than the mean rate for the whole country (0.23% per year) and is 112% higher than the rate estimated for all four development corridors in Mozambique (0.17% per year) (Ceagre & Winrock-International, 2016).

Some degraded miombo sites and other wooded areas will need active interventions to recover, *e.g.,* the production capacity of goods and to help tackle climate change. A number of ways to counteract DFD in tropical forests are suggested in the literature (Lamb and Gilmour, 2003; Griscom et al., 2009; Minag, 2009; Fao, 2010; Lamb, 2011; Unep, 2014; Ceagre & Winrock-International, 2016; Mitader, 2016). In the forest sector, mitigation actions with great potential to slow down DFD have been recognized in Mozambique, particularly under the national strategy for reducing emissions from deforestation and forest degradation (Mitader, 2016) and the national reforestation strategy (Minag, 2009). These strategies are in line with *e.g.,* the UN Convention on Climate Change (Un, 1992b) and the UN Convention on Biodiversity (Un, 1992a). Such mitigation actions include restoration of degraded forests to enhance carbon stocks and sequestration capacity, and to assist the recovery of biological diversity. Forest restoration in Mozambique needs to be implemented taking into account the concept of development corridors.

Allometric models for miombo woodlands that meet the need to accurately measure and monitor the impacts of forest restoration on total AGB stocks and changes in large geographical areas are needed in Mozambique. Such models should comply with the good practise guidance for biomass and carbon inventory provided by the International Panel on Climate Change (Ipcc, 2006) and should also be reliable tools for assessing the impacts of wood exploitation on total AGB. Some allometric models have recently been developed for mangrove forests (Sitoe et al., 2014) and mecrusse woodlands (Magalhães, 2015) in Mozambique, but these models are not suitable for miombo woodlands. In addition, species-specific biomass equations have been developed for four different miombo tree species in central Mozambique (Mate et al., 2014), but these models are not suitable for predicting biomass of mixed-species miombo woodlands. Ryan et al. (2011) developed a set of three mixed-species equations for miombo woodlands based on studies in the Nhambita community in Sofala province, which is near our study area. However, those allometric models are intended to directly estimate stem carbon, tree coarse root carbon, and above- and belowground carbon stocks (stem + roots), not total AGB as defined in this study, *i.e.,* stem + branches + foliage. Another limiting factor with the set of allometric models developed by Ryan et al. (2011) is the small geographical area sampled (~0.3 km^2), which is unlikely to include the regional variation in our study area (~29,000 km^2) in terms of physiognomic structure and tree species composition.

In this study, we developed two new interchangeable allometric models for estimating total AGB in lowland miombo woodlands in the Beira corridor region, based on stem diameter at breast height (DBH) and stump diameter (SDI). The models were designed for application to a mixture of miombo tree species in a large geographical area and for inventories of forest biomass and carbon in both standing forest (live trees) and in trees removed by logging. The SDI-based model is designed principally for estimating total AGB of harvested trees/shrubs when diameter cannot be measured at breast height, and thus for reconstructing the former biomass and carbon stocks.

2. Materials and methods

2.1. Study area

The study area is the Beira corridor region, located in the provinces of Manica and Sofala in central Mozambique (Fig. 1). The study area comprises approximately 29,000 km^2 and is represented by six districts/sites: Dondo, Nhamatanda, Gondola, Sussundenga, Manica, and Báruè (Fig. 1).

The sampled area lies in low altitude areas of the Beira corridor, at <1100 m above sea level (a.s.l.) and mostly between ~54 and 723 m a.s.l. (Table 1). The mean annual temperature range of the Beira corridor study area is 21–25 °C and the mean annual rainfall range is 847–1569 mm (Climate-Data.Org, 2016). According to the Köppen-Geiger climate classification (Peel et al., 2007), the region's climate ranges from tropical savannah (Aw) in Dondo and Nhamatanda districts to humid sub-tropical (Cwa) with dry winters and warm summers in Báruè, Gondola, Sussundenga, and Manica districts (Table 1).

Lowland miombo woodland is the dominant forest cover type in the Beira corridor region, covering about 21,500 km^2 (Fig. 1). It is characterized by a canopy cover of 10–60% dominated by tree species of the Leguminosae family, including *Brachystegia spiciformis* Benth. and *Julbernardia globiflora* (Benth.) Troupin. Total height of the dominant miombo tree species generally falls within the range 10–15 m (Sitoe, 2005, 2009), but with some large trees reaching about 25 m height (Mate et al., 2014). Fig. 2 gives an overview of the lowland miombo woodland in the Beira corridor. More information about the composition and structure of miombo woodlands in central Mozambique, including the Beira corridor study area, can be found in Sitoe (1999, 2005), Cuambe and Marzoli (2006), Mate et al. (2014), and Wild and Grandvaux Barbosa (1967).

2.2. Field and laboratory work

Forest inventory data from previous studies (Sitoe et al., 2001; Cuambe and Marzoli, 2006; Filipe, 2008; Sitoe, 2009; Mavie, 2012) were used to determine tree sizes (*i.e.*, DBH and total height) and species in the study area, in order to guide the sampling of biomass. In destructive sampling for biomass determination, a total of 187 trees were included (Table 2). Of these,

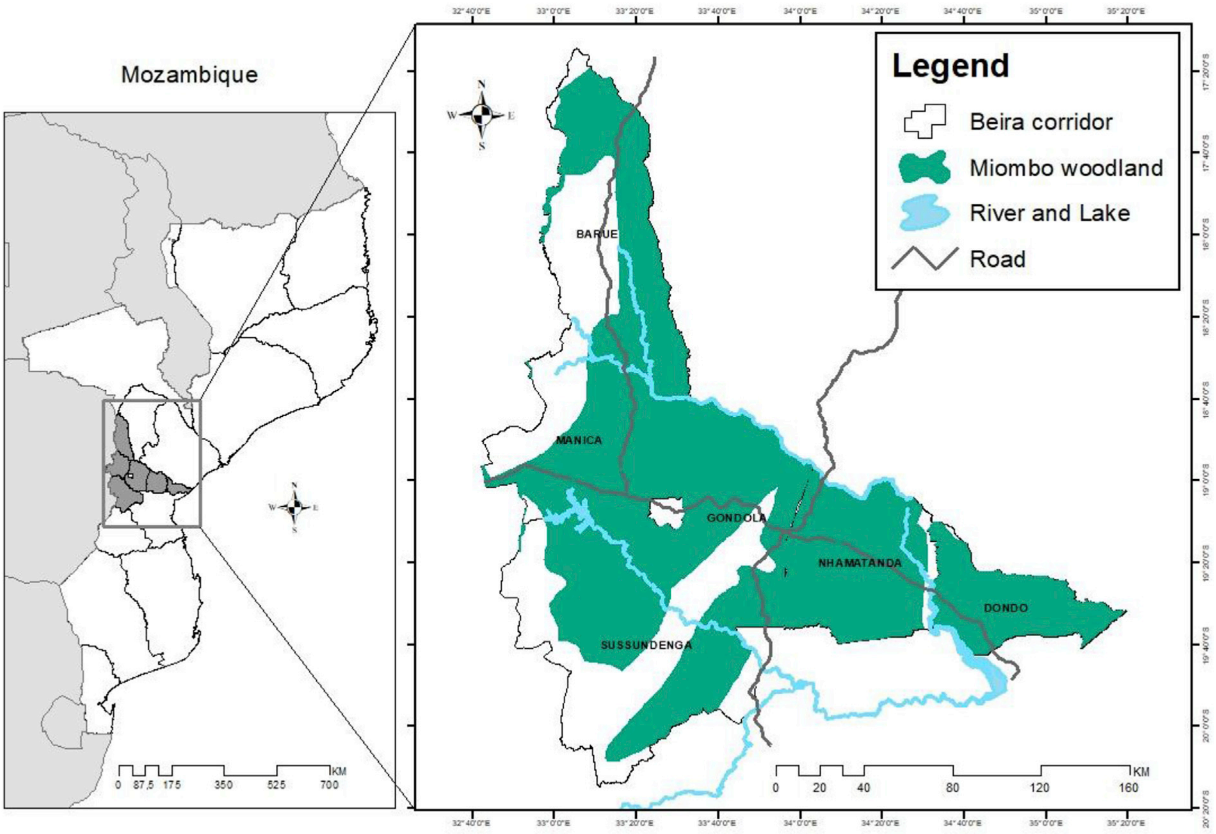

Fig. 1. Location of the Beira corridor study area in central Mozambique and (insert) map showing the distribution of lowland miombo woodland across the study sites: Dondo and Nhamatanda districts (both in Sofala province in the east) and Gondola, Sussundenga, Manica, and Báruè districts (all in Manica province to the west) (Map: Lisboa Sa Nogueira).

Table 1
Selected climate data for the Beira corridor study area in central Mozambique. According to the Köppen-Geiger climate classification system, Aw denotes a tropical savannah climate, while Cwa indicates a humid subtropical climate with dry winters and warm summers. Data from Climate-Data.Org (2016), except for Báruè, which are from Sitoe (1999).

District/Site	Province	Average altitude (m a.s.l.)	Mean annual rainfall (mm yr^{-1})	Temperature range (°C)[a]	Climate type
Manica	Manica	723	1036	14.3–28.1	Cwa
Gondola	Manica	616	1215	15.8–28.0	Cwa
Báruè[b]	Manica	600	1591	15.8–28.9	Cwa
Sussundenga	Manica	594	1112	15.4–27.7	Cwa
Nhamatanda	Sofala	69	944	18.0–31.6	Aw
Dondo	Sofala	54	1243	19.6–29.7	Aw

[a] Mean values of minimum-maximum temperature throughout the year.
[b] Data from a weather station in Catandica, the main town in Báruè district.

Fig. 2. Inside a lowland miombo woodland in the Beira corridor study area, within the provinces of Manica and Sofala, central Mozambique (Photos: Almeida Sitoe).

Table 2
Selected attributes of sample trees taken for construction of the allometric models for the Beira corridor region, central Mozambique. The abbreviation DBH means stem diameter at breast height measured at 1.3 m, SDI is stump diameter measured at 30 cm above the ground.

Parameter	Description
DBH range (cm)	5–53
SDI range (cm)	6–58
Total height range (m)	3–26
Construction dataset (number of trees)	155
Validation dataset (number of trees)	32
Total number of sampled trees	187

155 were used as the construction dataset and the remaining 32 as the validation dataset, *i.e.*, an independent dataset to measure the fit between observed and predicted total dry weight. The independent dataset was extracted, randomly and without replacement, from the total number of trees sampled. A summary of the attributes of the sampled trees is given in Table 2.

The sampled trees were randomly selected across the six study sites to cover the tree size range and the most dominant woody species of the miombo woodland within study area, particularly *Brachystegia spiciformis*, *B. allenii*, *B. boehmii*, *Julbernardia globiflora* and their accompanying species, such as *Pericopsis angolensis*, *Pterocarpus angolensis*, *Burkea africana*, *Millettia stuhlmannii*, *Combretum apiculatum*, *Pseudolachnostylis maprouneifolia*, *Pteleopsis myrtifolia*, *Diplorhynchus condylocarpon*, and *Uapaca kirkiana*. Tree density in the entire Beira corridor region varies between approximately 69 and 328 stems ha^{-1} and basal area varies between 5 and 12 m^2 ha^{-1} (Sitoe, 2005, 2009; Mate et al., 2014).

A diameter tape and a conventional measuring tape were used to measure the diameter (*i.e.*, DBH and SDI) and total height of all sampled trees, respectively. Tree diameter was measured over bark, at 1.3 m on the trunk, for DBH and at 30 cm above the soil surface for SDI. Total tree height was measured after the trees were cut down. For multi-stemmed trees with the fork below 1.3 m, each stem having the required DBH (≥5 cm) was considered as a separate tree and therefore measured (Fao, 2009). In the field, each sampled tree was then split essentially into two compartments (stem and branches + foliage) and fresh weight of each compartment was determined immediately using a mechanical weighing scale (precision 100 g).

One sub-sample (200–1000 g) of each compartment of individual trees was collected, fresh weight was recorded while still in the field, and the sub-samples were oven-dried in the laboratory (~85 °C) to constant weight. Fresh and dry weight of each sub-sample were recorded using a digital weighing scale (precision 0.5 g). Dry to fresh weight ratio of the sub-sample of each compartment was used to determine the dry weight of each compartment of a tree. The dry weight of the two compartments (stem and branches + foliage) was added together to give the total above-ground dry weight of individual trees.

2.3. Construction of the allometric models

Pearson product-moment correlation (r) analysis was used to evaluate the relationship between DBH and SDI, since we were interested in using both diameters as interchangeable dimensions to predict total AGB. Five general forms of biomass equations (Equations (1)–(5)) were tested in this study. Total height (TH) in Equations (3) and (4) was tested only in combination with DBH, not with SDI, considering that TH and DBH are useful predicting variables for applications involving live trees (standing forest) where the dimensions can be measured:

$$tDW = \beta_0 * \O^{\beta_1} \tag{1}$$

$$\ln(tDW) = \ln(\beta_0) + \beta_1 \ln(\O) + \ln(\varepsilon) \tag{2}$$

$$tDW = \beta_0 * (\O * \mathrm{HT})^{\beta_1} \tag{3}$$

$$tDW = \beta_0 * \left(\O^2 * \mathrm{HT}\right)^{\beta_1} \tag{4}$$

$$tDW = \beta_0 * Exp(\beta_1 * \O) \tag{5}$$

where tDW (kg tree^{-1}) is total above-ground dry weight (stem and branches + foliage) of individually weighed trees; Ø is either DBH (Table 4) or SDI (Table 5), thus depending on the model fitted, β_0 and β_1 are regression coefficients, and ε is a random error. The term ε is a multiplicative error after back-transformation of the regression error in Equation (2), given that the variance of tDW was not independent of SDI in this study (Baskerville, 1972).

The DBH-based model and SDI-based model which showed the lowest value of residual standard error (RSE) and Akaike's information criterion (AIC) (Chave et al., 2005; Sitoe et al., 2014; Mugasha et al., 2016) were chosen. The DBH-based model was fitted using the non-linear least squares approach in the 'nlstools' package (Baty et al., 2015). Due to the need to reduce heteroscedasticity, the SDI-based equation was fitted using log-transformed linear regression, followed by back-transformation of the fitted model. Values were back-transformed by applying a correction factor calculated according to Baskerville (1972), using the following equation:

$$CF = Exp\left(\frac{RSE^2}{2}\right) \tag{6}$$

where CF is correction factor and RSE is residual standard error (*i.e.,* 0.159; Table 5). Construction of the models, including all testing and calculations, was conducted using R software, version 3.1.2 (Rcoreteam, 2014).

Table 3
Allometric biomass equations selected from the literature based on stem diameter at breast height (DBH) (ID no. 1–5) and based on stump diameter (SDI) (ID no. 6), and used in comparisons to assess the predictive accuracy of the DBH- and SDI-based equations developed in this study. The variable tDW (kg tree^{-1}) denotes total above-ground dry weight of each individually weighed tree.

ID no.	Source	Biomass equation	DBH (cm)	Sampled trees	Forest type
1	Mugasha et al. (2013)	$tDW = 0.1027*(DBH)^{2.4798}$	1–110	167	Miombo
2	Chidumayo (2013)	$tDW = 0.0446*(DBH)^{2.765}$	2–39	101	Miombo
3	Kachamba et al. (2016)	$tDW = 0.2169*(DBH)^{2.3184}$	5–111	74	Miombo
4	Chamshama et al. (2004)	$tDW = 0.0625*(DBH)^{2.553}$	1–50	30	Miombo
5	Brown (1997)	tDW = Exp(-1.996 + 2.32*ln(DBH))	5–40	28	Dry forest
6	Chamshama et al. (2004)	$tDW = 0.018*(SDI)^{2.839}$	2–57[a]	30	Miombo

[a] Denotes SDI for that specific biomass equation, not DBH as in ID no. 1–5.

Table 4
Parameters estimated and statistics of the regression functions tested that predict total above-ground dry weight (tDW) based on diameter at breast height (DBH) and based on both DBH and total height (HT). The power regression function based on DBH alone fitted better to the data and was therefore selected in the subsequent analysis. The abbreviation AIC indicates Akaike's information criterion, RSE is residual standard error, and β0 and β1 are regression coefficients.

Parameter	Form of biomass equations tested			
	tDW = β0* (DBH)$^{\beta 1}$ [a]	tDW = β0* (DBH^2*HT)$^{\beta 1}$	tDW = β0*Exp (β1*DBH)	tDW = β0* (DBH*HT)$^{\beta 1}$
RSE	30	64	70	96
AIC	1493	1733	1761	1859
β0	0.1754●●●	0.0599●●●	46.8982●●●	0.0563●●
95% Conf. Inter. of β0	(0.1483–0.2069)	(0.0378–0.0933)	(42.1884–51.8979)	(0.0274–0.1103)
β1	2.3238●●●	0.9512●●●	0.0715●●●	1.4974●●●
95% Conf. Inter. of β1	(2.2788–2.3696)	(0.9070–0.9972)	(0.0691–0.0740)	(1.3914–1.6101)

●●●P < 0.001.
●●P < 0.01.
[a] Equation selected for further analyses.

Table 5
Parameters estimated and statistics of the regression functions tested to predict total dry weight (tDW) based on stump diameter (SDI) measurements. The power regression function written in logarithmic form fitted better to the data and was therefore selected in the subsequent analysis. The abbreviation AIC indicates Akaike's information criterion, RSE is residual standard error, and β0 and β1 are regression coefficients.

Parameter	Form of biomass equations tested		
	ln(tDW) = ln(β0) + β1*ln(SDI) + ln(ε)[a]	tDW = β0*(SDI)$^{\beta 1}$	tDW = β0*Exp(β1*SDI)
RSE	0.159	102	133
AIC	−124	1905	1960
β0	0.08495●●●	0.1996●●	48.0975●●●
95% Conf. Inter. of β0	(0.0622–0.1161)	(0.1023–0.3723)	(38.7238–58.6493)
β1	2.3987●●●	2.1705●●●	0.05893●●●
95% Conf. Inter. of β1	(2.2929–2.5044)	(2.0059–2.3461)	(0.0547–0.0634)

●●●P < 0.001.
●●P < 0.01.
[a] Equation selected for further analyses.

2.4. Evaluation of the adequacy of the fitted biomass equations

The predictive accuracy of the DBH-based model and SDI-based model developed in this study was evaluated using both the construction dataset (verification procedure) and the independent dataset (validation procedure). It included checking three assumptions of linear regression and calculation of root mean squared deviation (RMSD). The three assumptions of linear regression were: i) homoscedasticity (constant variance) between observed and estimated total above-ground dry weight (residuals), using the Bartlett test of homogeneity of variance; ii) normality of the residual distribution, using the Shapiro-Wilks normality test; and iii) linearity of the relationship between observed and estimated total above-ground dry weight, using the *t*-test ($\alpha = 0.05$). RMSD was calculated using the following equation, which represents the mean deviation of predicted values with respect to observed (Piñeiro et al., 2008):

$$\mathrm{RMSD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(tDW_{obs,i} - tDW_{est,i}\right)^2} \tag{7}$$

where tDWobs,i and tDWest,i (kg tree^{-1}) are observed and estimated total above-ground dry weight of individually weighed tree i, respectively, and n is total number of trees.

Moreover, as part of evaluating the adequacy of the DBH- and SDI-based models, we compared the predictive accuracy of these models with that of allometric models mainly taken from the miombo literature (Table 3). Six relevant models were tested by applying them on our data, namely five DBH-based models suggested by various authors (Brown, 1997; Chamshama et al., 2004; Chidumayo, 2013; Mugasha et al., 2013; Kachamba et al., 2016), and one SDI-based model reported in Chamshama et al. (2004). To compare the predictive accuracy of these models, we computed three statistics (Equations (8)–(10)): mean absolute error (Willmott and Matsuura, 2005), mean prediction error, and relative mean prediction error (Kachamba et al., 2016).

$$MAE = \frac{\sum_{i=1}^{n}\left|tDW_{obs,i} - tDW_{est,i}\right|}{n} \tag{8}$$

$$MPE = \sum_{i=1}^{n} \frac{(tDW_{obs,i} - tDW_{est,i})}{n} \tag{9}$$

$$RMPE = \sum_{i=1}^{n} \frac{MPE}{\bar{y}} \tag{10}$$

where MAE (kg tree^{-1}) is mean absolute error, MPE (kg tree^{-1}) is mean prediction error, RMPE (%) is relative mean prediction error, and $\bar{y}$ is mean observed dry weight.

3. Results

3.1. Allometric models developed

The SDI and DBH values recorded were positively ($r = 97\%$) and strongly correlated to each other ($t = 52.4$, $P < 0.0001$) (Fig. 3). These two dimensions were also statistically significant predictors of total above-ground dry weight ($P < 0.01$ in both cases; Tables 4 and 5). The results confirmed that SDI and DBH can be used as interchangeable dimensions to predict total AGB in lowland miombo woodland in the Beira corridor study area. For DBH and SDI, the model in Equation (1) and Equation (2), respectively, showed a better fit to observed dry weight data, since it had the lowest residual standard error (RSE) and AIC value. The model in Equation (1) (see also Table 4) and the model in Equation (2) (see also Table 5) were therefore selected in subsequent analyses. The inclusion of total height (Equations (3) and (4)) in the modelling as a second predicting variable of total above-ground dry weight in this study did not improve the predictive accuracy of our model, as shown in Table 4.

3.2. Predictive accuracy of the fitted models

The allometric models fitted explained satisfactorily the relationship between the predicting variables (DBH and SDI) and total above-ground dry weight. This was demonstrated by checks carried out on the construction dataset (verification procedure) and the independent dataset (validation procedure). Both the DBH-based model (Fig. 4) and the SDI-based model (Fig. 5) fulfilled the assumption of linearity.

Thus, the estimated value of total above-ground dry weight was a straight-line function of both DBH and SDI. The proportion of the variance in total above-ground dry weight predicted from the two models was satisfactory (Table 6), as demonstrated by the range of coefficient of determination (adjusted R-squared) of 86–99%. It can therefore be used with an acceptable degree of reliability to estimate total AGB of trees/shrubs of the lowland miombo woodland in the Beira corridor study area. As shown in Fig. 4d–e (DBH-based model) and Fig. 5d–e (SDI-based model), the *t*-test of the slope of the regression line differed significantly from zero and in both cases the 95% confidence interval of the intercept contained zero.

The variance of the residuals of the two allometric models, which was tested by the Bartlett test of homogeneity of variances, can be considered equal (test $P > 0.05$) (Figs. 4b and 5b). Thus, the following results were obtained for the DBH-based model: Bartlett's K-squared = 0.00522, degrees of freedom (df) = 1, P = 0.9424; and for the SDI-based model: Bartlett's K-squared = 0.12804, df = 1, P = 0.7205. The variance of the residuals of the two models was not equal over all observations, which indicates that the assumption of normality of the residuals was violated (Figs. 4c and 5c). This was also

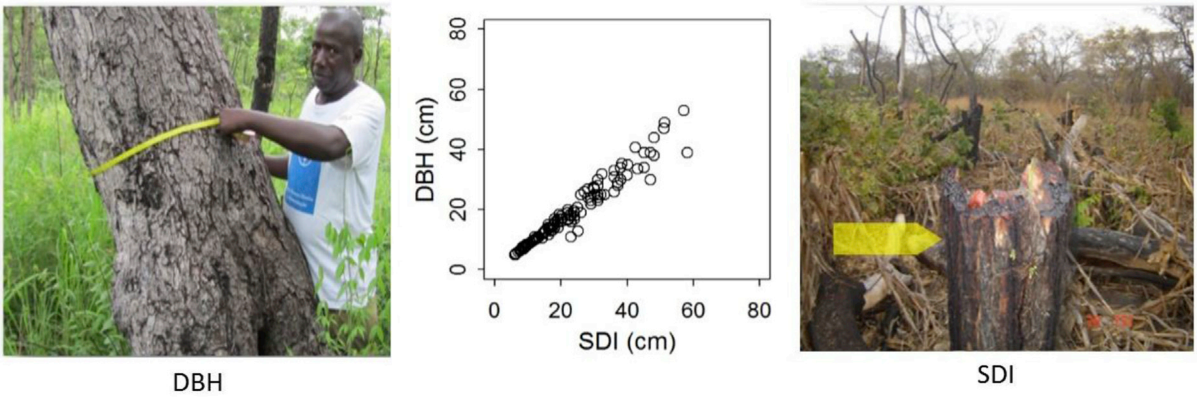

Fig. 3. Scatter plot (center) showing the correlation between diameter at breast height (DBH) and stump diameter (SDI) in lowland miombo woodland in the Beira corridor study area in central Mozambique. Pearson's correlation coefficient (r) = 97%, t = 52.4, P < 0.0001, degrees of freedom 154. Each mark (o) corresponds to an individually measured tree. Photos show the location of measurement of DBH (left) and SDI (right).

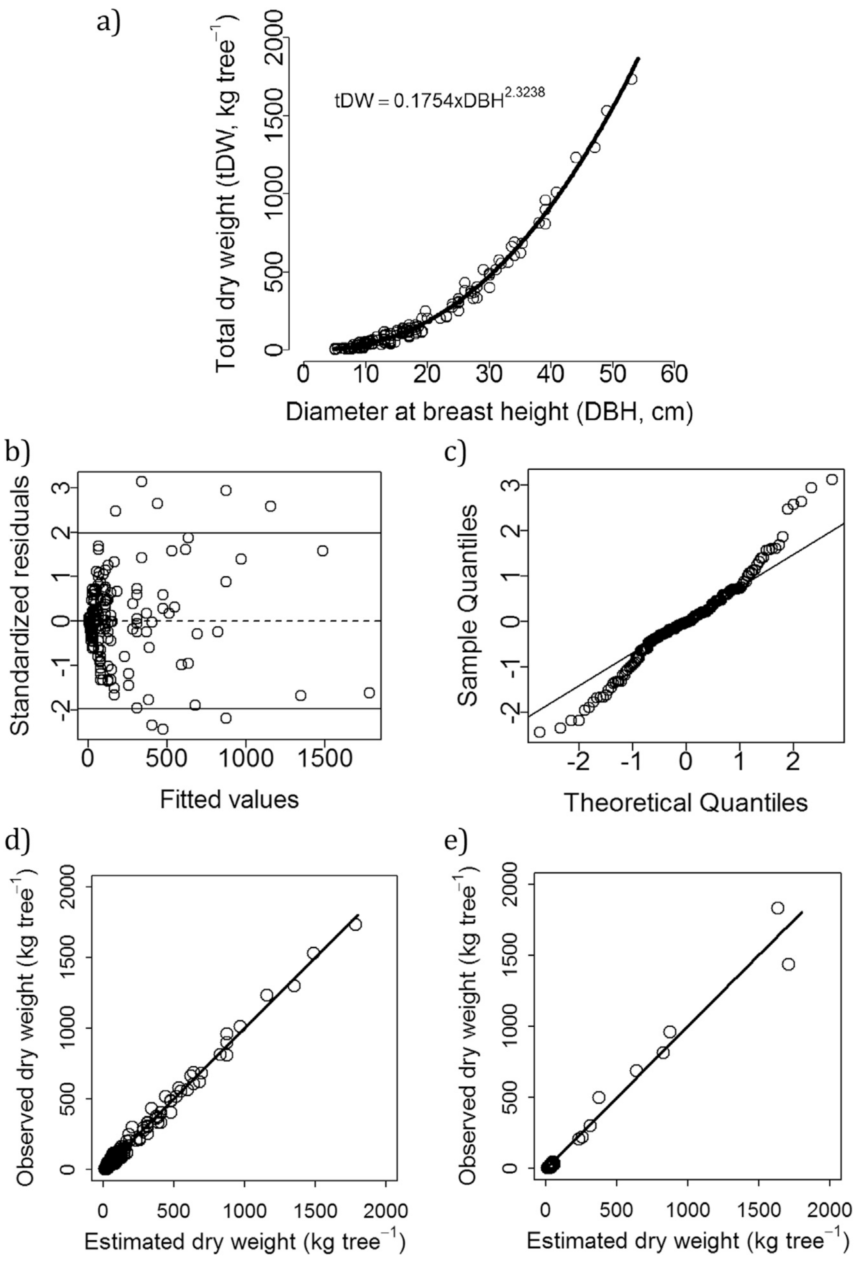

Fig. 4. Evaluation of the predictive accuracy of the diameter at breast height (DBH)-based model for the Beira corridor study area. (a) Relationship between total above-ground dry weight (kg) and DBH; (b) scatter plot of standardized residuals against predicted dry weight plotted using the construction dataset; (c) normal quantile-quantile plot constructed using the construction dataset; (d) relationship between observed and estimated total above-ground dry weight, checked using the construction dataset [where $Y = 1.00X + 0.11$, adjusted R-squared 99%, RSE 30.3 kg, $P < 0.0001$, $t = 120.9$, degrees of freedom 153]; and (e) relationship between observed and estimated total above-ground dry weight, checked using the validation dataset [where $Y = 1.01X - 4.70$, adjusted R-squared 98%, RSE 68.7 kg, $P < 0.0001$, $t = 35.3$, degrees of freedom 30]. Each mark (o) corresponds to total above-ground woody dry weight of an individually weighed tree.

confirmed by the Shapiro-Wilk normality test, which gave $P < 0.001$ and $W = 0.966$ for the DBH-based model and $P < 0.0001$ and $W = 0.644$ for the SDI-based model.

The predictive accuracy of the allometric models developed in this study was compared with that of DBH- and SDI-based models selected from the literature and with observed dry weight using both the construction dataset and the validation dataset. The predictive accuracy of the DBH-based model developed in this study (Table 7) was better than the five tested models, with respect to the three statistics computed (MPE, RMPE, and MAE) when applied on our data. However, the model by Mugasha et al. (2013) (ID no. 1, Table 7) also gave good estimates for the Beira corridor region. The SDI-based model developed in this study predicted dry weight better only with respect to MAE (Table 8). The SDI-model by Chamshama et al.

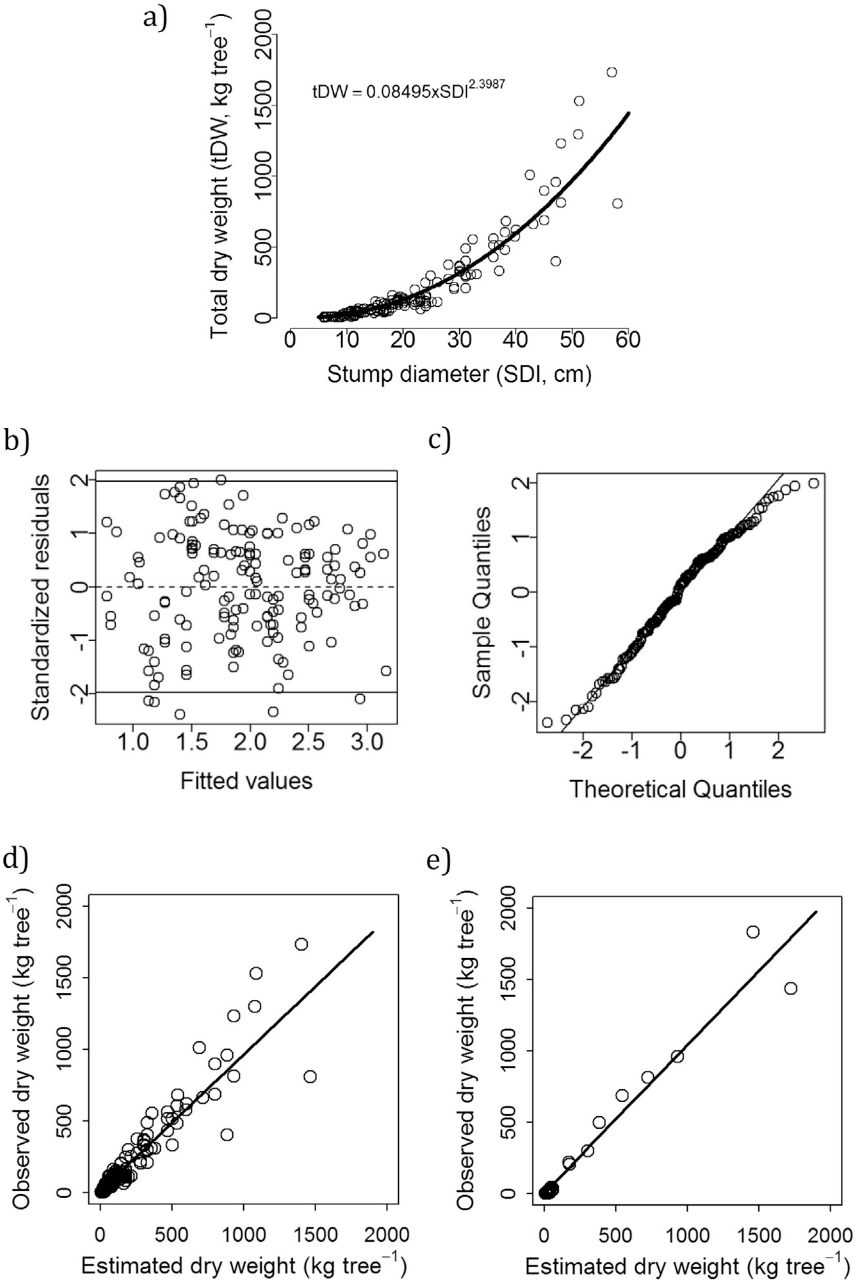

Fig. 5. Evaluation of the predictive accuracy of the stump diameter (SDI)-based model for the Beira corridor study area. (a) Relationship between total above-ground dry weight and SDI, with correction factor (CF) 1.013; (b) scatter plot of standardized residuals against predicted dry weight plotted using the construction dataset; (c) normal quantile-quantile plot constructed using the construction dataset; (d) relationship between observed and estimated total above-ground dry weight, checked using the construction dataset [where $Y = 12.66 + 0.95\times$, adjusted R-squared 86%, RSE 101.6 kg, $P < 0.0001$, $t = 30.1$, degrees of freedom 153]; and (e) relationship between observed and estimated total above-ground dry weight, checked using the validation dataset [where $Y = 2.89 + 1.04X$, adjusted R-squared 96%, RSE 93.5 kg, $P < 0.0001$, $t = 26.1$, degrees of freedom 30]. Each mark (o) corresponds to total above-ground woody dry weight of an individually weighed tree.

Table 6
Summary of the predictive accuracy of the diameter at breast height (DBH)-based and stump diameter (SDI)-based biomass equations proposed for the Beira corridor study area. The values are based on the outputs obtained from the datasets used for construction and for validation of the models.

Descriptive parameter	DBH-based model		SDI-based model	
	Construction dataset	Validation dataset	Construction dataset	Validation dataset
Adjusted R-squared (%)	99	98	86	96
Root mean squared deviation (RMSD; kg tree^{-1})	30.3	68.7	113.9	108.4

Table 7

Predictive accuracy of the diameter at breast height (DBH)-based model developed in this study compared with that of DBH-based models selected from the literature and with observed dry weight using both the construction dataset and the validation dataset. The parameter MPE is mean prediction error, RMPE is relative mean prediction error, and MAE is mean absolute error.

ID no.	DBH-based model	Construction dataset			Validation dataset		
		MPE (Kg tree^{-1})	RMPE (%)	MAE (Kg tree^{-1})	MPE (Kg tree^{-1})	RMPE (%)	MAE (Kg tree^{-1})
–	This study	0.2	0.1	21.8	−3.5	−1.5	6.9
1	Mugasha et al. (2013)	2.6	1.2	24.2	−9.4	−4.0	6.2
2	Chidumayo (2013)	−26.5	−12.7	51.5	−62.7	−27.0	14.9
3	Kachamba et al. (2016)	−42.9	−20.6	49.0	113.1	48.8	24.9
4	Chamshama et al. (2004)	47.9	23	48.8	40.6	17.5	6.9
5	Brown (1997)	49.1	0.1	52.4	52.0	22.4	12.3

Table 8

Predictive accuracy of the stump diameter (SDI)-based model developed in this study compared with that of the SDI-based model found in the literature and with observed dry weight using both the construction dataset and the validation dataset. The parameter MPE is mean prediction error, RMPE is relative mean prediction error, and MAE is mean absolute error.

ID no.	SDI-based model	Construction dataset			Validation dataset		
		MPE (Kg tree^{-1})	RMPE (%)	MAE (Kg tree^{-1})	MPE (Kg tree^{-1})	RMPE (%)	MAE (Kg tree^{-1})
-	This study	2.8	1.4	53.6	28.8	12.4	48.6
6	Chamshama et al. (2004)	2.2	1.0	57.8	10.2	4.4	48.8

(2004) (ID no. 6) also gave good estimates for the Beira corridor study area, especially with respect to MPE and RMPE, when applied on our data.

4. Discussion

It was shown that both the DBH-based model and SDI-based model developed in this study can be used to estimate total AGB (stem and branches + foliage) in lowland miombo woodlands of the Beira corridor study area with a high degree of reliability. The adequacy of these models for the study area was supported by verification procedures and validation carried out using independent destructive sampling data. Comparisons of the predictive accuracy of the two allometric models and that of some models selected from the literature indicated that our models were more accurate (Tables 7 and 8), when applied on our data. However, the findings also revealed that two of the six existing models tested, a DBH-based model suggested by Mugasha et al. (2013) and a SDI-based model discussed in Chamshama et al. (2004), both developed from Tanzanian miombo woodlands, are able to predict total AGB in lowland miombo woodlands of the Beira corridor with minor differences.

4.1. Allometric models developed

In this study, allometric models of the power regression form were selected to predict total AGB stocks in lowland miombo woodlands of the Beira corridor study area, using only DBH or SDI as the predicting variable. Although the models were thus simple in terms of predicting variables, they were able to explain most of the variation in total above-ground dry weight (Table 6). It is known that complex allometric models, *i.e.* models that include more than one dimension as the predicting variable of above-ground biomass and cover aspects of tree shape (diameter and height) and differences in species-specific wood density, tend to predict above-ground tree biomass better than equations that use only stem diameter as the predicting variable. However, adding more dimensions, such as total height and wood density, may not lead to substantial improvements.

The inclusion of total height as a predicting variable of total AGB was tested in this study, but did not lead to substantial improvements in the predictive accuracy of our models (Table 4). This supports findings in previous studies (Brown et al., 1989; Chave et al., 2005; Hofstad, 2005; Kridiborworn et al., 2012; Picard et al., 2015). The inclusion of wood density as a predicting variable was not tested in this study.

Adding wood density (WD) is reported to either improve (Chave et al., 2014) or not improve the performance of allometric models (Paul et al., 2016). However, inclusion of WD may be a limiting variable/factor if it cannot be measured for each individual tree during field inventories, together with other predicting variables included in allometric models. Wood density can vary widely among individual trees within a species and region, as the global wood density database shows (Zanne et al., 2009). In fact, WD can vary depending on a great number of factors, including tree density and environmental factors such climate, soil type, soil humidity, and altitude.

The use of stump diameter (SDI) for predicting total AGB in this study can be questioned, because accurate measurement of diameter at the root collar of trees with buttresses, or other structures such as stilt roots and pneumatophores, is generally difficult. However, this is not a severe problem in the Beira corridor study area. In dry forests, including miombo woodlands

(Blackie et al., 2014), exceptions can arise due to occurrence of gallery forest, which often contains trees with stilt roots (De Fraga et al., 2011). Gallery forest can also be found within miombo ecosystems (Malaisse, 1974; Cuambe and Marzoli, 2006), but is considered another forest type and was therefore excluded from this study. Overall, trees with the above structures are rarely found in dry forests on well-drained soils (Denny, 2012).

This study showed that DBH and SDI are interchangeable dimensions (Fig. 3) that can be used to accurately estimate total AGB in lowland miombo woodlands of the Beira corridor study area. However, the SDI-based model should be used only for reconstructing former total AGB in miombo sites subjected to cutting when stem diameter cannot be measured at breast height, which is the case *e.g.,* after full or partial logging.

In this study, we checked the possibility of using a third option for predicting total AGB, namely applying values of DBH determined indirectly with a linear model that uses SDI as the predicting variable of DBH. However, this option was discarded because of the magnitude of error associated with the predictions of total AGB (*e.g.,* RMPE $= -107\%$ and MPE $= 222$ kg tree^{-1}).

4.2. Predictive accuracy of the models developed

An indication of the adequacy and reliability of the DBH-based model and SDI-based model developed in this study was given by the verification and validation procedures, which included checks of the assumptions of linearity and homoscedasticity of these models. The assumption of normality of residuals was violated in both models, but we considered this not to be a serious problem because the regression coefficients of both models were significantly different from zero.

Additional verification was made by comparing the adequacy of the DBH- and SDI-based models of this study against other models obtained from the literature (Table 3). The findings (Tables 7 and 8) confirmed that our site-specific biomass equations were more accurate than the equations found in the literature when applied on our data. However, the DBH-based model developed by Mugasha et al. (2013) (Table 7) and the SDI-based model suggested by Chamshama et al. (2004) (Table 8) can also give good predictions of total AGB in lowland miombo woodland in our study area. The good performance of these models under the conditions in the Beira corridor study area may be attributable primarily to similarities between the miombo woodland we studied in Mozambique and that which they studied in Tanzania, in terms of tree size variation (DBH and total height) and climate conditions.

Although it gave good predictions in general, the SDI-based model by Chamshama et al. (2004) overestimated the weight of large trees when applied on our data (Fig. 6b), which may lead to great bias in biomass per unit area. Using a combination of SDI-based models (this study and that by Chamshama and colleagues) to determine the mean total AGB is an intermediate option to be considered in the Beira corridor study area, as shown in Fig. 6b.

The use of both the DBH- and SDI-based models developed here should be restricted to the lowland miombo type in the study area, not mountain miombo woodland found at high altitude (1100–1700 m a.s.l.) within the Beira corridor region. We compared the tree allometry of these two subtypes of miombo and found that it differs significantly ($P < 0.0001$; Fig. 7), although are similar with respect to dominant trees species. The miombo woodland that occurs in lowlands and that found at high altitude within the study area are also structurally different, with the latter consisting of short trees, with dominant height 7 m (e.g. Pereira et al., 1999) and maximum total height generally less than 12 m (Guedes et al., 2016). Thus, an allometric model specific for the mountain miombo type in the study area remains to be developed.

4.3. Implications for estimating forest biomass and carbon

Nowadays, estimates of carbon stocks in AGB for wider geographical areas in the tropics are made in an efficient way using remote sensing technologies (RST), such as optical, radar, and LIDAR techniques (Zianis et al., 2005; Ito et al., 2010; Barbosa et al., 2014; Gofc-Gold, 2015). However, the reliability of RST depends on the availability of measurements on the ground obtained from conventional field plots and using allometric models (Gofc-Gold, 2015). Moreover, RST may fail to produce reliable estimates of small changes in total above-ground biomass, for example after moderate selective cutting (Houghton, 2005; Murdiyarso et al., 2008; Don et al., 2011; Barbosa et al., 2014; Gofc-Gold, 2015).

The DBH- and SDI-based models developed in this study may be of great value in confirming measurements of total AGB, or for calibrating and validating remote sensing approaches (Zianis et al., 2005; Barbosa et al., 2014; Gofc-Gold, 2015; Scott et al., 2015). On the other hand, a combination of data collection on the ground using the allometric models derived here and RST technologies is needed to move from Tier 2 methodological level to applications at the Tier 3 level, which reflects increasing levels of accuracy, according to the good practise guidance for forest carbon inventory (Ipcc, 2006).

A combination of monitoring on the ground and RST can be valuable to ensure that changes in total carbon stocks in AGB are mapped, monitored, reported, and verified in a quick, consistent, and accurate way in a forest unit or regional level within the limits of the Beira corridor study area, *i.e.,* a large geographical area (Vashum and Jayakumar, 2012, Barbosa et al., 2014; Gofc-Gold, 2015; Scott et al., 2015). For instance, forest carbon stock mapping is important for successful implementation of climate change mitigation policies (Chave et al., 2014). Allometric models can also be used for estimating above-ground net primary production.

The key aspect of the SDI-based model developed in this study is the possibility to allow total above-ground carbon stocks of harvested trees to be estimated from measurements of stump diameter, and thus to reconstruct the former total AGB, *i.e.*, carbon stocks in forests subjected to selective logging and clear cutting for subsistence agriculture. In the latter case, it must

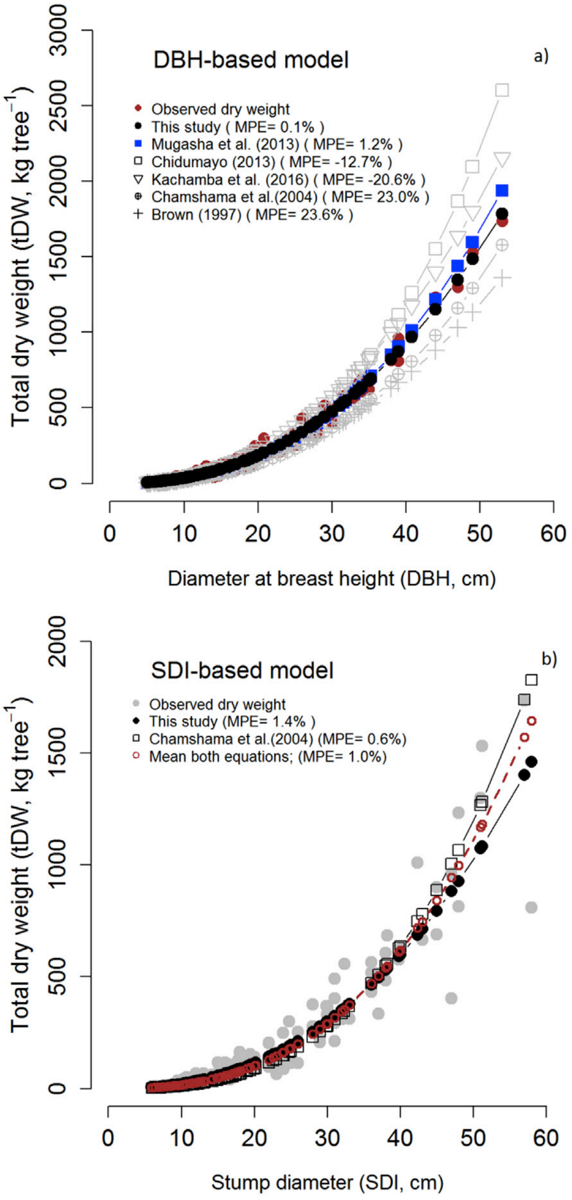

Fig. 6. Visualization of the predictive accuracy of the diameter at breast height (DBH)-based model developed in this study compared with that of (a) DBH-based models selected from the literature compared with our total dry weight (stem, branches, foliage) of sampled trees from the construction dataset; and (b) the stump diameter (SDI)-based model developed in this study compared with that of the only SDI-based model found in the literature, when applied on our data.

be assumed that stumps at least of large trees remain shortly after clear cutting, as depicted in Fig. 8. The diameter of the stump must be measured at 30 cm above the soil surface.

5. Conclusions

We developed allometric models for estimating total above-ground tree biomass (AGB) of multi-species lowland miombo woodlands of the Beira corridor region in Mozambique, based on stem diameter at breast height (DBH) and stump diameter (SDI). Both models can be applied with a high degree of reliability on a large geographical area (~29,000 km^2) within the study area for estimating total AGB and corresponding carbon stocks. The SDI-based equation is principally intended for carbon estimations of harvested trees, and thus to reconstruct the former carbon stocks in miombo woodlands subjected to logging. The DBH-based model is recommended for estimating carbon stocks of live trees, due its higher precision compared with the SDI-based model. Use of both models should be restricted to the lowland miombo type in the Beira corridor region, not the mountain miombo type.

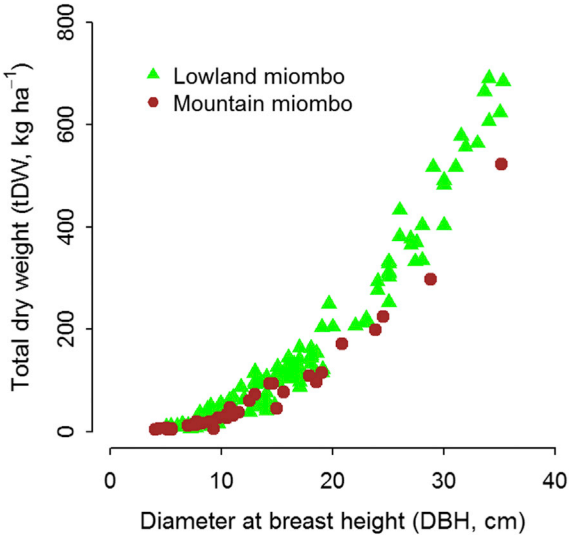

Fig. 7. Scatter plot showing the relationship between diameter at breast height (DBH) and total dry weight (stem, branches, foliage) in lowland Miombo (<1100 m a.s.l.) and mountain miombo woodland (1100–1700 m a.s.l.) of the Beira corridor study area in Mozambique. For the same DBH size, total dry weight of individual trees was significantly lower in mountain miombo (*t*-test = 36.84; P < 0.0001; unpublished data), suggesting that the allometry of these two Miombo types differs. No trees with DBH >40 cm were found in the mountain miombo sites in the Western highlands of Manica, so trees with similar DBH sizes to the lowland miombo type were used to perform this comparison.

Fig. 8. Clear-cutting for agriculture in lowland miombo woodland of the Beira corridor region, central Mozambique (Photo: Almeida Sitoe).

Author contributions

Benard S. Guedes was responsible for statistical analysis of the data, development of the manuscript, and submitted the article; Almeida A. Sitoe conceived the study, conducted field data collection, and participated in manuscript development; Bengt A. Olsson moderated the work and participated in manuscript development.

Conflicts of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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