

Effects of site and tree size on wood density and bark properties of Lebombo ironwood (*Androstachys johnsonii* Prain)

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Abstract

Background: Wood and bark are important renewable natural resources. Density is an important property that is used to describe wood and bark quality for a number of end uses. However, wood and bark density, bark proportion and dimensions vary with age and site, as well as among and within trees. The aim of this study was to investigate the effect of site, diameter class, and vertical position within the stem on the density of wood and bark, bark volume, bark dry-mass and thickness of Lebombo ironwood (*Androstachys johnsonii* Prain).

Methods: The study was conducted on 93 Lebombo ironwood trees growing in Mozambique. Eight discs were sampled from each selected tree and diameter over and under bark was measured. Bark thickness, bark mass and bark density were determined along with the basic wood density of each disc.

Results: The overall average whole-stem properties were estimated at: 786 kg m⁻³ wood density, 586 kg m⁻³ bark density, 19% bark volume, 19% bark dry-mass, and 9 mm bark thickness. Height level uniquely explained most of the variation in bark mass (97%), bark volume (95%) and wood density (86%). Diameter class explained most of the variation in bark density (51%) and bark thickness (51%). Site only explained a small proportion of the variation in all dependent variables.

Conclusions: Overall, the patterns of variation of all wood and bark properties were highly dependent on tree diameter class and vertical position within the stem. Site differences were not a significant source of variation in the properties studied. Improved knowledge of the wood and bark properties of this species will aid its sustainable management and utilisation.

Keywords: Bark traits; Commonality analysis; Regression effect; Suppressor effect; Wood traits

Introduction

Mecrusse is a forest type in which the dominant canopy species is *Androstachys johnsonii* Prain, the relative cover of which varies from 80% to 100% (Magalhães 2017a). *Androstachys johnsonii* is known vernacularly as Lebombo ironwood or Cimbirre. The wood of *A. johnsonii* is also known as Lebombo ironwood. Lebombo ironwood is a tree species native to Madagascar and Africa, however, presently it is almost restricted to Mozambique (Cardoso 1963), where it is mainly found in the southmost part of the country, in Inhambane and Gaza province (Magalhães 2015). In Mozambique,

it is classified as a first-class timber and it is lawfully harvested at 30 cm DBH. This tree species rarely exceeds 35 cm in diameter at breast height (DBH) (Magalhães and Seifert 2015).

Lebombo ironwood has distinct growth ring boundaries and is diffuse-porous with vessels of two distinct diameter classes (Bunster 2006; Cardoso 1963). The growth rings are wavy causing a fine streaked appearance (Bunster 2006). The fibres are very thick-walled with distinctly bordered pits common in both radial and tangential walls (Ali 2008). The heartwood is yellowish-pale brown, sometimes slightly pink (Bunster 2006).

Because of its durability (Bunster 2006), Lebombo ironwood is used as poles and stakes by the local community (Magalhães 2017a) and in construction of houses and bridges (Cardoso 1963). Due to its favourable mechanical properties (Cardoso 1963), Lebombo ironwood is also suitable for flooring, turnery, marine uses, furniture and interiors (Bunster 2006), stairs, laths, fences, railway sleepers, bridge piers, vehicle boards and draining boards (Ali et al. 2008; Cardoso 1963). These end uses are determined by the properties of this wood, hence the relevance of studying them. In the early 1960s, Lebombo ironwood had already been reported to be almost completely restricted to Mozambique (Cardoso 1963), presumably due to overexploitation. Five decades later, there is still a lack of studies on this species in any branch of forest science, especially studies related to wood and bark properties. This emphasises the need to study the wood properties of this species.

Basic wood density (hereafter referred simply as wood density) is an important wood quality characteristic. Wood density is used to describe wood quality in construction and in the mechanical and chemical pulp industries (Repola 2006). Various solid wood utilization characteristics such as timber strength and stiffness, machinability and drying, and some manufacture and performance reconstituted products such as raw material consumption, uptake of chemicals, pulp yield, and paper properties are dependent on wood density (Kimberley et al. 2015; Tian et al. 1995).

Along with volume, wood density is a key determinant of tree biomass (Bastin et al. 2015) and thus a key variable to make estimates of carbon pools in forests, and for studying other biochemical cycles and understanding the evolution and potential future changes of the climate system. Lebombo ironwood is heavy, with a density of 754 and 880 kg/m³ at 0 and 12% moisture content, respectively (Bunster 2006; Magalhães 2015). Its high density makes it attractive to the hardwood lumber industry.

Bark is also an economically important raw material. It is used in the production of cork, fibre, tannins, pallets, briquettes, insulation boards, fibreboards, hardboards, particleboards (Pásztor et al. 2016). Bark is also used in mulching and soil amendment (Pásztor et al. 2016). Specifically, due to its allelopathic effect (Magalhães 2017a; Molotja et al. 2011), the bark of Lebombo ironwood is used to sterilise the soils in rural home gardens where only adult trees are desired (i.e. to avoid weed and seed germination). This highlights the importance of quantifying the properties and quantity of bark. Except for chemical production, most of the uses of bark (e.g., production of boards) are influenced by its density.

Knowing the thickness of bark is critical to accurately estimate the relative volumes of solid wood and bark that are available (Thomas and Bennett 2014). Stem bark volume and bark dry-mass are important because bark and wood mass are separated while processing logs, and accurate determination of volume is problematic (Thomas and Bennett 2014). Wood and bark density, bark volume and mass, and bark thickness vary with age,

diameter, site, tree and within tree (longitudinally and radially) (Auty et al. 2014; Cellini et al. 2012; Kimberley et al. 2015; Machado et al. 2014; Murphy & Cown 2015; Paine et al. 2010; Quilhó & Pereira 2001; Repola 2006; Searle & Owen 2005; Sonmez et al. 2007). Thus, the variations of these wood and bark properties are of particular interest to the forestry sector and the related industries (e.g. construction, fuel industries, etc.).

Although considerable studies have been carried out on the extent and sources of variation in wood and bark properties of coniferous species in Europe, North America, South America and Australasia, similar studies are lacking for tropical African broad-leaved species. The current study aimed to quantify the effects of site, diameter class, relative height within the stem and their interactions on wood and bark density, bark volume, mass, and thickness of Lebombo ironwood. As these tree variables are often measured at a single specific sampling point, generally breast height (Hernández & Genes 2016; Tian et al. 1995), whole-stem-based properties (e.g. whole-stem wood density) were compared to the equivalent breast height-based properties.

Methods

Study sites

This study was carried out in Mecrusse woodlands of the Mandlakaze (24° 04' – 25° 02' S and 33° 47' – 34° 39' E), Funhalouro (22° 09' – 23° 42' S and 33° 40' – 34° 29' E) and Mabote (21° 18' – 22° 54' S and 33° 10' – 34° 39' E) districts of Mozambique (10° 30' – 26° 52' S and 30° 15' – 40° 45' E), in southern Africa. The physical and natural conditions of the study areas are shown in Table 1.

Data collection

Ninety-three trees with DBH varying from 5 to 32 cm (average = 17.6 cm) and total height varying from 5 to 16 m (average = 12.3 m) were randomly selected and destructively measured. The trees were distributed across each site and DBH class as shown in Table 2. Felled trees were scaled up to a 2.5 cm top diameter. The stem was defined as the length of the trunk from the predefined stump height (20 cm) to the height that corresponded to a stem diameter of 2.5 cm. The trees had stem lengths varying from 4.25 to 14.85 m (average = 10.78 m). Discs of approximately 5 cm thickness were taken from each tree at eight heights along the stem: breast height, 0, 10, 30, 50, 70, 90 and 100% of stem height.

Diameters over and under bark (DOB and DUB, respectively) were measured on each disc in the north-south direction (previously marked on the standing tree) using a ruler. The volume of the discs, before and after debarking, was determined using the water displacement method (Brasil et al. 1994). Therefore, it was possible to obtain disc volumes over and under bark. Bark volume was determined as the difference between disc volume over and under bark.

Wood discs and associated bark were oven dried at 105°C to constant mass. Wood and bark density were obtained by dividing the oven dry-mass of the disc and

TABLE 1: Description of the study sites

District	Description			
	Climate and hydrology	Relief, topography and elevation	N (ha ⁻¹)	G (m ² ha ⁻¹)
Mandlakaze	Climate: dry and humid tropical; AHM: 34; AI: 0.7; Hydrology: 63 lakes and 2 rivers.	Relief and topography: flat. Elevation: 50 to 200 m a.s.l.	732	17
Funhalouro	Climate: dry semi-arid; AHM: 52; AI: 0.4; Hydrology: not crossed by any river, occurrence of meteorological droughts.	Relief and topography: flat. Elevation: 100 to 200 m a.s.l.	1617	26
Mabote	Climate: dry tropical; AHM: 57; AI: 0.4; Hydrology: not crossed by any river, occurrence of meteorological droughts.	Relief and topography: flat. Elevation: 100 to 200 m a.s.l.	1333	21

Where N is number of Lebombo ironwood trees per hectare (DBH \geq 5 cm), G respective basal area, AHM annual heat moisture index, and AI aridity index. Source: MAE (2005a, 2005b, 2014), Magalhães (2017b).

the bark by the relevant volume (Magalhães & Seifert 2015). Bark volume proportion (hereafter referred simply as bark volume) was calculated as the percentage of bark volume relative to total disc volume. Similarly, bark mass proportion (hereafter referred simply as bark mass) was calculated as the percentage of bark oven dry-mass relative to the total disc oven dry-mass. Double bark thickness was determined as the difference between DOB and DUB. In total, 744 measurements of wood and bark density, bark volume and mass and double bark thickness were taken along the stems of the 93 sample trees.

Whole-stem wood and bark properties under study were calculated using data on the respective properties obtained at eight heights up the stem (i.e. breast height, 0, 10, 30, 50, 70, 90 and 100% of stem height). Table 3 shows the correlation matrix between the wood and bark properties.

Data analysis

Three-way nested multivariate analysis of variance (nested MANOVA) was performed to test the significance of site, diameter class, and height level on the wood and bark properties under study. Commonality analysis was carried out to quantify how much of the variation in wood and bark properties was explained by the variance of all the predictors (site, DBH class, height level) and quantify the variance that was unique to each

predictor and the variance that was common to groups of predictors. One-way nested analyses of variance (nested ANOVA), with Tukey's HSD test, were carried out to verify the difference between whole-stem wood and bark properties and the relevant properties at different height levels within the stem.

All statistical analyses and tests were carried out using R software (R Core Team 2019). One-way ANOVA and three-way MANOVA were run using the functions "aov" and "manova", respectively. Interactions plots were built using "ggplot2" package (Wickham et al. 2018). Commonality analyses were performed using "yhat" package (Nimon et al. 2015). All tests were performed at significance level of $\alpha = 0.05$.

Results

Basic wood density

The average (\pm SE) whole-stem wood density for all sites (whole population) was estimated at 786 (\pm 2.2) kg m⁻³, ranging among sites from 783 (\pm 3.0) to 790 (\pm 4.5) kg m⁻³. Whole-disc wood density ranged from 729 (\pm 6.7) to 872 (\pm 4.2) kg m⁻³ within a tree (longitudinally) and from 760 (\pm 6.6) to 807 (\pm 4.2) kg m⁻³ among diameter classes.

Whole-disc wood density decreased considerably with height. It increased slightly with diameter class from mid DBH of 7.5 to 12.5 cm and then it remained constant to the mid DBH of 22.5 cm from where it increased slightly again (Figure 1). However, it did not show a significant variation with site. For Mandlakaze and Mabote districts, the whole-stem wood density was only found to be different to the wood density at the base and top of the stem (relative heights of 0.0 and 1.0), but no significant differences were found between whole-stem density and the densities of other height levels. For Funhalouro district and for the whole population, significant differences were only observed with the densities at relative heights of 0.0, 0.9 and 1.0.

Diameter class and height level were found to be significant sources of variation of wood density ($P < 0.0001$; Table 4). Site was not a significant source of variation of wood density ($P = 0.15$). The interactions

TABLE 2: Number of harvested trees per site and diameter class

Mid DBH (cm)	Mandlakaze	Funhalouro	Mabote	Total
7.5	3	6	9	18
12.5	3	7	8	18
17.5	4	6	8	18
22.5	4	5	8	17
27.5 +	6	7	9	22
Total	20	31	42	93

TABLE 3: Person’s correlation matrix for wood and bark properties

	Wood density	Bark density	Bark volume	Bark content	Bark thickness
Wood density	1.0000	0.2577	- 0.4069	- 0.4846	0.3236
Bark density		1.0000	- 0.3064	- 0.2339	0.4345
Bark volume			1.0000	0.8136	- 0.2470
Bark content				1.0000	- 0.4441
Bark thickness					1.0000

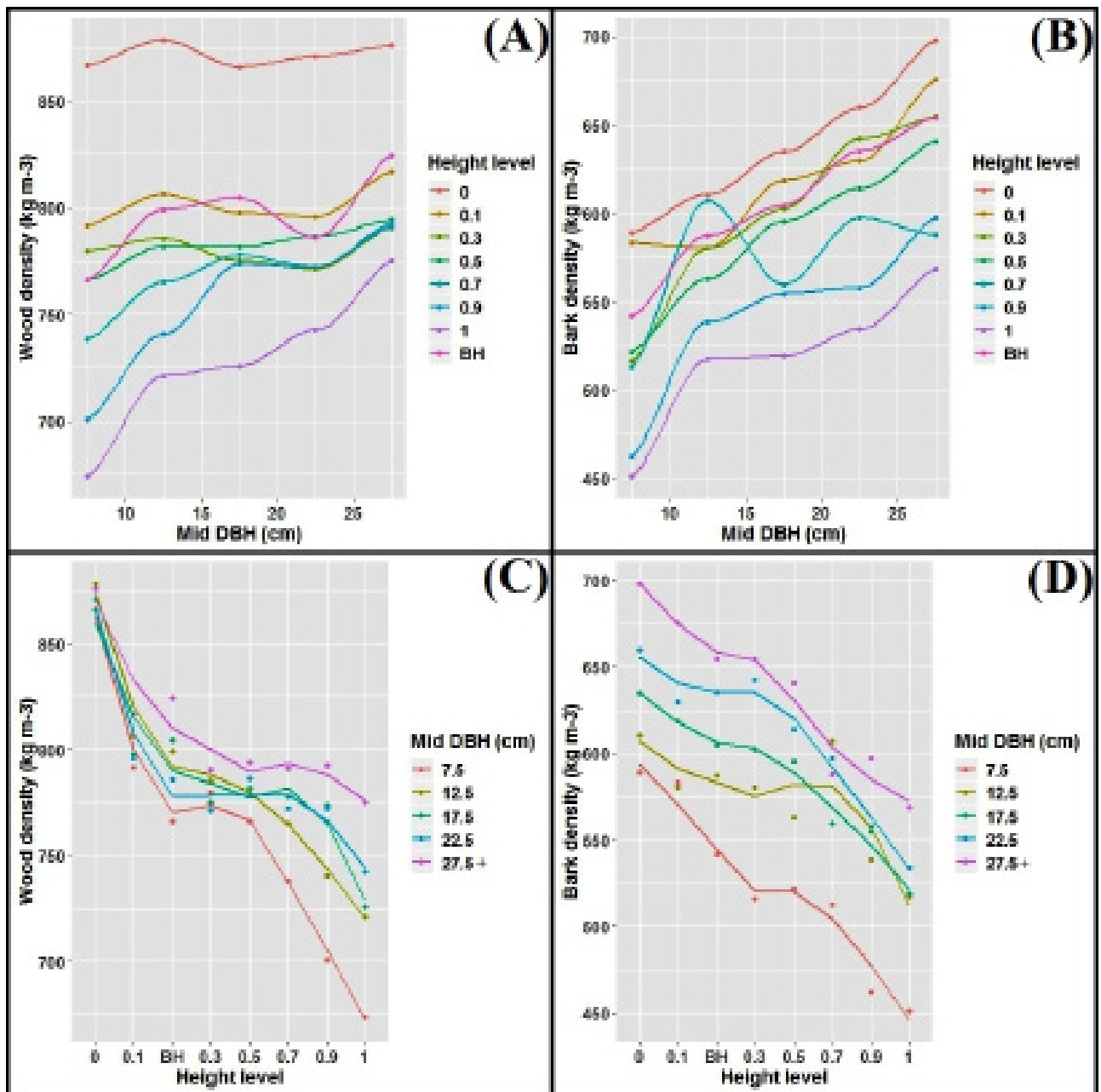


FIGURE 1: Pattern of variation of wood and bark density with DBH class (A and B) and height level (C and D).

TABLE 4: Multivariate analysis of variance and omega-squared (ω^2) for wood and bark properties

Factors and interactions	df	Wood density		Bark density		Bark volume		Bark mass		Bark thickness	
		P-value	ω^2 (%)	P-value	ω^2 (%)	P-value	ω^2 (%)	P-value	ω^2 (%)	P-value	ω^2 (%)
Site	2	0.1513	0.1	0.0085	0.7	0.0001	0.6	0.4742	0.0	0.0000	4.4
DBH class	4	0.0000	6.2	0.0000	14.2	0.0000	2.4	0.0000	2.4	0.0000	27.2
Height level	7	0.0000	39.9	0.0000	12.4	0.0000	65.0	0.0000	70.0	0.0000	21.2
Site × DBH class	8	0.0000	1.8	0.0014	1.7	0.2129	0.1	0.0000	1.2	0.0150	0.8
Site × Height level	14	0.0010	1.5	0.9429	0.0	0.0473	0.4	0.0044	0.4	0.2194	0.4
DBH class × Height level	28	0.0005	2.2	0.8773	0.0	0.0000	2.3	0.0000	7.2	0.0015	2.1
Site × DBH class × Height level	56	0.9505	0.0	0.3753	0.3	0.9948	0.0	0.0014	0.9	0.8667	0.0
Residuals	624										

Where df are degrees of freedom

between site and DBH class, site and height level, DBH class and height level had statistically significant effects on wood density ($P < 0.0001$). However, the interaction between site, DBH class and height level had no significant effect ($P = 0.95$; Table 4).

From the commonality analysis (Table 5) it was found that the unique effects and the common effects together explained 47.13% (sum of commonality coefficients) of the variation of wood density: i.e., the regression effect explained 47.13% of the variation of wood density. Most of that regression effect (85.78%) was explained by variance that was unique to height level. DBH class and site accounted for 13.68 and 0.44% of the regression effect, respectively. Together, the three independent variables uniquely accounted for 99.90% of the regression effect. The remaining 0.1% was due to the common effect of site and DBH class.

Basic bark density

Site, diameter class, and height level were found to be significant sources of variation in bark density ($P < 0.0001$; Table 4). Only the interactions between site and DBH class had a significant effect on bark density ($P < 0.0001$). Higher values of bark density were observed in Funhalouro district (with an average (\pm SE) whole-stem density of 597 (\pm 4.6) kg m^{-3}) and the lower ones in Mandlakaze district (with a whole-stem density of 574 (\pm 9.1) kg m^{-3}). Mabote district had intermediate bark density values.

Whole-stem bark density increased significantly with increasing diameter class, from an average (\pm SE) value of 522 (\pm 8.2) kg m^{-3} for the smallest diameter class to 634 (\pm 8.5) kg m^{-3} for the largest diameter class (Figure 1). Bark density decreased considerably with relative height up the stem, with an overall decrease of approximately 20% from the bottom to the top of the stem.

TABLE 5: Commonality analyses for wood and bark density

Factors and interactions	Wood density		Bark density	
	Commonality coefficient	% of total variance	Commonality coefficient	% of total variance
Site	0.0021	0.44	0.0157	5.50
DBH class	0.0645	13.68	0.1463	51.11
Height level	0.4043	85.78	0.1306	45.63
Site × DBH class	0.0005	0.10	-0.0064	-2.24
Site × Height level	0.0000	0.00	0.0000	0.00
DBH class × Height level	0.0000	0.00	0.0000	0.00
Site × DBH class × Height level	0.0000	0.00	0.0000	0.00
Total	0.4713	100.00	0.2862	100.00

The regression effect explained 28.62% of the variation of bark density (Table 5). Of that regression effect, 51.11% was explained by the variance that was unique to DBH class and 45.63% was explained by the variance that was unique to height level (Table 5). The variance unique to the site explained only 5.50% of the total regression effect. The interaction of site and height level had a negative effect on bark density, meaning that the predictor variables site and height level affected each other in the opposite direction. This suppression accounted for 2.24% of the regression effect. Overall, the first-order effects (variance unique to the independent variables), second-order effects (variance common to pair of predictors), and third-order effects (variance common to all three predictors together) accounted for 102.24, -2.24, and 0.0% of the regression effect, respectively, totalling 100%.

It was observed that in Mandlakaze and Mabote districts, bark density at different height levels was not significantly different from the whole-stem bark density. For Funhalouro district and for the whole population, the whole-stem bark density was only significantly different from the bark densities at relative heights of 0.0 and 1.0.

Bark volume

The average (\pm SE) whole-stem bark volume for all sites was 19 (\pm 0.4) %, ranging from 18 (\pm 0.6) to 20 (\pm 0.7) % among sites. Bark volume proportion ranged from 11 (\pm 0.4) to 33 (\pm 0.8) % within-tree, and from 18 (\pm 0.9) to 21 (\pm 0.6) % between DBH classes. Overall, Funhalouro district had the lowest values, followed in an increasing order by Mabote and Mandlakaze. In general, bark volume decreased slightly with DBH class and increased sharply with height level. The patterns of variation in bark volume at relative heights of 0.9 and 1.0 with site and DBH class were opposite to those observed at other height levels (Figure 2).

Site, diameter class, and height level were significant sources of variation of bark volume (Table 4). Although statistically significant, site and DBH class contributed very little to the total variation in bark volume (Tables 4 & 6). Site and DBH class accounted for only 1.25 and 3.75% of the total regression effect (68.64%). Thus, most of the regression effect was explained by the variance that was unique to height level (95.22%). The only significant common effect was between site and DBH class which, however, was a suppressor effect. Although the second- and third-order interactions had a statistically significant effect on bark volume (Table 4), none of them contributed to the total regression effect (Table 6).

Whole-stem bark volume was statistically different from the bark volume at different height levels, except at relative height of 0.3, 0.5 and 0.7 for Mandlakaze and Mabote districts and only at relative height of 0.5 for Funhalouro district and the whole population.

Bark mass

The average (\pm SE) whole-stem bark mass for all sites was estimated at 19 (\pm 0.3) %, and it was constant

all over the sites. Average bark mass ranged from 10 (\pm 0.3) to 32 (\pm 0.6) % within a tree (longitudinally), with the smallest values at the bottom of the stem. It ranged from 17 (\pm 0.8) to 21 (\pm 0.5) % among DBH classes. Overall, bark mass decreased slightly with DBH class and increased sharply with increasing height level (Figure 2). The pattern of variation of bark mass was independent of site ($P = 0.47$). However, it was dependent of other factors (DBH class and height level) and all interactions ($P < 0.0001$; Table 4). The regression effect explained 72.72% of the variation in bark mass, of which 96.56% was explained uniquely by the variance of the height level. The variance of DBH class ranked next, accounting for 3.39% of the regression effect. Site effects ranked last, accounting only for 0.05%. None of the common effects accounted for the regression effect.

For Funhalouro and Mabote districts and for the whole population, whole-stem bark mass was significantly different from the bark mass at all height levels, except at a relative height of 0.5. For Mandlakaze district, whole-stem bark mass was only significantly different from bark mass at relative heights of 0.0 and 1.0.

Double bark thickness

The average whole-stem double bark thickness and the double bark thickness at most height levels increased sharply from Funhalouro to Mabote district. However, from Mabote to Mandlakaze district it either showed a slight increase or decrease or remained constant. Double bark thickness was found to increase sharply and rapidly with increasing DBH class (Figure 3). Average double bark thickness, for all sites and most DBH classes, increased slightly with increasing height level to the breast height or to the relative height of 0.3, and then it decreased non-linearly and rapidly to the top of the stem, resembling a quadratic parabola function (Figure 3).

The average (\pm SE) whole-stem double bark thickness for all sites was estimated at 9 (\pm 0.2) mm, ranging between sites from 8 (\pm 0.2) to 10 (\pm 0.4) mm. Average double bark thickness also ranged from 4 (\pm 0.2) to 11 (\pm 0.5) mm within an individual tree (higher values at the base of the stem) and from 5 (\pm 0.2) to 12 (\pm 0.4) mm among DBH classes.

Site, diameter class, and height level were significant sources of variation of double bark thickness ($P < 0.0001$; Table 4). The interactions of site and DBH class, and DBH class and height level had a statistically significant effect on double bark thickness ($P < 0.02$).

The regression effect explained 53.45% of the variation of double bark thickness (Table 6). Of that regression effect, 51.24% was explained by the variance that was unique to DBH class and 40.27% was explained by the variance that was unique to height level (Table 6). The variance unique to the site explained 6.22% of the total regression effect. The only significant common effect was between site and DBH class, accounting for 2.27% of the regression effect. Double bark thickness at most of the height levels was not significantly different from the whole-stem bark thickness.

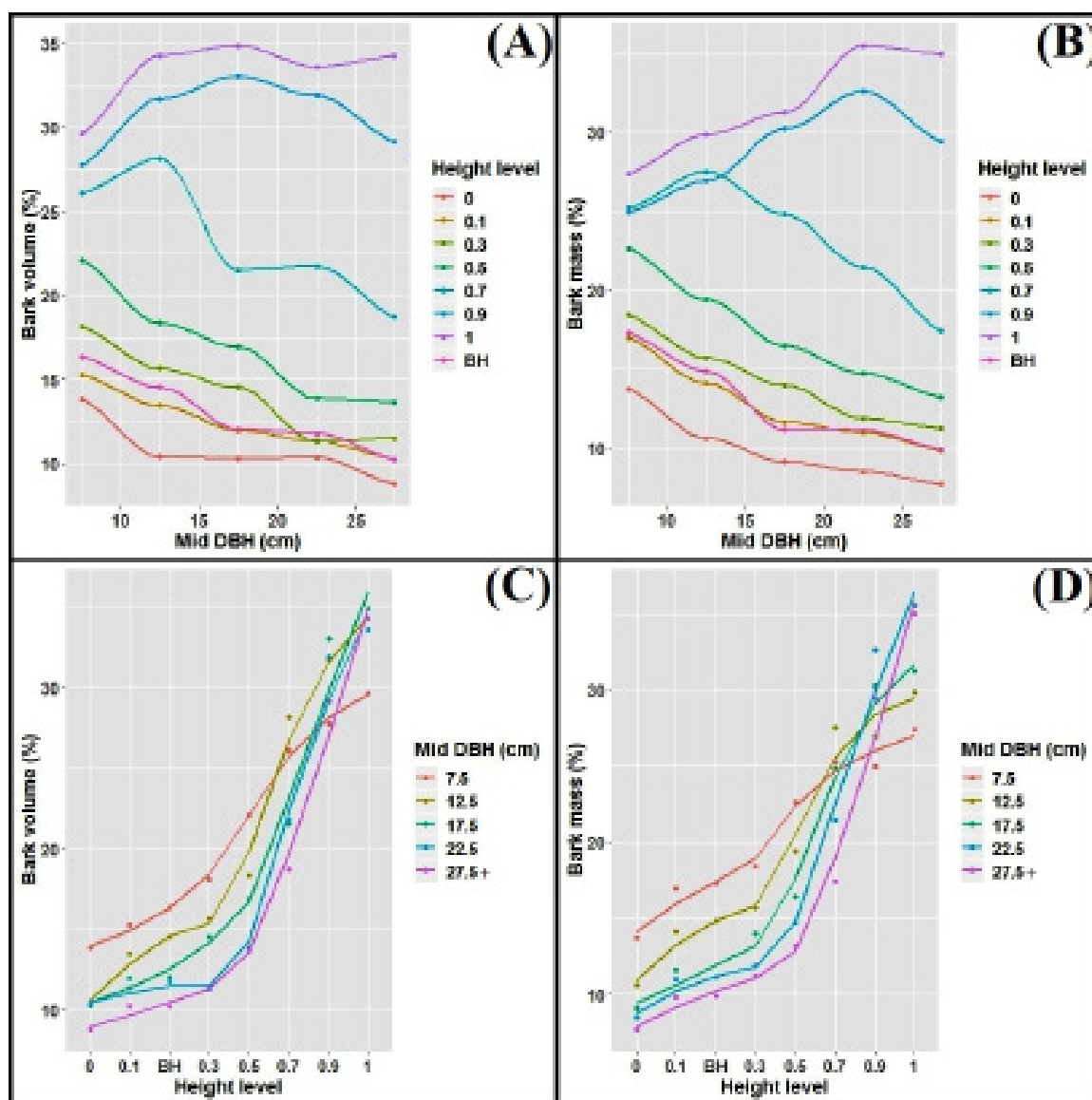


FIGURE 2: Pattern of variation of bark volume and bark mass with DBH class (A and B) and height level (C and D).

TABLE 6: Commonality analyses for bark volume, bark mass and bark thickness

Factors and interactions	Bark volume		Bark mass		Bark thickness	
	Commonality coefficient	% of total variance	Commonality coefficient	% of total variance	Commonality coefficient	% of total variance
Site	0.0086	1.25	0.0003	0.05	0.0332	6.22
DBH class	0.0257	3.75	0.0247	3.39	0.2739	51.24
Height level	0.6536	95.22	0.7022	96.56	0.2152	40.27
Site × DBH class	-0.0015	-0.22	0.0000	0.00	0.0121	2.27
Site × Height level	0.0000	0.00	0.0000	0.00	0.0000	0.00
DBH class × Height level	0.0000	0.00	0.0000	0.00	0.0000	0.00
Site × DBH class × Height level	0.0000	0.00	0.0000	0.00	0.0000	0.00
Total	0.6864	100.00	0.7272	100.00	0.5345	100.00

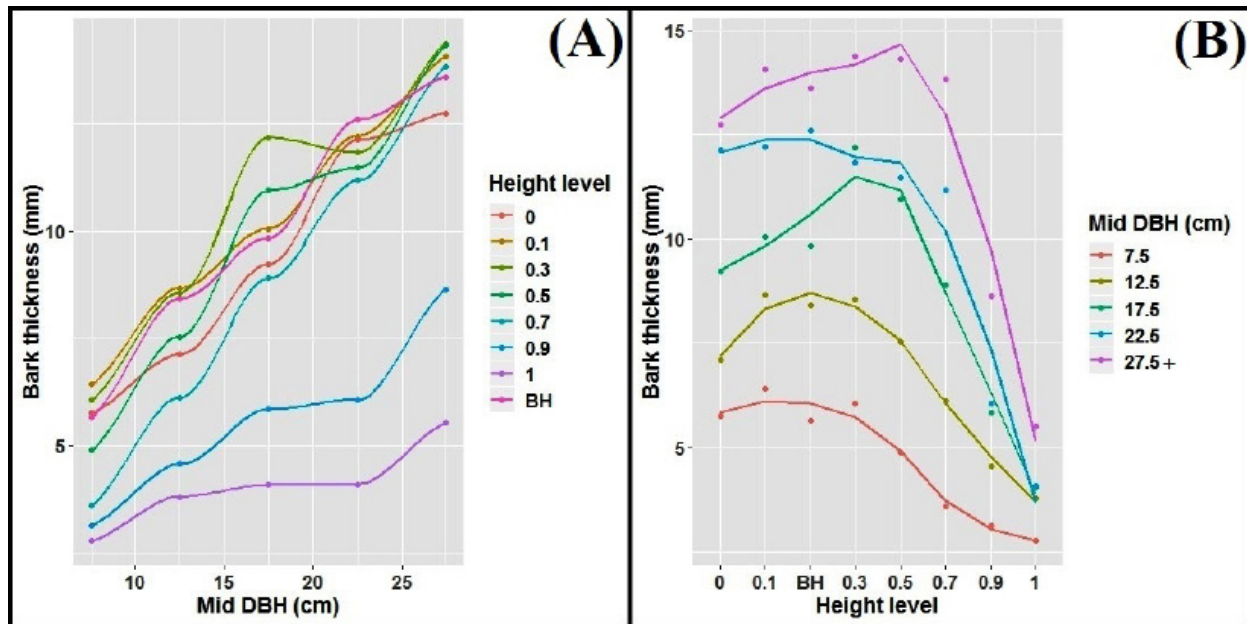


FIGURE 3: Pattern of variation of bark thickness with DBH class (A) and height level (B).

Discussion

The overall average wood density at breast height found in this study (786 kg m^{-3}) is higher than that reported by Bunster (2006) and Magalhães (2015) (754 kg m^{-3}). The reason for this difference is because, as opposed to this study, these authors reported wood density over bark. However, calculations based on the wood and bark density and bark volume and mass revealed that the density over bark for this study (749 kg m^{-3}) is close to the value reported by Bunster (2006) and Magalhães (2015).

The overall density of bark at breast-height of Lebombo ironwood (606 kg m^{-3}) was higher than that of the wood of some Miombo woodland species in Mozambique (Bunster 2006): *Pterocarpus angolensis* (558 kg m^{-3}), *Khaya nyasica* (599 kg m^{-3}), *Balanites maughamii* (584 kg m^{-3}), *Brachystegia spiciformis* (588 kg m^{-3}).

Overall, wood and bark density decreased with increasing height level of the stem and increased with increasing DBH class. Conversely, bark volume and bark mass increased with increasing height level of the stem and decreased with increasing DBH class. This is supported by the Person's correlation matrix (Table 3), which indicate a positive correlation between wood density and bark density, and a negative one between density (either of the wood or of the bark) with bark proportion (either on volume or on dry-mass basis). These results were consistent with the findings of Nyg and Elfving (2000) and Deng et al. (2014). Contrary to the findings of this study, Deng et al. (2014) found statistical differences between whole-stem wood density and the density at different height levels up the stem.

As in this study, no significant site effects on wood density were found by Nyg and Elfving (2000) for 57 African tree species. Knapic et al. (2008) and Miranda et

al. (2001) also found similar results. Wood density has been reported to be positively correlated to drought-prone areas or areas with drier climatic conditions (Ibanez et al. 2017; Nabais et al. 2018). Although Funhalouro and Mabote districts are approximately twice as dry as Mandlakaze district, as judged by annual heat moisture index (AHM) and aridity index (AI) (Table 1), wood density did not differ among districts (sites) (Table 4). This indicates that climatic conditions were not a source of variation of wood density of Lebombo ironwood or that wood density of this species does not adapt in response to climatic variations.

A decrease in wood density with increasing stem height has been reported by various authors (e.g. Machado et al. 2014, Kimberley et al. 2015). Machado et al. (2014) suggested that the highest values of wood density at stem base might be the result of the root system and the lowest values at the top of stem are the result of youngest layers of the wood. It was presumed in this study that the lowest wood density for smallest trees in DBH (trees at DBH class of 7.5 cm) is also a result of younger layers of wood in these trees.

The increase of wood density with increasing DBH class is a result of the age of the trees: holding all other factors constant, larger trees are often older than smaller ones. Beets et al. (2012) reported that wood density at a given height up the stem increased with increasing age.

Because density measurements were made on unextracted samples (i.e. without the resins and other chemical constituents of heartwood removed), some of the trends in density may be an artefact of the heartwood content in a disc. Heartwood is reported to decrease with height (Miranda et al. 2015) and to be absent above 7.0 m in height up the stem (Pérez et al. 2004). The decreased heartwood proportion with increasing

height and its absence in the upper portion of the stem may contribute to the trend of decreasing wood density with increasing height. This, in turn, may contribute to the increased proportions of bark volume and mass with increasing height. Heartwood is also known to increase with increasing stem diameter (Tewari & Mariswamy 2013), which possibly also explains the increased wood density with DBH class observed in this study. Therefore, the observed trend of decreased bark volume and mass with increasing DBH class may also be an artefact of increasing heartwood proportion with diameter.

Bark volume and bark mass estimated in this study are useful for estimating wood volume under bark and stem wood biomass. In Mozambique, members of the local communities use Lebombo ironwood trees for construction, as stakes or poles (Magalhães 2017a; Magalhães 2017b). The stakes and poles are debarked in the forest and the bark left in the forest floor and decompose (Magalhães 2017a). Thus, bark mass can be used to estimate the carbon dioxide that is released and the nutrients that are reclaimed by the site.

Bark volume values reported in this study (11 – 33%) are in line with those reported by Murphy and Cown (2015) for *Pinus radiata* (3.4 – 31.3%) and Pérez Cordero and Kanninen (2003) for *Tectona grandis* (14 – 37%). However, in this study, bark volume was found to increase sharply with increasing height level as opposite to the findings by Murphy and Cown (2015) and Antony et al. (2015). Similarly to the findings by various studies (e.g. Pérez Cordero and Kanninen 2003, Pérez et al. 2004, Antony et al. 2015, Murphy & Cown 2015), here bark volume percentage was higher for smaller diameter trees.

The average bark mass reported in this study (19%) was larger than that reported by Eberhardt et al. (2017) for *Pinus taeda* (12.5%) and *Pinus elliottii* (17%). The pattern of variation of bark mass and bark thickness were in agreement with that reported by Quilhó and Pereira (2001) and Cellini et al. (2012): bark mass was site independent and increased with relative height up the stem. Bark thickness, on the other hand, increased with DBH and decreased with relative height up the stem. Bark thickness is known to increase with tree age (Cellini et al. 2012; Williams et al. 2007) and, consequently, with tree diameter (Chowdhury et al. 2013; Nefabas and Gambiza 2007; Sonmez et al. 2007; Williams et al. 2007; Zeibig-Kichas et al. 2016). As in this study, Williams et al. (2007) found that the bark was thicker at lower portion of the stem for six South African tree species.

The average bark thickness of Lebombo ironwood (9 mm, range: 4 – 12 mm) was two times higher than that reported by Paine et al. (2010) for tropical rainforest trees in French Guinea, Western Africa (4.5 mm, range: 0.5 – 29 mm), however with a narrower range. In semi-arid savannahs of Zimbabwe, bark thickness was reported to vary from 4.3 to 15.2 mm (Nefabas & Gambiza 2007). Paine et al. (2010) found that bark thickness was strongly positively correlated with DBH, consistent with the finding of this study, where DBH explained the majority of the regression effect. Sonmez

et al. (2007) also found that most of the regression effect on bark thickness was accounted by variation in DBH class.

Site was a significant source of variation of bark thickness. Funhalouro and Mabote districts share similarities with regard to site quality (precipitation, soils, hydrology, metrological droughts) but both differ in comparison to Mandlakaze district (Magalhães 2017b). Nonetheless, although with marked differences in soil and climatic conditions, the average bark thickness of trees from Mandlakaze did not differ from those sampled at Mabote. On the other hand, although with no apparent differences in soil and climatic conditions, the bark of trees from Mabote district was, on average, 25% thicker than that of trees from Funhalouro district. This suggests that soil and climatic and/or environmental conditions were not the sources of variation of bark thickness between sites. A similar observation was made by Rosell (2016) who found that environmental conditions were less important driver of bark thickness.

In this study, it was found that DBH class explained most of the regression effect of bark thickness (51.24%), followed by height level (40.27%). Site explained the minority of the regression effect (6.22%). These findings are consistent with the results by Rosell (2016) who, based on 640 tree species from 153 angiosperm families, found that stem size was the main source of variation of bark thickness, with environmental conditions being less important.

Bark thickness is reported to be positively correlated with fire-prone habitats (Hoffmann and Solbrig 2003; Nefabas and Gambiza 2007; Nieuwstadt and Sheil 2005; Uhl and Kauffman 1990). Compared with Mandlakaze, Mabote and Funhalouro are more prone to forest fires due to low precipitation, intensive metrological draughts and intensive slash and burn agriculture. However, the differences in bark thickness are more marked between the fire-prone habitats (Mabote and Funhalouro) than otherwise (e.g. Mabote and Mandlakaze), suggesting that bark thickness was uncorrelated with tree association with fire-prone habitats. This is in agreement with the findings by Paine et al. (2010). In addition, Lebombo ironwood trees are known to be intolerant to fires. They die after being burnt and do not resprout (regrow) (Magalhães 2017a). This is supported by Nefabas and Gambiza (2007) who stated that “*although bark thickness contributes to fire tolerance of woody species, it can be misleading to rank species for fire tolerance based on a single variable such as bark thickness*”. Rosell (2016) found that stem diameter was 25 times more important than fire tolerance in explaining variations in bark thickness.

Wood density over and under bark, bark thickness and therefore bark proportions are often obtained at breast height by extracting wood cores (Chowdhury et al. 2013; Francis 1994; Hietz et al. 2013; Williamson & Wiemann 2010). This study proved that the above-mentioned whole-stem properties can be represented by the equivalent breast height properties, as no significant differences were observed between them.

Conclusions

Overall, the patterns of variation of all wood and bark properties of Leбомбо ironwood investigated in this study were found to be highly dependent on vertical position within the stem and tree diameter class. Vertical position along the stem uniquely accounted for most of the regression effects for wood density, bark volume and bark mass. Tree diameter class accounted uniquely for most of the regression effect for bark density and bark thickness. Site differences did not account for a significant proportion of the variation in the wood and bark properties investigated in this study. Overall, whole-stem average properties did not differ from the value measured at breast height.

Competing interests

The author declares that he has no competing interests.

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Abbreviations

DBH: Diameter at breast height; AHM: annual heat moisture index; AI: aridity index.

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