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# Models Predicting Above- and Belowground Biomass of Thicket and Associate Tree Species in Itigi Thicket Vegetation of Tanzania

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**Abstract:** Itigi thicket is a unique vegetation type for Tanzania and is regarded as ecologically sensitive, thus earmarked for conservation. The objective of this study was to develop species-specific biomass models for two dominating thicket species and mixed-species biomass models for associate trees in Itigi thicket vegetation. Data were collected through destructive sampling (60 thicket clumps and 30 associate trees) and covered two dominant thicket species: *Combretum celastroides* Laws and *Pseudoprosopis fischeri* (Tab) Harms and five dominant associate tree species: *Canthium burtii* Bullock sensu R. B. Drumm, *Cassipourea mollis* (R. E. Fr.) Alston, *Haplocoelum foliolosum* L, *Lannea fulva* (Engl.) England *Vangueria madagascariensis* J. F. Gmelin. Different nonlinear multiplicative model forms were tested, and models were selected based on Akaike Information Criterion. Large parts of the variation in biomass of thicket clumps were explained by basal area weighed mean diameter at breast height of stems in the clump and number of stems in the clump, i.e. for aboveground biomass (AGB) and belowground biomass (BGB) of *C. celastroides* up to 89% and 82% respectively and for AGB and BGB of *P. fischeri* up to 96% and 95% respectively. For associate trees most variation was explained by diameter at breast height (dbh) alone, i.e. up to 85% and 69% for AGB and BGB respectively. Although there will be some uncertainties related to biomass estimates for large areas, for practical reasons, we recommend the selected models to be applied to the entire area where Itigi thicket extends outside our study site, and also to those thicket and associate tree species present that were not included in the data used for modelling.

**Keywords:** Biomass Models, Above- and Belowground, Root Sampling, Root to Shoot Ratio

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## 1. Introduction

Thicket is a dense formation of evergreen deciduous shrubs and low trees (2-5 m), often thorny and festooned with vines [1]. Thicket is generally influenced by soil type and structure, and is found in Africa, western Asia (e.g. Saudi Arabia, India), eastern and northern Australia and America (e.g. Mexico, central America, northern Argentina, central Bolivia, Paraguay, eastern Brazil) [2]. In eastern Africa, thickets extend from central Tanzania to the lowlands of the Somalia-Masai region all the way to Eritrea [3-4]. The

climate of thicket's core area is semi-arid to sub-humid (rainfall 250-800 mm yr<sup>-1</sup>) and subtropical to warm-temperate (largely frost-free). Thicket vegetation is dominated by trees and shrubs; they are very long-lived and are capable of sprouting after defoliation from herbivores, frost and fire [3].

Plant families and genera in thicket include Brassicaceae (*Boscia spp*, *Maerua spp*), Loganiaceae (*Strychnos spp*), Malvaceae (*Grewia spp*), Ochnaceae (*Ochna spp*), Rubiaceae (*Canthium spp*, *Psydrax spp*, *Xeromphis spp*), Rutaceae (*Clausena spp*, *Zanthoxylum spp*) and Euphorbiaceae (*Euphorbia spp*) [3]. Thicket supports a diverse mammal

fauna, including for example African elephant, African buffalo, Burchell's zebra, kudu and eland [3, 5]. Thicket also offers both direct tangible benefits (e.g. fuel wood, construction and craft materials, medicines, food and fodder for animals) and indirect benefits including environmental services such as carbon sequestration, biodiversity, and soil and water conservation [5].

Itigi thicket (named from Itigi town in Manyoni district, Tanzania) is present in the semi-arid areas of the central parts in Tanzania. Itigi thicket extends from Manyoni district to Singida rural district and Bahi district in Dodoma region and is endemic to these areas. Itigi thicket covers an area of about 410,000 ha [6]. This vegetation type is unique in its occurrence, earmarked as ecologically sensitive for conservation and comprises about 12 thicket species and 15 associated tree species [5]. The dominant thicket species include *Pseudoprosopis fischeri* (Tab) Harms, *Combretum celastroides* Laws and *Dicrostachys cinerea* (L) Wight & Arn, while the dominant associate tree species in Itigi thicket vegetation include *Vangueria infausta* Burch, *Albizia petersiana* (Bolle) Oliv, *Canthium burtii* Bullock sensu R. B. Drumm and *Cassipourea mollis* (R. E. Fr.) Alston [6]. A recent sample plot inventory in the area showed that *P. fischeri* and *C. celastroides* contribute more than 50% of all stems (unpublished results).

Quantifying amounts of biomass and carbon for different forest types has recently become important all over the world [7-10]. Among others, it is central to the implementation of the carbon credit market mechanism Reducing Emission from Deforestation and Forest Degradation (REDD+) in developing countries. Biomass of trees can be estimated either by means of stem volume and biomass expansion factors, or by applying biomass models. Typically, biomass models predict biomass by means of easily measurable tree parameters like as diameter at breast height (dbh) and total tree height (ht). Provided information on individual trees is available, biomass models is generally a more accurate way to quantify the amount of biomass than using biomass expansion factors.

Biomass models are also useful tools in assessing forest structure and conditions. They may provide information on supply of industrial wood, biomass for domestic energy and even on availability of animal fodder from the forest. Biomass models are also relevant as parts of remote sensing forest inventory applications and for field inventories related to conventional forest management planning. In recent years, various biomass and volume models have been developed in sub-Saharan Africa. A review report describing such models from sub-Saharan Africa [11] shows that biomass and volume models are unevenly distributed among vegetation types. While for example 43% of the biomass models and 63% of the volume models were developed for tropical rainforests, only 16% of the biomass models and 23% of the volume models were developed for shrub-land.

In Tanzania, biomass models have previously been developed for miombo woodland [12-15]. A few models estimating biomass of shrubs in subtropical thicket in south-

east Africa have been reported [16]. However, no biomass models have been documented for thicket vegetation in Tanzania, and the need for the development of such models is therefore obvious. This is of particular importance since Tanzania recently has established a national forest inventory (National Forest Resources Monitoring and Assessment, NAFORMA) to monitor the woodlands and forests of the entire country [17].

The objective of this study was to develop species-specific biomass models for two dominating thicket species and mixed-species biomass models for associate trees in Itigi thicket vegetation in Tanzania. Models for aboveground, belowground and total biomass models were developed. Statistics on the root to shoot ratio (RS-ratio) are also presented.

## 2. Materials and Methods

### 2.1. Site Description

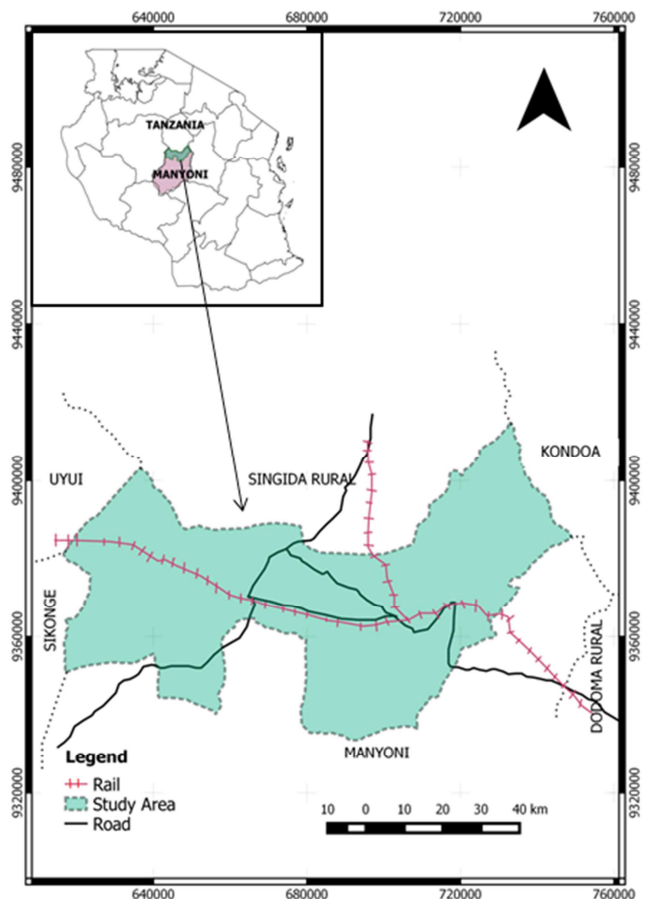


Figure 1. Location of the study site.

The study site was located in the northern part of Manyoni district in Singida region (5°31' to 5°50'S and 34°31' to 34°49'E) (Figure 1). The site is located between 1,244 m and 1,300 m above mean sea level [6]. This area has three distinct seasons; a cool dry season from May to August, a hot dry season from August to November, and a rainy season from November through April. Manyoni district has a unimodal

distribution in rainfall, the average number of rainy days is 49 per year and the mean annual rainfall is 624 mm in the higher altitudes of Manyoni district where majority of thickets are found. The monthly temperature of the area varies from 19°C in July to 24.4°C in November.

Geologically, the area is underlain by a basement floor of granite. The soil is not stony and thereby favours the root systems of thicket species [4, 18]. Itigi thicket is floristically rich and dominated by *P. fischeri* and *C. celastroides*. Other thicket species includes; *Craibia abbreviata* subsp. *burtii*, *Combretum paniculatum*. Vent, *D. cinerea*, *Croton scheffleri* Pax, *Excoecaria bussei* (Pax) Pax, *Grewia forbesii* Harv. ex Mast, *Grewia similis* K. Schum, *Ochna ovata* F. Hoffm, *Rinorea angustifolia* Grey-Wilson, *Tennantia sennii* (Chiov.) Verdc. & Bridson, and *Zanthoxylum chalebium* Engl [6]. Within the Itigi thicket vegetation there are also small trees (associate trees) such as *Acacia tortilis* (Forsk.) Hayne, Arzeyk., *Baphia massaiensis* Taub., *C. mollis*, *H. foliolosum*, *L. fulva*, *Senna singueana* (Delile) Lock, *Maerua triphylla* A. Richard *V. madagascariensis*. In addition, there are also small patches of miombo woodlands composed of miombo dominants such as *Brachystegia boheimii* Benth, *Brachystegia spiciformis* Benth, *Julbernardia globiflora* (Benth) and *Burkea africana* Hook [5-6].

## 2.2. Sampling Thicket Clumps and Associate Trees

As a basis for biomass models, 60 clumps of two dominant thicket species (30 clumps of *P. fischeri* and 30 clumps of *C. celastroides*) and 30 associate trees were sampled. A thicket clump here refers to a close group of stems originating from the same root sucker. Associate trees refer to a small trees (usually with a dbh below 20 cm and height below 8 m) found scattered in thicket stand and tending to grow up when the thicket canopy cover is reduced to below 40%.

The fieldwork was carried out in two stages. The first stage involved a reconnaissance survey in order to become acquainted with the study site, delineate thicket boundaries

and stratify the thicket area into either open thicket or closed thicket. Open thicket here refers to an area with thicket cover below 50% and closed thicket is an area with thicket cover above 50%. The second stage involved establishment of plots for selecting thicket clumps and associate trees. From a map displaying the thicket vegetation we randomly selected coordinates for 30 plots in the two strata open and closed thicket vegetation, respectively. The coordinates of the plot centres were located in the field using a hand held GPS. The plot size was 154 m<sup>2</sup> (7 m radius). For each stratum (open and closed), 15 clumps of each of the two thicket species and 15 associate trees were selected.

Within each plot, two clumps of each thickets species and one associated tree were selected for destructive sampling. We selected the two clumps from the respective species with more than 5 stems that were closest to the plot centre. Among the associate tree species we selected the closest tree to the plot centre. If an associate tree was not found inside the plot, the closest tree to the plot centre outside the plot was selected.

Before felling, the thicket species was identified, the number of stems in the clump (stem count, i.e. st) was recorded and all stems measured for diameter at breast height (dbh) using a calliper. In addition, the total height of tallest stem (ht) in a clump was measured. For each clump, a basal area weighed mean diameter at breast height of stems (dbh<sub>w</sub>) was computed in the following way;

$$dbh_w = \sqrt{\frac{\sum BA_i \times 4}{st \times 3.14159}}$$

where BA<sub>i</sub> is basal area of the i<sup>th</sup> stem in a clump.

Similarly, for each selected associate tree, the tree species was identified and measurements of dbh and ht taken. Table 1 and 2 show statistical summaries of the selected thicket clumps and associated trees.

Table 1. Statistical summary for selected thicket clumps.

Species	n	Basal area weighted mean dbh (cm)			Height (m)			Number of stems in a clump		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
<i>Combretum celastroides</i>	30	2.4	1.5	3.2	4.5	3.5	6.5	15	6	29
<i>Pseudoprosopis fischeri</i>	30	2.2	1.2	3.0	4.1	3.0	6.0	22	9	57

n= number of thicket clumps, min=minimum, max=maximum

Table 2. Statistical summary for selected associate trees.

Species	n	Diameter at breast height (cm)			Height (m)		
		Mean	Min	Max	Mean	Min	Max
<i>Canthium burtii</i>	2	7.4	7.3	7.5	5.5	5.0	6.0
<i>Cassipourea mollis</i>	2	10.2	9.9	10.4	7.2	6.9	7.5
<i>Haplocoelum foliolosum</i>	8	10.7	6.1	18.0	5.9	5.0	7.0
<i>Lannea fulva</i>	6	10.8	10.1	11.7	5.3	5.0	6.0
<i>Vangueria madagascariensis</i>	12	10.0	7.0	15.2	6.2	5.0	7.2
All	30	10.0	6.1	18.0	6.0	5.0	7.5

n= number of trees, min=minimum, max=maximum

### 2.3. Destructive Sampling and Laboratory Procedures

We first divided the thicket clumps into above- and belowground components. The aboveground component was considered as all biomass above a stump height of 10 cm. It was divided into; main stems (diameter > 2 cm), branches (diameter ≤ 2 cm and ≥ 1 cm) and twigs (diameter < 1 cm). Leaves and sawdust from cutting were not included in biomass because the thicket had started to shed them when we carried out the destructive sampling and sawdust mainly because of the workload associated with collecting sawdust from ground. The main stems, branches and twigs were separated into bundles and their green weights were weighed using a spring balance. For each selected clump, three sub-samples from main stems, branches and twigs, respectively, were measured for green weight using an electronic balance. Finally, all sub-samples were labelled and prepared for laboratory analyses.

For all thicket clumps, the root crown and all roots originating from root crown were excavated up to a minimum diameter of 0.5 cm (located 1.0 to 1.5 m from centre of root crown). Then the root crown and roots were pulled from the soil, and subsequently tightened into a bundle, cleaned for soil and weighed. Three sub-samples were taken from root crown and one from root bundle.

The associate trees were also divided into above- (biomass above a stump height of 10 cm) and belowground components. The aboveground component was divided into main stem (diameter > 5.0 cm), branches (diameter ≤ 5.0 cm and ≥ 2.5 cm) and twigs (diameter < 2.5 cm). Leaves and husks were not included. Stem, branches and twigs were trimmed and cross cut into manageable billets ranging from 1 to 2.5 m in length their green weights were determined. Finally, three sub-samples from main stems, branches and from twigs were taken and measured for green weight.

For the belowground component of associate trees we applied a root sampling procedure [14]. We first excavated until all main roots initiating from the root crown were visible. Then three main roots (largest, medium and smallest) originating from the root crown were selected and excavated in full (including up to three side roots) until the point where their diameters were 1 cm. These main roots were measured for basal diameter (diameter at the branching point from the root crown) and then weighed. During the process, up to three side roots were selected from the excavated main roots and measured for basal diameter (diameter at the branching points from the main root) and then weighed. The remaining side roots from the excavated main roots were measured for basal diameter. For each tree, three sub-samples were taken from root crown, main roots and side roots respectively, and then measured with an electronic balance for green weight.

In the laboratory, all collected above- and belowground sub-samples were oven dried to a constant weight at 70°C for at least 48 hours and then the weight was monitored at intervals of 6 hours until there was no change. Finally, biomass was determined with an electronic balance.

### 2.4. Determination of Observed Biomass Dry Weight

For the aboveground component of thicket clumps and associate trees, we computed tree- and component specific (stems, branches and twigs) dry to green weight ratios (DG-ratios) based on the sub-samples. The biomass of all components of a clump or tree was then obtained as the product of DG-ratios and green weight of the respective thicket clump and associate tree components. The AGB weight was computed as the sum of stems, branches and twigs.

For the belowground component of thicket clumps, we first converted green weights from root crown and roots into biomass as the product of the DG-ratio and their green weights. The BGB was computed as the sum of root crown and roots.

For the belowground component of associate trees, we also first converted green weights from all excavated parts of root crown, main roots and side roots into dry weight biomass as the product of the DG-ratios and their green weights. Then the following procedure was applied;

A side root model ( $n = 123$  side roots) was developed by regressing biomass and basal diameter of the side roots. The side root model was as follows:

$$B = 0.091 \times D^{1.740}; \text{RMSE}=0.125; R^2=0.70; \text{MPE}_r = -1.02$$

where B is side root biomass (kg) and D is basal diameter of side root (cm). RMSE is Root Mean Square Error (kg),  $R^2$  is coefficient of determination and  $\text{MPE}_r$  is relative mean prediction error (%).  $\text{MPE}_r$  was not significantly different from zero.

This side root model was applied to predict biomass of all side roots not excavated. To determine total biomass of the selected main roots, the predicted biomass of side roots not excavated were added to the biomass of excavated side roots and those parts of the main root that were excavated. Then, main root models were developed by regressing total biomass and basal diameter of selected main roots. The model ( $n = 90$  main roots) for the main roots was as follows:

$$B = 0.504 \times D^{0.668}; \text{RMSE}=0.293; R^2=0.54; \text{MPE}_r = -0.39$$

where B is main root biomass (kg) and D is basal diameter of main root (cm).  $\text{MPE}_r$  was not significantly different from zero.

Finally, the main root model was applied to predict biomass of unexcavated main roots originating from the root crown. The BGB was computed as the sum of all predicted and measured main root biomass and the biomass of the root crown. Scatter plots of AGB and BGB versus diameter ( $\text{dbh}_w$  and  $\text{dbh}$ ) for individual thicket clumps and associate trees are presented in Figures 2 and 3.

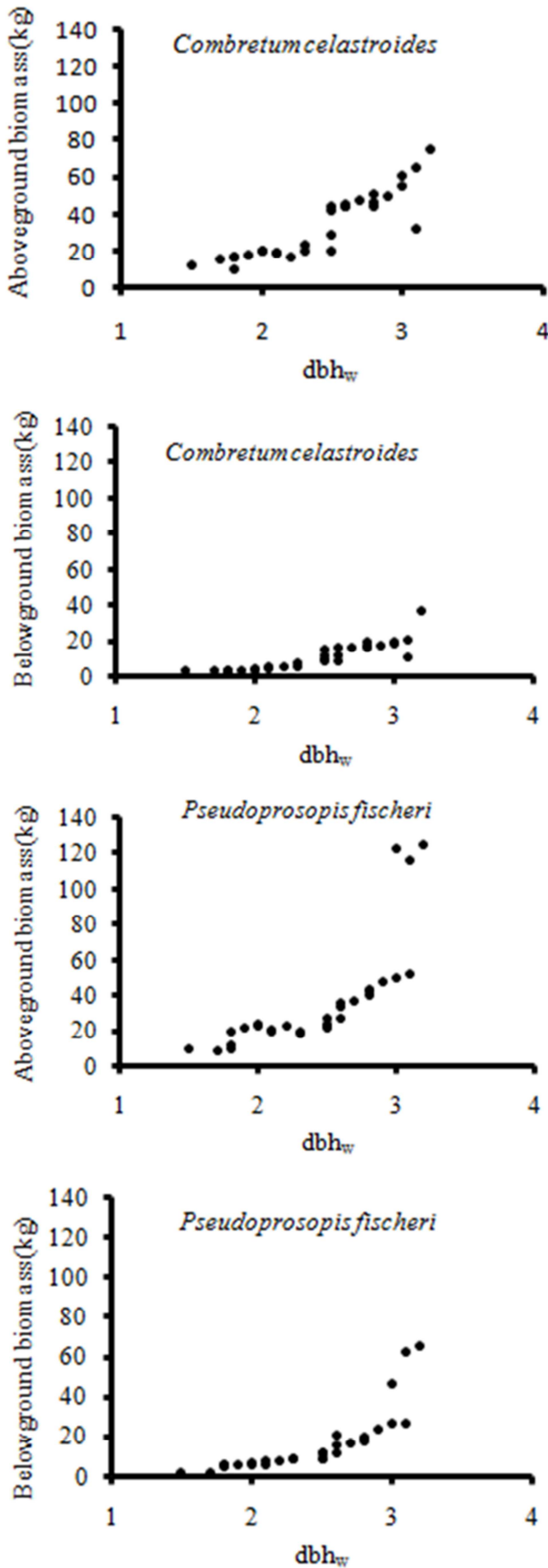


Figure 2. Scatter plots of AGB and BGB versus  $dbh_w$  for individual thicket clumps.

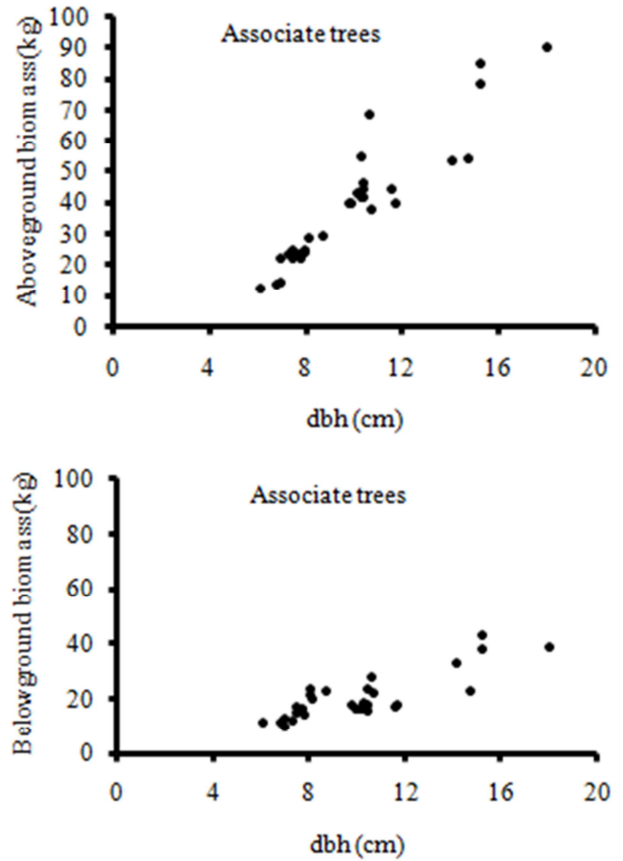


Figure 3. Scatter plots of AGB and BGB versus  $dbh$  for associate trees.

2.5. Model Development, Selection and Evaluation

For the thicket clumps, two models were tested, i.e. model 1 with  $dbh_w$  and  $st$  as independent variables and model 2 with  $dbh_w$ ,  $ht$  and  $st$  as independent variables. Also for the associate trees, two models were tested, i.e. model 3 with  $dbh$  only and model 4 with  $dbh$  and  $ht$  as independent variables. The tested model forms (multiplicative) are commonly used to develop biomass models in the literature [9-10].

$$B = \beta_0 \times dbh_w^{\beta_1} \times st^{\beta_2} \text{ (model 1)}$$

$$B = \beta_0 \times dbh_w^{\beta_1} \times ht^{\beta_2} \times st^{\beta_3} \text{ (model 2)}$$

$$B = \beta_0 \times dbh^{\beta_1} \text{ (model 3)}$$

$$B = \beta_0 \times dbh^{\beta_1} \times ht^{\beta_2} \text{ (model 4)}$$

where B is AGB or BGB or total biomass (TB),  $\beta_0$ ,  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are model parameters.

The PROC NLN procedure in SAS software [19] was used to estimate the model parameters ( $\beta_0$ ,  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$ ). The procedure produces the least squares estimates of the parameters of a nonlinear model through an iteration process.

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

Prediction Error (MPE<sub>r</sub>) was reported for each model as:

$$MPE_r = \left(\frac{100}{n}\right) \times \sum \left[ \frac{y_i - \hat{y}_i}{y} \right],$$

where  $y_i$  is observed biomass of clump/tree  $i$ ,  $\hat{y}_i$  is predicted biomass of clump/tree  $i$ ,  $\bar{y}$  is the mean of observed biomass, and  $n$  is the number of clumps/trees. Paired  $t$ -tests were employed for testing if MPE was significantly different from zero.

### 3. Results

Root to shoot ratios (RS-ratios) for thicket species and associated trees are presented in Table 3. The mean RS-ratios for *C. celastroides* and *P. fischeri* were 0.38 and 0.51, respectively, and they were significantly different ( $p = 0.04383$ ). The RS-ratios both thicket species were not significantly different between dbh-classes; *C. celastroides* ( $p = 0.4295$ ) and *P. fischeri* ( $p = 0.3967$ ). The mean RS-ratio for the associate trees was 0.41. For these trees, the RS-ratio was significantly different between dbh-classes ( $p < 0.000$ ).

**Table 3.** Root to shoot ratio (RS-ratio) over species and diameter classes.

Species	Dbh-class (cm)	n	RS-ratio			
			Mean	Min	Max	STD
<i>Combretum celastroides</i>	- 2.1	10	0.44	0.17	0.71	0.18
	2.2 - 2.6	10	0.34	0.16	0.51	0.12
	2.7 -	10	0.35	0.16	0.54	0.13
	All	30	0.38	0.16	0.71	0.15
<i>Pseudoprosopis fischeri</i>	- 1.9	11	0.57	0.21	0.92	0.25
	2.0 - 2.4	10	0.48	0.29	0.67	0.14
	2.5 -	9	0.46	0.31	0.60	0.11
	All	30	0.51	0.21	0.92	0.18
Associate trees	- 8.0	11	0.57	0.27	0.88	0.20
	8.1 - 10.4	10	0.30	0.14	0.45	0.12
	10.5 -	9	0.34	0.16	0.51	0.13
	All	30	0.41	0.14	0.88	0.16

Parameter estimates and performance criteria for the two thicket species models are summarized in Table 4. For AGB of *C. celastroides*, both models had significant parameter estimates. Since model 2 provides the lowest AIC, this was selected for further analyses (bold in Table 4). For BGB, the parameter estimates were not consistently significant for any of the two models. However, since model 1 has signs as expected in the parameter estimates for dbh<sub>w</sub> and st, i.e. increasing biomass with increasing dbh<sub>w</sub> and st, we still considered this model as valid and selected it for further analyses. For total biomass (TB) of *C. celastroides*, model 1

was selected since model 2 has insignificant parameter estimates. For *P. fischeri*, none of the models including ht as independent variable (model 2) consistently have significant parameter estimates. For all components of this species, model 1 was therefore selected for further analyses.

Parameter estimates and performance criteria for the associate tree models are summarized in Table 5. For all biomass components, no models including ht as independent variable (model 4) had consistently significant parameter. Model 3 was accordingly selected (bold in Table 5) for further analyses for all biomass components.

**Table 4.** Parameter estimates and performance criteria of biomass models for thicket species.

Species	Component	Model	Parameter estimates				RMSE (kg)	R <sup>2</sup>	MPE <sub>r</sub> (%)	AIC
			b <sub>0</sub>	b <sub>1</sub>	b <sub>2</sub>	b <sub>3</sub>				
<i>Combretum celastroides</i>	AGB	1	0.877373	2.956328	0.356776		6.510	0.89	0.18	200.38
		2	0.726938	2.670954	0.573718	0.203860	6.030	0.90	-0.21	196.65
	BGB	1	0.106055*	4.006166	0.349925		3.526	0.82	-0.16	163.59
		2	0.083440*	3.462122	1.033348*	0.047325*	3.202	0.85	-0.61	196.65
	TB	1	0.914780	3.211717	0.355552		9.141	0.90	0.14	220.74
		2	0.745887	2.866816	0.679345	0.169968*	8.234	0.91	-0.32	215.96
<i>Pseudoprosopis fischeri</i>	AGB	1	0.427622	3.405307	0.52902		6.699	0.96	1.75	202.09
		2	0.383697	3.373528	0.132574*	0.511206	6.793	0.96	1.72	203.79
	BGB	1	0.144225	4.153442	0.411693		3.853	0.95	1.06	168.90
		2	0.164340*	4.205059	0.16898*	0.433325	3.908	0.95	1.14	170.63
	TB	1	0.572087	3.642461	0.488888		9.259	0.96	1.54	221.51
		2	0.550836	3.630150	0.047091*	0.482675	9.429	0.96	-0.10	223.47

\*Parameter estimate not significant ( $p > 0.05$ ), selected models in bold

**Table 5.** Parameter estimates and performance criteria of biomass models for associate tree species.

Component	Model	Parameter estimates			RMSE (kg)	R <sup>2</sup>	MPE <sub>r</sub> (%)	AIC
		b <sub>0</sub>	b <sub>1</sub>	b <sub>2</sub>				
AGB	3	1.201291	1.507567		8.086	0.85	-0.55	212.48
	4	0.755707*	1.368491	0.436371*	8.024	0.86	-0.45	212.92
BGB	3	1.380314	1.167124		4.732	0.69	0.22	180.33
	4	0.530607*	0.883575	0.895054	4.384	0.74	0.39	176.65
TB	3	2.341904	1.400620		10.552	0.86	-0.20	228.45
	4	1.236287*	1.210285	0.599351*	10.021	0.88	-0.05	226.26

\*Parameter estimate not significant ( $p > 0.05$ ), selected models in bold

The selected models for thicket clumps were further evaluated over dbh-classes by means of relative mean prediction error (MPE<sub>r</sub>) (Table 6). Based on all observations, MPE<sub>r</sub> were not significantly different from zero for any species or components. Furthermore, for *C. celastroides*, MPE<sub>r</sub> were not significantly different from zero for any of the dbh-classes. For *P. fischeri*, however, MPE<sub>r</sub> was significantly different from zero for some of the dbh-classes.

The predicted biomass when applying the AGB and BGB models separately summarized to 45.34 kg and 52.80 kg for *C. celastroides* and *P. fischeri*, respectively, while the

corresponding predicted biomass when applying the TB models were 45.20 kg and 52.79 kg (Table 6).

The evaluations of the selected associate tree models (Table 7) showed that overall for all observations, MPE<sub>r</sub> was not significantly different from zero for any of the components. However, for both the AGB and BGB models, MPE<sub>r</sub> was significantly different from zero in the smallest dbh-class. For the associate trees, the summarized predicted biomass when applying the AGB and BGB models separately was 60.51 kg while the corresponding predicted biomass when applying the TB model was 60.48 kg.

**Table 6.** Evaluation of selected models for thicket clumps.

Species	Component	Model	dbh-class (cm)	n	Biomass (kg)		MPE <sub>r</sub> (%)	P-value	
					Observed	Predicted			
<i>Combretum celastroides</i>	AGB	2	-2.1	10	16.66	15.90	0.74	0.3957	
		2	2.2-2.6	10	32.92	33.44	-0.51	0.8269	
		2	2.7-	10	52.61	53.05	-0.44	0.7961	
		2	All	30	34.06	34.13	-0.21	0.9428	
	BGB	1	-2.1	10	3.63	3.57	0.19	0.8484	
		1	2.2-2.6	10	10.41	10.38	0.07	0.9730	
		1	2.7-	10	19.55	19.69	-0.42	0.9308	
		1	All	30	11.20	11.21	-0.16	0.9748	
		TB	1	-2.1	10	20.29	18.61	1.24	0.2686
			1	2.2-2.6	10	43.33	44.20	-0.64	0.7522
<i>Pseudoprosopis fischeri</i>	AGB	1	2.7-	10	72.16	72.78	-0.45	0.8579	
		1	All	30	45.26	45.20	0.14	0.9660	
		1	-1.9	11	17.64	13.67	3.94	0.0122	
		1	2.0-2.4	10	27.00	30.77	-3.41	0.0384	
	BGB	1	2.5-	9	71.41	69.92	1.21	0.5763	
		1	All	30	36.89	36.25	1.75	0.5864	
		1	-1.9	11	5.76	4.96	1.75	0.0228	
		1	2.0-2.4	10	12.88	13.17	-0.58	0.7312	
		1	2.5-	9	34.40	34.46	-0.10	0.9790	
		1	All	30	16.73	16.55	1.06	0.7953	
TB	1	-1.9	11	23.40	18.54	3.32	0.0075		
	1	2.0-2.4	10	39.88	43.99	-2.55	0.0490		
	1	2.5-	9	105.81	104.43	0.77	0.7570		
	1	All	30	53.62	52.79	1.54	0.6142		



**Table 7.** Evaluation of selected models for associate tree species.

Component	Model	dbh-class (cm)	n	Biomass (kg)		MPE <sub>r</sub> (%)	P-value
				Observed	Predicted		
AGB	3	-8	11	20.90	24.30	-3.12	0.0026
	3	8.1-10.4	10	41.15	37.80	2.79	0.3417
	3	10.5-	9	61.42	61.70	-0.22	0.1380
	3	All	30	39.81	40.00	-0.55	0.8812
BGB	3	-8	11	15.15	14.14	1.81	0.0413
	3	8.1-10.4	10	18.70	19.92	-1.98	0.3420
	3	10.5-	9	29.22	28.96	0.38	0.9450
	3	All	30	20.55	20.51	0.22	0.9577
TB	3	-8	11	36.05	38.24	-1.33	0.9473
	3	8.1-10.4	10	59.85	57.69	1.19	0.9085
	3	10.5-	9	90.64	90.77	-0.07	0.9833
	3	All	30	60.36	60.48	-0.20	0.9488

## 4. Discussion

The biomass models presented in this study are the first ones developed for thickets in Tanzania. We focused on the two dominant thicket species (*C. celastroides* and *P. fischeri*), mainly because of limited resources to cover all the thicket species present in Itigi thicket. The selection of thicket clump data for modelling the two species was based on randomly distributed sample plots within the study site to secure the clumps to be as representative as possible. Also within each plot, the thicket clumps were selected randomly. Thus, clumps with wide ranges regarding different sizes were covered, i.e. dbh<sub>w</sub> ranged from 1.2 cm to 3.2 cm, ht from 3 m to 6.5 m and st from 6 to 57 (Table 1). Use of modelling data with appropriate numbers of both small and large clumps is important in order to avoid extrapolation, and the uncertainty related to this, as much as possible.

The number of sampled thicket clumps for each species was relatively small (30) compared to for example recently developed biomass models for miombo woodlands and mangrove forest in Tanzania [14-15, 20]. However, a large number of previously developed models in sub-Saharan Africa have also used fewer observations than in the present study [11].

Leaves were excluded from our AGB because the clumps had started to shed leaves when we carried out destructive sampling. This is a common challenge for biomass studies in seasonally dry forests as acknowledged by [10]. A recent study for miombo woodlands in Mozambique by [21] found that leaves comprised only 3% of the AGB during the peak leaf season. Such a number would probably also be a good estimate of how much AGB that is missing in our data. We also decided not to include sawdust from cutting stems into billets, mainly because of the workload associated with collecting sawdust from ground. However, although this will lead to an observed biomass that is lower than reality, sawdust constitute a very small part of the total biomass (<0.3%) [14].

The mean RS-ratios of the sampled thicket clumps varied between the species, i.e. for *C. celastroides* and *P. fischeri*, they were 0.38 and 0.51, respectively (Table 3). The difference in RS-ratio could be due to real morphological differences between the two species, but also due to differences in size for the sampled clumps between the two species (Table 1). The

RS-ratios reported, however, is not unique for thicket as similar levels have been reported in Tanzania for miombo woodlands [14] and mangrove forest [20].

Generally for the thicket clumps, large parts of the variations in biomass were explained by dbh<sub>w</sub> and st while ht explained variations only marginally. For *P. fischeri*, none of the component models with ht as independent variable (model 2) consistently had significant parameter estimates. The obvious choice for this species was therefore model 1 with dbh<sub>w</sub> and st (Table 4). For *C. celastroides*, the selection of appropriate models was more complicated. For AGB, model 2 was selected while for TB model 1 was selected since these models had consistently significant parameter estimates and low AIC values. For BGB of *C. celastroides*, however, no models consistently had significant parameter estimates. Since separate estimation of BGB sometimes may be useful also for this species, we recommend the use of model 1 because the signs of the parameter estimates were as expected. The relevance of such a recommendation is also supported by the evaluation of this model that revealed an appropriate performance with no significant differences between observed and predicted biomass (Table 6).

The presented models for thicket clumps are meant to be applied, based on forest inventories, for estimating biomass per area unit or in total for a certain forest area. The most accurate biomass estimate will of course be achieved by measuring dbh of all stems in the clumps. However, since measuring dbh of all stems is time consuming, an alternative could be to measure dbh of for example the smallest, a medium and the largest stem regarding dbh in a clump, and then apply the dbh<sub>w</sub> of these three stems as input for the models. Such a procedure will of course increase the uncertainty in the biomass estimates when applying the models, but it will also reduce time consumption in practical inventories considerably.

The species-specific thicket clump models developed may generally be applied inside the study site (Manyoni). The models may also be applied outside this site where Itigi thicket extends (i.e. Singida rural district and Bahi district in Dodoma region) because growing conditions here are very similar. Although Itigi thicket comprise of more than 10 different species, a recent sample plot inventory in the area showed that the two selected species contribute to more than



50% of the total stem density (Unpublished results). For practical reason when estimating biomass for larger areas we therefore recommend the models to be applied also to remaining thickets species with similar morphology. The uncertainty in biomass estimates will of course increase by doing this, but this is the only option since models do not exist for the remaining species.

The selection of associate trees for modelling was also based on randomly distributed sample plots to secure the associate trees to be as representative as possible. Within each plot, an associate tree was also selected randomly. Thus, associate trees with wide ranges regarding different sizes were covered, i.e. dbh ranged from 6.1 cm to 18 cm (Table 2). Five different tree species (*C. burtii*, *C. mollis*, *H. foliolosum*, *L. fulva* and *V. madagascariensis*), out of a total of 15 tree species, were selected. Since the trees were selected randomly, the five species will comprise a large part of the biomass in the area, and as such, the uncertainty related to the relatively few species included in the mixed-species models will be relatively low when applying them also to the remaining species.

The average RS-ratio for the associate trees was 0.41, which is similar with what was reported for miombo woodlands in Tanzania [14]. The RS-ratio varied significantly between dbh classes with a high RS-ratio for small trees and lower RS-ratios for larger trees (Table 3). A similar pattern for miombo woodland trees was observed by [22] who found that the RS-ratio was decreasing significantly and non-linearly with increasing dbh. The use of RS-ratio is recommended for estimating belowground biomass in cases where models are not available [23] and mean RS-ratios are frequently applied to estimate belowground biomass [24]. However, by using a fixed mean RS-ratio for a relationship that most probably is non-linear, a bias will be introduced. Therefore, application of mean RS-ratios to estimate belowground biomass should be done with caution, and avoided if BGB models exist.

## Appendix. Sample Clumps and Associate Trees Used to Develop Biomass Models and Their Respective Names and Sizes

Table A1. Thicket clumps.

<i>Combretum celastroides</i>			<i>Pseudoprosopis fischeri</i>		
dbh <sub>w</sub> (cm)	ht (m)	st	dbh <sub>w</sub> (cm)	ht (m)	st
1.5	4.5	15	1.2	4.0	20
1.7	4.4	12	1.5	3.5	18
1.8	4.0	9	1.6	3.0	12
1.8	4.5	29	1.7	4.0	36
1.8	5.0	27	1.7	4.0	23
1.9	4.5	8	1.7	4.0	13
2.0	4.4	14	1.8	4.0	25
2.0	4.4	11	1.8	4.5	31
2.1	3.9	13	1.9	4.5	18
2.1	4.0	25	1.9	3.5	16
2.2	4.8	29	1.9	3.0	16
2.3	4.0	12	2.0	4.5	20
2.3	4.4	8	2.1	4.0	22

Generally for the associate trees, large parts of the variations in biomass were explained by dbh while ht explained variations in biomass only marginally. None of the selected mixed-species models for associate trees included ht as independent variable (Table 5). Model 3 with dbh only as independent variable was therefore selected for all biomass components. The application recommendations for these models are similar to those of the thicket clumps; for the study site, and outside where the Itigi ticket vegetation extends.

## 5. Conclusions

The developed species-specific models for thicket and mixed-species models for associate trees were based on a comprehensive and well-documented set of data comprising dominant thicket and associate tree species. The model fitting showed that large parts of the variation in biomass of thicket were explained by basal area weighed mean diameter at breast height and number of stems in the clumps while for associate trees most variation was explained by diameter at breast height only. Although there will be some uncertainties related to biomass estimates for large areas, for practical reasons, we recommend the selected models to be applied to the entire area where Itigi thicket extends outside our study site, and also to those thicket and associate tree species present that were not included in the data used for modelling.

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<i>Combretum celastroides</i>			<i>Pseudoprosopis fischeri</i>		
dbh <sub>w</sub> (cm)	ht (m)	st	dbh <sub>w</sub> (cm)	ht (m)	st
2.5	3.5	13	2.1	5.5	38
2.5	4.3	10	2.1	3.0	18
2.5	4.4	21	2.1	4.5	19
2.5	6.5	25	2.1	3.0	17
2.6	4.3	10	2.2	4.5	16
2.6	3.5	20	2.3	4.0	21
2.6	5.2	17	2.4	6.0	17
2.7	5.0	19	2.4	3.5	22
2.8	4.5	17	2.5	4.5	13
2.8	4.3	8	2.5	4.0	19
2.8	4.2	17	2.5	4.0	13
2.9	4.5	10	2.7	4.0	10
3.0	5.0	12	2.7	4.0	21
3.0	5.6	18	2.8	5.0	57
3.1	4.9	14	2.8	4.5	42
3.1	3.5	6	2.9	4.0	9
3.2	5.2	13	3.0	5.0	38

Table A2. Associate trees.

Scientific name	dbh (cm)	ht (m)
<i>Haplocoelum inopleum</i>	6.1	6.0
<i>Haplocoelum inopleum</i>	6.8	6.0
<i>Haplocoelum inopleum</i>	7.0	5.2
<i>Vangueria madagascariensis</i>	7.0	5.0
<i>Canthium burtii</i>	7.3	5.0
<i>Canthium burtii</i>	7.5	6.0
<i>Haplocoelum inopleum</i>	7.5	5.0
<i>Vangueria madagascariensis</i>	7.7	5.0
<i>Vangueria madagascariensis</i>	7.8	5.3
<i>Vangueria madagascariensis</i>	8.0	6.0
<i>Vangueria madagascariensis</i>	8.0	5.0
<i>Vangueria madagascariensis</i>	8.1	7.0
<i>Vangueria madagascariensis</i>	8.7	7.0
<i>Vangueria madagascariensis</i>	9.8	6.0
<i>Cassipourea mollis</i>	9.9	6.9
<i>Lannea fulva</i>	10.1	5.0
<i>Haplocoelum inopleum</i>	10.3	6.0
<i>Haplocoelum inopleum</i>	10.3	5.1
<i>Lannea fulva</i>	10.4	5.5
<i>Cassipourea mollis</i>	10.4	7.5
<i>Lannea fulva</i>	10.4	5.0
<i>Lannea fulva</i>	10.6	5.0
<i>Vangueria madagascariensis</i>	10.7	7.0
<i>Lannea fulva</i>	11.6	6.0
<i>Lannea fulva</i>	11.7	5.5
<i>Vangueria madagascariensis</i>	14.1	7.0
<i>Haplocoelum inopleum</i>	14.7	6.7
<i>Vangueria madagascariensis</i>	15.2	7.2
<i>Vangueria madagascariensis</i>	15.2	7.2
<i>Haplocoelum inopleum</i>	18.0	7.0

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