Chapter

Characteristics of the Tropical Hardwood—Tree Species for Renewable Energy Production in Zambia

Obote Shakacite, Phillimon Ngandwe, Vincent Nyirenda and Donald Chungu

Abstract

This work studied the diversity, abundance, and distribution of 25 most suitable indigenous tropical hardwood tree species for value-added renewable energy production. The study aimed to assess relative abundance, diversity, distribution, current status, and uses by local communities of these species which are still poorly known. The study is based on data from nationwide remeasured permanent sample plots for Zambia covering different types of forests in agro-ecological zones 1 and 2. Diameter at breast height (DBH) ≥2.5 cm was collected and analyzed in all plots. The study approach included informant interviews that focused on species' uses and their availability in the surrounding forests and woodlands and species population inventory of the natural forests and woodlands. The tree species for renewable energy production were determined. The species were identified on the basis of abundance, diversity, regeneration status, and perceived utilization. The study observed the need to manage hardwood supply sustainably, promote lesser-known hardwood tree species, and diversify their use in the wood industry. The intervention of government and other stakeholders to tackle wood fuel production problem using collaborative approach is emphasized.

Keywords: abundance, anthropogenic activities, distribution, diversity, regeneration, species

1. Introduction

Forests and woodlands in Africa play an important role in the livelihood of many rural communities and in the economic development of many developing countries [1]. Globally, it is estimated that 52% of the total forests are in tropical regions, and they are known to be the most important resource in terms of bioenergy production [2]. Tropical hardwoods are important for supplying wood fuel and timber [3, 4]. Tropical hardwoods are preferred owing to a number of characteristics that set it apart from other tree species. Some of the characteristics among species that influence commercial importance include wood color, energy, density, durability, and grain texture. The hardwood species are also influenced by economic factors (availability, wood properties, and market acceptance). *Baikiaea plurijuga* is an important species in Zambia as it is a source of hardwood timber used for railway sleepers, furniture, and flooring [5]. The wood is heavy, with a density of 800–950 kg/m^3 at 12% moisture content. Another important hardwood species in Zambia preferred for its characteristics is *Guibourtia coleosperma*. The wood is heavy, with a density of 670–960 kg/m^3 at 12% moisture content. The attractive appearance of this wood influences its commercial importance as it is widely used in construction, flooring, and joinery among others [5]. The local community had been traditionally using specific hardwood tree species for fuel wood for the generation of energy. Some hardwood species such as *B. boehmii*, *Brachystegia spiciformis* Benth., *J. globiflora*, *Parinari curatellifolia* Planch. ex Benth, and *Uapaca kirkiana* Müll. Arg are mainly used for fuel by local communities [6]. The literature on characterization of properties of hardwood tree species in Southern Africa has expanded [7]; however, there are still limited studies on these species [8]. There is lack of scientific data to validate their preferences of these species in terms of determination of their density, volatile matter, ash, moisture, and fixed carbon content [9].

In Zambia, wood is one of the most abundant natural resource, but there has been limited investment in the wood industry [10]. The country has the largest forest resource in Southern Africa despite its forest cover declining over the years from over 66% (49.9 million ha) in 2008 to 58.7% (44.1 million ha) in 2016, and the current total growing stock has been estimated at 3.2 billion m^3 of which 43% is considered of commercial importance [10]. Some of these forests are managed as protected areas for future development of the wood industry. The demand for wood industry products is increasing paving way for productivity improvement and further development of the wood sector. The current wood consumption is estimated to be 201 million m^3/annum, with almost 98% of this wood originating from natural forests. Zambia consumes about 8.1 million m^3/annum of wood for wood charcoal, and 9.7 million m^3/annum is mainly used for cooking in rural and peri-urban areas. Traditional charcoal production, a major source of employment for the rural poor, relies on the traditional earth kiln which is blamed to be a major contributor to preferred tree species loss in many rural and urban regions of sub-Saharan Africa. The traded wood fuels are used by 70–90% of the 50 million urban population in the region [11, 12] and support a significant flow of money from urban to rural population mainly in areas producing charcoal. The woodlands are a major source of biomass fuel (firewood and charcoal) for household consumption and income for a large proportion of rural livelihoods [13]. Earlier studies have shown that charcoal business is a lucrative local economy, estimated to generate an annual income of about US$ 350 million in Tanzania [14, 15], US$ 30 million in Zambia [13], average annual income of about US$ 250–300 per family in Mozambique [4], and equally in Malawi and Kenya many people owe their livelihoods to the charcoal business [16]. Global charcoal production which generates income for many people is expected to increase despite lack of regulation means and inefficiency in its production [17].

Wood fuel issues in Zambia are increasingly becoming urgent given that wood fuel provides for about 90% of domestic energy needs both in urban and rural areas; hence, demand is rising [18]. Wood fuel production and trade may be blamed for woodland loss where charcoal production from open and protected forest areas alone is shown to have contributed to about 25% of forest loss. Therefore, it is important to understand abundance, diversity, and distribution of the most preferred hardwood tree species for wood fuel production and enhance sustainability. However, any strong dependence on wood fuel for domestic energy consumption in Zambia increasingly puts pressure on production areas. However, the miombo woodland species possesses good potential for recovery through proper care of natural regeneration. There is considerable potential to introduce alternatives to fuel wood and wood charcoal as well as expanding commercial forest plantation for industrial wood. The estimated wood wastes (including harvested and mill wastes) produced on an annual basis from miombo woodland is about 600,000 m^3 which offers a huge opportunity to be developed into fuel wood. According to [10], the surplus is potential supply from natural woodlands that provide a sustainable avenue for future expansion of wood products industry.

Renewable energy is considered an important resource virtually in every aspect of the economic and social development in many countries around the world [19], but globally less than 15% of primary energy supply is renewable energy, and the major part is hydropower and wood fuels in developing countries. The major drivers of wood fuel consumption are population growth, rapid urbanization, poverty, and lack of income growth [17]. In Africa, most countries still depend heavily on wood to meet energy requirements. According to [20], wood fuel share in Africa ranges 60–86% of primary energy consumption, 90–98% is consumed by household, and per capita wood fuel consumption is estimated at 0.89 m^3/year. Most of this wood is from forests and woodlands of hardwood wood tree species, and only a small volume is produced sustainably [17]. The use of wood for energy in developing countries continues to attract a great deal of attention, because the majority of the population in these countries face acute shortages of biomass energy due to the combined effects of increasing demand and diminishing supplies of this source of energy. As wood fuel becomes scarce, preferred tree species are harder to find or become locally extinct, and the women and children need to travel longer distances to reach supplies.

Presently, industrial wood in Zambia amounts to about 2.3 million m^3/annum, sawmilling accounts for 2 million m^3, while wood poles and other wood uses account for 0.3 million m^3.The wood industry is slowly growing scattered across the country comprising mainly sawmilling and pit-sawing units. The current consumption of sawn wood and all wood types (approx.. 600,000 m^3) is predicted to reach 980,000 m^3 by the year 2030. However, the sawmilling industry needs expansion of log resources and improvement of firms, recovery, value addition, skills, utilization of residues, and technology. There is only limited production of particle board, plywood, and block board produced in the country. The current consumption of wood-based panels (approx. 40,000 m^3) is predicted to attain about 110,000 m^3 by the year 2030 justifying the need to develop the wood-based panel industry. Wood furniture industry is low, but there is potential to improve it both at the firm level and sector level. The export opportunity exists for furniture to adjacent countries in Southern Africa. In addition, several investments including solar and bioenergy aiming to diversify the electricity generation in the country are mostly either in planning or implementing phase. According to the United Nations report [21], exports of wood from hardwood tree species has been increasing at an average annual change of 62% since 2010. This increase is probably due to the availability of markets and price premiums for industrial hardwoods in China and Europe. The increasing demand for hardwood tree species such as *Colophospermum mopane*, Kirk Ex J. Leornard, *Julbernardia paniculata* (Benth) Troupin, *Pterocarpus angolensis* DC, *Combretum molle* R.Br.ex G. Don, and other species belonging to Brachystegia species provide great opportunities for private sector involvement through value addition processing and bioenergy production [18]. However, raw material insecurity, unknown patterns of distribution, and uncertainty of the potential supply are often considered as potential risks to attracting investment in the wood industry in Zambia [18]. In 2005 and 2010, Zambia conducted a nationwide Integrated Land Use Assessment (ILUA) that provided data on various aspects of forests and woodlands to give information on the available growing stock for use by the wood industry sector, investors, policy-making, and other stakeholders [22]. However, the data require additional analysis targeting certain interests and other user groups. We hypothesized that wood fuel deficits vary by ecological regions and that Zambia's urban regions experience an energy crisis. The aim of this study was to assess the distribution, diversity, and abundance of the most suitable tree species for value-added renewable energy production from the miombo woodlands. This study's information is critical to developing strategies for the management of wood material for bioenergy production in developing countries in Africa and other parts of the world.

1.1 Domestic and commercial importance of selected hardwood tree species

The selected tropical hardwood tree species are preferred by most local people for both domestic and commercial use for a number of reasons to include color of wood, texture, density, and fiber for construction works [23]. In addition, the commercial importance and use of each of these species are influenced by economic factors such as availability, wood properties, and market acceptance [20]. The use of wood as a fuel for most local people plays an important role as an energy source. Brachystegia, Julbernardia, and Isoberlinia species are being the preferred genus for its high basic density and energy quality [24] for inclusion as biofuels in the form of firewood and its transformation into charcoal to obtain a more efficient fuel. According to [25], basic density of wood is a variable attribute because it changes according to geographical area and climate of the area. Moisture content is another important factor, and [26] reported that moisture contents of less than 8% are required to reduce the consumption of material to evaporate the water and also with these values a charcoal less susceptible to attack by biological agents is obtained. Twenty-five species studied have good potential as a source of locally available energy either in the form of firewood or charcoal with significantly better energetic properties. In addition, these species are abundant forest resources in the country, and hence their inclusion in management plans could be important in the development of the wood sector industry.

2. Materials and methods

2.1 Data acquisition

Inventory data were obtained from the Integrated Land Use Assessment inventory database maintained by Forestry Department, Ministry of Tourism, Environment and Natural Resources (MTENR)[27]. Although the ILUA II inventory covered the whole country, this study is based on filtered data from agro-ecological zones 1 and 2 covering Central, Eastern, Southern, and Western regions of the country (**Figure 1**). Zambia is broadly divided into three agro-ecological regions based on rainfall and soil and other climatic conditions [29]. These regions also experience high forest loss rates due to household heavy dependence on wood fuel (firewood and charcoal) collection to meet their energy requirements [30]. Earlier research studies also indicate that these regions are within a low rainfall projection for the future; hence, the area under miombo woodlands will decrease with up to 50% [31, 32], because poor rural farmers are heavily dependent on forest resources as safety nets.

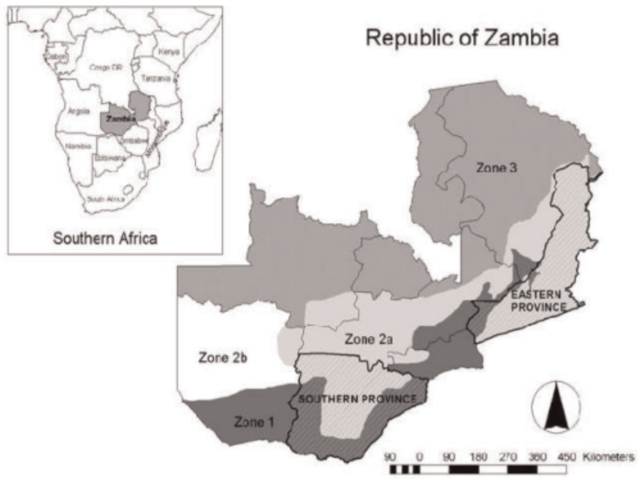

Figure 1.
Map of Zambia showing agro-ecological zones 1 and 2 covering parts of Eastern, Central, Southern, and Western provinces on which assessments for this study were based [28].

2.2 Rationale for selecting tree species

Tree species were initially selected following a survey**.** A team of experts conducted ethnobotanical survey through semi-structured interviews with selected community informants to identify the most preferred wood fuel tree species. These data were compared to the national database of the Integrated Land Use Assessment (ILUA) at the Forestry Department, Zambia [27]. A list of 25 tree species were drawn up from different families of which 15 of these species are listed in **Table 1**, and the most important included Fabaceae (Caesalpinioideae), Leguminosae (Mimosoideae), Combretaceae, and Mimosaceae (**Table 2**). The list of species was checked for spelling errors and scientific names, and those bearing different names were noticed and corrected accordingly. To obtain valid results in terms of tree species abundance and distribution, any unique names of species from the inventory data and duplications or spelling mistakes that would have affected the evaluation of abundance were removed. The rationale behind the selection of these species is that these are commonly used timber and wood fuel species and among the most preferred species of the miombo woodland [24, 33] on the basis of their commercial and economic importance. The studied species were further classified by their forest successional status based on literature review, expert consultation, and the authors' own field experience.

2.3 Data filtering and cleaning

The Integrated Land Use Assessment (ILUA II) raw data set collected within the limits of the tracts, plots, and subplots was acquired from the national database at Forestry Department, Ministry of Lands, Environment and Natural Resources, Lusaka, Zambia [27]. To determine the diversity, relative abundance, and distribution of the 25 most preferred wood fuel hardwood tree species for renewable energy, we filtered the data and grouped these species from agro-ecological zones 1 and 2 using Microsoft Excel. The filtered raw data were further cleaned. Data obtained include tree species scientific names, diameter, merchantable height, and GPS locations.

Species	Uses	Vegetation	Successional status
Brachystegia spiciformis	FE, CC	P,S	LS
Brachystegia floribunda	CC, FE	P,S	MS
Brachystegia longifolia	CC, FE	P,S	MS
Brachystegia boehmii	FE, CC	P,S	MS
Julbernardia globiflora	CC, FE	P,S	MS
Julbernardia paniculata	CC, FE	P,S	MS
Isoberlinia angolensis	FE, CC	P,S	MS
Colophospermum mopane	FE, CC	S	ES
Combretum molle	FE, CC	S	ES
Albizia versicolor	FE, CC	P,S	MS
Erythrophleum africanum	CC, FE	P,S	ES
Terminalia mollis	FE, CC	S	ES
Albizia antunesiana	FE, CC	P,S	MS
Pericopsis angolensis	FE, CC	P,S	ES
Acacia nigrescens	FE, CC	P,S	LS

Notes: CC = charcoal, FE = firewood, P = primary forest, S = secondary forest, ES = early successional, LS = late successional, MS = mid-successional.

Table 1.
Information on the most common 15 of the 25 selected tree species.

Family name	No. of species	% of family
Fabaceae	10	40
Caesalpinioideae	7	28
Combretaceae	3	12
Mimosaceae	1	4
Phyllanthaceae	1	4
Chrysobalanaceae	1	4
Papilionaceae	1	4
Apocynaceae	1	4
Total	25	100

Table 2.
List of families, number of species in each family, and percentage of each family of the tree species recorded.

3. Data analysis

The filtered data were organized and recorded in Microsoft Excel 2019 data sheet. Using the filtered and cleaned data from the national data set, we computed species densities, diameter distribution, abundance, and diversity for the wood fuel preferred hardwood tree species. All tree species were assigned to families, and relative diversity (number of species in a family) was obtained for tree species diversity classification.

3.1 Diameter class distribution

Does forest structure vary by region of the study area? In order to address this, density, diameter at breast height (DBH), and frequency were used for the description of vegetation structure. Diameter distribution is one of the most commonly and widely studied variables in wood science studies [34,35] including tropical hardwood tree species [36]. Knowing the status of diameter distribution in the forest woodland provides information about forest structural attributes and serves as an integral part of wood management and planning for the near future. Density is the number of individuals per unit area or volume. The density of a species exhibits the abundance of a species in a given area [37]. The density was determined for each selected tree species from absolute density calculated from the total number of individual of a species counted in a plot divided by the total area sampled (0.1 ha). Relative density (RD) is the study of the numerical strength of a species in relation to the total number of individuals of all the species and was calculated as:

$$\text{Relative density (RD)} = \frac{\text{Number of individuals of tree species}}{\text{Total number of individuals}} \times 100 \tag{1}$$

Basal area for each tree species was calculated with the basal area function as follows:

$$\text{BA} = \frac{\pi d^2}{4(100)^2} \tag{2}$$

where BA is the basal area (m^2), π is the constant (3.142), and d is the diameter at breast height (cm). The total basal area of each species was obtained by adding together the basal areas of the individual trees of the species. Basal area of each species per hectare was estimated by extrapolating the total basal areas of the species using the formula as:

$$\text{BA} = \frac{H}{A} \times D \tag{3}$$

where BA is the basal area, H is the one hectare, A is the area of plot in hectares, and D is the basal area in each plot.

The frequency is a statistical parameter which reflects the spread of a species in a given area:

$$\text{Frequency} = \frac{\text{Number of plots in which a species occurs}}{\text{Total number of plots sampled}} \times 100 \tag{4}$$

The relative frequency of species was obtained from absolute frequency, dividing the number of sampling units in which the species occurs by the total number of sampling units as follows:

$$\text{Relative frequency (RF)} = \frac{\text{Frequency of respective tree species}}{\text{Total frequency of all tree species}} \times 100 \tag{5}$$

Regeneration status of the woodland was analyzed by comparing saplings and seedlings with mature trees of the area to insure adequate wood products supply. According to [27], the status was considered good regeneration if number of seedlings were greater than saplings and greater than mature trees; the regeneration status was relatively fair if number of seedlings were greater or less than or equal to saplings and less than or equal to mature trees; the status was poor regeneration if the species survives only under the first category.

3.2 Distribution and abundance of selected tree species

What influences the relative abundance of tree species for wood fuel? To answer this question, we computed the Shannon-Wiener index (H′) to measure species abundance and richness and quantify the tree species [38, 39]. Shannon-Wiener index is defined as:

$$H = -\sum_{i-1}^{s}\left(\frac{ni}{n}\right)x\ ln\left(\frac{ni}{n}\right) \quad (6)$$

where (H) is the Shannon-Wiener index, ni is the number of individuals of species i, n is the overall number of trees surveyed in the plot, ln is the natural logarithm, S is the number of species, and $\sum$ is the sum of the calculations. The index increases with the number of species in the area [2] and incorporates the species richness and the proportion of each species in all sampled plots (evenness) [40]. The Shannon diversity index ranges often from 1.5 to 3.5 and rarely reaches 4.5 [41]. The knowledge of species diversity is useful for establishing the influence of resource management, human disturbance, and the state of succession and stability in the area [42, 43]. Pielou's measure of species evenness formula was used to calculate species evenness defined as follows:

$$J = H'/\ln(S) \quad (7)$$

where J is the evenness, H is the Shannon-Wiener diversity index, ln is the natural logarithm, and S is the number of tree species recorded in the considered plot [44, 45]. According to [46], a value for evenness is usually in the range 0 to 1, with 1 indicating that all species have the same abundance. Margalef's index was used as a simple measure of species richness [8]. Margalef's index is defined as:

$$(S-1)/\ln N \quad (8)$$

where S is the total number of species, N is the total number of individuals in the sample, and ln is the natural logarithm measurement of evenness for calculating species' evenness. The economic and ecological importance of tree species in agro-ecological regions 1 and 2 was analyzed using the Importance Value Index which is the summation of the relative values of frequency, abundance, and dominance [47] and is useful to compare the values of species [43]. According to [48], species with the highest importance value are the leading dominant species of specified vegetation. The Importance Vlue Index (IVI) describes the floristic structure and composition of forest woodlands and has often been used in the miombo forest systems [37, 49, 50]:

$$\text{Importance Value Index (IVI)} = RF + RA + RD \quad (9)$$

where IVI is the Importance Value Index, RD the is relative dominance, RF is the relative frequency, and RA is the relative abundance.

3.3 Abundance and distribution of tree species

What tree species are preferred for each region? In order to address this question, we determined the abundance and distribution of wood fuel tree species for each region, and data were obtained from the national database of the Integrated Land Use Assessment (ILUA II) at Forestry Department, Zambia [27]. Based on expert knowledge and secondary information sources of preferred hardwood wood fuel tree species on high demand [18, 51], we filtered the commonly used wood fuel tree species from this database and the filtered data were cleaned to remove errors. Abundance (A) = Number of respective tree species/extent of sampling area. Using these data, we computed relative abundance based on the formula as follows:

$$\text{Relative abundance} = \frac{\text{Abundance of respective tree species}}{\text{Total abundance of all tree species}} \times 100 \qquad (10)$$

4. Results

4.1 Tree species abundance, distribution, and frequency

What influences the relative abundance of tree species for wood fuel? Abundance of wood fuel tree species in the study area may be influenced by many environmental factors; among these variables, soil type and topographic variables and other factors related to human impact are probably considered the most significant affecting species diversity and woody vegetation. However, this may require further investigations. The most frequently distributed tree species in the study area was *C. mopane* (6.5%) followed by *Julbernardia paniculata* (2.9%), *Brachystegia boehmii* (2.3%), *Brachystegia spiciformis* (1.8%), and the least was *Brachystegia globiflora* (1.2%). The frequency distribution of selected tree species in the study area is quite variable which can be explained by frequent use of these tree species in the study area for charcoal making and construction material. The most commonly used trees species for charcoal production are *Combretum molle, C. mopane, Isoberlinia angolensis, Brachystegia*, and Julbernardia species [42, 52]. The tree species with highest relative abundance was also dominant on the frequency of each individual tree. The higher the frequency, the higher the dominance index and vice versa. The relative abundance, relative density, basal area, frequency, relative dominance, and importance value indices of selected tree species for wood fuel energy production are shown in **Table 3**. The result shows the most abundant of these tree species being *C. mopane* (Benth), J. Leonard (550), with a relative abundance of 14.5%. It was followed by *Julbernardia paniculata* (Benth), Troupin (450), with a relative abundance of 11.9%, *Brachystegia boehmii* Taub. (396), with a relative abundance of 10.4%, *Brachystegia spiciformis* Benth (300) with relative abundance of 7.9%, *Diplorhynchus condylocarpon* Mull.Arg (337) with relative abundance of 8.9%, *Pseudolachnostylis maprouneifolia* Pax(270), with relative abundance of 7.2%, *Brachystegia longifolia* Benth. (218), with relative abundance of 5.8%, and *Combretum molle* R.Br.ex G.Don (195), with relative abundance of 5.2%, and the rest of species had relative abundance less than 5%. At the provincial level, the distribution of the hardwoods on demand was highest in the Western province with

No	Scientific name	No of individuals	BA (m^2)	F%	RA%	RD%	RF%	IVI%
1	Colophospermum mopane	550	22.4	6.5	14.5	21.4	21.5	57.4
2	Julbernardia paniculata	450	15.2	2.9	11.9	9.6	9.6	31.1
3	Brachystegia boehmii	396	13.1	2.3	10.4	7.6	7.6	25.6
4	Brachystegia spiciformis	300	13.7	1.8	7.9	5.9	5.9	19.7
5	Erythrophleum africanum	182	0.9	1.8	4.8	5.9	5.9	16.6
6	Diplorhynchus condylocarpon	337	5.6	1.6	8.9	5.3	5.3	19.5
7	Pseudolachnostylis maprouneifolia	270	0.8	1.3	7.2	4.3	4.3	15.8
8	Brachystegia utilis	75	2.9	1.3	2.0	4.3	4.3	10.6
9	Brachystegia longifolia	218	5.7	1.3	5.8	4.3	4.3	14.4
10	Brachystegia floribunda	123	3.4	1.2	3.5	4.0	4.0	11.5
11	Combretum molle	195	4.5	1.0	5.2	3.3	3.3	11.8
12	I. angolensis	52	2.0	0.7	1.4	2.3	2.3	6.0
Summary		**3148**	—	23.7	83.5	78.2	78.3	
Other species		**638**	—	6.6	16.5	21.8	21.7	

Note: BA = basal area, F = frequency, RA = relative abundance, RD = relative density, RF = relative frequency, IVI = Importance Value Index

Table 3.
Species, abundance, frequency, basal area, and Importance Value Indexes of most commonly used trees for fuel wood observed in agro-ecological zone.

relative abundance of 34.1%, followed by Luapula (19.7%) and Northern province (10.8%). The relative distribution of these hardwoods equally varied greatly across other provinces (i.e. Central 3.4%, Eastern 3.9%, and Southern 5.1%). Among the 200 hardwood species known for timber and energy found in Zambia, *P. angolensis* is known to be the natural resource among most top species in use [22]. Other species such as *Julbernardia paniculata*, *Brachystegia bohemii*, *C. mopane*, and several other Brachystegia species which were reported as the most abundant hardwoods in Zambia should be promoted for bioenergy, sustainable charcoal production, and carbon trade [53].

4.2 Diameter class distribution

Bar graphs were developed using the DBH versus number of individuals for seven arbitrary diameter classes (2.5–7.5 cm), (7.5–11.5 cm), (11.5–15.5 cm), (15.5–19.5 cm), (19.5–23.5 cm), (23.5–27.5 cm), and (≥27.5 cm) of the selected tree species (**Figure 2**).

Based on the assessment of diameter class distribution, the population structure pattern of the selected tree species recorded from the study area exhibited reverse J-shaped distribution (**Figure 2**). Inverse J-shaped pattern shows more trees in the small diameter classes (4-20 cm). The result showed significance at $p < 0.05$, t (24) = 2.73, and p = .05 despite small diameter trees (M = 99,SD = 89) recording largest number of trees than larger diameter class trees (M = 43, SD = 45), R-squared (R^2) = 90.7%, correlation (R) = 0.908, F statistic = 232.7), and p-value = 0.0087. This may be indicative of good reproduction and growing population in which young trees will

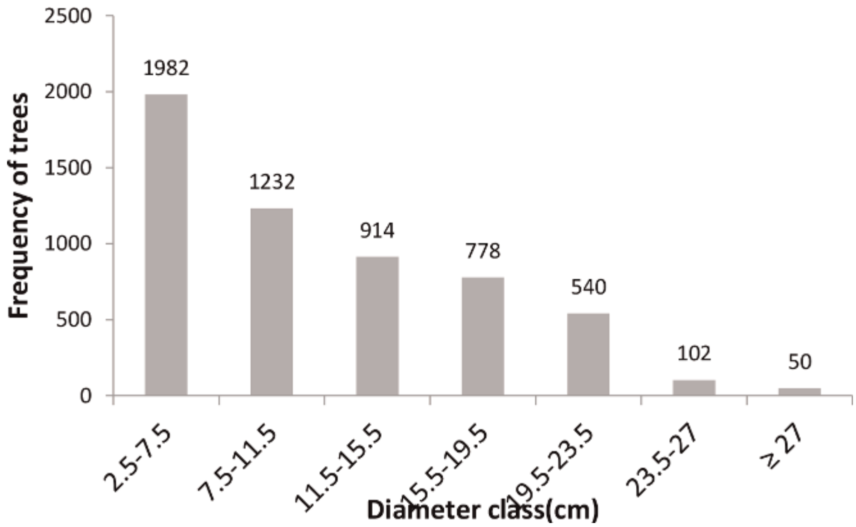

Figure 2.
Diameter distribution of standing trees ≥2.5 Dbh by diameter classes in agro-ecological zones 1 and 2.

grow into mature size classes. This may also suggest the occurrence of high disturbance of older trees due to frequent harvesting of trees for charcoal production, construction works, timber, and other miscellaneous uses. Tree frequency decreased with increasing diameter which is common for miombo woodlands with selective cutting where regeneration is active, an indication of a healthy recruitment of the individuals in the area [45, 50]. Other research studies within the miombo woodlands reported similar size class distribution [54, 55]. However, [56] argues that caution must be exercised in the use of inverse J-distribution as stock control in management, since the distribution assumes equal mortality rates among size classes and regarded it as biologically unrealistic.

4.3 Forest composition, structure, and richness

Do forest structure and composition for wood fuel tree species vary by region? Composition is used to refer to all plant species found in a stand or landscape including trees, shrubs, and grasses. Structure refers to the physical arrangement of various physical and biological components of an ecological system. In the study area, structure varied between agro-ecological zones 1 and 2 (**Figure 3**). In earlier research studies, it was reported that about 40% of Zambia's forest land is described as

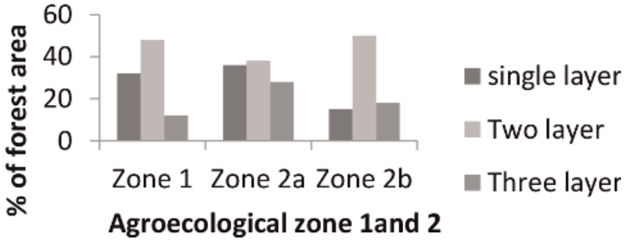

Figure 3.
Stand structure in forest land showing vegetation types (single-layer, two-layer, and three-layer) in agro-ecological zones 1 and 2 (Southern (zone 1), Central (zone 2a), and Eastern (zone 2b).

two-layer vegetation [22];hence, the forest is characterized by two distinct canopy layers. In the study area, the forest with stand structure of single layer ranged 15–36%, two-layer vegetation ranged 38–50%, and three-layer vegetation ranged 12–30% (**Figure 3**). The highest proportion of forest land (≥30%) with single-layer vegetation was observed in Southern and Central provinces, suggesting that tree cutting for charcoal production and construction activities is high in these areas. A total of 6486 individuals with diameter ≥ 2.5 at breast height representing 149 tree species were recorded in agro-ecological zones 1 and 2 from which 25 species were selected for this study representing 6 families and 13 genera (**Table 2**). The species richness (149 species) of trees and the densities of species observed in this study compare well with miombo woodland occurring in other areas such as reported in Tanzania, Zimbabwe, and Zambia [2, 33, 37, 49, 57]. In Zambia, [58] enumerated a total of 238 woody species belonging to 154 genera showing high diversity and endemism over the country. The high number of species richness in the study area may be attributed to the pressure that plants undergo due to dry conditions in the two regions that contribute to emerging and growth of many new tree species. Climatic, edaphic variability, and anthropogenic activities are other factors associated with species richness [2]. According to [59], anthropogenic activities play a big role in the dynamics of miombo woodlands. The average tree density of 150 ± 30 trees per/ha is comparable with those reported by [2, 37]. Basal area provides an excellent indicator of the degree of stocking in a forest stand. This study showed that *Colophospermum mopane* (Benth), J.Leonard, gave a basal area of (22.4 m^2) per hectare followed by *Julbernardia paniculata* (Benth), Troupin, with the basal area of 15.2 m^2 suggesting that these tree species are well stocked, while *Acacia nigrescens* Oliv. (Knobthorn) with the basal area of 0.25 m^2 was understocked. The low stem density and basal area recorded in this study may be a consequence of frequent forest fires [27] and increased wood exploitation rate for charcoal production and construction materials [29, 42] in the area. Reference [58] observed a decline in biomass of some of the most productive and dominant species (*B. spiciformis, C.mopane*, *and I.angolensis*) in Zambia despite their high productivity. These species are heavily extracted by local people in their daily livelihood activities. The decline in biomass may be associated with low stem density and basal area recorded in this study.

4.4 Multipurpose values of selected tree species

Some of the selected tree species in the study area were found to have multipurpose values such as fuel wood (charcoal and firewood), timber, construction material, and other miscellaneous uses (**Table 1**). These species, *Julbernardia paniculata*,*Tamarindius indica*, *Pericopsis angolensis*, *Parinari curatellifolia*, and *Brachystegia spiciformis* were among the most commonly used trees for charcoal production and timber [16]. It is common that these species are rapidly removed from woodland once charcoal production starts in an area, hence affecting the species composition of miombo woodland [29]. The increase in demand for charcoal in Zambia and other parts of Africa has led to depletion of preferred hardwood tree species resulting in the use of a wider range of other tree species, suggesting that forests may be changing in structure and composition even in the near future. Where consumption is high, unselective harvesting has overexploited certain species especially near urban areas, and this suggests for the need to promote sustainable use of lesser known tree species for the wood industry [60].

4.5 Regeneration of tree species

The active regeneration and recruitment of tree species in agro-ecological regions 1 and 2 as depicted by this study is a good indication of sustainability of the forest woodlands which can ensure sustainable supply of wood products, hence sustaining the livelihoods of local people who depend on the forest woodland [61]. The middle diameter class (1–19 cm) had the highest number of stems, species, and family. Diameter for the tree species was inclined toward the small-sized diameter with diameter breast height below 20 cm. In the study area, different diameter distributions were observed, suggesting human disturbances which are probably linked with farming and tree harvesting activities and bush fires. A large proportion of total regeneration comprised small seedlings (70–80%) comparably to saplings (**Figure 4**). The highest density of seedlings was found in Eastern and Western provinces, while the lowest was recorded for Southern province due to frequent tree cutting for construction activities, fuel wood and charcoal production. The distribution of tree species such as *Julbernardia paniculata* and *Brachystegia boehmii* was widely spread in Central province, while *C. mopane* was concentrated in Eastern province. Disturbances in miombo woodlands to include uncontrolled harvesting of trees by local people for wood fuel and building materials are most likely to affect the size class distribution of the harvested trees and hence may change the composition and structure of tree species diversity and subsequently may result in increased tree mortality [56]. Efforts to enforce the forest law and regulations by government to provide absolute protection from illegal activities seem to be difficult because of the big demand of the wood products and services by local people for their livelihoods. However, to our understanding, there are no empirical studies in the study area to assess the impacts of anthropogenic disturbances on diameter distribution and forest health, and such information is required for sustainability management of these ecosystems.

4.6 Species density and basal area

C. mopane (CM) Kirk Ex J.Leonard (Fabaceae) had the highest number of stems (550 stems/ha) and a relative density of 21.4 and basal area of 22.4 m^2 (**Table 3**); hence, it was regarded as the most abundant species in the study area. This was followed by *Julbernardia paniculata (JP)* (Benth) Troupin (Fabaceae) with 450 stems/ha, relative density of 9.6 and basal area of 15.2 m^2. The third abundant species was *Brachystegia boehmii (BH)* (Taub) (Leguminosae) with 396 stems/ha, relative density of 7.6, and basal area of 13.1 m^2, *Diplorhynchus condylocarpon (DC)* (Welw ex Ficalho

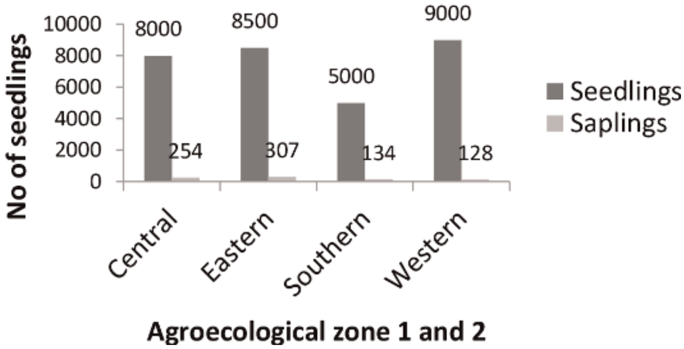

Figure 4.
Number of seedlings and saplings recorded regenerating in agro-ecological zones 1 and 2.

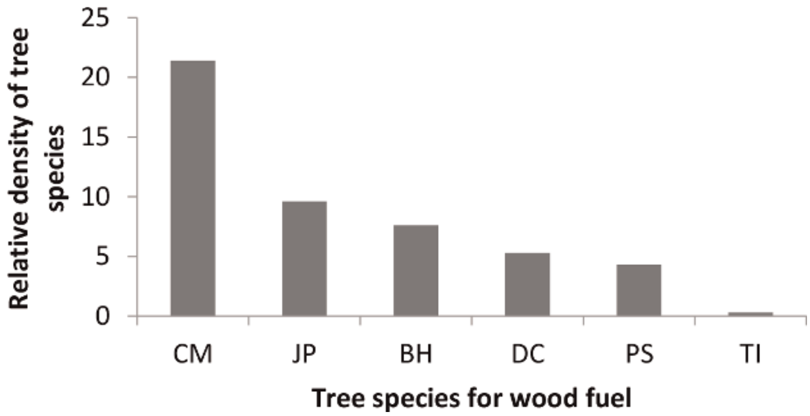

Figure 5.
Relative density of wood fuel tree species abundance in agro-ecological zones 1 and 2. Note: CM = Colophospermum mopane, JP = Julbernardia paniculata, BH = Brachystegia boehmii, DC = Diplorhynchus condylocarpon, PS = Pseudolachnostylis maprounefolia, TI = Tamarindus indica.

&Hiern) (Apocynaceae) with 337 stems/ha, relative density of 5.3, and basal area of 5.6 m^2, and *Tamarindus indica (TI)*, L (Fabaceae) lone tree assessed in the area had the largest mean DBH of 85 cm, relative density of 0.3, and basal area of 1.1 m^2, while the least DBH of 6 cm, with 270 stems/ha, relative density of 4.3, and basal area of 0.8 m^2 for the selected species was recorded for *Pseudolachynostylis maprouneifolia (PS)* Pax (Phyllanthaceae) (**Figure 5**).

4.7 Species diversity and Importance Value Index

What tree species are appropriate for each region? There is limited information on wood fuel species appropriate for each agro-ecological zone, particularly high altitude (≥2000 m) and semiarid zones. The abundance of wood fuel tree species in these areas is primarily based on rainfall, soil type, human activities, and also other climatic characteristics. Generally, the appropriate wood fuel tree species for each region are key legume trees of miombo and mopane woodlands, Brachystegia Benth (*Brachystegia boehmii* and *Brachystegia spiciformis*), *Julbernardia globiflora* (Benth) Troupin, *Pterocarpus angolensis* DC, and *Colospermum mopane*. Species diversity is a complex ecological characteristic of a particular forest area, that is, commonly used representation of ecological diversity. It contributes to ecosystem health and can be measured from the number of species (species richness) and relative abundance of individuals within each species (species abundance) [62]. Importance Value Index (IVI) gives knowledge on most important economically or ecologically tree species of a particular forest area. In this study based on Importance Value Index, 12 dominant thus economically and ecologically most important tree species (**Table 3**) are *Colophospermum mopane* (J.Kirk ex Benth), 57.4% was most dominant species followed by *Julbernardia paniculata* Benth. Troupin (31.1%), *Brachystegia boehmii* Taub. (25.6%), *Brachystegia spiciformis* Benth. (19.7%), Diplorhynchus condylocarpon Mull.Arg. (19.5%), *Erythrophleum africanum* (Welw.ex Benth) Harm (16.6%), *Pseudolachnostylis maprouneifolia* Pax. (15.8%), *Brachystegia longifolia* Benth. (14.4%), *Combretum molle* R.Br.ex G. Don (11.8%), *Brachystegia floribunda* Benth. (11.5%), *Combretum zeyheri* Sond. (11.1%), and *Brachystegia utilis* Hutch. (10.6%). The results show that the most important tree species in the study area have high diversity in the scale of Shannon-Weiner index of diversity. According to [63], Importance Value Index (IVI) ranks

Parameter	Values
Richness (total number of species)	146
Density (stems/ha)	150
Shannon-Wiener index (H′)	2.75
Pielou's evenness index(E)	0.85
Margalef's evenness index	2.9
Simpson's index of diversity	0.92

Table 4.
Characteristics of selected tree species in agro-ecological regions 1 and 2.

species in a way as to give an indication on which species come out as important element of the miombo tree species. The study revealed Shannon-Wiener index of diversity (H′) of 2.75, Pielou's index of 0.85, Simpson index of diversity of 0.92, and Margalef's Evenness index of 2.91 of the selected wood fuel tree species of the miombo woodland (**Table 4**). The Shannon index tells about species richness (number of species) and evenness (species distribution). Reference [39] reported that the larger the value of H′, the greater the species diversity and vice versa. An ecosystem with H′ value greater than 2 has been regarded as medium to high diverse [2]. This study shows higher diversity comparably to other studies in the miombo woodland where Shannon indexes ranged from 1.05 to 1.25 [64–66] but quite similar to other diversity study records such as by [44] who reported Shannon-Wiener index of 3.03 to 3.64. The H′ value of 2.75 from this study may be due to frequent bush fires and anthropogenic disturbances that opened the canopy and provided regeneration of light-demanding species such as *Uapaca* and *Albizia species* [49].

5. Discussion

Overexploitation of valuable tree species of miombo woodland in Zambia and other parts of Africa not only causes severe environmental impacts but also obstructs long-term use of wood fuel tree species for income generation, construction materials, charcoal, and fuel wood supply. Wood fuel from woodlands contribute to security of income and livelihoods of rural and peri-urban households. Presently, the availability of wood for wood fuel production and the quality of forest woodlands are not being sufficiently addressed by both traditional authorities and the Forestry Department; hence, filling this gap may demand overseeing harvesting, production, and charcoal trade activities. While wood fuel production is on the increase in Zambia and many other developing countries, management systems and use of efficient harvesting and production methods lag behind. Therefore, there is need for doubling extension and advisory services on wood fuel management and providing adequate research information to extension field officers.

The characteristic diameter distribution of wood fuel tree species in the study area may indicate the typical disturbance regime and subsequently the type of silvicultural system that should be used to achieve sustainable utilization for the wood industry. The inverse J-shaped curve observed in the study seems to agree with the findings by [49], since the miombo species are exposed to periodic annual fires that occur in the miombo vegetation [24]. The abundant regeneration in the study area may suggest that miombo wood fuel tree species are generally resilient and hence show good regeneration capacity, but this may demand targeted management of wood fuel sources. The overall stand structure (negative exponential curve) indicates that older trees probably provide minimal shading to the regeneration and saplings, and this promotes good growth of regeneration in larger numbers to insure sufficient wood resources for the future. Therefore, in order to improve regeneration in areas with closed canopy of larger trees,the canopy should be opened up by cutting mature trees for wood fuel and timber to allow penetration of light to the ground that would further facilitate regeneration growth. The large number of regeneration may also indicate utilization regime of tree species by local people who frequently cut and use Brachystegia species (*B. bussei, B. utilis*, and *B. spiciformis*) for construction material (poles and fiber). Reference [58] observed that increased wood extraction for wood fuel production and construction material in Zambia showed a negative balance for some of the most preferred productive and dominant species. This resulted into a decline in biomass for wood fuel trees species such as *B. spiciformis*, *C. mopane*, and *I. angolensis* suggesting that despite their high productivity, these species are heavily extracted from the woodlands a practice that could be unsustainable in the near future.

6. Conclusion and recommendation

The study revealed that the miombo woodlands in agro-ecological zones I and II in Zambia fairly have good species composition and distribution. Miombo woodlands play a significant role in sustaining the livelihood of many poor people in rural and urban areas in Southern Africa. However, the woodlands are under threat from evergrowing population in need of more wood, overharvesting of preferred hardwood tree species for wood fuel, poles, and timber. This calls for integrated approach for improving wood supply management and restoration and monitoring of woodlands to ensure sustainable wood energy. The status of preferred tree species density, abundance, composition, and distribution is at critical stage of threat with extinction as shown by low frequency of occurrence per hectare and hence needs quick action to tackle the problem sustainably.

The relative abundance, composition, and distribution varied across tree species. *C. mopane* (Benth) J. Leonard recorded the highest relative abundance (14.5) and basal area (22.4 m^2) per hectare among the 25 selected preferred hardwood species followed by *Julbernardia paniculata* (Benth) Troupin with abundance (11.9) and basal area (15.2 m^2). The diameter class distribution showed an inverse J-shaped trend with more trees in the small diameter classes. Different diameter distribution was observed, suggesting human disturbances probably linked with cutting activities for construction materials and wood fuel. However, further research should be geared toward the effects of anthropogenic disturbances and environmental factors (climate, soil, and topography) on tree growth, abundance, and species population changes of important tree species in the area as this will help proper management of wood resources in these ecosystems. Efforts are needed to promote collaboative management practices of wood resources that will ensure sustainable supply of wood products and services. Awareness and orientation should be given to local communities on existing forest laws and regulations on sustainable use of valuable tree species as well as the negative effects of illegal harvesting activities to enable them appreciate the role of trees to the wood industry in their environment. In rural areas and urban areas, local people still predominantly use fuel wood and wood charcoal for their cooking. In view of the foregoing, there will be need to promote investments in solar and bioenergy to diversify the electricity generation in the country. Furthermore, in recognition of the abundant wood resources and the growth of paper and paper board consumption in Southern Africa, there will be need to expand the pulp and paper industry in the country.

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Declaration of competing interest

Obote Shakacite, Phillimon Ngandwe, Donald Chungu, and Vincent Nyirenda, the authors of the paper, declare that there is no conflict of interest regarding this publication.

Author details

Obote Shakacite[1], Phillimon Ngandwe[2]*, Vincent Nyirenda[3] and Donald Chungu[4]

1 Department of Plant and Environmental Sciences, School of Natural Resources, The Copperbelt University, Kitwe, Zambia

2 Department of Biomaterial Science and Technology, School of Natural Resources, The Copperbelt University, Kitwe, Zambia

3 Department of Zoology and Aquatic Sciences, School of Natural Resources, The Copperbelt University, Kitwe, Zambia

4 Directorate of Distance Education and Open Learning, The Copperbelt University, Kitwe, Zambia

*Address all correspondence to: pngandwe2015@gmail.com

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