Biomass and Volume Estimates for Valuable Timber Species in Mozambique

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Abstract

Accurate aboveground biomass and stem volume estimates are crucial for the management of Mozambique's forests. This study focused on the development of aboveground biomass and stem volume equations for the three most valuable commercial timber species in Mozambique, *Afzelia quanzensis* Welm. (Chanfuta), *Milletia stuhlmannii* Taub. (Jambire) and *Pterocarpus angolensis* D.C. (Umbila). A total of 57 plots were surveyed in three localities: Inhaminga, Mavume and Tome. The diameter at breast height, commercial height, and total height was recorded for all tree species in the surveyed plots. Fifty-eight trees were sampled (24 Chanfuta, 15 Jambire, and 19 Umbila) and used to obtain biomass and volume data by means of destructive methods. Felled trees were subdivided into 5 sections by cutting at 10, 30, 50, 70 and 90% of their total stem height. The recorded data included the top and bottom diameters of each stem section, the length of each section, and the fresh weights of each section as well as the other tree fractions (i.e. branches and leaves). Sub-samples for dry weight and basic wood density determination in the lab were collected from each stem section, at breast height, and from branches and leaves. Biomass values were calculated from the ratios of the dry and fresh weights for each sub-sample. The stem volumes of the sampled trees were estimated from the volumes of the stem sections, which were in turn estimated using Smalian's formula. Biomass and volume data were fitted using non-linear power equations. Diameter at breast height was the best predictor of the total and stem biomass ($R^2 \geq 0.89$), while diameter and height best explained the stem volume data ($R^2 \geq 0.94$).

Jambire was found to have the highest biomass of the three species and Umbila the lowest. The stems of Chanfuta and Jambire accounted for the majority of their total biomass but the branches accounted for most of the biomass of Umbila. The commercial stem length accounted for between 30% and 70% of the total length, indicating that commercial logging could produce substantial quantities of biomass residues that could be used for other purposes such as the generation of bioenergy. This would reduce the need to fell forests for energy in Mozambique. Future studies focusing on site-specific biomass and volume estimates as well as annual growth estimates will be required to improve the quality of the estimates presented herein and to support the planning and utilization of Mozambique's forest resources.

Keywords: aboveground biomass, Miombo woodlands, Chanfuta, Jambire, Umbila, species-specific equations, commercial stem volume, logging residues

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Dedication

To my family, Teófilo, Dylan and Lakisha

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Mate, R., Johansson, T., Almeida S. (2014). Biomass equations for tropical tree species in Mozambique. *Forests*, 5, 535-556

II Mate, R., Johansson, T., Almeida S. (2014). Stem volume equations for valuable timber species in Mozambique. Submitted to *Journal of Sustainable Forestry* (manuscript)

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The contributions of Rosta Mate to the papers included in this thesis were:

I Performed approximately 80% of the data collection planning, data gathering, processing and analysis, and paper writing.

II Performed approximately 80% of the data collection planning, data gathering, processing and analysis, and paper writing.

Abbreviations

AGB	Aboveground Biomass
DBH	Diameter at Breast Height
DNFFB	Direcção Nacional de Florestas e Fauna Bravia “National Directorate of Forestry and Wildlife”
DNTF	Direcção Nacional de Terras e Florestas “National Directorate of Land and Forests”
FAO	Food and Agriculture Organization
INE	Instituto Nacional de Estatística “National Institute of Statistics”
MAE	Ministério da Adminsitração Estatal “Ministry of State Administration”
ME	Ministry of Energy

1 Introduction

1.1 Background

Forests provide over 9% of the total primary energy supply for cooking and/or heating to more than two billion people worldwide (FAO, 2012). Wood is the main source of fuel for about 80% of people in Africa (FAO, 2010). In Mozambique, 80% of the population lives in rural areas and is heavily dependent on forests for timber, non-timber products (NTFPs), construction materials, medicinal plants, and diverse environmental services such as eco-tourism, biodiversity conservation and carbon sequestration (Campbell et al., 2007; Nhacale et al., 2009). However, the world's tropical regions are undergoing rapid deforestation due to the harvesting of fuel wood, the reclamation of land for agricultural purposes, and timber logging (Campell *et al*, 2007; FAO, 2012). Tropical deforestation is currently a major global environmental concern (Geist and Lambin, 2002). Uncertainties regarding the extent of deforestation (Hunter et al. 2013) and the amount of standing biomass remaining (Houghton, 2005) make it difficult to assess tropical forests' effects on carbon stocks and other environmental parameters.

1.2 The Mozambican forest sector

Natural forests with the potential for timber production cover around 51% of Mozambique's land surface (Marzoli, 2007). Its forests contain 118 identified commercial timber species (DNFFB, 2002), of which only 34 are currently harvested and only 10 are well known in the domestic and international markets. The most harvested species are Jambire (*Milletia stuhlmannii*), Chanfuta (*Afzelia quanzensis*), Umbila (*Pterocarpus angolensis*), Pau-preto (*Dalbergia melanoxylon*), Pau-ferro (*Swartzia madagascariensis*), Mecruse

(*Androstachys johnsonii*), Pau-rosa (*Berchemia zeyheri*), Monzo (*Combretum imberbe*), Umbaua (*Khaya nyasica*) and Tule (*Milicia excelsa*); more exotic species include *Eucalyptus sp.* and *Pinus sp.*

The total commercial timber stock in Mozambique's natural forests is about 1.74 billion m^3, with an allowable annual cut of 516,000 - 640,000 m^3 (Marzoli, 2007). National statistics from 2001-2012 (DNFFB, 2001-2007; DNTF, 2010-2012) indicate that annual harvested volume is around 40% below the allowable annual level, as shown in Figure 1.

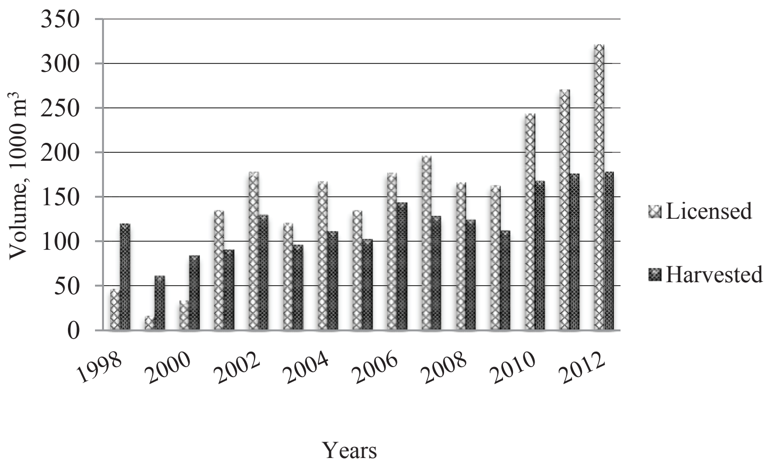


Figure 1. Licensed and harvested timber volumes in Mozambique between 1998 and 2012.

The Mozambican forestry sector is dominated by small-medium scale processing industries that produce material for internal consumption and export (Fath, 2002; DNTF, 2010). The industrial units are located in major cities that provide access to existing markets and infrastructure such as roads and ports. Forest products are among the country's ten most important exports (Alberto, 2006): the forest sector's contribution to Mozambique's exports increased from around 2.6% in 2002 (Alberto, 2006) to 9% in 2007 (Nhancale et al., 2009). The sector also provides direct formal and informal employment to around 600,000 people (Nhancale et al, 2009). Unfortunately, the scope for rigorous analysis of its contribution is limited by a lack of data together with weak control and recording systems (Alberto, 2006).

The country's major timber products are logs or round wood, sawn timber, railway sleepers, poles, parquet blanks (DNTF, 2011) furniture, boxes, doors and window frames, and crafted products (Nhancale et al, 2009). The production of processed sawn timber as a proportion of the volume of logs harvested has increased from 25% in 1998 to >120% in 2011 (DNFFB 1998-2007; DNTF 2010-2011). Conversely, the volume of timber logs allocated for export as a proportion of the total harvested volume has decreased from around 65% in 2004 to 18% in 2011(DNFFB 2004-2007; DNTF 2010-2012). This increase in the production of processed timber and reduction in the proportion of exported logs was partly due to changes in the regulations governing the forest industry – taxes on log exports were increased and some tree species were reclassified in a way that restricted the export of their logs. However, it was also partially due to the limited technological capabilities of existing sawmills and other industries (DNFFB, 2006).

Mozambique also has planted forests that cover around 62, 0000 ha (FAO, 2010a) and are dominated by the genera *Pinus* and *Eucalyptus*. The Central and Northern regions of the country have the greatest potential for large-scale industrial plantation in terms of soils and climate (DNTF, 2012; Nhantumbo et al., 2013). Most of the existing plantations were established by private sector actors for commercial and energy generation purposes; this is especially true in cases where local communities were involved in the planning of the plantation (DNTF, 2012). However, energy plantations established in the 70s and 80s by the Food and Agriculture Organization (FAO) have collapsed due to high production costs and management problems (Mangue, 2000) as well as the impacts of the country's civil war.

1.3 Energy supplies

Biomass, i.e. firewood and charcoal, accounts for 82% of Mozambique's energy consumption. Electricity accounts for another 13%; the remaining 5% is due to hydrocarbons such as diesel, petroleum fuels, LPG, and natural gas (ME, 2012). In addition, solar energy is used for food drying and conservation as well as lighting. However, its contribution is too small to warrant estimation.

Fuelwoods are mainly obtained by cutting secondary and sometimes primary natural forests (Mangue, 2000; Argola, 2004; Cangela, 2008; Puná, 2008; Sitoe *et al.* 2012). The country's annual fuelwood consumption is 27.8 million m^3 (Sitoe et al., 2007), which is 50 times greater than the average annual allowable cut volume. Fuelwood harvesting and the expansion of agricultural land are estimated to be responsible for the deforestation of 219,000 ha per year, corresponding to 0.58% of the country's total forest cover (Marzoli, 2007). Nhacale et al. (2009) estimated that around 96% of the country's fuelwood is harvested informally without any licensing and goes unrecorded. The impact of its use is therefore very difficult to estimate. The low incomes and high population growth rates in Southern Africa (Abbot *et al*., 1997; Abbot and Homewood, 1999; Williams *et al*, 2008), and in Mozambique in particular, mean that the pressure on forests to meet people's needs for agricultural land and energy will increase in future. These regions therefore require alternative energy sources.

More than a third of the timber volume felled in Mozambique is left un-utilized due to the use of inefficient logging techniques (Fath, 2001). Such material represents potentially readily available biomass that should be quantified and evaluated to determine its potential uses. This work focuses on the country's three most harvested species, Chanfuta, Jambire and Umbila, as potential sources of residual biomass from logging operations that could be mobilized for bioenergy use. While planted forests of fast-growing species also have great potential for the production of energy wood, they are beyond the scope of this investigation.

1.4 Major Mozambican tree species and their distribution

Chanfuta is a medium to large deciduous tree from the Fabaceae-Caesalpinioideae family. It occurs in dry forests, lowland thickets and dry woodlands at altitudes of 0 to 1,800 m a.s.l in regions with a mean annual rainfall of around 1,000 mm (Wyk & Wyk, 1997; DFSC, 2000). In Mozambique, it occurs mainly in the Southern and Central regions, with a total available commercial stock of 2,514,000 m^3 (Mackenzie, 2006; Marzoli, 2007). Chanfuta trees are usually up to 15 m tall with a short bole, a wide umbrella shaped crown and large leaves. They prefer deep and well drained sandy soils (Gérard, 2001). The tree provides good shade (DFSC, 2000), produces high quality timber, and is moderately resistant to termites (Gomes e Sousa, 1964). Its wood is hard, heavy, and durable, and is mainly used to produce furniture, building materials and canoes as well as for crafting (Hines & Eckman, 1993). Its basic density is reported to be between 0.692 and 0.781 g cm^{-3}–(Bunster, 1995; Mate et al., 2014). The harvesting of Chanfuta trees is permitted once their stem DBH exceeds 50 cm ob (DNFFB, 2002).

Jambire, from the Fabaceae family, is a medium to large deciduous tree that reaches heights of 15 to 25 m with a spreading crown. It is locally dominant (Lemmens, 2008) and is distributed across Mozambique and Eastern Zimbabwe (ECCM, 2005; Marzoli, 2007), commonly growing in bushveld and forests, often on rocky hillsides (Wyk & Wyk, 1997) at altitudes of up to 900m a.s.l in areas with relatively high rainfall (Lemmens, 2008). Its timber is commonly used for furniture, flooring, the manufacture of musical instruments, inlay work, and in railway sleepers. The unusual configuration of its annual rings gives its flat sawn timber a delicate appearance that is highly appreciated. Its harvesting is permitted once its DBH exceeds 40 cm ob (DNFFB, 2002). The wood is moderately hard with basic densities ranging from 0.558 to 0.841 g cm^{-3} (Bunster, 1995; Mate et al., 2014). Moreover, it is durable and resistant to fungi and termites (WAD, 2005; ECCM, 2005).

Umbila is a medium to large tree that is typically 10 – 20 m tall but may reach heights of 28 m under ideal conditions (Wyk & Wyk, 1997). It belongs to the subfamily Papilionoideae and is distributed over large areas in the Miombo woodlands of central and southern Africa, which extend across Malawi, Mozambique, Zambia, Zimbabwe and Botswana (Therrell et al., 2007; Marzoli, 2007). It grows well on drained sandy soils and also on hillsides at altitudes up to 1650 m a.s.l with 700 to 1500 mm precipitation per year (Orwa et al., 2009). Its wood is used for timber and its reddish brown heartwood makes it to one of the most valuable timber trees in southern tropical Africa (Palgrave, 2002; Stahle et al., 1999). The minimum stem DBH (ob) for harvesting is 40 cm (DNFFB, 2002) and its reported basic densities range from 0.640 to 0.636 g cm^{-3} (Bunster, 1995; Mate et al., 2014). It is resistant to fire and widely used for carving and traditional medicine (Fichtler et al., 2004).

1.4.1 Growth cycles of the studied species

Tropical tree species often produce false, irregular or unclear annual growth rings. Consequently, the estimation of their age is challenging and has occasioned some scientific controversy (Whitmore, 1990; Baker, 2003). However, annual growth rings have been identified and reported in some studies (Chambers et at., 1998; Worbes and Junk, 1999; Stahle *et al*., 1999; Worbes, 2002; Therrell *et al*., 2007; Steenkamp *et al*., 2008; Syampungani *et al*., 2010; Tshisikhawe *et al*., 2011 and Remane, 2013). Few age-estimation studies have been conducted in Mozambique, and those that have been reported (Table 1) all used different methodologies, which makes it difficult to compare their results. Sitoe (1997) examined used permanent sample plots (yielding indirect age estimates) whereas Therrell *et al*. (2007), Syampungani *et al*. (2010) and Remane (2013) performed annual growth ring analyses (a direct method). The lack of data on tree age has limited the development of site index curves for the studied species. Site indices are powerful tools for estimating a site’s ability to produce high volumes in stands (Johansson, 2006).

Table 1. *Reported mean annual diameter increments for the studied species*

Species	Study area	MAI[1] (cm/year)	Author
Chanfuta	Mozambique	0.13 – 1.79	Schikowski *et al*. (2010)
Jambire	Mozambique	0.51	Remane (2013)
Jambire	Mozambique	0.38	Sitoe (1997)
Umbila	Mozambique	0.27 – 1.86	Schikowski *et al*. (2010)
Umbila	Zimbabwe	0.33 – 0.40	Therrell *et al*. (2007)
Umbila	Zimbabwe	0.30 – 0.41	Stahle *et al*. (1999)

1.MAI stands for mean annual diameter increment

1.5 Biomass and Volume Estimation Methods

Established methods for biomass estimation include: i) destructive direct measurement and ii) non-destructive measurement (indirect estimation). Destructive methods involve tree harvesting, measuring the fresh weights of the trees' individual components (stem, branches, twigs, leaves and roots), drying samples of each component, comparing the fresh and dry masses of the samples, and using the resulting values to estimate the biomass of each component, the tree as a whole, and the biomass per unit land area (GTOS, 2009). This approach is viable for small areas but is quite time-consuming and impractical for larger areas because it makes it impossible to evaluate biomass growth over longer periods of time (Stewart et al. 1992). In contrast, non-destructive methods do not require tree felling (Montés et al., 2000). Based on the sampled tree biomass, the stand biomass is calculated by multiplying the biomass of sampled trees by the average number of trees per unit area (Johansson, 1999). Using remote sensing techniques, stand-level biomass estimates can be scaled up to the landscape level (Case and Hall, 2008; GTOS, 2009).

The tree volume is generally estimated based on tree diameter and height measurements by using specific formulas such as those of Smalian, Hubber, and Newton (Husch *et al.,* 2003) or Hohenadl (da Cunha, 2004). Direct volume measurements are usually made by sectioning a tree into smaller pieces, which are assumed to be cylindrical (Husch *et al,* 2003). The volume is then expressed in cubic meters as a function of diameter or some combination of diameter and height or commercial length (Husch *et al.*, 2003; Gier, 1992). Equations featuring additional variables such as tree form (Husch *et al*, 2003), basal area, stem length, site quality or climate can also be used. No taper as well as tree form have been documented for tropical species. In Mozambique, arbitrary form factors of 0.80 and 0.65 have been used to estimate commercial and total volumes, respectively (Marzoli, 2007).

1.6 Challenges of Biomass and Volume Estimates

Accurate estimation of tree volume and biomass is essential for efficient forest management (Gillespie et al, 1992; Návar-Cháidez, 2009, Nur Hajar et al, 2010) because it facilitates the estimation of forest stand productivity, carbon stocks, and the flows of energy and nutrients (Gillespie et al, 1992¸ Adenkule, 2007, Guendehou et al, 2012) as well as the assessment of the forest's structure and condition (Chavé et al, 2003; Zianis and Mencuccini, 2004). Several volume and biomass equations have been developed for major tree species in Europe (Zianis et al, 2005), Asia and America (Brown 1997; Chavé et al. 2005). However, only a few studies have examined the full range of tropical African species. Most published African studies have focused on tropical rainforest species (Akindele & LeMay 2006; Onyekwelu 2004; Adekunle 2007; Mbaekwe and Mackenzie 2008) and so their results are not applicable to the deciduous and semi-deciduous miombo forest species found in Mozambique.

Miombo forests account for two thirds of Mozambique's forest cover (Marzoli, 2007) and occur in a wide range of climates. Most of the country's miombo forests are in moist tropical regions but they also exist in dry climates and climates modified by altitude (FAO, 2005). The development of appropriate allometric equations is a vital step (Mwakalukwa et al, 2014) in the creation of reliable methods for estimating volume and biomass. Before this work was conducted, no species-specific biomass and volume equations had been reported for Chanfuta, Jambire and Umbila. However, generic biomass and volume equations for forest vegetation of the types found in Central Mozambique have been developed by Tchaúque (2004) and Marzoli (Marzoli, 2007) respectively. Tchaúque (2004) created a biomass equation, while Marzoli (2007) reported a volume equation for forest stock estimates. In addition, Machoco (2008) and Tomo (2012) published biomass expansion factors and biomass and carbon estimates for different vegetation types in Central Mozambique, although neither author presented any species-specific data.

Despite the apparent validity of generic allometric equations, trees' allometric relationships are expected to depend on environmental factors (e.g., soil and climate) and the functional characteristics of individual species such as their wood density and crown architecture (Chavé et al., 2005, 2009; Henry et al., 2010; Vieilledent et al, 2010). Moreover, existing biomass estimates for Mozambique have been obtained by direct conversion of volume data due to the limited availability of primary biomass data. Most tree volume estimates are in turn obtained from forest inventories based on measurements of diameter and height. Such measurements exclude the crown volume and the volume of the branches. This is a problem because woodland species allocate more than 50% of their woody biomass to branches (Geldenhuys and Goldings, 2008). As such, biomass estimates based on stem volumes alone will substantially underestimate the total tree biomass. It is therefore important to develop equations that will provide improved estimates for the most heavily harvested timber species to promote the efficient use of Mozambique's forest resources.

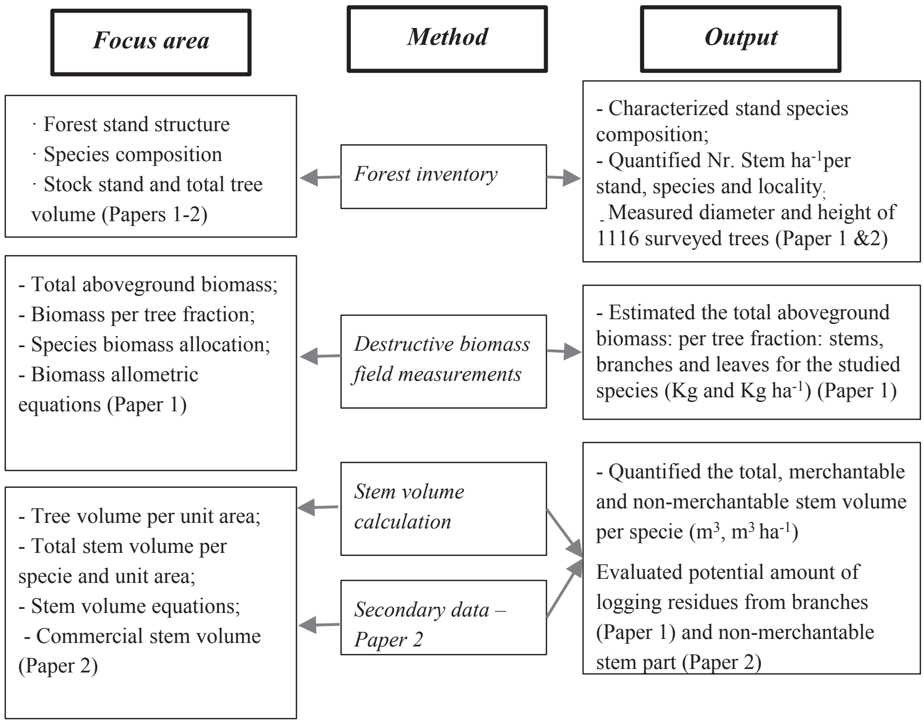
2 Objectives

The overall objective of this work was to provide improved estimates of the standing volume and aboveground biomass stock of Chanfuta, Jambire and Umbila species in Mozambique. Such data will provide a more accurate picture of the country's forest resources than is available at present. The specific objectives were to:

- Develop species-specific total aboveground biomass equations (Paper I)
- Develop species-specific stem volume equations (Paper II)
- Evaluate the potential of logging residues from the studied species for use in applications such as bioenergy generation (Papers I&II).

2.1 Structure of the Work

This thesis is based on two papers dealing with biomass equations (Paper I) and stem volume equations (Paper II), respectively. The conceptual framework of the thesis is outlined below:



Paper I presents equations that enable accurate biomass estimates for individual tree components (stems, branches and leaves) and describes the quantification of biomass and biomass allocation within the studied species.

Paper II presents equations that enable accurate volume estimates for the three studied species as well as estimates of the volumes of timber and residual stock that could be obtained. Such estimates will make it possible to ensure that Mozambique's demands for energy and timber can be met in a way that minimizes the need for further forest clearance.

3 Material and methods

3.1 Study Areas and Data used for Equation Development

The study was carried out in the Southern and Central regions of Mozambique, in the Inhambane and Sofala Provinces respectively (Papers I and II), Figure 1. The studied stands in Sofala province were located within a 'forest concession' in Cheringoma District, Inhaminga locality, at 18°58' S and 34°10' E. The area has an average rainfall of 1000-1100 mm/year (MAE, 2005a) and is dominated by yellowish or reddish oxisols (Mafalacusser and Marques, 2000; MAE, 2005a; Mafalacusser, 2013). The studied stands in Inhambane province were located at the Mavume and Tome localities in Funhalouro District, at 23°52' S and 35°23' E (MAE, 2005b). This region has a tropical savannah climate with an average annual rainfall of 500-800 mm and mainly has deep sandy soils (MAE, 2005b). The studied stands at Mavume and Tome are located in public forests managed by the Provincial Forestry Authority. The study areas were chosen based on the occurrence of the species of interest (Chanfuta, Jambire and Umbila) as reported by Marzoli (2007), and the accessibility of the sites throughout the year.

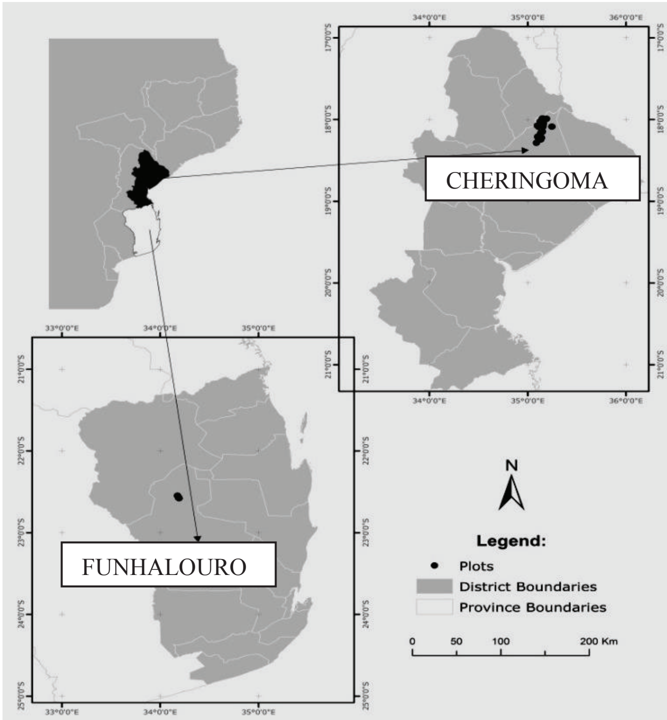


Figure 2. Geographic locations of the studied areas

A total of 58 trees were sampled to facilitate the development of aboveground biomass (AGB) and stem volume equations for three targeted species. Table 2 provides details concerning the locations of the studied stands and the characteristics of the species growing within them.

Table 2. *Location and characteristics of trees growing in the visited stands*

Plot no.	Locality	Lat. S	Long. E	DBH, cm Mean ± SD	Height, m Mean ± SD	Dominant vegetation
			Chanfuta			
6	Inhaminga	18°15'	35°15'	60.5 ± 27.0	14.4 ± 6.9	*Dense deciduous*
7	Inhaminga	18°01'	35°17'	43.6 ± 0	18.6 ± 0	*Dense deciduous*
9	Inhaminga	17° 99'	35°19'	61.1 ± 0	20.6 ± 0	*Dense deciduous*
10	Inhaminga	18°74'	35°86'	60.0 ± 9.0	17.5 ± 2.1	*Ticket*
15	Inhaminga	17°99'	35°15'	35.4 ± 0	15.0 ± 0	*Ticket*
22	Inhaminga	18°08'	35°11'	22.3 ± 15.8	9.6 ± 3.7	*Open deciduous*
39	Inhaminga	18°23'	35°13'	48.4 ± 0	15.8 ± 0	*Open deciduous*
43	Inhaminga	18°09'	35°25'	38.5 ± 0	20.9 ± 0	*Open evergreen*
202	Inhaminga	18°40'	35°14'	41.4 ± 0	19.6 ± 0	*Open evergreen*
501	Inhaminga	17°99'	35°15'	51.0 ± 0	22.1 ± 0	*Open deciduous*
502	Inhaminga	18°10'	35°08'	44.6 ± 1.0	17.0 ± 1.7	*Open deciduous*
503	Inhaminga	18°17'	35°05'	39.6 ± 5.6	13.2 ± 1.6	*Dense evergreen*
2	Mavume	22°34'	34°11'	21.0 ± 0	9.0 ± 0	*Dry deciduous*
22	Mavume	23°27'	34°31'	30.1 ± 9.1	11.4 ± 1.8	*Dry deciduous*
3	Tome	22°34'	34°11'	21.0 ± 0	12.0 ± 0	*Dry deciduous*
4	Tome	22°34'	34°11'	18.5 ± 0	7.5 ± 0	*Dry deciduous*
5	Tome	22°34'	34°11'	20.8 ± 10.5	7.5 ± 0	*Dry deciduous*
6	Tome	22°35'	34°11'	21.0 ± 0	9.5 ± 0	*Dry deciduous*
7	Tome	22°35'	34°12'	29.0 ± 11.5	11.5 ± 1.8	*Dry deciduous*
8	Tome	22°35'	34°11'	21.6 ± 6.5	11 ± 1.9	*Dry deciduous*
9	Tome	22°33'	34°11'	34.1 ± 10.0	14.2 ± 1.1	*Dry deciduous*
			Jambire			
1	Inhaminga	18°50'	35°08'	25.2 ± 0	14.0 ± 0	*Dense deciduous*
4	Inhaminga	18°06'	35°15'	28.8 ± 2.0	16.3 ± 1.8	*Dense deciduous*
6	Inhaminga	18°09'	35°09'	41.2 ± 5.5	21.8 ± 6.2	*Dense deciduous*
8	Inhaminga	18°05'	35°09'	25.7 ± 6.8	15.5 ± 4.5	*Dense deciduous*
10	Inhaminga	18°07'	35°09'	35.0 ± 0	16.0 ± 0	*Dense deciduous*
11	Inhaminga	18°05'	35°16'	31.8 ± 0	18.8 ± 0	*Dense deciduous*
15	Inhaminga	17°99'	35°15'	38.2 ± 0	13 ± 0	*Dense deciduous*
27	Inhaminga	18°05'	35°06'	16.2 ± 0	7.0 ± 0	*Ticket*
29	Inhaminga	18°09'	35°11'	26.9 ± 12.7	17.6 ± 2.8	*Ticket*
34	Inhaminga	18°14'	35°08'	34.1 ± 1.4	13 ± 1.4	*Open deciduous*
36	Inhaminga	18°20'	35°12'	32.5 ± 0	12.9 ± 0	*Open deciduous*
37	Inhaminga	18°24'	35°13'	42.4 ± 0	16.3 ± 0	*Open deciduous*
38	Inhaminga	18°21'	35°10'	21.5 ± 2	14.9 ± 1.3	*Open deciduous*
39	Inhaminga	18°23'	35°13'	23.7 ± 9.9	10.1 ± 4.8	*Open deciduous*
41	Inhaminga	18°13'	35°09'	65.0 ± 0	13 ± 0	*Open deciduous*
42	Inhaminga	18°21'	35°11'	25.6 ± 6.5	18.2 ± 0.7	*Open deciduous*
43	Inhaminga	18°09'	35°25'	55.1 ± 0	19.5 ± 0	*Open evergreen*
101	Inhaminga	18°01'	35°08'	33.4 ± 27.0	15.5 ± 6.4	*Dense deciduous*
501	Inhaminga	17°59'	35°09'	34.3 ± 8.9	17.3 ± 2.6	*Open deciduous*
502	Inhaminga	18°10'	35°08'	36.5 ± 5.1	16.9 ± 6.8	*Open deciduous*
			Umbila			
1	Mavume	23°37'	34°29'	20.6 ± 7.3	10.3 ± 3.1	*Open/dry deciduous*
10	Mavume	23°37'	34°30'	24.3 ± 7.6	9.8 ± 3.3	*Open/dry deciduous*
11	Mavume	23°37'	34°30'	24.6 ± 10.4	11.2 ± 2.5	*Open/dry deciduous*
12	Mavume	23°37'	34°30'	28.0 ± 13.2	8 ± 3.1	*Open/ dry deciduous*
13	Mavume	23°37'	34°30'	22.8 ± 18.0	6.9 ± 1.6	*Open/dry deciduous*
14	Mavume	23°37'	34°37'	22.5 ± 7.8	8.5 ± 2.8	*Open/dry deciduous*
15	Mavume	23°37'	34°30'	25.0 ± 12.7	10.5 ± 5.7	*Open/dry deciduous*
16	Mavume	23°37'	34°30'	27.5 ± 3.5	7.9 ± 4.7	*Open/dry deciduous*
17	Mavume	23°37'	34°30'	21.6 ± 9.9	8.2 ± 2.3	*Open/dry deciduous*
18	Mavume	23°37'	34°30'	12.6 ± 1.3	6.3 ± 0.6	*Open/dry deciduous*
20	Mavume	23°37'	34°30'	16.0 ± 0.0	6.5 ± 0	*Open/dry deciduous*
21	Mavume	23°37'	35°30'	22.8 ± 5.5	7.7 ± 1.2	*Open/dry deciduous*
35	Inhaminga	18°25'	35°13'	25.5 ± 0.0	12.0 ± 0	*Open deciduous*
36	Inhaminga	18°20'	35°12'	14.3 ± 0.0	8.5 ± 0	*Open deciduous*
40	Inhaminga	18°14'	35°07'	46.5 ± 0.0	12.0 ± 0	*Open deciduous*

3.2 Sampling Design and Sampling Units

To provide an accurate representation of the species diversity within the study areas, a total of 90 plots were defined randomly. The limitations of the region's road infrastructure and heavy rain meant that only 57 of these plots could be surveyed: 36 in Inhaminga, 14 in Mavume and 7 in Tome (Papers I and II). Each plot covered 100 m × 20 m based on previous studies conducted in Mozambique (Cuambe and Marzoli, 2006). Plots were demarcated using sticks and ropes. The diameter at breast height (DBH) and height (total and commercial) was recorded for all trees within the plots whose DBH was 10 cm or more (Cuambe and Marzoli, 2006). Trees forked below 1.3 m were excluded and those with forks above 1.3 m were measured separately. No samples were collected for age determination due to the difficulty of identifying annual rings and the need to use sophisticated methods to obtain reliable age estimates. Therefore, to avoid errors, age was not used as a variable.

3.3 Biomass and Stem Volume Measurements

A total of 58 trees were harvested to facilitate the development of biomass and stem volume equations: 24 Chanfuta trees, 15 Jambire, and 19 Umbila. The forest operators stipulated that no more than one sample tree from each plot could be used for biomass and volume measurement. Sampled trees were healthy, undamaged, and non-forked, with fairly straight stems. DBH was measured using callipers while height was measured using Haglöf Vertex 3 or 4 hypsometers. The commercial height was measured from the base of the stem to the first living branch. After all of the necessary measurements had been made in the field and recorded, Chanfuta, Jambire and Umbila stems were identified and marked. The mean DBH per species per plot and stem quality indicators (e.g. straightness, health) were systematically used to identify sample trees to be felled. The stump height was defined at 20 cm above ground before the tree was felled.

Most of the trees had umbrella-shaped crowns with no readily-identified natural top, which made it difficult to unambiguously determine which branch in the crown corresponded to the main stem. This problem was solved by assuming that the crown branch whose direction of growth most closely matched that of the main stem below the branching point represented the continuation of the main stem (Figure 3).

Figure 3. Identification of the main stem direction match

Having identified the main stem, all of the branches were numbered (Figure 4a) and removed from the stem. The total stem length was recorded and the stem was divided into five sections by cutting it at 10%, 30%, 50%, 70% and 90% of its total length (Figure 4b). The length, top diameter, and bottom diameter of each section was recorded and used to estimate its volume based on Smalian's formula (II:5). Additional diameter measurements were taken at the base of the stem and at a height of 1.3 m. The volume of the top section (i.e. the part of the tree above the 90% cutting point) was estimated using the formula for a cone (II:6). The total over bark (ob) stem volume was obtained by summing the volumes of each individual stem section (II:7).

(a)

(b)

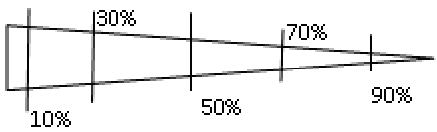


Figure 4. Numbering of branches (a) and the cutting of the stem into sections (b)

The fresh weights of the stem and branch sections were then measured. Sample disks (10-15 cm) were collected from the mid-point of each stem section and at a height of 1.3 m for dry weight estimation. The average number of branches per tree was five; three from the middle of the crown of each tree were sampled for dry weight determination. In addition, the total fresh weight of leaves was recorded and samples of 30 to 50 leaves were taken from different levels of the crown. The stumps were not accounted for in the AGB measurements because it is recommended that they should be left in place for coppice management in Mozambique. All collected subsamples were taken to a laboratory where their dry weight, moisture content, and basic wood density (g cm^{-3}) were determined. To this end, the sub-samples were oven dried to constant weight at 103 °C–105 °C (Brown and Lugo, 1992; Parresol, 1999; Pearson et al., 2005; Johansson, 2011). Their basic density was then estimated using the standard water-immersion method described by Andersson and Tuimala (1980). AGB, moisture content (MC), and basic wood density were determined using equations I:2 and I:7. Table 3 lists the equations used to calculate the various parameters discussed in the preceding paragraphs.

Table 3. *Used formulas for the biomass and volume estimates*

Parameters	Formulas	Paper and Equation
Dry Mass, Kg	$Dry\ mass = \frac{sdw}{sfw} \times fwC$	I:1
Moisture Content, %	$MC = \frac{fw - dw}{fw}$	I:2
Basic Density , g cm^{-3}	$Bd = \frac{M}{V}$	I:7
Basal Area, m^2	$BA = (\pi/4) \times D^2$	II:4
Volume of Stem Sections, m^3	$V_s = \left((BA_1 + BA_2)/2 \right) \times L$	II:5
Volume of the Top Section, m^3	$V_{top} = (BA/3) \times L$	II:6
Total Volume, m^3	$V_{total} = \sum (V_s) + V_{top}$	II:7

where:

Sdw = dry weight of sub-sample (g); *Sfw* = fresh weight of sub-sample (g); *fwC* = fresh weight of component; *fw* = fresh weight (g); *dw* = oven-dry weight (g); *M*: Dry weight of stem or branch sample (g).; *BA* = cross-sectional area of stem at base (m^2); *V*: Fresh volume of stem or branch sample (cm^3);

D=diameter, cm at 0%, 10%, 1.3 m, 30%, 50%, 70% and 90%; L = length of section, m.

3.3.1 Biomass and Stem Volume Equations

Linear, polynomial, exponential, logarithmic and power equations were fitted to the measured and estimated data to characterize the relationship between the aboveground biomass and the DBH, height, and basic density. The non-linear power equation performed well and was therefore investigated further. Non-linear equations have previously been shown to yield good results for predictions of this sort (Kittredge, 1944; Návar, 2010; Návar-Cháidez et al., 2013) and have also been used successfully to predict stem volumes (Cao et al., 1980; Lumbres and Lee, 2013; Tewari et al., 2013). The stem volume was modelled as a function of DBH alone and DBH with height. The biomass and stem volume equations used for model fitting are presented in Table 4.

Table 4. *Tested biomass and stem volume equations for the three studied species*

Equations	Paper and Equation
Biomass	
$AGB = \beta_0 D^{\beta_1}$	I:3
$AGB = \beta_0 D^{\beta_1} \beta_2 Bd$	I:4
$AGB = \beta_0 (BdDH)^{\beta_1}$	I:5
$AGB = (\beta_0 + \beta_1 Bd) D^{\beta_2}$	I:6
Stem Volume	
$V = \beta_0 D^{\beta_1}$	II:1
$V = \beta_0 D^2 H$	II:2
$V = \beta_0 D^{\beta_1} H^{\beta_2}$	II:3
$V = \beta_0 D^2 H^{\beta_1}$	II:4

where:

AGB = Aboveground biomass, kg d.w. tree^{-1}; D = DBH over bark (ob), mm; Bd = Basic density, g cm$^{-3;}$ H = Tree height, m. β_0, β_1 and β_2 are parameters.

The most common procedure for validating biomass and stem volume equations is to test them against an independent dataset (Kozak & Kozak, 2003). However, this was not possible for the biomass equation in this case due to the limited number of available stands. The volume models were therefore validated using a “leave-one-out cross-validation”. The entire dataset was left out one at a time and the parameters were estimated for the reduced dataset. Similar procedures for model validation in the context of growth equations have been used by Zhang (1993), Nord-Larsen et al. (2009) and Webb and Copsey (2011).

3.4 Merchantable Stem Volume Estimates

According to Burkhart (1977), Alemdag (1988), and Barrio Anta et al. (2007) the merchantable volume ratio can be estimated based on a tree’s top diameter and height limits. An alternative method is to use taper equations to predict the diameter at any stem height. However, neither volume ratios nor taper functions have been established for the native forest species of Mozambique (Chanfuta, Jambire and Umbila). We therefore estimated merchantable volumes using data on the dimensions of Chanfuta, Jambire and Umbila logs harvested by forest operators working in two concession areas in Sofala Province between 2004 and 2011 (Paper II). The average dimensions (diameter and height) of the logs were compared to the field data gathered in the present study to derive expressions for estimating merchantable stem volume and potential residual volume, which is not calculated by most existing tools for biomass estimation in Mozambican tree species.

3.5 Statistical Analysis for Biomass and Volume Equations

Statistical analysis was conducted using the non-linear regression procedure of the SAS/STAT system for personal computers (SAS, 2006). Assessments of best fit for biomass equations were performed using the coefficient of determination (R^2) (Zar, 1999), average bias, (AB), average absolute bias (AAB), root mean square error (RMSE) and residual plots. AAB was used because Parresol *et al.* (1987) found that it clearly discriminated between a set of similar equations. Some additional parameters were considered when assessing the stem volume equations, namely the *Residual Standard Error (RSE)* and *Akaike Information Criterion (AIC)* (Akaike, 1974; Burnham and Anderson, 2002; Chavé et al., 2005). The formulas used to calculate these statistical parameters are presented in Table 5.

The calculation of the AIC depended on the *maximum likelihood "L" value, number of parameters (p) and sample size* (II:11). The maximum likelihood "L" was calculated based on the formula of Xiao et al. (2011), (II:10). An overall ranking analysis was used to find the "best" stem volume equation (Cao et al., 1980 and Figueiredo-Filho et al., 1996). In this analysis, the highest rank of 1 was assigned to the models with the highest R^2 value and the lowest AB, ABB and RMSE values. The quality of the stem volume equations was estimated using the AIC and RSE; in both cases, lower values indicate a better model fit and thus a higher rank (Chavé et al., 2005). The model with the best fit was deemed to be that with the highest overall rank with respect to all of the chosen statistical parameters.

Table 5. *Parameters used for the statistical analysis of biomass and stem volume equations*

Parameters		Paper and equation
Coefficient of Determination	$R^2 = 1 - [SSE/SST \text{ (No. observations)}]$	I:8 & II:5
Sum of Square Errors	SSE is $\sum_{i=1}^{n} (w_i - \overline{w}_i)^2$	I:9
Sum of Total Squares	SST is $\frac{1}{n} \sum_{i=1}^{n} (w_i - \hat{w}_i)^2$	I:9
Root Mean Square Error	$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(w_i - \hat{w}_i)^2}{n}}$	I:10 & II:8
Average Bias	$AB = \frac{1}{n}\sum_{i=1}^{n}(v_i - \hat{v}_i)$	I:1 & II:6
Average Absolute Bias	$AAB = \frac{1}{n}\sum_{i=1}^{n}\lvert v_i - \hat{v}_i \rvert$	I:12 & II:7
Residual Standard Error	$RSE = \frac{1}{n}\sum_{i=1}^{n}(v_i - \hat{v}_i)^2 / \sqrt{n}$	II:9
Likelihood	$L = \sum_{i=1}^{n}\left[1/\sqrt{(2\pi\sigma^2)}EXP(-SSE/2\sigma^2)\right]$	II:10
Akaike Information Criterion	$AIC = 2k - 2 * Log(L) + 2k(k+1)/(n-k-1)$	II:11

4 Results

4.1 Stand Characteristics in the studied Localities

In total, 1,116 different trees were found in the study area and measured to determine their DBH, total height, and commercial height. Species identification was possible for 762 of these but the remaining 354 could not be identified by local people or botanists. The 11.4 ha sampled area (57 plots) contained at least 48 different tree species, 34 of which belonged to the *Fabaceae* family. The most abundant species, *Brachystegia spiciformis*, is a typical miombo species and was present at a density of 725 stems ha^{-1} (Papers I and II).

The studied stands contained 155 trees belonging to the chosen species: 48 Chanfuta, 55 Jambire and 52 Umbila. The stem densities at the Tome, Inhaminga and Mavume localities were 147 stems ha^{-1}, 119 stems ha^{-1}, and 104 stems ha^{-1}, respectively. Other species accounted for 89 %, 79 %, and 67 %, respectively, of the total tree count in the stands at these three localities. The somewhat haphazard species distribution within the studied area and the use of randomly allocated plots may have influenced the recorded species types. The sites exhibited considerable species variability – while Chanfuta was found at all three sites, Jambire and Umbila were not. The Inhaminga site tended to have larger trees than Mavume and Tome. Table 6 lists the abundance and characteristics of the 3 studied species at the Inhaminga, Mavume and Tome sites.

Table 6. *Characteristics of trees species growing in stands at Inhaminga, Mavume and Tome, expressed as average values ± standard deviation (SD) and ranges.*

Species	Stems ha^{-1}	DBH, cm		Height, m		Commercial height, m		Basal area, m² ha^{-1}
	Mean ± SD	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
				Inhaminga				
Chanfuta	8 ± 4	44.4 ± 13.7	11.1–79.6	16.3 ± 4.1	7.0–22.1	5.8 ± 1.6	3.0 – 9.0	1.32 ± 0.87
Jambire	13 ± 12	31.2 ± 11.4	13.4–65.0	15.8 ± 4.4	6.0–28,9	4.9 ± 3.3	0.8 – 18.8	1.13 ± 0.93
Umbila	5 ± 0	28.8 ± 16.3	14.3–46.5	10.8 ± 2.0	8.5–12.0	3.6 ± 1.5	2.0 – 5.0	0.39 ± 0.40
Others	93 ± 55	23.0 ± 14.3	7.6–129.6	10.1 ± 3.7	3.0–25.1	3.0 ± 1.5	0.0 – 10.5	5.35 ± 3.98
				Mavume				
Chanfuta	15 ± 14	28.6 ± 9.0	17.2–42.5	10.9 ± 1.9	8.8–13.2	7.0 ± 3.4	4.0 – 12.4	1.04 ± 1.23
Umbila	20 ± 14	22.8 ± 9.6	10.0–44.5	8.8 ± 2.9	3.8–16.2	4.0 ± 1.7	0.5 – 8.5	0.98 ± 0.84
Others	69 ± 73	19.8 ± 8.1	10.0–49.0	6.6 ± 2.0	2.0–14.0	1.9 ± 1.2	0.0 – 5.5	2.58 ± 2.06
				Tome				
Chanfuta	17 ± 16	25.9 ± 9.6	13.5–48.0	11.5 ± 2.6	7.5–5.5	6.1 ± 5.2	1.0 – 14.8	3.42 ± 1.22
Others	130 ± 83	17.4 ± 8.6	10.0–54.0	7.2 ± 2.8	3.0–15.0	2.2 ± 1.1	0.0 – 6.0	3.83 ± 1.47

4.2 Biomass and Stem Volume Estimates

The total biomass per unit area was 11.8, 9.9, and 4.1 tons ha^{-1} for Chanfuta, Jambire and Umbila, respectively. The studied species varied in their total AGB and their allocation of biomass across different tree fractions. Jambire trees had the highest mean dry weight (1016 ± 438 kg tree^{-1}, range 411–2086), followed by Chanfuta (864 ± 548, range 107–2018) and Umbila (321 ± 240, range 52–1121) (Tables 3 and 4, Paper I). The three species also differed with respect to their allocation of biomass to different components: the stem accounted for 74% of the total biomass for Jambire but only 54% for Chanfuta. Conversely, the bulk of the biomass of Umbila trees was allocated to the branches, which accounted for 51% of the total ABG, compared to only 46% for the stems. Leaves accounted for a small proportion of the biomass of the studied species – around 3%, 1%, and 3% for Chanfuta, Jambire and Umbila respectively.

The moisture content of the species varied from 52 to 56% for stems, 46 to 51% for branches, and 29 to 50% for leaves. The species also differed with respect to basic wood density: Jambire had the highest mean (0.850 g cm^{-3}) followed by Chanfuta and Umbila at 0.781 and 0.643 g cm^{-3}, respectively. In general the total AGB and the biomass of stems and branches tended to increase with the DBH. Figure 5 shows the biomass distributions of the studied tree species.

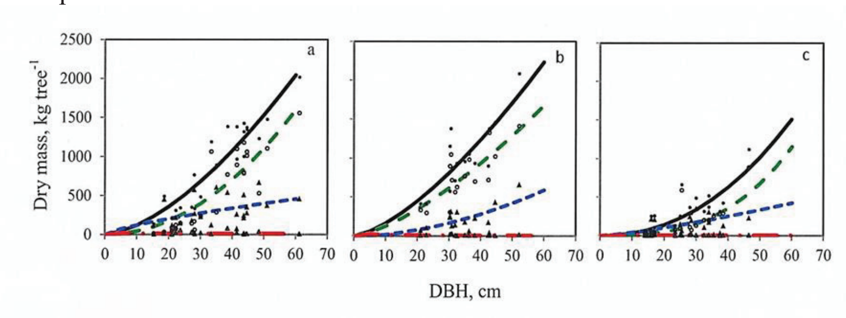


Figure 5. Biomass (kg tree^{-1}) plotted as a function of DBH for whole trees (—— ●), stems (– – –○), branches (------ ▲) and leaves (— · — ▲) based on samples of Chanfuta (a), Jambire (b), and Umbila (c)

Based on the sampled trees, the mean estimated stem volumes for Chanfuta, Jambire, and Umbila were 0.827 m^3, 0.626 m^3, and 0.372 m^3, respectively (Table 2, Paper II). Interestingly, this is not the same as the DBH order: Jambire had the greatest DBH but Chanfuta had a higher stem volume. The estimated commercial stem lengths for each species as a proportion of the total tree length ranged from 30 - 70%, corresponding to mean commercial stem lengths of 6, 4 and 4 m for Chanfuta, Jambire and Umbila, respectively. The proportions of trees whose commercial lengths were less than or equal to 30%, 50%, and 70% of their total stem height were 63%, 21% and 12%, respectively, for Chanfuta; 60%, 27% and 13% for Jambire; and 32%, 58% and 11% for Umbila (Paper II). Based on those findings it was assumed that 50% of the stem will be of commercial value. The potential residual stem volumes for Chanfuta, Jambire and Umbila were estimated to: 0.414, 0.313 and 0.186 m^3 tree^{-1}, respectively. By combining these values with the biomasses of the branches and leaves, total residual biomass values of 3.5, 3.8 and 1.6 dry tons ha^{-1} were estimated for the three species, respectively.

We also analysed the diameters and lengths of Chanfuta, Jambire and Umbila logs harvested in two concessions: "Indústria Madeireira de Moçambique, IMM" and "Inchope Madeiras". The average lengths of logs from all three species were around 3 meters and thus differed from the average commercial lengths estimated in this work. The average measured diameters, lengths, and volumes for each species are listed in Table 7.

Table 7. *Characterization of harvested logs from two concession areas in Mozambique*

Species	Diameter, cm				Length, m		Observed log volume, m^3	
	Base		Top					
	Mean±SD	Range	Mean±SD	Range	Mean ± SD	Range	Mean ± SD	Range
Chanfuta	46 ± 0.1	20 - 112	41 ± 0.1	16 - 105	3.1 ± 1.1	1.4 - 7.6	0.500 ± 0.372	0.052 - 2.147
Jambire	39 ± 1	15 - 77	35 ± 0	19 - 72	3.7 ± 1.1	1.4 - 8.0	0.424 ± 0.224	0.063 - 2.010
Umbila	44 ± 2	30 - 70	40 ± 3	27 - 87	3.0 ± 0.6	2.1 - 4.4	0.402 ± 0.154	0.181 - 0.920

4.3 Data Fitting and Selection of Best Fit Equations

The power equation (I:3) fitted the AGB data best and was thus most capable of explaining the relationship between AGB and DBH. Power equations also yielded the highest coefficients of determination for the three tree species, especially for total AGB and stem volume ($R^2 > 0.89$), indicating that these models fitted the data well. Their R^2 values for branch biomass were slightly lower, ranging from 0.69 to 0.79. While the equation for the leaf biomass of Chanfuta trees had a comparatively low R^2 value (0.40), those for Jambire and Umbila leaf biomass performed quite well ($R^2 = 0.72$ and 0.71, respectively). These models had positive bias (AB) values, indicating underestimation of the chosen predictors, especially for Jambire and Umbila.

There was a large difference between the AAB and RMSE values for the Chanfuta equations but not for Jambire and Umbila. This indicates that there was substantial variation in the error values for the sample trees. Summary statistics for the fitting of the power equation to the AGB data for Chanfuta, Jambire and Umbila are presented in Table 8.

Table 8. *Statistical parameters of the fitted aboveground biomass equations for Chanfuta, Jambire, and Umbila*

Components	Parameters	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	0.69	120.68
Leaves	$4.0400 \times D^{0.1680}$	0.0	3.3	0.71	4.71

Four different stem volume power equations were fitted to the volume data, using either DBH alone or DBH and height as explanatory variables. All four equations yielded good statistical fits to the data, with R^2 values of ≥ 0.81. However, the equations differed with respect to their RSE, RSME, bias (AB and AAB) and AIC values. The difference between AAB and RSME was large for Chanfuta, indicating substantial variation in the errors for the sample tree volume estimates. The bias (AB) was generally low and positive for all species, indicating that the predictor equations may slightly underestimate the biomass of Umbila and slightly overestimate that for Chanfuta and Jambire. After computing the various statistical parameters and weighing them against one-another using an overall rank approach, it was found that the observed variation in stem volumes was best explained by treating stem volume as a function of both DBH and height (Paper II: Equation 3) (Table 9).

Table 9. *Statistical parameters for the four tested volume equations for Chanfuta, Jambire and Umbila*

Parameters		SE	R^2	RSE	RMSE (m^3)	AB (m^3)	AAB (m^3)	RMSE[1] (m^3)	AIC	Overall rank
					Chanfuta					
					Equation (1)					
β_0	0.001270	0.001180	0.93	0.053	0.265	0.020	0.208	0.265	4.97	4
β_1	1.807100	0.241800								
					Equation (2)					
β_0	0.000036	0.0000015	0.96	0.038	0.193	0.056	0.147	0.194	4.64	2
					Equation (3)					
β_0	0.000101	0.000084	0.97	0.035	0.183	-0.001	0.118	0.182	5.51	1
β_1	1.655500	0.142000								
β_2	1.107900	0.233300								
					Equation (4)					
β_0	0.000033	0.000024	0.96	0.038	0.193	0.050	0.144	0,198	5.03	3
β_1	1.0338	0.2580								
					Jambire					
					Equation (1)					
β_0	0.006440	0.015000	0.81	0.085	0.343	-0.001	0.237	0.344	4.39	4
β_1	1.287800	0.637700								
					Equation (2)					
β_0	0.000036	0.0000027	0.92	0.053	0.207	0.033	0.154	0.207	4.30	2
					Equation (3)					
β_0	0.000353	0.000555	0.94	0.049	0.205	-0.002	0.131	0.206	6.05	1
β_1	1.429100	0.380700								
β_2	0.937100	0.199900								
					Equation (4)					
β_0	0.000898	0.000500	0.93	0.043	0.209	0.030	0.159	0.209	5.00	3
β_1	0.9114	0.1990								
					Umbila					
					Equation (1)					
β_0	0.000037	0.000053	0.91	0.033	0.148	0.018	0.108	0.149	4.52	4
β_1	2.706900	0.394900								
					Equation (2)					
β_0	0.000045	0.0000013	0.99	0.013	0.058	-0.011	0.036	0.058	3.95	3
					Equation (3)					
β_0	0.000009	0.000004	0.99	0.009	0.045	0.009	0.033	0.044	5.39	1
β_1	2.262900	0.097800								
β_2	1.256500	0.117900								
					Equation (4)					
β_0	0.000022	0.000007	0.99	0.012	0.052	-0.012	0.034	0.052	4.50	2
β_1	1.3012	0.1352								

1 Cross validation "Leave-one-out" procedure

5 Discussion

The visited stands were found to contain Chanfuta, Jambire, and Umbila even though an earlier forest inventory report indicated that some of them did not contain these species (Marzoli, 2007). This may be due to the low sampling intensity of earlier forest inventories, the use of different sampling methods and strategies, the examination of different sampling sites, or the haphazard distribution of the studied species. Regardless of the cause, the results presented herein suggest that earlier inventories are more useful as generalized descriptions of species distributions rather than sources of site- and species-specific data. In addition, the density of the three targeted species in the studied areas was low. This is consistent with the findings of Fath (2001), who pointed out that Mozambican natural forests are rich in biodiversity but are dominated by low stock levels of commercial species and low increment wood biomass.

Tree age data are not generally available in Mozambique. Therefore, no site productivity index values could be calculated for the studied localities. Based on reference growth rates (Table 1), the applied cutting cycle of 40 years seems to be somewhat short because the studied species may need 75-100 years of growth to reach the minimum allowable cut diameter. Small wood biomass increments in Mozambican forests were previously reported by Fath (2001). It will therefore be necessary to obtain more reliable age estimates for Mozambican trees in order to support sustainable forest management in this country.

The present study showed that the studied species allocated biomass differently among their various tree fractions. While stems accounted for the bulk of the AGB in Chanfuta and Jambire, the branches accounted for the majority in Umbila. Branches accounted for 43% and 22% of the total biomass in Chanfuta and Jambire, but 51% in Umbila. This allocation was unexpected for miombo woodland tree species. Geldenhuys and Goldings (2008) argued that branch biomass normally accounts for more than 50% of the timber of trees growing on forest land. Moreover, it has been suggested that site conditions influence the distribution of biomass between tree fractions (Segura and Kanninen, 2005; Chamshama *et al.,* 2004; Abbot et al., 1997; Nelson et al., 1999). The localities differed with respect to tree sizes: trees at Inhaminga tended to have larger DBH values than those in Tome and Mavume. Inhaminga is located in a region with a growth rate of 1.2 m^3 ha^{-1} $year^{-1}$ whereas Mavume and Tome are in drier regions with growth rates of 0.6 m^3 ha^{-1} $year^{-1}$ (Marzoli 2007). Competition for light and space in dense forests limits the development of large branches more than in open forests (Segura and Kanninen, 2005; Murali et al., 2005). The average annual rainfall at Inhaminga is 1000 mm whereas that at Mavume and Tome is below 800mm; this difference is associated with a change in the dominant vegetation (Table 2). Site conditions may also have influenced the trees' growth rates, sizes, and biomass distributions, causing differences both between and within species. Anthropogenic activities, harvesting and forest fires have all been identified as driving forces of changes in the structure and composition of miombo forests (Ribeiro *et al.*, 2008). In this context, it is noteworthy that all of the sampled areas had been subject to timber harvesting in the past. Further studies will be needed to identify driving factors that influence biomass distribution in different forest types with different environmental factors.

The species-specific volume estimation methods developed in this work provided more accurate estimates than were obtained using the generic formula recommended by Marzoli (2007). The three entry variable equation of Marzoli (2007) overestimated stem volumes by 37%, 13% and 9% for Chanfuta, Jambire and Umbila, respectively. The stem volume estimation method developed in this work proved to be suitable for tropical tree species with multi-branched crowns, although gathering the data needed to use the equations is somewhat laborious and time-consuming. However, the formula of Marzoli (2007) has a major drawback in that it uses an arbitrary form factor; no such form factors have been determined for Mozambique and there are no established methods for their estimation in this country.

5.1 Biomass and Stem Volume Equations

While DBH alone was the best predictor variable for AGB estimation (Paper I), it did not yield good results for the stem volume. However, the inclusion of height as an additional variable greatly improved the performance of the stem volume models (Paper II). The fitted AGB and stem volume equations exhibited determination coefficients (R^2) in excess of 0.70, indicating that the fitted models fitted the data well. Predictions of the total AGB and stem fraction biomass are more stable than those of more short-lived branches and leaves (Návar 2009). While attempts were made to gather all of the leaves from the felled trees that were measured in this work, the trees' large crowns made it difficult to find leaves that landed some distance from the felling site. The observation that the predictions of the stem volume were improved by including height as a variable in the model is consistent with previous findings (Brown et al., 1989; Abbot et al., 1997; Chavé et al., 2005; Berhe, 2009; Mni and O.¸2010; Fonweban et al., 2012). However, the accurate indirect measurement of height is challenging and this may limit the general applicability of models in which it appears as a variable (Kanime and Laamanen, 2002; Dorado et al., 2006; Sharma and Parton; 2007).

The inclusion of the basic density as a variable in the equations for total AGB and the biomass of other tree fractions only yielded predictive improvements for the total AGB of Umbila (R^2 = 0.95–0.97, RMSE = 88–147). However, it also increased the average bias of the model and was therefore excluded from further consideration. Biomass models that use basic density as a variable have been reported by Vieilledent et al. (2012) and Návar-Cháidez et al. (2013).

This work presents the first specie-specific equations for predicting the AGB and stem volume of Chanfuta, Jambire and Umbila trees. Because all of the studied Jambire samples were collected from the same locality, the equations for this species should be considered to be site-specific for the time being. The development of both biomass and stem volume equations is useful because it avoids the limitations associated with biomass prediction on the basis of stem volumes alone. The equations presented herein should help Mozambican forest planners to accurately estimate the potential of their resources and to use them efficiently. Miombo tree species of the same DBH class do not vary greatly in height (Mugasha et al., 2013). Based on the range of sample trees examined in this work, the developed equations are suitable for trees with DBH values ranging from 10 to 70 cm and total heights of 5 – 30 m.

The models for total AGB and the biomasses of individual tree fractions that best fit the experimental data were selected based on their R^2, RMSE and bias (AB, AAB) values (Table 5). According to Parresol et al. (1987), AAB values are particularly useful for this purpose. Because several different types of power equation were tested for predicting stem volume, multiple statistical criteria were used to identify that with the best fit, including RSE, AIC and an overall rank test. Chavé et al (2005) recommended a combination of R^2 and RSE while Burnham & Anderson (2002) recommended AIC for model selection. In this work, an overall rank assessment based on every calculated statistical parameter (R^2, RMSE, RSE, AAB, AB, AIC) was adopted. This approach proved to be robust. It is possible that models with superior fits could be developed by including other locale-specific variables such as precipitation, climate, or soil type (Chavé et al., 2005 and Henry et al., 2010). In addition, further research will be required to develop equations that can describe variation in miombo species that have not been extensively studied or documented.

5.2 Forest Residues Estimates

The developed biomass and stem volume equations were used to estimate the theoretical potential of forest residues that could be obtained from logging operations involving Chanfuta, Jambire and Umbila species. It was determined that 50% these species' stem volumes are not commercially valued and are thus available as residues. Similar results for other species in Mozambique were reported by Fath (2001). If we assume that 50% of the wood biomass of tropical species is allocated to branches (Geldenhuys and Goldings, 2008) and depending on biomass allocation due to environmental factors (Abbot et al., 1997; Nelson et al., 1999; Segura and Kanninen, 2005; Murali et al., 2005), it is clear that the amount of residual biomass will vary between species.

The estimated commercial stem lengths generated during this work were greater than the log dimensions listed in local forest companies' records. However, direct comparisons between the two datasets are not necessarily meaningful because the companies' records did not state how many logs were derived from individual trees, how many logs were obtained from thick branches, or the number of missing records. The findings of this study indicate that the Mozambican forest industry produces large quantities of unutilized residual biomass that is not well accounted for.

Historical data show that the three studied species dominated Mozambique's harvested volumes over the last 13 years. The models and findings presented herein should thus be useful for the management of country's existing commercial stock. However, further research on the availability of logging residues in terms of stand stock, market demand and logistical issues is needed. Moreover, little is known about the potential environmental consequences of harvesting forest residues because they are currently regarded as unwanted by-products of harvesting operations and left in place. This deficiency should be addressed. However, the negative environmental impacts of cutting natural forests in Mozambique to harvest fuelwood have been documented (Sitoe *et al.,* 2012). Fuelwood harvesting and the clearing of forest land for agricultural use are the major causes of deforestation in Mozambique today (Marzoli, 2007; Sitoe *et al.,* 2012). The results presented herein suggest that residual material from the harvesting of the studied tree species could represent a viable source of bioenergy whose exploitation could address the country's demand for fuelwood and thus alleviate some of the pressure on its primary and secondary forests.

6 Conclusions

The first equations that predict the aboveground biomass and stem volume for three of Mozambique's most valuable native trees species - Chanfuta, Jambire and Umbila – have been developed. The biomass equation can estimate the biomass of individual tree fractions and woody biomass residues derived from logging activity that could potentially be used to generate bioenergy. The stem volume study was the first attempt to develop species-specific volume equations for native commercial tree species in Mozambique. The equations presented herein represent valuable contributions because they will enable the creation of tools that will allow Mozambican forest planners to predict merchantable volumes with greater accuracy than was previously possible, estimate forest resource stocks, and define appropriate management strategies. However, tropical Miombo forests exhibit high species diversity, and further work will be required to develop species-specific volume and taper equations that will complement the models presented herein by accounting for geographical and ecological variability in regions harbouring miombo species.

The main conclusions of this thesis are:

- The studied species differed with respect to the mean total biomass per standing tree, which was 0.9 tons for Chanfuta, 1 ton for Jambire and 0.3 tons for Umbila.
- The studied species allocated their biomass across their various fractions in different ways: Chanfuta and Jambire allocated most of their woody biomass to their stems while Umbila allocated more to the branches.
- The biomass of the studied species is best predicted as a function of the diameter (DBH) alone using a non-linear power equation, $AGB= \beta_0 D^{\beta 1}$.
- The stem volume of the studied species is best predicted as a function of both the DBH and stem height, $V= \beta_0 D^{\beta 1} H^{\beta 2}$.

- The total merchantable stem length was between 30 and 70% of the total stem length for the studied species.
- At the individual species level, the bulk of the logging residues would derive from Umbila because it allocates most of its biomass to its branches, which are not used commercially by Mozambican forest companies.
- The developed biomass and volume equations are suitable for use in Mozambique and provide accurate estimates of biomass and stem volume at the stand and landscape levels that can be used to support forest resource use planning.

7 Further work

Future studies for the PhD should aim to:

- Use the developed biomass and volume equations to assess the potential of raw material from native and planted forests for energy generation and assess the associated logistical issues;
- Determine relevant fuel quality parameters for the residual material left behind after timber harvesting of the studied species, e.g. its heating value and ash content;
- Perform a life cycle assessment for the use of whole tree biomass (*Eucalyptus*) as an energy source (on-going work in collaboration with other PhD student at the Department).

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