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*Article*

# Biomass Equations for Tropical Forest Tree Species in Mozambique

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**Abstract:** Chanfuta (*Afzelia quanzensis* Welw.), Jambire (*Millettia stuhlmannii* Taub.) and Umbila (*Pterocarpus angolensis* D.C.) are, among others, three of the main tropical tree species producing commercial timber in Mozambique. The present study employed destructive biomass estimation methods at three localities in Mozambique (Inhaminga, Mavume, and Tome) to acquire data on the mean diameter at breast height (DBH), and height of trees sampled in 21 stands each of Chanfuta and Jambire, and 15 stands of Umbila. Mean diameter at breast height (DBH) (ob) for Chanfuta, Jambire, and Umbila was: 33.8 ± 12.6 (range 13.5–61.1), 33.4 ± 7.4 (range 21.0–52.2), and 27.0 ± 9.5 (range 14.0–46.5) cm. The mean total values for biomass (kg) of trees of Chanfuta, Jambire, and Umbila trees were 864, 1016, and 321 respectively. The mean percentages of total tree biomass as stem, branch and leaf respectively were 54, 43, and 3 for Chanfuta; 77, 22, and 1 for Jambire; and 46, 51, and 3 for Umbila. The best fit species-specific equation for estimating total above ground biomass (AGB) was the power equation with only DBH considered as independent variable yielding coefficient of determination ($R^2$) ranging from 0.89 to 0.97. At stand level, a total mean of 27.3 tons ha$^{-1}$ biomass was determined of which studied species represented 94.6%. At plot level, total mean biomass for Jambire was 11.8 tons ha$^{-1}$, Chanfuta and Umbila 9.9 and 4.1 tons ha$^{-1}$ respectively. The developed power equation fitted total and stem biomass data well and could be used for biomass prediction of the studied species in Mozambique.

**Keywords:** *Afzelia quanzensis*; biomass; basic density; Chanfuta; Jambire; *Millettia stuhlmannii*; Miombo woodlands; *Pterocarpus angolensis*; species-specific; Umbila

## 1. Introduction

### *1.1. Study Background*

About 31% of the world's land surface is covered by forests and Africa accounts for 17% of the world's forests [1]. The percentage forest area in Mozambique is about 51% of which 67% is classified as productive forest [2]. Around 80% of the Mozambican population live in rural areas and is dependent on the forest to satisfy their subsistence and energy needs [3].

In Mozambique there are 118 identified forest species, which are classified based on their commercial values [4]. Forest logging is mainly concentrated on timber production from native forest species with limited use of either primary residues from the harvesting (tree tops, branches, leaves) or secondary residues from the processing industry [5]. Chanfuta (*Afzelia quanzensis* Welw.), Jambire (*Millettia stuhlmannii* Taub.) and Umbila (*Pterocarpus angolensis* D.C.) account for 78% of the total timber production in Mozambique [2,6]. Native species are therefore potential sources of a considerable amount of woody biomass residues that can be used as a raw material for renewable bioenergy [7,8]. In this study Chanfuta, Jambire, and Umbila are considered as potential contributors to the total amount of usable forest residues.

Chanfuta (Fabaceae-Caesalpinioideae) is a deciduous tree found at altitudes between sea level and 1800 m in areas with a mean annual rainfall of around 1000 mm and a temperature ranging from 17 °C to 30 °C. It commonly occurs in Miombo forests, in low-lying areas and dry forests, and in lowland thickets or dry woodlands [9,10]. Chanfuta prefers medium-light, well-drained soils. It is drought resistant but frost sensitive and slow growing in colder areas. It provides good shade due to its short bole and large leaves. It is a medium to large tree with a greyish-brown bark, usually standing 12 m–15 m tall, sometimes reaching 35 m [10]. Chanfuta produces high value timber and is moderately resistant to termites [11]. The wood is hard, heavy, durable, and is mainly used for furniture, building materials, and canoes, as well as crafting [12]. The species has a basic density of 692 kg $m^{-3}$ [13]. Chanfuta is easy to propagate from seed with good germination rates and no need for pre-treatment. In Mozambique the current available commercial volume for Chanfuta is about 2,514,000 $m^3$ [2]. The regulation size for harvesting is a DBH ≥ 50 cm [4].

Jambire is another member of the Fabaceae family. It is distributed from Southern to Central Mozambique and is also found in Eastern Zimbabwe and in isolated pockets in the NE Limpopo province. The available volume for Jambire is reckoned at around 4,200,000 $m^3$ [2]. Jambire is a medium to large deciduous tree species with spreading crown [14]. It occurs in bushveld and forest, often on rocky hillsides [9] and grows to heights ranging between 15 m and 25 m [14]. The species is commonly used for furniture, flooring, musical instruments, inlay work, as well as railway sleepers. The bark is smooth, yellow to grey-green in color. The wood is moderately hard, durable, and resistant to fungi and termites under temperate climatic conditions [14,15]. The basic density varies from 720 to

990 kg m$^{-3}$ [16]. The wood is porous and has close annual rings with a straight grain, which gives a delicate figure to flat-sawn timber. The regulation size for harvesting is a DBH ≥ 50 cm [4].

Umbila is a leguminous tree in the subfamily Papilionoideae. It is distributed over large areas in Miombo woodlands in areas of Central and Southern Africa [17]. The species is widespread across Malawi, Mozambique, Zambia, Zimbabwe, and Botswana. Umbila is a medium-sized to large tree 10 and 20 m tall, but reaching 28 m under ideal conditions [9]. Growth rates of Umbila through annual ring-width studies by Therrell *et al.* [17], and Fichtler *et al.* [18] have revealed that it might takes 29 years for a tree to reach a DBH of 10 cm, and around 100 years to reach a DBH of 30 cm–40 cm; but ages up to 300 years are possible and growth rates vary depending on environmental factors at specific sites. Umbila is a valuable timber species and is resistant to fire. The heartwood is reddish brown and is considered to be one of the most valuable in south tropical Africa. It is widely used for carving, timber and traditional medicine [19]. The main seed dispersal agent is wind, which can occasionally spread the fruits for several kilometres [19]. Establishing the species in plantations has not been successful [20,21]. Umbila has a basic density of 640 kg m$^{-3}$ [13]. The species is nitrogen fixing [14]. In most Southern African countries the minimum DBH for harvest timber of the tree is 35 cm–40 cm [17]. In Mozambique the estimated available volume is about 5,620,000 m$^3$ and the regulation DBH for harvesting is ≥40 cm [4].

### *1.2. Study Justification*

Fuelwood and charcoal is the main energy used in Mozambique sharing 82% of the total energy used [22]. This increases the pressure for the forest to provide energy and other products necessary for subsistence such as food, construction materials, other non-wood forest products, and certain other environmental services [23]. The deforestation rate that is associated with increased fuelwood consumption and agricultural expansion is around 219,000 ha per year, which is equivalent to an annual reduction in forest cover of 0.58% [2]. With an increase of the population in future, the situation will become even more serious. The demand for biomass fuel will still be high and alternative energy sources that require less forest clearance are urgently required. Studies documenting available biomass potentials from forest residues and species-specific biomass equations in particularly for Chanfuta, Jambire, and Umbila for which specific studies on their volumes and biomass are sparse [24]. Tree volume and biomass are useful quantities in forest inventories since the production of timber volume is the basic aim of forest management [25,26]. Biomass studies relating to African tropical species are limited, and the existing ones are based on American and Asian tropical species [27–30]. Development of site specific biomass models was recommended by Brown *et al.* [27] and Návar [30].

The present study aims to address the lack of knowledge concerning biomass estimates of tropical forest tree species in Mozambique.

### *1.3. Objectives*

The main objective of the present study was to develop species-specific biomass equations for tree components for three main commercial tropical forest species in Mozambique described above. The equations are intended for use in estimating the amount of woody biomass residues generated from logging activity; such residues could be made available for bioenergy use in the Sofala and Inhambane Provinces in Mozambique.

## 2. Materials and Methods

### *2.1. Study Area*

The study was carried out in the Sofala and Inhambane provinces in Mozambique. The forest vegetation type that characterizes the study area is Miombo Woodlands. Miombo Woodlands is a term used to describe the vegetation belt that covers great parts of Central, Southern and Eastern Africa. Miombo forests can be classified based on mean annual rainfall as dry and wet, where the wet Miombo is characterized by annual rainfall above 1000 mm, canopy height higher than 15 m, and high diverse floristic composition, while the drier Miombo is the opposite [31,32]. It is generally characterized by the presence of three tree genera from the *Fabaceae* family, subfamily *Caesalpinioideae*: *Brachystegia*, *Julbernardia*, and *Isoberlinia* [33]. The Miombo woodlands are poor sites but have high plant diversity.

Three study sites were used. One of these was a 'forest concession' located at Inhaminga in Sofala province, which is centered on 18°58' S and 34°10' E; it covers 68,018 km² with a population of 1,676,131 inhabitants [34]. The climatic type is predominantly tropical savannah. Inhaminga locality falls into the wetter Miombo area, while Mavume and Tome are part of the dry Miombo based on the above description. The region experiences an annual rainfall from 1000 mm to 1400 mm concentrated between December and March. The annual temperature varies between 16 °C and 34 °C, with a mean of 22 °C to 27 °C. Soil types vary and include sandy soils, calcareous soils and quartz soils; alluvial soils predominate. Vast plains along the coastal area, areas that undulate between low to medium altitude, mountainous areas, and plateaus characterize the topography. Sofala Province is among the three provinces that produce the highest volumes of commercial timber: Sofala produces 7.1 $m^3$ $ha^{-1}$ while Zambézia and Cabo Delgado produce 7.7 and 7.3 $m^3$ $ha^{-1}$, respectively [2].

The two other study sites were public forest areas at Mavume and Tome, located in Inhambane Province, which is centred on 23°52' S and 35°23' E and comprises an area of 68,615 km² with a population of 1,412,349 inhabitants [34]. The climate is tropical but more humid along the coast and dryer inland. The coast has a number of mangrove swamps.

### *2.2. General Characterization of Species in Stands*

A number of different species grew in the studied stands but species of commercial value, such as Chanfuta, Jambire, and Umbila, which had low representation (Table 1).

The stand density at Tome locality was 147 stems $ha^{-1}$ with a basal area of 7.25 $m^2$ $ha^{-1}$ from which Chanfuta represented 17 stems $ha^{-1}$ with a basal area of 3.42 $m^2$ $ha^{-1}$. In Inhaminga locality 119 stems $ha^{-1}$ were found with a basal area of 8.19 $m^2$ $ha^{-1}$, where Chanfuta, Jambire, and Umbila were represented by 8, 13, and 5 stems $ha^{-1}$ with basal area of 1.32, 1.13, and 0.39 $m^2$ $ha^{-1}$ respectively. In Mavume locality the density was 104 stems $ha^{-1}$ with a basal area of 5.60 $m^2$ $ha^{-1}$ from which, Chanfuta and Umbila had 15 and 20 stems $ha^{-1}$ with a basal area of 1.04 and 0.98 $m^2$ $ha^{-1}$ (Table 1).

**Table 1.** Characterization of species growing in stands at three visited localities.

| Species type | Stems ha$^{-1}$ | DBH, cm | | Height, m | | Basal area, m² ha$^{-1}$ |
|---|---|---|---|---|---|---|
| | Mean ± SD | Mean ± SD | Range | Mean ± SD | Range | Mean ± SD |
| Locality of Inhaminga, Sofala Province (Lat.18°58’ S.; Long. 34°10’ E, 100–200 m a.s.l) | | | | | | |
| Chanfuta | 8 ± 4 | 44.4 ± 13.7 | 11.1–79.6 | 16.3 ± 4.1 | 7.0–22.1 | 1.32 ± 0.87 |
| Jambire | 13 ± 12 | 31.2 ± 11.4 | 13.4–65.0 | 15.8 ± 4.4 | 6.0–28,9 | 1.13 ± 0.93 |
| Umbila | 5 ± 0 | 28.8 ± 16.3 | 14.3–46.5 | 10.8 ± 2.0 | 8.5–12.0 | 0.39 ± 0.40 |
| Others | 93 ± 55 | 23.0 ± 14.3 | 7.6–129.6 | 10.1 ± 3.7 | 3.0–25.1 | 5.35 ± 3.98 |
| Locality of Mavume, Inhambane Province (Lat. 23°28’ S.; Long. 34°33’ E, 100–200 m a.s.l) | | | | | | |
| Chanfuta | 15 ± 14 | 28.6 ± 9.0 | 17.2–42.5 | 10.9 ± 1.9 | 8.8–13.2 | 1.04 ± 1.23 |
| Umbila | 20 ± 14 | 22.8 ± 9.6 | 10.0–44.5 | 8.8 ± 2.9 | 3.8–16.2 | 0.98 ± 0.84 |
| Others | 69 ± 73 | 19.8 ± 8.1 | 10.0–49.0 | 6.6 ± 2.0 | 2.0–14.0 | 2.58 ± 2.06 |
| Locality of Tome, Inhambane Province (Lat. 22°32’ S.; Long. 34°12’ E, 100–200 m a.s.l) | | | | | | |
| Chanfuta | 17 ± 16 | 25.9 ± 9.6 | 13.5–48.0 | 11.5 ± 2.6 | 7.5–5.5 | 3.42 ± 1.22 |
| Others | 130 ± 83 | 17.4 ± 8.6 | 10.0–54.0 | 7.2 ± 2.8 | 3.0–15.0 | 3.83 ± 1.47 |

### *2.3. Sampling Design and Sampling Unit*

The studied area covered different forest types defined based on the forest land use and cover types [2]. Limited access to the plots resulted in long walking distances with heavy materials together with rainy weather in the area have limited the number of visited plots per day to about 2–3 plots. As plots were located in privately operated forest concession areas with approved management plans we were not allowed to cut more than one tree per plot. Permission was given by the forest authorities to harvest trees below the minimum DBH allowed for the species. A total of 57 sampling plots were established and surveyed. In Sofala Province 36 plots were examined in the locality of Inhaminga, and in Inhambane Province 21 plots were examined in two localities; 14 in Mavume and 7 in Tome. The plots were 100 m × 20 m, corresponding to 0.2 ha. Plot size larger than 0.1 ha are recommended for reliable biomass estimates for Miombo woodland [33]. Within each plot, species, DBH, and height of all existing species were recorded. Because age determination is complicated, time-consuming, and prone to errors, no such analyses were made.

The following quantities were estimated or measured from the sampled material:

- Biomass measurements in the field
- Biomass estimation
- Moisture content and basic density estimation

### *2.4. Biomass Measurements in the Field*

In the study 24 Chanfuta, 15 Jambire, and 19 Umbila tree species were felled for biomass measurements. The minimum DBH considered was 10 cm as measured by calliper. The height was measured by Haglöf Vertex 3 and 4 hypsometers. The stump height was defined as 20 cm above ground. After felling, the stem was marked out although in some cases no natural top could easily be defined (Figure 1). The aboveground biomass (AGB) components of stem, branches (including smaller branches and twigs) and leaves were defined. Trees with stems that forked below 1.3 m above the ground were excluded. If the stem was forked above 1.3 m, then each fork of the stems was measured separately. The stumps were not measured and not accounted in the AGB. In Mozambique stumps are not harvested and are highly recommended for coppice management.

**Figure 1.** Definition of stem section for a felled tree based on tree architecture.

Stems and branches were divided into smaller sections to facilitate weighing process. The components were weighed fresh and then stored for later dry weight determination. The fresh weights were recorded in the field using scales (spring scales MWL 15 and 150 kg; electronic scale MWL 500 kg; manual MWL 300 kg). Disks were cut from the stem at 1, 10, 30, 50, 70, and 90% of stem height and at breast height. An average of three sub-samples of branches was taken from the middle of the crown. Sub-samples of stems and branches were weighed and stored for later dry mass determination in the lab. All leaves on a tree were collected and weighed with a precision scale with a maximum working load (MWL) of 15 kg. Samples of 30 to 50 leaves were taken at different levels of the crown.

*2.5. Biomass Estimation*

Sub-samples were oven-dried in the laboratory at 103 °C–105 °C down to a constant weight [35–38]. On average, subsamples of the stems took 72 h to reach a constant weight, branches took 48 h, and leaves took 24 h. The total dry weight of each AGB component was calculated using the ratio between the dry and fresh weight of the sub-samples, multiplied by the total fresh weight of the respective components.

$$Dry\,mass = \frac{sdw}{sfw} \times fwC \tag{1}$$

Where:
*Sdw* = dry weight of sub-sample (g)
*Sfw* = fresh weight of sub-sample (g)
*fwC* = fresh weight of component

*2.6. Moisture Content Estimation*

The moisture content (MC) for the oven-dried sub-samples of the different tree components was calculated based on an oven-dry weight [39].

$$MC = \frac{fw - dw}{fw} \tag{2}$$

Where:
MC = moisture content
$fw$ = fresh weight (g)
$dw$ = oven-dry weight (g)

The total dry masses of stems, branches and leaves for each sampled tree were then estimated from the percentage ratio of respective fresh weight to dry weights calculated from the sub-samples.

*2.7. Biomass Equations*

Non-linear regression procedures were used to estimate the best-fit model for the biomass of stems, branches and leaves of the studied species. The dry mass production for stems, branches and leaves were added together to get the total AGB. The dry mass production per tree was then estimated from curves describing the correlation between DBH and dry mass production (kg tree$^{-1}$) derived from all of the measured trees.

Power equation was tested:

$$AGB = \beta_0 \times D^{\beta_1} \tag{3}$$

This equation is flexible and frequently used to predict dry mass [30,40–44].

Power equation including basic density values and in one including basic density and tree height parameters were combined was fitted the data as in Návar-Cháidez *et al.* [45] for tropical dry forests of Mexico.

$$AGB_{Total} = \beta_0 \times D^{\beta_1} \times \beta_2 \times Bd \text{ [45,46]} \tag{4}$$

$$AGB_{Total} = \beta_0 \times (Bd \times D^2 \times H)^{\beta_1} \text{ [29]} \tag{5}$$

$$AGB_{Total} = (\beta_0 + \beta_1 \times Bd) \times D^{\beta_2} \text{ [30]} \tag{6}$$

Where:
AGB = Kg d.w. tree$^{-1}$
D = DBH over bark (ob), mm
Bd = Basic density, gcm$^{-3}$
H = Tree height, m
$\beta_0$, $\beta_1$ and $\beta_2$ are parameters

The actual dry mass production of each of the studied tree species included in the study was then estimated from their respective mean diameters.

*2.8. Basic Density Estimation*

The basic density (g cm$^{-3}$) of stem disks sampled at different heights, and of branches, was estimated according to the water-immersion method described by Andersson and Tuimala [47]. Samples were saturated in water for 24 h and then weighed and their volume (cm$^3$) determined [38]. The dry matter content of the debarked wood proportion (g) of the sub-samples was determined after drying at 105 °C in an air-ventilated oven for 3–5 days depending on their dimensions. Dry weight to fresh volume ratios of the debarked disk and branches were then calculated as the basic density (g cm$^{-3}$). Means of basic density from the chosen height levels of 24 stems of Chanfuta, 15 of Jambire, and 19 of Umbila were plotted and linear curves constructed from the data:

$$Bd = \frac{M}{V} \tag{7}$$

Where:
*Bd*: Basic density (g cm$^{-3}$).
*M*: Dry weight of stem or branch sample (g).
*V*: Fresh volume of stem or branch sample (cm$^3$).

### 2.9. Statistical Analyses

Data were analysed by non-linear regression using the SAS/STAT system for personal computers [48]. A measure of the fit of the non-linear regressions was based on the coefficient of determination [49]:

$$R^2 = 1 - [\text{SSE/SST (No. observations)}] \tag{8}$$

$$\text{SSE is } \sum_{i=1}^{n} (w_i - \overline{w}_i)^2 \text{ and SST is } \frac{1}{n} \sum_{i=1}^{n} (w_i - \hat{w}_i)^2 \tag{9}$$

The equations were also tested using average bias, (AB), average absolute bias (AAB) and root mean square error (RMSE). According to Parresol *et al.* [50] AAB reveals a clear distinction between the equations examined.

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(w - \hat{w}_i)^2}{n}} \tag{10}$$

$$\text{AB} = \frac{1}{n} \sum_{i=1}^{n} (v_i - \hat{v}_i) \tag{11}$$

$$\text{AAB} = \frac{1}{n} \sum_{i=1}^{n} \left| v_i - \hat{v}_i \right| \tag{12}$$

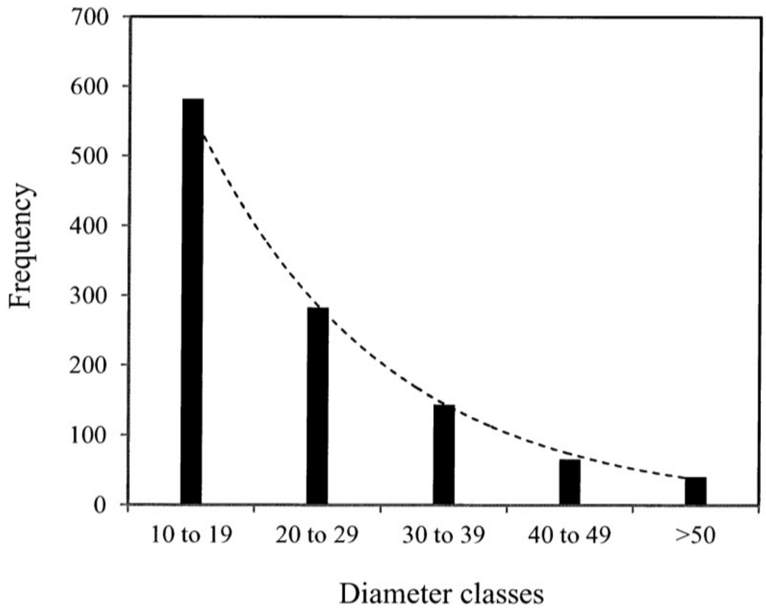
Where:
$\overline{w}_i$ = Mean values of dry mass (w)
$v_i$, $\hat{v}$, $w_i$ and $\hat{w}_i$ = are observed and predicted values of dry mass (*w*)
Throughout the report, means are presented together with the standard deviation (SD).

## 3. Results

### 3.1. Stand Characteristics

In the study 1116 trees were recorded in the plots from which 762 (68.3%) were identified to species by their scientific names and 354 individuals were not recognized by botanical guides as well as local people. In average 30, 35, and 74 stemsha$^{-1}$ were found in Inhaminga, Mavume and Tome localities. The distribution of the individuals followed a reversed J-shape curve (Figure 2). Individuals with smallest DBH accounted for 52.1% (<19 cm) of the sampled population, and with largest DBH represented 3.7% (>49 cm) of the population.

**Figure 2.** Frequency of stem number by diameter classes (DBH, cm).




Stem density for Chanfuta, Jambire and Umbila was 240, 275 and 260 individuals corresponding to an average of 13, 17, 12 stemsha$^{-1}$, respectively. Chanfuta, Jambire, and Umbila were represented in 21, 21, and 15 plots, respectively. Detailed characteristics of the individuals are presented in Table 2.

**Table 2.** Stand characteristics of species growing in sample plots in the three localities.

| Plot no. | Locality | Lat. S | Long. E | Stems ha$^{-1}$ | DBH, cm | | Height, m | | Basal area, m$^2$ ha$^{-1}$ | Biomass, tons ha$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mean ± SD | Range | Mean ± SD | Range | Total | Total |
| | | | | | *Chanfuta* | | | | | |
| 6 | Inhaminga | 18°15’ | 35°15’ | 10 | 60.5 ± 27.0 | 41.4–79.6 | 14.4 ± 6.9 | 9.5–19.2 | 3.16 | 21.7 |
| 7 | Inhaminga | 18°01’ | 35°17’ | 5 | 43.6 ± 0 | 43.6 | 18.6 ± 0 | 18.6 | 0.75 | 6.2 |
| 9 | Inhaminga | 17° 99’ | 35°19’ | 5 | 61.1 ± 0 | 61.1 | 20.6 ± 0 | 20.6 | 1.47 | 10.6 |
| 10 | Inhaminga | 18°74’ | 35°86’ | 10 | 60.0 ± 9.0 | 44.6–57.3 | 17.5 ± 2.1 | 16.0–18.9 | 2.07 | 15.9 |
| 15 | Inhaminga | 17°99’ | 35°15’ | 5 | 35.4 ± 0 | 35.4 | 15.0 ± 0 | 15 | 0.49 | 4.4 |
| 22 | Inhaminga | 18°08’ | 35°11’ | 10 | 22.3 ± 15.8 | 11.1–33.4 | 9.6 ± 3.7 | 7.0–12.3 | 0.49 | 4.8 |
| 39 | Inhaminga | 18°23’ | 35°13’ | 5 | 48.4 ± 0 | 48.4 | 15.8 ± 0 | 15.8 | 0.92 | 7.3 |
| 43 | Inhaminga | 18°09’ | 35°25’ | 5 | 38.5 ± 0 | 38.5 | 20.9 ± 0 | 20.9 | 0.58 | 5.1 |
| 202 | Inhaminga | 18°40’ | 35°14’ | 5 | 41.4 ± 0 | 41.4 | 19.6 ± 0 | 19.6 | 0.67 | 5.8 |
| 501 | Inhaminga | 17°99’ | 35°15’ | 5 | 51.0 ± 0 | 51.0 | 22.1 ± 0 | 22.1 | 1.02 | 7.8 |
| 502 | Inhaminga | 18°10’ | 35°08’ | 15 | 44.6 ± 1.0 | 43.6–45.5 | 17.0 ± 1.7 | 15.4–18.8 | 2.34 | 19.2 |
| 503 | Inhaminga | 18°17’ | 35°05’ | 10 | 39.6 ± 5.6 | 35.7–43.6 | 13.2 ± 1.6 | 12–14.3 | 1.25 | 10.7 |
| 2 | Mavume | 22°34’ | 34°11’ | 5 | 21.0 ± 0 | 21.0 | 9.0 ± 0 | 9.0 | 0.17 | 1.9 |
| 22 | Mavume | 23°27’ | 34°31’ | 25 | 30.1 ± 9.1 | 17.2–42.5 | 11.4 ± 1.8 | 8.8–13.2 | 1.91 | 17.7 |

**Table 2.** *Cont.*

| Plot no. | Locality | Lat. S | Long. E | Stems ha$^{-1}$ | DBH, cm | | Height, m | | Basal area, m$^2$ ha$^{-1}$ | Biomass, tons ha$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Mean ± SD | Range | Mean ± SD | Range | Total | Total |
| | | | | | *Chanfuta* | | | | | |
| 3 | Tome | 22°34’ | 34°11’ | 5 | 21.0 ± 0 | 21.0 | 12.0 ± 0 | 12.0 | 0.17 | 1.9 |
| 4 | Tome | 22°34’ | 34°11’ | 5 | 18.5 ± 0 | 18.5 | 7.5 ± 0 | 7.5 | 0.13 | 1.6 |
| 5 | Tome | 22°34’ | 34°11’ | 10 | 20.8 ± 10.5 | 13.5–28.0 | 7.5 ± 0 | 7.5 | 0.38 | 4.0 |
| 6 | Tome | 22°35’ | 34°11’ | 5 | 21.0 ± 0 | 21.0 | 9.5 ± 0 | 9.5 | 0.17 | 1.9 |
| 7 | Tome | 22°35’ | 34°12’ | 15 | 29.0 ± 11.5 | 20.0–42.0 | 11.5 ± 1.8 | 9.6–13.0 | 1.09 | 10.2 |
| 8 | Tome | 22°35’ | 34°11’ | 45 | 21.6 ± 6.5 | 13.5–35.0 | 11 ± 1.9 | 8.0–14.5 | 1.79 | 18.9 |
| 9 | Tome | 22°33’ | 34°11’ | 35 | 34.1 ± 10.0 | 22.5–48.0 | 14.2 ± 1.1 | 13.0–15.5 | 3.42 | 30.2 |
| | | | | | *Jambire* | | | | | |
| 1 | Inhaminga | 18°50’ | 35°08’ | 5 | 25.2 ± 0 | 25.2 | 14.0 ± 0 | 14.0 | 0.25 | 3.1 |
| 4 | Inhaminga | 18°06’ | 35°15’ | 10 | 28.8 ± 2.0 | 27.4–30.3 | 16.3 ± 1.8 | 15.0–17.6 | 0.65 | 7.7 |
| 6 | Inhaminga | 18°09’ | 35°09’ | 15 | 41.2 ± 5.5 | 35.0–45.5 | 21.8 ± 6.2 | 18.1–28.9 | 2.02 | 19.4 |
| 8 | Inhaminga | 18°05’ | 35°09’ | 20 | 25.7 ± 6.8 | 16.6–33.1 | 15.5 ± 4.5 | 9.0–19.0 | 1.09 | 13.2 |
| 10 | Inhaminga | 18°07’ | 35°09’ | 5 | 35.0 ± 0 | 35.0 | 16.0 ± 0 | 16.0 | 0.48 | 5.1 |
| 11 | Inhaminga | 18°05’ | 35°16’ | 5 | 31.8 ± 0 | 31.8 | 18.8 ± 0 | 18.8 | 0.40 | 4.4 |
| 15 | Inhaminga | 17°99’ | 35°15’ | 5 | 38.2 ± 0 | 38.2 | 13 ± 0 | 13.0 | 0.57 | 5.8 |
| 27 | Inhaminga | 18°05’ | 35°06’ | 5 | 16.2 ± 0 | 16.2 | 7.0 ± 0 | 7.0 | 0.10 | 1.7 |
| 29 | Inhaminga | 18°09’ | 35°11’ | 55 | 26.9 ± 12.7 | 13.4–44.6 | 17.6 ± 2.8 | 11.0–20.2 | 3.75 | 40.6 |
| 34 | Inhaminga | 18°14’ | 35°08’ | 10 | 34.1 ± 1.4 | 33.1–35.0 | 13 ± 1.4 | 12.0–14.0 | 0.91 | 9.9 |
| 36 | Inhaminga | 18°20’ | 35°12’ | 5 | 32.5 ± 0 | 32.5 | 12.9 ± 0 | 12.9 | 0.41 | 4.7 |
| 37 | Inhaminga | 18°24’ | 35°13’ | 5 | 42.4 ± 0 | 42.4 | 16.3 ± 0 | 16.3 | 0.70 | 6.7 |
| 38 | Inhaminga | 18°21’ | 35°10’ | 10 | 21.5 ± 2 | 20.1–22.9 | 14.9 ± 1.3 | 13.9–158 | 0.36 | 5.0 |
| 39 | Inhaminga | 18°23’ | 35°13’ | 20 | 23.7 ± 9.9 | 13.7–33.4 | 10.1 ± 4.8 | 6.0–14.6 | 1.00 | 12.1 |
| 41 | Inhaminga | 18°13’ | 35°09’ | 5 | 65.0 ± 0 | 65.0 | 13 ± 0 | 13.0 | 1.66 | 12.5 |
| 42 | Inhaminga | 18°21’ | 35°11’ | 10 | 25.6 ± 6.5 | 21.0 ‒ 30.3 | 18.2 ± 0.7 | 17.7–18.7 | 0.53 | 6.5 |
| 43 | Inhaminga | 18°09’ | 35°25’ | 5 | 55.1 ± 0 | 55.1 | 19.5 ± 0 | 19.5 | 1.19 | 9.9 |
| 101 | Inhaminga | 18°01’ | 35°08’ | 10 | 33.4 ± 27.0 | 14.3–52.5 | 15.5 ± 6.4 | 10.9–20.0 | 1.16 | 10.6 |
| 501 | Inhaminga | 17°59’ | 35°09’ | 30 | 34.3 ± 8.9 | 24.5–46.2 | 17.3 ± 2.6 | 14.0–21.3 | 2.92 | 30.2 |
| 502 | Inhaminga | 18°10’ | 35°08’ | 20 | 36.5 ± 5.1 | 31.2–43.3 | 16.9 ± 6.8 | 10.3–25.8 | 2.12 | 21.7 |
| | | | | | *Umbila* | | | | | |
| 1 | Mavume | 23°37’ | 34°29’ | 25 | 20.6 ± 7.3 | 11.0–28.5 | 10.3 ± 3.1 | 6.8–13.4 | 0.92 | 4.2 |
| 10 | Mavume | 23°37’ | 34°30’ | 15 | 24.3 ± 7.6 | 17.5–32.5 | 9.8 ± 3.3 | 7.2–13.5 | 0.74 | 3.5 |
| 11 | Mavume | 23°37’ | 34°30’ | 40 | 24.6 ± 10.4 | 14.5–42.0 | 11.2 ± 2.5 | 8.5–16.2 | 2.20 | 10.6 |
| 12 | Mavume | 23°37’ | 34°30’ | 35 | 28.0 ± 13.2 | 10.0–44.5 | 8 ± 3.1 | 3.8–11.0 | 2.56 | 12.6 |
| 13 | Mavume | 23°37’ | 34°30’ | 10 | 22.8 ± 18.0 | 10.0–35.5 | 6.9 ± 1.6 | 5.8–8.0 | 0.53 | 2.6 |
| 14 | Mavume | 23°37’ | 34°37’ | 10 | 22.5 ± 7.8 | 17.0–28.0 | 8.5 ± 2.8 | 6.5–10.4 | 0.42 | 2.0 |
| 15 | Mavume | 23°37’ | 34°30’ | 10 | 25.0 ± 12.7 | 16.0–34.0 | 10.5 ± 5.7 | 6.5–14.5 | 0.55 | 2.7 |
| 16 | Mavume | 23°37’ | 34°30’ | 10 | 27.5 ± 3.5 | 25.0–30.0 | 7.9 ± 4.7 | 4.6–11.2 | 0.60 | 2.8 |
| 17 | Mavume | 23°37’ | 34°30’ | 50 | 21.6 ± 9.9 | 13.5–42.0 | 8.2 ± 2.3 | 4.5–11.6 | 2.18 | 10.4 |
| 18 | Mavume | 23°37’ | 34°30’ | 20 | 12.6 ± 1.3 | 11.0–14.0 | 6.3 ± 0.6 | 5.5–7.0 | 0.25 | 1.0 |
| 20 | Mavume | 23°37’ | 34°30’ | 5 | 16.0 ± 0.0 | 16.0 | 6.5 ± 0 | 6.5 | 0.10 | 0.4 |
| 21 | Mavume | 23°37’ | 35°30’ | 15 | 22.8 ± 5.5 | 17.0–28.0 | 7.7 ± 1.2 | 6.5–8.5 | 0.64 | 3.0 |
| 35 | Inhaminga | 18°25’ | 35°13’ | 5 | 25.5 ± 0.0 | 25.5 | 12.0 ± 0 | 12.0 | 0.25 | 1.2 |
| 36 | Inhaminga | 18°20’ | 35°12’ | 5 | 14.3 ± 0.0 | 14.3 | 8.5 ± 0 | 8.5 | 0.08 | 0.3 |
| 40 | Inhaminga | 18°14’ | 35°07’ | 5 | 46.5 ± 0.0 | 46.5 | 12.0 ± 0 | 12.0 | 0.85 | 4.4 |

### *3.2. Sample Tree Characterization*

For all species, the percentage of the total dry weight as stem material ranged from 46% to 77%; as branches from 22% to 51%; and as leaves from 1% to 3%. Jambire trees had the highest mean dry weight (kg $tree^{-1}$) (1016 ± 438, range 411–2086) compared with Chanfuta (864 ± 548, range 107–2018) and Umbila (321 ± 240, range 52–1121) (Tables 3 and 4). The proportion of the fresh weight of tree material as dry weight varied between the tree components and between species. Between tree components the proportion of fresh weight as dry weight was 52% to 56% for stems; 46% to 51% for branches and 29% to 50% for leaves (Tables 3 and 4).

**Table 3.** Fresh weight of tree components and their proportional composition.

| | | | Fresh weight (kg $tree^{-1}$) | | | Percentage of total fresh weight. % | | |
|---|---|---|---|---|---|---|---|---|
| | **DBH,cm** | **Total** | **Stem** | **Branches** | **Leaves** | **Stem** | **Branches** | **Leaves** |
| | | | *Chanfuta* (*n = 24*) | | | | | |
| Mean ± SD | 33.8 ± 12.6 | 1563 ± 928 | 970 ± 838 | 552 ± 339 | 42 ± 43 | 51 ± 26 | 45 ± 25 | 4 ± 3 |
| Range | 13.5–61.1 | 221–3018 | 28–2882 | 111–1187 | 0–47 | 6–96 | 4–90 | 0–10 |
| | | | *Jambire* (*n = 15*) | | | | | |
| Mean ± SD | 34.8 ± 8.2 | 1840 ± 651 | 1389 ± 473 | 423 ± 250 | 28 ± 21 | 76 ± 9 | 22 ± 9 | 2 ± 1 |
| Range | 21.0–52.2 | 750–3504 | 536–2489 | 94–981 | 5–78 | 64–94 | 5–36 | 0–4 |
| | | | *Umbila* (*n = 19*) | | | | | |
| Mean ± SD | 27.0 ± 9.5 | 630 ± 400 | 276 ± 231 | 339 ± 221 | 14 ± 10 | 42 ± 18 | 54 ± 17 | 3 ± 4 |
| Range | 14.0–46.5 | 140–1785 | 34–946 | 57–820 | 3–38 | 14–87 | 12–84 | 1–18 |

### *3.3. Biomass Equation for Individual Trees*

Parameters were estimated in a nonlinear from. In many reports nonlinear form has been used which means that the error might be multiplicative cf. [45,51–53]. A common technique is to calculate the parameters by linear regression of the logarithmic transformed data. The power Equation (3) fitted the data relating AGB to DBH as such, only this equation is described in Table 5. The value of the coefficient of determination ($R^2$) indicated a good correlation between the fitted curves and the estimated values for total and stem data. The correlation between fitted curves for branches and leaves is lower especially for leaves of Chanfuta. Further information about parameter estimates is given in Table 5. Equations (4–6) improved the determination coefficient for total ABG for Umbila: $ABG_{Total} = 3.1082 \times D^{2.0212} \times 0.0303^{Bd}$, $R^2 = 0.96$, RMSE = 88.58, $ABG_{Total} = 0.1490 \times (Bd \times D^2 \times H)^{0.8954}$, $R^2 = 0.88$, RMSE = 147.1 and $ABG_{Total} = (1.0030 - 1.0567 \times Bd) \times D^{2.0390}$, $R^2 = 0.95$, RMSE = 93.06 respectively but not for the other species. Average biomass for tree components showed that the equations overestimated biomass for Chanfuta and underestimated for Jambire and Umbila, Table 5. The percentage AB by observed biomass component means ranged between 0% and 6% and for leaves for Chanfuta 16%. A bias test on equations 4-6 for total biomass for Umbila trees showed AB values between −19.0 and −83.1, which is higher than for the preferred equation. The greater difference between AAB and RMSE for Chanfuta equations than for Jambire and Umbila indicates greater variation in errors in the sample.

**Table 4.** Dry weight of tree components and their proportional composition.

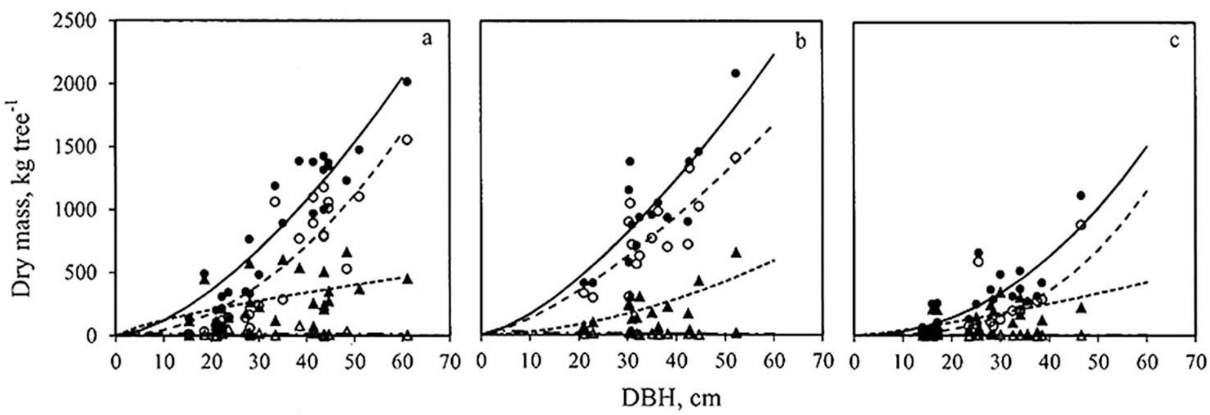
| | | **Dry weight (kg tree$^{-1}$)** | | | | **Percentage of total dry weight. %** | | | **Percentage dry weight by fresh weight** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | DBH, cm | Total | Stem | Branches | Leaves | Stem | Branches | Leaves | Stem | Branches | Leaves |
| *Chanfuta* (*n = 24*) | | | | | | | | | | | |
| Mean ± SD | 33.8 ± 12.6 | 864 ± 548 | 569 ± 524 | 280 ± 187 | 15 ± 19 | 54 ± 27 | 43 ± 26 | 3 ± 4 | 56 ± 7 | 50 ± 9 | 29 ± 19 |
| Range | 13.5–61.1 | 107–2018 | 14–1956 | 57–667 | 0–77 | 6–97 | 3–92 | 0–16 | 36–75 | 29–65 | 0–70 |
| *Jambire* (*n = 15*) | | | | | | | | | | | |
| Mean ± SD | 34.8 ± 8.2 | 1016 ± 438 | 782 ± 341 | 222 ± 161 | 11 ± 7 | 77 ± 11 | 22 ± 10 | 1 ± 1 | 56±13 | 51 ± 8 | 43 ± 14 |
| Range | 21.0–52.2 | 411–2086 | 296–1412 | 42–659 | 1–27 | 53–96 | 3–44 | 0–3 | 21–77 | 35–67 | 18–2 |
| *Umbila* (*n = 19*) | | | | | | | | | | | |
| Mean ± SD | 27.0 ± 9.5 | 321 ± 240 | 152 ± 140 | 162 ± 133 | 7 ± 5 | 46 ± 22 | 51 ± 21 | 3 ± 4 | 52 ± 5 | 46 ± 13 | 50 ± 4 |
| Range | 14.0–46.5 | 52–1121 | 16–96 | 16–516 | 1–17 | 13–92 | 6–84 | 1–17 | 45–66 | 5–63 | 42–60 |

**Table 5.** Estimated parameters of the fitted power Equation (3) for AGB estimations of Chanfuta, Jambire, and Umbila.

| Components | Parameter estimates | AB | AAB | $R^2$ | RMSE |
|---|---|---|---|---|---|
| | *Chanfuta* | | | | |
| Total | $3.1256 \times D^{1.5833}$ | −10.6 | 159.8 | 0.97 | 194.37 |
| Stem | $0.4369 \times D^{2.0033}$ | −20.0 | 171.6 | 0.91 | 227.90 |
| Branches | $22.7577 \times D^{0.7335}$ | −0.1 | 15.0 | 0.79 | 168.19 |
| Leaves | $19.9625 \times D^{-0.0836}$ | 2.1 | 13.2 | 0.40 | 19.14 |
| | *Jambire* | | | | |
| Total | $5.7332 \times D^{1.4567}$ | 49.5 | 250.0 | 0.95 | 256.83 |
| Stem | $4.8782 \times D^{1.4266}$ | 43.5 | 217.6 | 0.94 | 220.25 |
| Branches | $0.3587 \times D^{1.8091}$ | 10.3 | 90.7 | 0.78 | 142.48 |
| Leaves | $77.0114 \times D^{-0.5511}$ | −0.7 | 6.3 | 0.72 | 4.09 |
| | *Umbila* | | | | |
| Total | $0.2201 \times D^{2.1574}$ | 9.6 | 103.8 | 0.89 | 140.69 |
| Stem | $0.0083 \times D^{2.8923}$ | −1.6 | 23.1 | 0.95 | 51.43 |
| Branches | $2.3596 \times D^{1.2690}$ | 3.7 | 96.0 | 0.70 | 120.68 |
| Leaves | $4.0400 \times D^{0.1680}$ | 0.0 | 3.3 | 0.71 | 4.71 |

The above presented equations are species-specific for the studied species. However as data for Jambire were sampled from one site the fitted model also could be site-species-specific. Samples from the other two species were pooled together to build stronger species-specific equations as these did not show out-layers that could justify developing different equations for the different sites (see also Figure 3).

**Figure 3.** Dry mass per tree (kg tree$^{-1}$) in relation to DBH (mm), of total (—— ●), stem (- - - ○) branches (---- ▲) and leaves (– · – △) for samples of Chanfuta (**a**), Jambire (**b**), and Umbila (**c**).




### *3.4. Biomass Estimates at Plot and Stand Level*

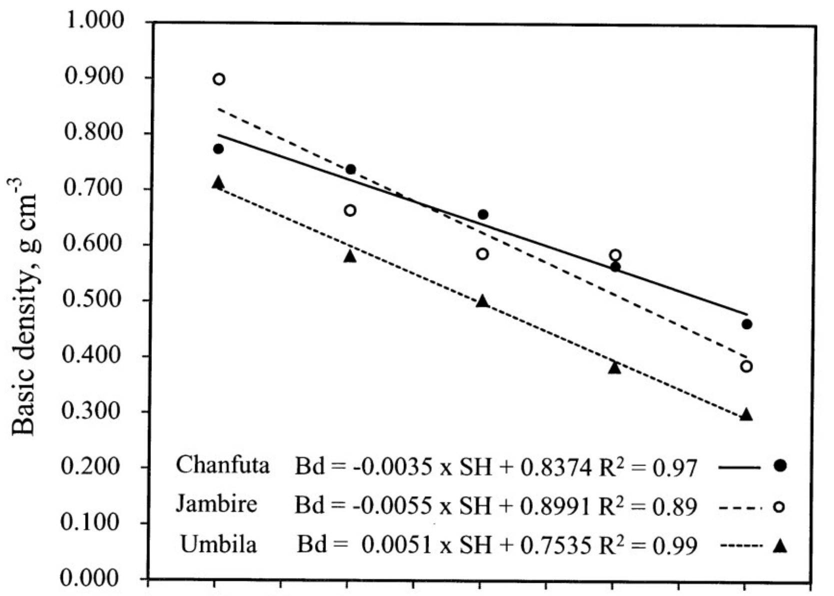
The Equation (3) developed in the study was used, Table 5. Detailed results of individual plot biomass are shown in Table 2. The mean biomass per plot for Chanfuta, Jambire and Umbila was 9.9, 11.8 and 4.1 tons ha$^{-1}$ respectively. The mean biomass per locality was similar for Chanfuta presenting in Inhaminga 9.9 tons ha$^{-1}$ and 9.8 tons ha$^{-1}$ in both Mavume and Tome localities. The mean biomass of Umbila in Mavume (4.6 tons $ha^{-1}$) represented more than a double of Inhaminga (2 tons $ha^{-1}$). Differences between sites should be used with caution as some species had lower representation in specific sites, influencing the results.

The biomass for all species surveyed at plot level was computed using a generic equation ($ABG_{Total} = 0.056 \times D^{2549}$ $R^2 = 93.7$, $p = 0.0918$, $n = 31$) developed for Miombo forest species by Tomo [54]. Results indicated an average total biomass of 27.3 tons $ha^{-1}$ of which studied species shared 94.6% of total biomass.

### *3.5. Basic Density*

The mean basic density (g $cm^{-3}$) at breast height was 0.781 ± 0.074 (range 0.606–0.952) for Chanfuta, 0.841 ± 0.029 (range 0.786–0.889) for Jambire and 0.636 ± 0.090 (range 0.500–0.769) for Umbila. Basic density varied along the stem height. The mean basic density for the stem at different stem heights was plotted and linear curves were fitted. The stem basic density decreased from base to top for all species. All species had high coefficient of determination (Figure 4).

**Figure 4.** Basic density (Bd) variation along tree stem.




## 4. Discussion

### *4.1. Biomass Equations*

The power equation fit the data well and the determination coefficients were >0.70 (range 0.70–0.97). Statistics of the fitted equations for the estimation of stem, branches and total biomass are given in Table 5. The power equation best fitted the data for total and stem biomass. In general correlation between fitted parameters for branches and leaves was lower especially for leaves of Chanfuta ($R^2 = 0.40$). When predicting tree biomass, total above ground and stem biomass are more stable than that of more short-lived branches and leaves [46]. The parameters of the presented power equations were calculated using a nonlinear form of regression. A calculation by a linear regression when the equation was expressed in a logarithmic form, did not improve the accuracy of error estimate. Basic density incorporated in the power equation predicted the total biomass for Umbila tree well ($R^2$ = 0.95–0.97, RMSE = 88–147) but not for the other species. DBH is the most commonly used predictor variable. Tree height is more timewasting to measure [46]. As the power equation with DBH fitted the data well we suggest this equation for prediction of tree biomass components for the studied species.

The equations presented in the present study are species-specific. Based on the DBH and biomass distribution in Figure 3, the sampled individual trees species from different sites show a similar pattern. Data for Jambire were sampled from one locality and the fitted models also could be used as site-specific. Species and site-specific allometric models are most accurate for quantifying tropical forests biomass [27,30,55–57] and also enable capturing architectural variation among trees of a certain species [58]. The species-specific equations developed in the present study provided information regarding spatial and temporal variability of biomass for the studied species in Mozambique, comparatively to generic regional equation by Tchaúque [59] and Tomo [54]. Research should be carried out for the development of site-specific equation for more accurate estimates of biomass at regional level, taking into account climate variations, forest type and other relevant factors.

### *4.2. Biomass Distribution*

In the present study stems of Chanfuta and Jambire contained more biomass than the branch and leaf components, but for Umbila the branch biomass was higher than stem biomass (Tables 3 and 4). Biomass allocation among tree components for Umbila is common for Miombo woodlands tree species. Geldenhuys and Goldings [60] reported that more than 50% of the timber in woodlands is branch biomass. The stem component for Chanfuta and Jambire contributed most of the biomass, which is not typical for Miombo species. It might be influenced by the harvesting activities that have changed the structure and composition of the stands. Ribeiro *et al.* [61] reported similar pattern in Miombo woodlands where change to shrub forest type was a driving factor for allocation of biomass among tree components. Henry *et al.* [62] found percentage stem biomass (69%) to be higher than for branch (27%) and leaf (4%). Chamshama *et al.* [63] found a significantly higher percentage biomass for branches than stems among species in the Miombo woodland stands. The umbrella-shaped crown, which is characteristic of the Miombo, makes a major contribution to the branch volume for these species [64,65]. Segura and Kanninen [66] found that the distribution of biomass among different tree components might be related to the site conditions where the trees are growing. In dense forests with strong competition for light and space, the trees tend to develop smaller branches and foliage biomass than in open forest types [66,67].

In the studied stands there low density of Chanfuta, Jambire, and Umbila compared to other species found in the area (Table 1). Nevertheless for Inhaminga locality the results obtained are higher that recorded average for the province of Sofala based on the National inventory report by Marzoli [2]. The referred report pointed that Chanfuta and Jambire had around 6 and 5 stems $ha^{-1}$, while in the present study 8 and 13 stems $ha^{-1}$ were found (Table 1). In addition, Umbila species is classified as having less than 1 $m^3$ $ha^{-1}$ and therefore not presented the figure in the report. However, in the present study 5 stems $ha^{-1}$ was found. Different sampled plots considered and scattered distribution might be behind the differences. For the localities of Tome and Mavume higher records compared to Marzoli's report were found for the Chanfuta and Umbila species present in the area. The same report recorded around 5 stems $ha^{-1}$ for Chanfuta but no reference for Umbila due the reasons stated above.

The biomass of the studied species at plot was 9.9, 11.8 and 4.1 tons $ha^{-1}$ for Chanfuta, Jambire and Umbila respectively. Generic equation by Tomo [54] showed an average total of 27.3 tons $ha^{-1}$ biomass a stand level, where the studied species accounted the most in the total biomass. The yielded result at stand level is in accordance with other studies conducted in Miombo forest in Mozambique with biomass ranging from 17.1 to 64.2 tons $ha^{-1}$ [59] and 20.9 tons $ha^{-1}$ in dry Miombo forest in Zambia [68]. Values indicating higher biomass in Miombo forest of 67.2 tons $ha^{-1}$ [31], and from 48.8 to 130.3 tons $ha^{-1}$ according to Tomo [54] are presented. The biomass at stand level is considered as an indicative value, as comparison between studies is limited and the present equations adopted were developed in a different location, with use of different methodologies and years. The stands in the present study were surveyed in areas that were subject for harvesting activities.

Species density in the study area is considered to be related to selective logging practices that took place in the areas that is focused in the three studied species. Chanfuta, Jambire and Umbila account for 78% of commercialized volume in Mozambique [2,6]. Visited stands should be harvested later on according to forest concession and forest authorities when cutting cycle is completed. Availability of logging residues will therefore be related to commercial volume and changes in market demand of specific timber species. Harvest of forest residues in general is considered to have no impact on species abundance directly as the residues are by-product of harvesting operations. Sitoe *et al.* [69] reported that even though selective commercial logging is performed in unsustainable way in Mozambique, is of lower impact in ecosystem changes when compared to fuel wood harvesting. Uncontrolled fires and selective harvesting have reduced species diversity and biomass availability. Recent studies by Cuvilas *et al.* [24] and Ali *et al.* [70] have characterized up to eight lesser-known species to be used as timber and energy raw material. Nevertheless their use is expected to be in long-term as they still need large dissemination efforts and market development.

### *4.3. Basic Density*

In the present study basic density differed both between and within trees species. Umbila presented lowest basic density (0.636 g $cm^{-3}$) and Jambire the highest (0.841 g $cm^{-3}$). Variation among species in the density of their wood is closely related to variation in light demand [71,72]. Miombo species are semi-light demanding Geldenhuys and Goldings [60]. Wood density is negatively associated with growth rate [73–75]. As Miombo woodlands species are slow growing [76] the studied species are considered as medium to high basic density. Regarding variation of basic density along the stem height, it was observed a decreasing trend from base to top. Similar findings were reported for pine and oak trees of Northern Mexico [77,78] and for other tropical species in Mozambique, Ncurri (*Icuria dunensis* Wieringa) and Ntholo (*Pseudolachnostylis maprounaefolia* Paxthe) [70]. Higuchi *et al.* [79] found a similar trend among moist forest species in the Central Amazon. A study of 12 species in humid forests in Manaus, Brazil, found that basic density decreased by around 9.7% from breast height to the top of the commercial bole, just below the first branch [80]. Yet another study of 14-year-old *Patria gigantocarpa* growing in Brazil, found that the basic density decreased with increasing tree height [81]. That behaviour can be associated with higher compaction of the stump tissues exerted by overlapping cells along the bole and tree crown as reported by Ali *et al.* [70]. In a study of 16-year-old *Eucalyptus regnans* growing in Chile, basic density decreased from the base to 4.5% of the stem height, and then increased linearly up to a height at 70% of the tree's total height [82].

## 5. Conclusions

This study has estimated the biomass content of three of the most valuable native trees species in Mozambican forest sector, Chanfuta, Jambire, and Umbila, in order to support estimates of woody biomass residues derived from logging activity and which can be used for generating bioenergy. Power equation using DBH as independent variable fitted the data best and is suggested to be used for estimating tree biomass components in similar studies due to its simplicity and easy to measure with accuracy the variable in the field. Combination of diameter, basic density or combination of the two variables with tree height improved the determination coefficient and RMSE for total ABG for Umbila.

Jambire species had the highest mean tree dry weight, 1016, Chanfuta, 864, and Umbila 334 kg tree$^{-1}$. A similar pattern was found at plot level; Chanfuta 9.9; Jambire 11.8, and Umbila 4.1 tons ha$^{-1}$.

The stem component contributed the greatest proportion of the total tree biomass for Chanfuta and Jambire, while branches contributed the most for Umbila.

The basic density differed between and within trees species. At breast height Umbila had a mean basic density of 0.636, Jambire 0.841, and Chanfuta, 781 g cm$^{-3}$ and along stem height for all species, have decreased from the bottom to the top of the stem.

Studied species show to be potential source of logging residues from branches as well as fraction of the stem. However proportion of stem wood residues will be defined by stem quality for timber. Further research into specific biomass and growth rates for each species is needed in order to better evaluate the implications that cutting rotations might have on the sustainable management of forests to which Mozambique is committed.

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## Author Contributions

The study contains two main parts: field work with sampling of tree components and an analyzing part. Mate conceptualized the research design, site selection, conducted the field data collection, processing and analysis, and performed the laboratory analysis. Johansson assisted with research design, statistical analysis and writing. Sitoe took part in the research design and discussion of the results of the manuscript.

## Conflicts of Interest

The authors declare no conflict of interest.

## References

1. *Global Forest Resources Assessment*; 2010 Main Report; FAO Forestry Paper 163; FAO: Rome, Italy, 2012; p. 60.
2. Marzoli, A. National Forest Inventory; In *Integrated Forest Assessment of Mozambique (AIFM), Maputo*; National Directorate of Land and Forest (DNTF)-Ministry of Agriculture: Maputo, Mozambique, 2007; p. 92.
3. Brouwer, R.; Falcão, M.P. Wood fuel consumption in Maputo, Mozambique. *Biomass Bioenergy* **2004**, *27*, 233–245.
4. National Directorate of Forest and Wildlife (DNFFB). Regulation for the forestry and wildlife policy. *Govern. Bull*. **2002**, *1*, 25.
5. Fath, H. Commercial Timber harvesting in the natural forest of Mozambique. In *FAO Forest Harvesting: Case Study*; Food and Agricultural Organization of the United Nations: Rome, Italy, 2001; p. 50.
6. *Annual Statistic Report*; National Directorate of Land and Forestry (DNTF): Maputo, Mozambique, 2010, p. 21.
7. Hoogwijk, M.; Faaij, A.; van den Broek, R.; Berndes, G.; Gielen, D.; Turkenberg, W. Exploration of the ranges of the global potential of biomass for energy. *Biomass Bioenergy* **2003**, *25*, 119–133.
8. Richardson, J.; Bjorheden, R.; Hakkila, P.; Lowe, A.T.; Smith, C.T. *Bioenergy from Sustainable Forestry: Guiding Principles and Practice-Kluwer*; Academic Publishers: Dordrecht, The Netherlands, 2002; p. 344.
9. Wyk, B.V.; Wyk, P.V. *Field Guide to Trees of Southern Africa*; Struik Publisher: Cape Town, South Africa, 1997; p. 525.
10. Danida Forest Seed Center (DFSC). Afzelia Quanzensis Welw. *Seed Leafl.* **2000**, *31*, 2.
11. Gomes e Sousa, A. Dendrology of Mozambique: A General Study. In *Memories*; Institute of Agrarian Research of Mozambique: Maputo, Mozambique, 1966; pp. 1–822.
12. Hines, D.A.; Eckman, K. *Indigenous Multipurpose Trees of Tanzania: Uses and Economic Benefits For People*; Cultural Survival Canada and Development Services Foundation of Tanzania & Tree Roots Canada: Ottawa, Canada, 1993.
13. Bunster, J.H. *52 Woods of Mozambique "52 Madeiras de Moçambique": Technologic Cathalogue*; UEM/FAEF/Forestry Department: Maputo, Mozambique, 1995; pp. 1–80.
14. Edinburgh Centre for Carbon Management (ECCM). *Technical Specification*; Mozambique Technical Specification Boundary Planting: Edinburgh, UK, 2005; p. 8.
15. Woodcrafters Association of Durban (WAD). Wood of the month. *Newsl. Woodcrafters Assoc. Durb. Issue* **2005**, *15*, 9.
16. Lemmens, R.H.M.J. *Millettia stuhlmannii* Taub. In *Timbers/Bois d'œuvre 1*; [CD-Rom]; Louppe, D., Oteng-Amoako, A.A., Brink, M., Eds.; Plant Resource of Tropical Africa (PROTA): Wageningen, The Netherlands, 2008.

17. Therrell, M.D.; Stahle, D.W.; Mukelabai, M.M.; Shugart, H.H. Age and radial growth dynamics of *Pterocarpus angolensis* in Southern Africa. *For. Ecol. Manag*. **2007**, *244*, 24–31.
18. Fichtler, E.; Trouet, V.; Beeckman, H.; Coppin, P.; Worbes, M. Climatic Signals in Tree Rings of *Burkea Africana* and *Pterocarpus Angolensis* from semiarid forests in Namibia. *Trees* **2004**, *18*, 442–451.
19. Vermeulen, W.J. *A Monograph on Pterocarpus angolensis*; SARCCUS Standing Committee for Forestry: Pretoria, South Africa, 1990; p. 133.
20. Van Daalen, J.C.; Vogel, J.C.; Malan, F.S.; Fuls, A. Dating of *Pterocarpus angolensis* trees. *S. Afr. For. J*. **1992**, *162*, 1–7.
21. Shackleton, C.M. Growth patterns of *Pterocarpus angolensis* in Savannahs of the SOUTH African Lowveld. *For. Ecol. Manag*. **2002**, *166*, 85–97.
22. *Mozambique Biomass National Strategy*; Final Report; Ministry of Energy: Maputo, Mozambique, 2012; p. 171.
23. Sitoe, A.; Mirira, R.; Tchaúque, F. *Assessment of Consumption levels of biomass energy in Tete, Nampula, Zambézia, Sofala, Gaza and Maputo Provinces. Ministry of Energy/Faculty of Agronomy and Forestry Engineering*; Ministry of Energy: Maputo, Mozambique, 2007; p. 50.
24. Cuvilas, C.A.; Llate, I.; Jirjis, R.; Terziev, N. The characterization of wood species from Mozambique as a fuel. *Energy Sources. Part A* **2014**, *36*, 851–857.
25. Gillespie, A.J.; Brown, S.; Lugo, A.E. Tropical forest biomass estimation from truncated stand tables. *For. Ecol. Manag.* **1992**, *48*, 69–87.
26. Návar-Cháidez, J.J. Allometric equations and expansion factors for tropical dry forest trees of eastern Sinalo, Mexico. *Trop. Subtrop. Agroecossystems* **2009**, *10*, 45–52
27. Brown, S.; Gillespie, A.J.; Lugo, A.E. Biomass estimation methods for tropical forests with applications to forest inventory data. *For. Sci*. **1989**, *35*, 881–902.
28. Chambers, J.Q.; dos Santos, J.; Ribeiro, R.J.; Higuchi, N. Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. *For. Ecol. Manag*. **2001**, *152*, 73–84.
29. Chavé, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q.; Eamus, D.; Fölster, H.; Fromard, F.; Higuchi, N.; Kira, T.; *et al.* Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* **2005**, *145*, 87–99.
30. Návar, J. Measurement and assessment methods of forest aboveground biomass: a literature review and challenges ahead. In *Biomass*; Momba, M., Bux, F., Eds.; Sciyo: Rijeka, Croatia, 2010; pp. 27–64.
31. Frost, P. The ecology of miombo woodlands. In *The Miombo in Transition: Woodlands and Welfare in Africa*; Campbell, B.M., Eds.; Center for International Forestry Research: Bogor, Indonesia, 1996; pp. 11–55.
32. Lawton, R.M. Natural resources of miombo woodland and recent changes in agricultural and land-use practices. *For. Ecol. Manag.* **1982**, *4*, 287–297.
33. Chidumayo, E.N. Above-ground woody biomass structure and productivity in Zambezian woodlands. *For. Ecol. Manag*. **1990**, *36*, 33–46.
34. Mozambique National Institute of Statistics. Available online: http//www.ine.gov.mz/pt/Data analysis (assessed on 15 May 2013).

35. Brown, S.; Lugo, A.E. Aboveground biomass estimates for tropical moist forests of the Brazilian Amazon. *Interciencia* **1992**, *1*, 8–18.
36. Parresol, B.R. Assessing tree and stand biomass: A review with examples and critical comparisons. *For. Sci.* **1999**, *45*, 575–593.
37. Pearson, T.; Walker, S.; Brown, S. *Sourcebook for Land Use, Land-Use Change and Forestry Project*; BioCarbon Fund WinRock International: Bryssels, Belgium, 2005.
38. Johansson, T.; Karacic, A. Increment and biomass in hybrid poplar and some practical implications. *Biomass Bioenergy* **2011**, *35*, 1925–1934.
39. Grundy, I.M. Wood biomass estimation in dry miombo in Zimbabwe. *For. Eco. Manag.* **1995**, *72*, 109–117.
40. Kittredge, J. Estimation of the amount of foliage of trees and stands. *J. For*. **1944**, *42*, 905–912.
41. Payandeh, B. Choosing regression models for biomass prediction models. *For. Chron*. **1981**, *57*, 229–232.
42. Satoo, T.; Madgewick, H.A.I. *Forest Biomass*; Martinus Nijhoff/DR W. Junk. Publishers: London, UK, 1985; p. 23.
43. Bolstad. P.V.; Gower. S.T. Estimation of leaf area index in fourteen southern wisconsin forests stands using a portable radiometer. *Tree Physiol.* **1990**, *7*, 115–124.
44. Johansson, T. Biomass equations for determining fractions of pendula and pubescent birches growing on abandoned farmland and some practical implications. *Biomass Bioenergy* **1999**, *16*, 223–238.
45. Návar-Cháidez, J.; Rodríguez-Flores, F.J.; Domínguez-Calleros, P.A. Allometric equations for tropical trees: Application of forest inventory of Sianloa, México. *Agron. Mesoam.* **2013**, *24*, 347–356.
46. Návar, J. Allometric equations for tree species and carbon stocks for forests of north-western Mexico. *For. Ecol. Manag*. **2009**, *257*, 427–434.
47. Andersson, E.; Tuimala, A. *Definitioner, mm, vid vedundersökningar* (*Definitions for Wood Technology*) (in Swedish); The Nordic Joint Group in Wood Technology Research Note, No. 4; Joint Group for Wood Technology and Producers: Ås, Norway, 1980; pp. 53–66.
48. *SAS*, Version 9.1; SAS Institute Inc.: Cary, NC, USA, 2006.
49. Zar, J.H. *Biostatistical Analysis*; Prentice-Hall: Englewood Cliffs, NJ, USA, 1999.
50. Parresol, B.R.; Hotvedt, J.E.; Cao, Q.V. A Volume and taper prediction system for bald cypress. *Can. J. For. Res. Res.* **1987**, *17*, 250–259.
51. Verwijst, T.; Telenius, B. Biomass estimation procedures in short rotation forestry. *For. Ecol. Manag*. **1999**, *121*, 137–146.
52. Karacic, A.; Verwijst, T.; Weih, M. Above-ground woody biomass production of short-rotation *Populus* plantations on agricultural land in Sweden. *Scand. J. For. Res.* **2003**, *18*, 427–437.
53. Zewdie, M.; Olsson, M.; Verwijst, T. Above-ground biomass production and allometric relations of *Eucalyptus Globulus* Labill. coppice plantations along a consequence in the central highlands Of Ethiopia. *Biomass Bioenergy* **2009**, *33*, 421–428.
54. Tomo, F.A. *Estimates of Carbon Stock in Miombo Forest in Gondola District*; Faculty of Agronomy and Forestry Engineering: Maputo, Mozambique, 2012; p. 63.

55. Chave, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q.; Eamus, D.; Fölster, H.; Fromard, F.; Higuchi, N.; Kira, T.; *et al.* Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* **2005**, *145*, 87–99.
56. Litton, C.M.; Kauffman, J.B. Allometric models for predicting aboveground biomass in two widespread woody plants in Hawaii. *Biotropica* **2008**, *40*, 313–320.
57. Henry, M.; Picard, N.; Trotta, C.; Manlay, R.J.; Valentini, R.; Bernoux, M.; Saint-André, L. Estimating tree biomass of Sub-Saharan African forests: A review of available allometric equations. *Silva Fenni*. **2011**, *45*, 477–569.
58. Ketterings, Q.M.; Coe, R.; van Noordwijk, M.; Ambagau, Y.; Palm, C.A. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *For. Eco. Manag.* **2001**, *146*, 199–209.
59. Tchaúque, F.D.D.L.J. *Assessment of Aboveground Biomass in Beira Corridor*; Faculty of Agronomy and Forestry Engineering: Maputo, Moçambique, 2004; p. 49.
60. Geldenhuys, C.J.; Golding, J.S. Resource use activities, conservation and management of natural resources of African Savannas. In *Savannas: Challenges and Strategies for Equilibrium between Society and Agribusiness and Natural Resources*; Faleiro, F.G., Lopez, A., Neto, D., Eds.; Embrapa Cerrados: Brasilia, Brazil, 2008; pp. 225–260.
61. Ribeiro, N.S.; Shugart, H.H.; Washington-Allen, R. The effects of fire and elephants on species composition and structure of the Niassa Reserve, northern Mozambique. *For. Ecol. Manag*. **2008**, *255*, 1626–1636.
62. Henry, M.; Besnard, A.; Asante, W.A.; Eshun, J.; Adu-Bredu, S.; Valentini, R. Woody density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. *For. Ecol. Manag*. **2010**, *260*, 1375–1386.
63. Chamshama, S.A.O.; Mugasha, A.G.; Zahabu, E. Stand biomass and volume estimation for miombo woodlands at Kitulangalo, Morogoro, Tanzania. *South. Afr. For. J.* **2004**, *200*, 59–70.
64. Abbot, P.; Lowero, J.; Werren, M. Models for the estimation of single tree volume in four miombo woodlands types. *For. Ecol. Manag*. **1997**, *97*, 25–37.
65. Nelson, B.W.; Mesquita, R.; Pereira, J.L.G.; de Souza, S.G.A.; Batisad, G.T.; Coutoe, L.B. Allometric regressions for improved estimate of secondary forest biomass in the central Amazonia, Brazil. *For. Ecol. Manag*. **1999**, *117*, 149–167.
66. Segura, M.; Kanninen, M. Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica. *Biotropica* **2005**, *37*, 2–8.
67. Murali, K.S.; Bhat, D.M.; Ravindranath, N.H. Biomass estimation equation for tropical deciduous and evergreen forests. *Int. J. Agric. Resour. Gov. Ecol*. **2005**, *1*, 81–92.
68. Chidumayo, E.; Timberlake, J.; Sawadogo, L. Distribution and characteristics of African dry forests and woodlands. In *The Dry Forests and Woodlands of Africa: Managing for products and services*; Earthscan: London,UK, 2010; pp. 11–41.
69. Sitoe, A.; Salomão, A.; Wertz-Kanounnikoff, S. *The Context of REDD+ in Mozambique: Causes, Actors and Institutions*; CIFOR Occasional Paper 76; CIFOR: Bogor, Indonesia, 2012.
70. Ali, A.M.; Chirkova, J.; Terziev, N.; Elowson, T. Physical properties of two tropical species from Mozambique. *Wood Mat. Sci. Engin.* **2010**, *5*, 151–161.

71. Givnish, T.J. Adaptation to sun and shade, a whole plant perspective. *J. Plant Phys.* **1988**, *15*, 63–92.
72. Poorter, L.; Lianes, E.; Moreno-de las Heras, M.; Zavala, M.A. Architecture of iberian canopy tree species in relation to wood density, shade tolerance and climate. *Plant Ecol.* **2012**, *213*, 707–722.
73. Enquist, B.J.; West, G.B.; Charnov, E.L.; Brown, J.H. Allometric scaling of production and life-history variation in vascular plants. *Nature* **1999**, *401*, 907–911.
74. Whitmore, T.C. Potential impact of climate change on tropical forest seedling and forest regeneration. *Clim. Chang.* **1998**, *39*, 429–438.
75. Nock, C.A.; Geihofer, D.; Rabner, M.; Baker, P.J.; Bunyavejchewin, S.; Hietz, P. Wood density and its radial variation in six canopy tree species differing in shade-tolerance in western Thailand. *Ann. Bot.* **2009**, *104*, 297–306.
76. Chidumayo, E.; Gambiza, J.; Grundy, I. Managing miombo woodlands. In *The Miombo In Transition: Woodlands and Welfare in Africa*; Campbell, B.M., Eds.; Center for International Forestry Research: Bogor, Indonesia, 1996; pp. 175–193.
77. Silva-Arredondo, F.M.; Návar-Cháidez, J.J. Estimating bole wood specific gravity in trees of temperate forest communities of northern Durango, Mexico. *Madera y Bosques* **2012**, *18*, 77–88.
78. Silva-Arredondo, F.M.; Návar-Cháidez, J.J. Biomass expansion factors in temperate forest communities of north Durango, Mexico. *Rev. Mex. Cien. For.* **2011**, *1*, 55–62.
79. Higuchi, N.; Dos Santos, J.; Ribeiro, R.F.; Minette, L.; Biot, Y. Aboveground biomass of tropical humid forest vegetation in Terra Firme, Amazonia. *Acta Amazonica* **1998**, *2*, 153–166.
80. Nogueira, E.M.; Nelson, B.W.; Fearnside, P.M. Wood density in dense forest in the central Amazonas, Brazil. *For. Ecol. Manag.* **2005**, *208*, 261–286.
81. De Miranda, M.C.; Castelo, P.A.R.; De Miranda, D.L.C.; Rondon, E.V. Physical and mechanical properties of the wood from *Parkia gigantocarpa* Ducke. *Braz. J. Wood Sci*. **2012**, *3*, 55–65.
82. Omonte, M.; Valenzuela, L. Radial and longitudinal basic density variation in 16 years old *Eucalyptus regnans* trees. *Maderas. Ciencia y Tecnología* **2011**, *13*, 211–224.