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Assessing the Impact of Charcoal Production on Southern Angolan Miombo and Mopane Woodlands

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Abstract: About 80% of Angola's forest surface is covered by Miombo and Mopane woodlands, which are explored for diverse activities such as fuelwood and food. This study aimed to assess the recovery dynamics of Miombo and Mopane woodlands after the selective cutting of tree species for charcoal production. For that, the structure and composition of plant communities in 37 plots, located in southwestern Angola, were characterized in fallows of different ages. Results showed that the diameter at breast height, basal area, biomass, and biovolume of trees all rose as the age of the fallow increased, and there were no significant differences in richness, diversity, or dominance of trees between adult–young classes or recent–older fallows. In Mopane, fallows took longer to regenerate, were more affected by environmental and anthropogenic factors, and also presented a higher species adaptation to disturbance. There were more sprouter and seeder trees in Miombo, and new kilns were more distant from roads and villages. Moreover, the selective removal of species deeply altered the community structure and dynamics, despite not directly affecting tree diversity. Thus, new management strategies are needed to ensure the survival of these woodlands such as expanding protected areas and increasing systematic research.

Keywords: *Brachystegia* spp.; *Colophospermum mopane*; fallows; forest degradation; Southern Africa

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1. Introduction

More than half of southern Africa's surface is covered with tropical dry forests and woodlands. The most representative forest vegetation types are the Miombo and Mopane woodlands [1,2]. Approximately 2.7 million km^2 of Angola, Malawi, Mozambique, the Democratic Republic of the Congo, the Republic of the Congo, Tanzania, Zambia, and Zimbabwe are covered by the miombo [3]. Mopane occupies an area of about 600,000 km^2 distributed by Angola, Botswana, Malawi, Mozambique, Namibia, Zimbabwe, Zambia, and South Africa [4].

Most of the tree species occurring in these woodlands are semi-deciduous non-nitrogen-fixing Caesalpinioideae legumes with broad leaves, which rely on the help of mycorrhizae as significant nutrient sources [3]. In Miombo woodland, species of *Brachystegia*, *Julbernerdia*, and *Isoberlinia* predominate, which are widely distributed on nutrient-poor soils in the Zambezian region of southern Africa with over 700 mm of annual rainfall and pronounced seasonality [5]. Mopane woodland is dominated by *Cholophospermum mopane*, which typically receives less than 700 mm of annual rainfall and is located on poor soils that are confined to lower-lying places [6].

Woody species in the Miombo and Mopane woodlands play an essential ecological role, but they additionally hold significant social and economic significance for the local population. For example, it is estimated that Miombo supports the livelihoods of more than 100 million people in both urban and rural areas [7]. Nonetheless, most African populations who depend on forest resources are impoverished [8]. Moreover, several human activities that improve family income and living conditions, including agricultural expansion, logging, burning, and charcoal and firewood consumption, impose significant pressure on land resources [9–12]. An important topic of debate today is how the needs of resident populations can be reconciled with the sustainability of forest resource use [13].

About 90% of urban people in Africa use charcoal, a forest product, primarily as a source of heat for cooking but, in many circumstances, as a source of family income [14,15]. Rural people typically produce charcoal to sell to consumers living in cities and, to a lesser extent, for their own consumption, which has helped to reduce poverty [16]. Charcoal production and trade in the Miombo region contribute between 60% and 80% of the household income of the families involved in both rural and urban areas [6,12]. Several studies demonstrate the benefits of this activity in diversifying the rural and domestic economies [12,17,18]. According to Mensah et al. [19], the Sub-Saharan Africa system accounts for an estimated 65% of global charcoal output with Nigeria, Ethiopia, Ghana, Tanzania, and Madagascar being among the top producers. Therefore, the production of charcoal and its impact on socio-economic, socio-ecological, and the environment have been important issues in various African countries [20–22]. The effects of charcoal production can never be overemphasized, behind the benefits, there have been also negative effects on the environment and human health [23]. A major concern is that this exploration could negatively impact forest regeneration once the annual rate of growth of these forests is low [24,25], as most of the trees in Miombo and Mopane woodlands are slow-growing. The net primary production in Miombo woodlands is estimated to be 900–1600 g m^{-2} yr^{-1} and the annual increment of the woody-plant biomass is no more than 3–4% in mature stands [3]. Some authors showed that it could take 19 to 55 years to recover the structure after logging [24–27]. Also, the exposure to wood smoke has been treated as a public health concern meanly the carbon monoxide and the mixture of solid and liquid particles suspended in the air for a long time [28–31].

Angola is a unique African country with great and diversified biomes and ecoregions, from tropical and subtropical moist forests to deserts and xeric shrublands and a strong endemism rate [32]. Like throughout the rest of sub-Saharan Africa, Angola is characterized by numerous intensively exploited forest resources, including wood (such as timber, firewood, and charcoal) and non-wood products (such as honey, fruits, leaves, roots, and mushrooms). However, the extraction of wood products has the largest impact on forest ecosystems [33,34]. Approximately 80% of Angolans depend on biomass for most of their energy needs, with Miombo contributing more than 75% of the charcoal produced, the largest source in Angolan territory [32,35]. Charcoal is valued in peri-urban and urban areas due to its greater purchasing power, ease of transport, and convenience of use, while firewood is more widely used in rural areas [35].

According to FAO [36], Angola is ranked fourth in the world for the largest forest area losses, with a forest loss of 500,000 ha per year and a net annual change of −0.8%. Moreover, the scarcity of energy options to replace biomass as an energy source is a cause for concern [37]. Therefore, the production of charcoal and its impact on forest ecosystems and the environment are important issues and integrated multidisciplinary studies are needed to mitigate the effects of the use of woody resources in ecosystems. However, few studies on forest degradation and deforestation caused by charcoal production have been conducted in Angola and they have been focused in some areas of the country should be highlighted, namely in Kwanza Sul [38,39], Bengo [40], Bié [41,42], and Huambo [24,43,44]. Moreover, according to FAOSTAT [45], the consumption of charcoal has continuously grown over the last decades (e.g., 1976: 82,129 tons; 1990: 130,139 tons; 2002: 220,768 tons; 2021: 417,563 tons).

In summary, the plant communities of the Miombo and Mopane forests could be severely affected by wood extraction for charcoal production since this activity may compromise species regeneration and productivity. Thus, this study aims to analyze the changes in the composition and structure of woody plant communities located in fallows abandoned after cutting for charcoal production. This was carried out by assessing the recovery dynamics of Miombo and Mopane charcoal fallows with different ages: recent fallows (<10 years), intermediate fallows (10–20 years), and mature plots (>20 years) in southwestern Angola.

2. Materials and Methods

2.1. Study Area

The study area was located in Huíla and Namibe provinces in southwestern Angola (13°59′–15°13′ S, 14°47′–12°27′ E), comprising 14,197 km^2 (Figure 1). It presents elevations ranging from 300 to 2200 m of altitude, belonging to the central plateau of Angola (covering Lubango and Cacula municipalities in Huila) and the sub-plateau (covering Bibala municipality in Namibe). The climate is temperate in the central plateau, with dry winters, and semi-arid in the sub-plateau zone, with two seasons: the dry season (mid-May to mid-August) and the rainy season (mid-August to mid-May), but the sub-plateau region has a longer dry period. The central plateau area has mean annual temperatures of 18.5 °C and annual precipitation ranging from 750 to 1200 mm, whereas the sub-plateau region experiences mean annual temperatures of 21.5 °C and annual precipitation ranging from 300 to 400 mm [46,47].

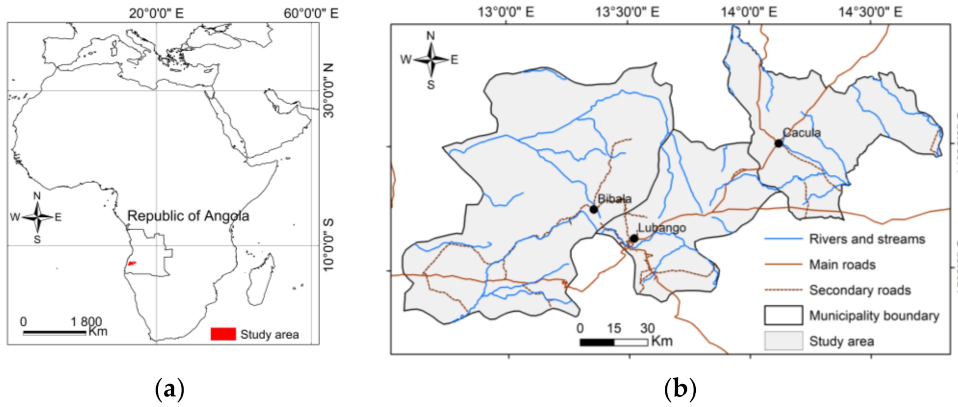

Figure 1. Location of the study area in Africa (**a**) and the study area (**b**).

Miombo and Mopane woodlands are the dominant vegetation in the plateau and subplateau zones of the study area, respectively, and there are around one million people living here [48]. It is a multicultural land with several ethnolinguistic groups, such as the Ovimbundo, Muila, Handa, Koissan, and Mucubal peoples, who live in rural areas. Agriculture and pastoralism, as well as charcoal production, are the main economic activities of the population [49,50].

2.2. Vegetation Sampling and Explanatory Variables

Sampling of wood vegetation was performed in three areas: Humbia and Garganta in Bibala municipality, where Mopane woodland is dominant, and Mawengue in Cacula municipality, where Miombo predominates. Based on a model developed by Oldeland et al. [51] and applied by other researchers, including Gonçalves et al. [52], a total of 37 charcoal fallow sites, over a total area of about 3.7 ha, were sampled. Plots of 1000 m^2 (20 × 50 m) with a central sub-plot of 100 m^2 (10 × 10 m) were used. Regeneration plots were selected based on the information provided by local charcoal producers. According to the number of years since the last disturbance, three different classes were established: recent plots (<10 years), intermediate plots (from 10 to 20 years), and mature plots (>20 years), with 20 made in Miombo woodlands (9 recent, 5 intermediate, and 6 mature) and 17 in

Mopane (4 recent, 6 intermediate, and 7 mature). Plot geographical coordinates and their altitude, slope, and distance to the nearest road were recorded. For slope, there were considered three classes: flat: <5% slope; slightly sloping: 5–10%, and sloping: >10%. The distance to the road was measured using the QGIS 2.18.16 software [53].

DBH and height were measured in each plot for individuals with DBH $\geq$ 5 cm, and they were categorized as seeders (seed-growing) or sprouters (stump-growing). All seeders and sprouters with DBH $\geq$ 5 cm were classified, size classes, as adults (adult class), while those with DBH 5 cm were classified as young (young class). Adult seeders and adult sprouters were separated from the adult class.

Individuals from the young class were only sampled in the 100 m^2 sub-plot, and results were extrapolated to the 1000 m^2 plots. They were classified into three groups: (1) young from seed regeneration with a height greater than 1.30 m (young seeders), (2) young from seed regeneration with a height less than 1.30 m (seedlings), and (3) young from stump regeneration (young spouters).

To estimate the aboveground biomass (AGB) and above-ground biovolume in charcoal fallows and mature woodlands, two allometric equations developed in the miombo woodlands of Tanzania and Malawi were calculated [54,55].

1. Biomass equation [54]: Biomass = $0.1027 \times DBH^{2.4798}$
2. Biovolume equation [55]: Biovolume = $0.0213 + 0.000011DBH^3$

The results were transformed into hectares. Values for the charcoal-bearing species were also calculated. Plant nomenclature followed the African Plants Database [56], and the field guide developed by Van Wyk and Van Wyk [57]. Species identification was performed in situ, except for those that were unknown, for which herbarium vouchers were collected. The local names of trees were obtained in Umbundu and Lunyaneka from local field guides. The vouchers were identified with the support of experts from the University of Lisbon herbarium (LISC), and by comparison with other specimens, and deposited in the ISCED-Huíla Herbarium, at Lubango (LUBA).

2.3. Comparative Analyses

First, plant richness and diversity indices were calculated, namely Shannon and Dominance (D = Simpson index), using the vegan package in R [58,59] in both communities. The numbers of seeder and sprouter species were also calculated.

Gradients in plant composition through time for each vegetation type were described using Non-metric Multidimensional Scaling ordinations (NMDS) [60] based on tree species density [61], using the "metaMDS" function of the R package vegan v2.5-7 [62]. All the analyses were performed separately for adult and young trees in both Miombo and Mopane woodlands (see Supporting information, Tables S1A–D and S3A,B). Then, the relationships between a set of broad exploratory variables and the dynamics of vegetation regeneration were explored by correlating these variables with the NMDS ordination using the "envfit" function of vegan [63,64]. These variables included the number of individuals per plot by size class (adult and young) and regeneration type (seeders and sprouters); allometric variables such as DBH, basal area, the total and charcoal-bearing biomass, the biovolume, tree height; species richness (for all species and only for species bearing charcoal), the Shannon and Dominance indices; lastly, altitude, slope, and distance to roads (Tables 1 and 2). The strength of those relationships was evaluated through the squared correlation coefficient (r^2). Multicollinearity among potential explanatory variables was handled by dropping collinear covariates [65,66] when correlated at |Spearman r| > 0.8 [67] Pairwise comparisons were then performed to assess differences in all exploratory variables among recent, intermediate, and mature plots throughout Wilcoxon tests using the Bonferroni correction for p value adjustment (Table S1).

Table 1. Tree species richness and structural variables for the Recent, Intermediate and Mature fallows of Miombo and Mopane woodlands. (Ind.: individuals; avg: average; SD: standard deviation.

	Maturity	No. Tree Species	No. Adult Tree Species	No. Young Tree Species	Charcoal-Bearing Species	Adult Charcoal-Bearing Species	Young Charcoal-Bearing Species	Density of Adults (Ind ha^{-1}; avg ± SD)	Density of Young (Ind. ha^{-1}; avg ± SD)	DBH of Adults (cm; avg ± SD)	Height of Adults (m; avg ± SD)	Basal Area (m^2 ha^{-1} avg ± SD)	Biovolume (m^3 ha^{-1} avg ± SD)	Biomass (ton ha^{-1} avg ± SD)	Biomass Charcoal Bearing (ton ha^{-1} avg ± SD)
Miombo	**Recent**	26	11	22	14	7	13	830 ± 229	5022 ± 2683	9.1 ± 2.8	5.0 ± 1.4	4.8 ± 1.0	29.6 ± 7.0	19.2 ± 5.8	18.8 ± 5.2
	Intermediate	18	8	17	11	4	11	1170 ± 882	6360 ± 2466	4.2 ± 7.0	7.9 ± 3.3	9.2 ± 4.4	82.7 ± 29.1	57.9 ± 19.8	55.0 ± 22.9
	Mature	21	13	17	14	9	12	525 ± 193	4417 ± 950	24.4 ± 5.3	13.3 ± 1.8	17.5 ± 7.0	232.0 ± 260.0	130.0 ± 95.3	107.0 ± 40.4
	Total	32	19	30	18	11	18	824 ± 506	5175 ± 2260	14.9± 8.1	8.2 ± 4.1	9.7 ± 7.0	103.7 ± 160.9	62.1 ± 69.4	54.2 ± 44.9
Mopane	**Recent**	12	10	10	5	5	5	1098 ± 275	3325 ± 1626	8.0 ± 3.0	6.2 ± 1.25	5.3 ± 3.3	36.7 ± 20.6	21.2 ± 17.3	19.5 ± 16.9
	Intermediate	32	17	24	9	6	9	1205 ± 205	2817 ± 1485	10.5 ± 3.8	6.3 ± 1.4	9.8 ± 2.9	67.2 ± 43.7	38.4 ± 15.9	31.8 ± 10.6
	Mature	14	11	10	6	5	5	974 ± 107	1343 ± 932	18.4 ± 3.1	8.1 ± 1.4	18.8 ± 6.6	174.0 ± 96.3	108.0 ± 48.8	68.6 ± 25.2
	Total	31	21	29	9	7	9	1085 ± 206	2329 ± 1508	13.2 ± 5.6	7.0 ± 1.6	12.4 ± 7.4	104.0 ± 89.1	63.0 ± 50.7	44.1 ± 28.2

Table 2. Data on the species recorded in Miombo (MI) and Mopane (Mo) woodlands. Languages: Nya—Nyaneka, Por—Portuguese; Umb—Umbundu.

Family/Species	Acronym	Forest Type (MI/Mo)	Average Dens. Adults (stem/ha)	Average Dens. Young (stem/ha)	Basal Area (m^2/ha)	Biomass (ton/ha)	Volume (m^3/ha)	Max Average Heigth (m)	Average Adult DBH ≥ 5 cm	Sprout Observation	Charcoal-Bearing Species	Others Uses	Local Names
Anacardiaceae													
Sclerocarya birrea (A. Rich.) Hochst.	Sbir	Mo	4.0	6.0	3.3	26.6	43.7	24.0	45.5	No	No	Food, alcoholic beverage (fruits), oil (seeds), shadow tree	Omungongo (Nya)
Annonaceae													
Hexalobus monopetalus (A. Rich.) Engl. & Diels	Hmon	Mi	-	50.0	-	-	-	-	-	Yes	No	-	Omutundu (Nya, Umb)
Xylopia odoratissima Welw. ex Oliv.	Xodo	Mi/Mo	-	5/12	-	-	-	-	-	No	No	Medicinal (roots)	Mumbungululu (Nya, Umb)
Apocynaceae													
Carissa spinarum L.	Cspi	Mo	-	11.8	-	-	-	-	-	No	No	Food, juice, alcoholic beverage (fruits)	Oiangola (Nya), Mirangolo (Umb)
Diplorhynchus condylocarpon Müll. Arg.	Dcon	Mi	-	10.0	-	-	-	-	-	Yes	No	Medicinal (roots)	Muli (Umb)
Burseraceae													
Commiphora angolensis Engl.	Cang	Mo	6.5	23.5	0.6	2.4	4.0	6.0	10.0	Yes	No	Medicinal (bark)	Omulema-wowo (Nya)
Commiphora mollis (Oliv.) Engl.	Comol	Mo	27.1	41.2	3.2	19.9	29.2	16.0	55.1	Yes	No	Medicinal (bark)	Mulenda (Nya)
Chrysobalanaceae													
Parinari curatellifolia Planch. ex Benth.	Pcur	Mi	-	5.0	-	-	-	-	-	No	No	Food, juice, alcoholic beverage (fruits)	Oloncha (Umb)
Combretaceae													
Combretum molle R. Br. ex G. Don	Cmol	Mi/Mo	1/0	5/47	0.3	2.0	2.3	11.0	22.5	Yes	Yes	Medicinal (bark)	Mupupu (Umb)

Table 2. *Cont.*

Family/Species	Acronym	Forest Type (Mi/Mo)	Average Dens. Adults (stem/ha)	Average Dens. Young (stem/ha)	Basal Area (m^2/ha)	Biomass (ton/ha)	Volume (m^3/ha)	Max Average Heigth (m)	Average Adult DBH ≥ 5 cm	Sprout Observation	Charcoal-Bearing Species	Others Uses	Local Names
Combretum collinum Fresen.	Ccol	Mi/Mo	17/18	785/18	0.57/0.61	2.02/1.94	3.73/4.49	5.2/6.0	9.71/6.25	Yes	Yes	Medicinal (bark)	Mupupu (Umb)
Combretum imberbe Wawra	Cimb	Mo	23.5	11.8	0.6	2.4	3.4	6.0	9.0	Yes	Yes	Medicinal (bark)	Mukuku (Nya)
Combretum zeyheri Sond.	Czey	Mi	-	100.0	-	-	-	-	-	Yes	Yes	Medicinal (bark)	Mumbumbungi (Umb), Mupupu (Nya)
Pteleopsis anisoptera (Welw. ex M.A. Lawson) Engl. & Diels	Pani	Mi/Mo	11/1	150/0	12.1/0.05	143.18/0.06	377.4/0.41	17.0/5.5	30/3.5	Yes	No	Charcoal bag cover	Omuhihi (Nya, Umb)
Terminalia prunioides M.A. Lawson	Tpru	Mo	141.8	441.2	7.1	38.2	104.4	15.0	28.5	yes	yes	Medicinal (bark)	Omuhaina (Nya)
Terminalia sericea Burch. ex DC.	Tser	Mi/Mo	-	20/6	-	-	-	-	-	yes	yes	Medicinal (leaves, roots)	Mungolo (Nya, Umb)
Ebenaceae													
Diospyros mespiliformis Hochst. ex A. DC.	Dmes	Mo	-	18.0	-	-	-	-	-	No	No	Food (fruits)	Munhangue (Nya)
Euclea divinorum Hiern	Ediv	Mo	6.0	12.0	0.6	2.1	3.1	6.0	10.0	Yes	No	Food (fruits)	Munhime (Nya)
Euphorbiaceae													
Bridelia cathartica G. Bertol.	Bcat	Mi	-	30.0	0.1	0.4	0.5	5.0	11.0	Yes	No	Food (fruits)	Olohuliungo (Umb)
Croton mubango Müll. Arg.	Cmub	Mo	2.0	47.0	0.7	0.2	0.6	5.0	5.5	Yes	No	Medicinal (roots)	Mumbango (Nya)
Spirostachys africana Sond.	Safr	Mo	248.2	358.8	4.4	24.8	102.5	13.0	21.2	yes	yes	Medicinal (bark)	Omupapa (Nya)
Fabaceae													
Acacia ataxacantha (DC.) Kyal. & Boatwr.	Aata	Mo	0.6	11.8	0.0	0.1	0.2	3.5	5.0	yes	No	Fibre (bark)	Mukete (Nya)
Acacia senegal (L.) Willd.	Asen	Mo	73.5	129.4	2.3	11.6	13.0	16.0	26.1	Yes	Yes	Medicinal (roots)	Mukondo (Nya)
Albizia adianthifolia (Schumach.) W. Wight	Aadi	Mi	16.0	140.0	2.1	8.3	11.9	8.2	11.3	Yes	Yes	Medicinal (roots)	Homem amargo (Port)

Table 2. *Cont.*

Family/Species	Acronym	Forest Type (Mi/Mo)	Average Dens. Adults (stem/ha)	Average Dens. Young (stem/ha)	Basal Area (m^2/ha)	Biomass (ton/ha)	Volume (m^3/ha)	Max Average Heigth (m)	Average Adult DBH ≥ 5 cm	Sprout Observation	Charcoal-Bearing Species	Others Uses	Local Names
Baphia massaiensis subsp. *obovata* (Schinz) Brummitt	Bmas	Mi	-	5.0	-	-	-	-	-	Yes	Yes	Fibre (bark)	Pau-ferro (Port)
Brachystegia boehmii Taub.	Bboe	Mi	-	135.0	-	-	-	-	-	Yes	Yes	Fibre (bark)	Munsamba (Umb)
Brachystegia floribunda Benth.	Bflor	Mi	-	5.0	-	-	-	-	-	Yes	Yes	Fibre (bark)	Mutundu (Nya)
Brachystegia longifolia Benth.	Blon	Mi	8.5	80.0	1.7	9.8	13.7	12.0	21.7	Yes	Yes	Fibre (bark)	Mungolo (Umb)
Brachystegia spiciformis Benth.	Bspi	Mi	328.5	745.0	17.9	173.8	377.9	17.3	34.6	Yes	Yes	Medicinal, fibre (bark)	Mupanda (Um)
Brachystegia tamarindoides Welw. ex Benth.	Btam	Mi	0.5	5.0	0.0	0.1	0.2	4.5	6.0	Yes	Yes	Fibre (bark)	Mungai (Umb)
Burkea africana Hook.	Bafr	Mi	70.0	6.0	0.3	1.1	2.3	9.5	11.5	Yes	No	Construction (stem)	Osese (Umb)
Colophospermum mopane (J. Kirk ex Benth.) J. Kirk ex J. Léonard	Cmop	Mo	514.7	958.8	13.1	66.6	86.3	11.1	28.4	Yes	Yes	Medicinal (leaves, roots)	Mutiati (Nya)
Erythrina baumii Harms	Ebau	Mi	5.0	345.0	0.2	0.8	1.6	4.0	7.8	Yes	Yes	-	Pau-ferro (Port)
Julbernardia paniculata (Benth.) Troupin	Jpan	Mi	390.0	1520	14.0	80.1	110.7	12.5	31.5	Yes	Yes	Medicinal (roots), fibre (bark)	Omumwe (Umb)
Peltophorum africanum Sond.	Pafr	Mo	-	12.0	-	-	-	-	-	No	No	Medicinal (roots)	Mupala (Nya)
Pericopsis. angolensis (Baker) Meeuwen	Pang	Mi	-	10.0	-	-	-	-	-	Yes	Yes	Medicinal (bark, leaves, roots)	Pau-ferro maco (Umb)
Pterocarpus lucens subsp. *antunesii* (Taub.) Rojo	Pluc	Mi/Mo	1/1	15/18	0.03/0.02	0.11/0.07	0.23/0.21	3/5.5	6.5/6	yes	No	Handicrafts (stem)	Muviu (Nya), Muvibu (Umb)
Pterocarpus rotundifolius (Sond.) Druce	Prot	Mi/Mo	-	15/12	-	-	-	-	-	No	yes	Handicrafts (stem)	Muviu (Nya), Ulumba (Umb)

Table 2. *Cont.*

Family/Species	Acronym	Forest Type (Mi/Mo)	Average Dens. Adults (stem/ha)	Average Dens. Young (stem/ha)	Basal Area (m^2/ha)	Biomass (ton/ha)	Volume (m^3/ha)	Max Average Heigth (m)	Average Adult DBH ≥ 5 cm	Sprout Observation	Charcoal-Bearing Species	Others Uses	Local Names
Hernandiaceae													
Gyrocarpus americanus Jacq.	Game	Mo	-	6.0	-	-	-	-	-	No	No	Medicinal (bark, leaves)	Omuxilia (Nya)
Kirkiaceae													
Kirkia acuminata Oliv.	Kacu	Mo	24.0	12.0	5.7	38.8	53.5	12.3	35.0	Yes	No	Medicinal (stem, latex)	Mumbowo (Nya)
Loganiaceae													
Strychnos cocculoides Baker	Scoc	Mi/Mo	1/0	0/12	0.5	2.7	3.3	15.0	24.0	No	No	Food, alcoholic beverage (fruits)	Omwi (Umb), Maboka (Nya)
Malvaceae													
Adansonia digitata L.	Adig	Mo	1.8	11.8	6.0	53.3	115.9	7.5	42.9	No	No	Food, oil, medicinal (fruits, seeds), shadow tree, fibre (bark)	Omukwa (Nya)
Ochnaceae													
Ochna cf. *pulchra* Hook.	Opul	Mi	25.5	480.0	2.8	14.2	17.3	8.0	12.0	Yes	Yes	-	Omia (Umb)
Olacaceae													
Ximenia americana L.	Xame	Mo	1.0	-	0.1	2.4	3.4	5.5	9.0	yes	No	Food, medicinal, cosmetic (fruits)	Omingua, Omumpeke (Nya)
Schrebera alata (Hochst.) Welw.	Sala	Mo	-	18.0	-	-	-	-	-	yes	No	-	Omulica Nya)
Phyllanthaceae													
Uapaca nitida Müll. Arg.	Unit	Mi	1	45.0	0.3	2.0	2.3	7.0	21.0	yes	yes	Food, juice, alcoholic beverage (fruits)	Lombula (Umb)
Proteaceae													
Faurea rochetiana (A. Rich.) Chiov. ex Pic. Serm.	Froc	Mi	6.0	15.0	0.4	5.4	6.2	6.5	16.0	Yes	No	Construction (stem)	Ondjunge (Umb)
Rubiaceae													

Table 2. *Cont.*

Family/Species	Acronym	Forest Type (Mi/Mo)	Average Dens. Adults (stem/ha)	Average Dens. Young (stem/ha)	Basal Area (m^2/ha)	Biomass (ton/ha)	Volume (m^3/ha)	Max Average Heigth (m)	Average Adult DBH ≥ 5 cm	Sprout Observation	Charcoal-Bearing Species	Others Uses	Local Names
Afrocanthium lactescens (Hiern) Lantz	Alac	Mo	-	5.9	-	-	-	-	-	No	No	Construction (stem), food (fruits)	Muholiholi (Nya)
Gardenia ternifolia subsp. *jovis-tonantis* (Welw.) Verdc.	Gter	Mi	6.0	100.0	0.4	2.3	2.8	11.0	22.5	Yes	No	Food (fruits)	Otchilavi (Umb)
Gardenia volkensii subsp. *spatulifolia* (Stapf & Hutch.) Verdc.	Gvol	Mo	1.0	6.0	0.0	1.0	0.2	6.0	5.0	Yes	No	-	Muvali (Nya)
Rothmannia engleriana var. *terniflora* (Ficalho & Hiern) Somers	Reng	Mi	1.0	270.0	0.3	2.0	2.3	10.0	21.0	yes	No	Food (fruits)	Upu (Umb)
Vangueriopsis lanciflora (Hiern) Robyns	Vlan	Mi	-	-	-	-	-	-	-	yes	No	Food (fruits)	Mandjunju (Nya)
Ptaeroxylon obliquum (Thunb.) Radlk.	Pobl	Mi/Mo	-	5/18	-	-	-	-	-	yes	No	Medicinal (bark, leaves, roots)	Omumbungululu (Nya, Umb)
Sapotaceae													
Englerophytum magalismontanum (Sond.) T.D. Penn.	Emag	Mi	1.0	-	0.0	0.1	0.2	3.0	5.0	No	No	Food (fruits)	Omutomboti (Umb)
Tiliaceae													
Grewia flavescens Juss.	Gfla	Mo	1.0	-	0.2	0.1	1.1	3.3	16.0	No	No	Food, juice, alcoholic beverage (fruits)	Munamba (Nya)
Ulmaceae													
Chaetachme aristata Planch.	Cari	Mo	0.6	35.3	0.0	0.1	0.2	3.5	6.0	Yes	No	Medicinal (roots)	Munguedja (Nya)

Finally, the indicator value for each species (IndVal) was calculated aiming to identify the indicator species in Miombo and Mopane woodlands [68]. Indicator species are used as ecological indicators of communities and ultimately represent the qualitative characteristics of the ecosystem [69]. This index measures each species' specialization and faithfulness to a certain kind of community. IndVal was calculated using the R package labdsv (v2.0-1) [70].

3. Results

3.1. Diversity and Abundance of Woody Species

A total of 55 species of trees were identified, with 32 found in Miombo woodlands, 19 adults and 30 young, and 31 in Mopane woodlands, with 21 adults and 29 young (Table 1). Nine species were found in both woodlands. In Mopane, a total of 5804 individuals were measured or counted: 3960 young and 1844 adults; in Miombo, 11,998 individuals were measured or counted: 10,350 young and 1648 adults (see Supporting Information, Table S1A–D).

Concerning charcoal-bearing species, 18 species were recorded in Miombo and nine in Mopane. All the charcoal-bearing species are present in young classes, but only 11 were found as adults in Miombo and seven in Mopane (Table 1). At the vegetation structure level, in both woodland types, the density of both adult and young trees increases from recent to intermediate fallows and decreases from intermediate to mature. The average height of adult trees increases steadily from recent to mature fallows but is remarkably higher in Miombo than in Mopane (13.30 and 8.12 m, respectively). A similar pattern is also verified in the mature fallows for biovolume, total biomass, and charcoal-bearing biomass (Table 1).

From the total of 23 plant families identified, the most representative was Fabaceae with 17 species, followed by Combretaceae with seven, Rubiaceae (five species), Euphorbiaceae (three species), Annonaceae, Apocynaceae, Burseraceae, and Ebenaceae with two species each; the remaining 15 families have a single representative species (Table 2). At Miombo, of the total 55 species, 18 are charcoal-bearing species, 11 are found in the adult class, and 18 are in the young class. At Mopane, of the total of 31 species, nine were charcoal-bearing species, seven were adults and nine young (Table 1). The average values of the Shannon and Dominance indices were low for both formations, except for the Shannon indices for some young fallows. The values for recent, intermediate, and mature fallows of the young class ranged, respectively from H′ = 1.58 to 2.39, H′ = 2.14 to 2.68, and H′ = 0.7 to 0.24 for Miombo and H′ = 0.44 to 1.52, H′ = 1.09 to 2.92, and H′ = 0 to 2.03 for Mopane (see Supporting Information, Table S2A–D).

In both the young and adult classes, *Brachystegia spiciformis* and *Julbernardia paniculata* are the Miombo species with the greatest number of individuals (Table S1). *Baphia massaiensis* subsp. *obovata*, *Diplorhynchus condylocarpon*, *Hexalobus monopetalus*, *Parinari curatelifolia*, *Pericopsis angolensis*, *Ptaeroxylon obliquum*, *Strychnos cocculoides*, and *Xylopia odoratissima* were found only in the recent fallows, and except for *X. odoratissima* and *P. curatilifolia* that were seedlings, all the species were young sprouters. *Brachystegia floribunda* was recorded only in intermediate fallow in young sprouters' class. Some species were found in different age and regeneration stages, such as *Faurea rochetiana* and *Erythrina baumii* found in recent and intermediate fallows, whereas others occur in intermediate and mature fallows, namely *Pterocarpus lucens* subsp. *antunesii* and *Vangueriopsis lanciflora* (found only as young sprouters).

In Mopane, *Colophospermum mopane*, *Spirostachys africana*, *Acacia senegal*, and *Terminalia prunioides* are the species with the largest number of individuals (Table 1) and were found in all age stages and regeneration types and counted in all the fallows. Two species, *Peltophorum africanum* and *Ximenia americana* var. *microphylla*, were only found in recent fallows as young and adult sprouters, respectively. A larger number of species were found in intermediate fallows, and there was a great variation in regeneration type and age. For example, *Croton mubango* and *Euclea divinorum* were found as seeders and sprouters, young and adult trees; *Terminalia sericea* tree was found only as a sprouter, *Pterocarpus lucens* subsp. *antunesii*, *Pterocarpus rotundifolius*, *Diospyros mespiliformis*, and *Xylopia odoratissima*, were only found as seeders. Also, several species were found at the same time in recent and intermediate fallows such as *Combretum collinum*, which was found in all fallow ages and regeneration stages, and others occur in both intermediate and mature fallows such as *Adansonia digitata*, only as seeder, *Chaetachme aristata* and *Combretum imberbe*, both in all forms and regeneration stages, *Ptaeroxylon obliquum* and *Strychnos cocculoides*, both in the young class (see Supporting Information, Table S1A–D). The most common species were *Brachystegia floribunda*, *Combretum collinum*, *Ptaeroxylon obliquum*, *Pteleopsis anisoptera*, *Pterocarpus lucens* subsp. *antunesii*, *Pterocarpus rotundifolius*, *Strychnos cocculoides*, *Terminalia sericea*, and *Xylopia odoratissima*.

3.2. Effect of Charcoal Production on Diversity, Structure, and Regeneration of Miombo and Mopane Woodlands

The main gradients in vegetation composition were described by the two-dimensional ordination of the plots based on the species density data, with final stresses of 15.64% and 17.01% in Miombo and 17.44% and 15.79% in Mopane for adult and young individuals, respectively (Figure 2). In Miombo woodlands, the ordination separated young (recent fallows) from older communities (intermediate and mature fallows) for both adults (Figure 2a) and young trees (Figure 2b). Whereas for Mopane woodlands, there was a distinction between recent, intermediate, and mature fallows in the adult class (Figure 2c), but no distinction in the young class (Figure 2d).

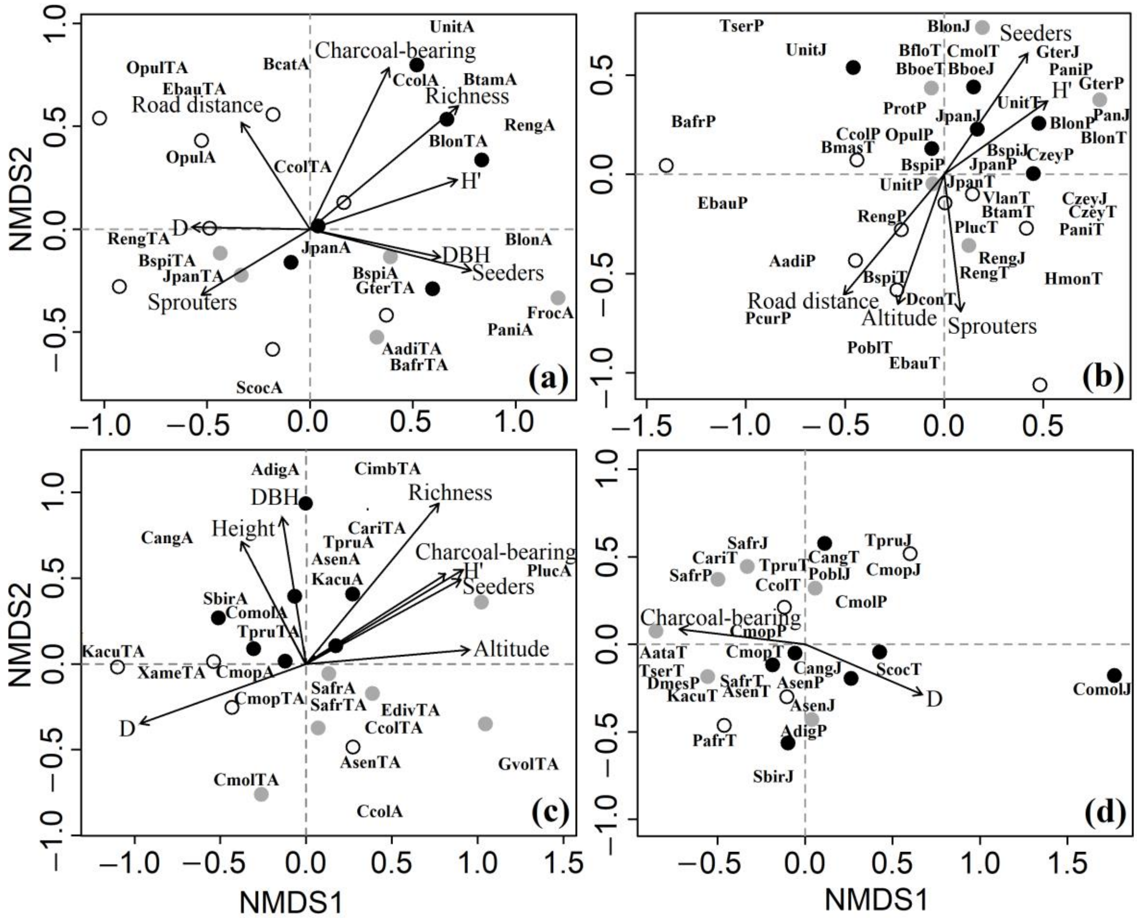

Figure 2. Axes 1 and 2 of the 3-dimensional non-metric multidimensional scaling ordinations of study sites based on the individual's number of trees species. (NMS1 and NMS2). Adult class (**left**) and young class (**right**), trees of Miombo (**a**,**b**) and Mopane (**c**,**d**). Recent fallow (white circles), intermediate

fallow (grey circles), and old growth/mature fallow (black circles.). Vectors represent significant correlations between species composition and the environmental variables, DBH and diversity indices. D (Dominance index); H′ (Shannon index). Species codes according to Table 1, when added A (means adult seeders), TA (means adult sprouters), J (means young seeders), T (means young sprouters,) and P (means seedling).

At Miombo, the first axis accounts for most variance for adult trees (40.18% of 41.43%), whereas the second axis is for young trees (33.96% of 57.41%). Both axes described a gradient between the oldest fallows (both intermediate and mature) and recent ones in both age classes (Figure 2a,b). According to the correlation analyses (Table 3), oldest fallows are richer in the total number of tree species (r^2 = 0.84 ***), in charcoal-bearing species (r^2 = 0.72 ***), seed regeneration individuals (r^2 = 0.63 ***), and stump regeneration individuals (r^2 = 0.35 *). These fallows also presented a higher diversity (Shannon-H′ index, r^2 = 0.54 **) and larger trees (DBH average, r^2 = 0.40 **). While recent fallows are located further away from roads (r^2 = 0.35 *) and had a lower level of diversity (Dominance index, r^2 = 0.31 *). In the young class, recent fallows were also further away from roads (r^2 = 0.52 **) and higher in altitude (r^2 = 0.40 **) and had a higher number of sprouter individuals (r^2 = 0.40 **), whereas older fallows were more diverse (Shannon-H index, r^2 = 0.34 *) and presented a higher number of seeder individuals (r^2 = 0.46 **).

Table 3. Significant squared correlation coefficient (r^2) of environmental factors and functional groups onto the NMS ordination.

Miombo Woodland	r^2	Mopane Woodland	r^2
Adult trees		**Adult trees**	
Altitude	ns	Altitude	0.52 **
Road distance	0.35 *	Road distance	ns
Slope	ns	Slope	ns
Average DBH	0.40 *	Average DBH	0.39 *
Average height of trees	ns	Average height of trees	0.37 *
Richness	0.84 ***	Richness	0.84 ***
Richness charcoal-bearing	0.72 ***	Richness charcoal-bearing	0.52 **
Seeders	0.63 ***	Seeders	0.61 **
Sprouters	0.35 *	Sprouters	ns
Diversity indices		*Diversity indices*	
Dominance index	0.31 *	Dominance index	0.60 ***
Shannon index	0.54 **	Shannon index	0.65 ***
Young trees		**Young trees**	
Altitude	0.40 **	Altitude	ns
Road distance	0.52 **	Road distance	ns
Slope	ns	Slope	ns
Altitude	0.40 **	Altitude	ns
Road distance	ns	Road distance	ns
Richness	ns	Richness	ns
Richness charcoal-bearing	ns	Richness charcoal-bearing	0.36 *
Seeders	0.46 **	Seeders	ns
Sprouters	0.40 *	Sprouters	ns
Diversity indexes		***Diversity indexes***	
Shannon index	0.34 *	Shannon index	ns
Dominance index	ns	Dominance index	0.36 *

Significance level * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

At Mopane vegetation, the first axis explained most of the variance in both cases: 33.31% of 49.22% for adult trees and 35.09% of 55.25% for young trees. Concerning adults, all fallow classes were distinct (Figure 2c), with a clear separation of the mature fallows. Regarding young trees, only mature fallows were distinctly separated (Figure 2d). According to correlation analyses, adult trees in the oldest fallows were larger (average DBH and Height of trees, r^2 = 0.39 * and r^2 = 0.37 *, respectively), both mature and intermediate fallows were richer in a total number of species (r^2 = 0.84 ***), number of seeders, and charcoal-bearing individuals (r^2 = 0.61 and r^2 = 0.52, respectively), and more diverse (Shannon-H′ index and Dominance, r^2 = 0.65 *** and r^2 = 0.60 ***, respectively). In the young class, mature fallows had lower levels of diversity (Dominance r^2 = 0.36 *) while both recent and intermediate fallows were richer in charcoal-bearing individuals (r^2 = 0.36 *).

Overall, these data showed a trend for an increase in tree size (DBH, tree height, biovolume, and biomass) and richness as the age of the fallow increases, both in Miombo and Mopane woodlands. Also, there was an increasing trend for seed regeneration individuals and a reduction in the number of stump regeneration individuals as the age of the fallows increased (see Supporting Information, Tables S3 and S4A–D).

Pairwise Wilcoxon tests confirmed that Miombo recent fallows had considerably lower values of average height, DBH, and basal area than mature fallows (p = 0.001, 0.0012, and 0.001, respectively). Biovolume, total, and charcoal-bearing biomass also presented higher values in intermediate at mature fallows than in recent fallows (p = 0.003 and 0.001, respectively). The differences in average tree height among Mopane fallows were not statistically significant, although it was important in Non-metric Multidimensional Scaling ordinations (NMDS) analysis. Other variables, including mean DBH (p = 0.012 and 0.012), basal area (p = 0.009 and 0.007), biovolume (p = 0.018 and 0.021), total biomass (p = 0.009 and 0.004), and charcoal-bearing biomass (p = 0.018 and 0.014), had considerably greater values in mature and intermediate fallows compared to recent fallows, in Mopane fallows (see Supporting Information, Table S3).

Still, according to the Pairwise Wilcoxon test, there were no significative differences in the richness, Shannon, and Dominance indices among recent, intermediate, and mature fallow, for adult and young tree classes. Other non-significant differences found were the number of individuals of sprouters and seeders at Mopane, including the average height of trees. At Miombo, the value of young and adult tree sprouters was significantly higher in recent fallow than in mature fallow (p = 0.04 and p = 0.008, respectively), whereas the value of adult seeders occurs opposite, i.e., the number of individuals that grew by seed was significantly higher in intermediate and mature fallows than in recent ones (Figure 3, Table S3).

Except for **the** road distance in Miombo, environmental variables showed no significantly different values between fallows. The recent fallows are significantly farther from the roads if compared to mature fallows (p = 0.021) (Figure 3, Table S3).

The IndVal analyses identified two species, *Julbernadia paniculata* and *Brachystegia spiciformis*, as indicators in Miombo and three species, *Colophospermum mopane*, *Spirostachys africana*, and *Combretum molle*, as indicators in Mopane (Table 4).

The Miombo species with the highest IndVal values were both from seed regeneration individuals: *J. paniculata* (0.62) for intermediate fallow and *Brachystegia spiciformis* (0.54) for mature fallow. *Julbernadia paniculata* and *B. spiciformis* are common in all plots but predominate in intermediate and mature fallows, respectively. No indicator species were found in the recent fallows of Miombo for the adult class and for all fallows for the young class.

The Mopane species with the highest IndVal values were essentially for adult class and stump regeneration and for *Colophospermum mopane* (0.50) in recent fallow. No indicator species were found in the mature fallow, and these values may indicate easy regeneration in open areas. However, the species with the greatest IndVal for the young class were the seedlings of *Combretum molle* (0.57) in mature fallows and both the seedling and young seeders of *Spirostachys africana* (with values of 0.58 and 0.50, respectively) in intermediate fallows.

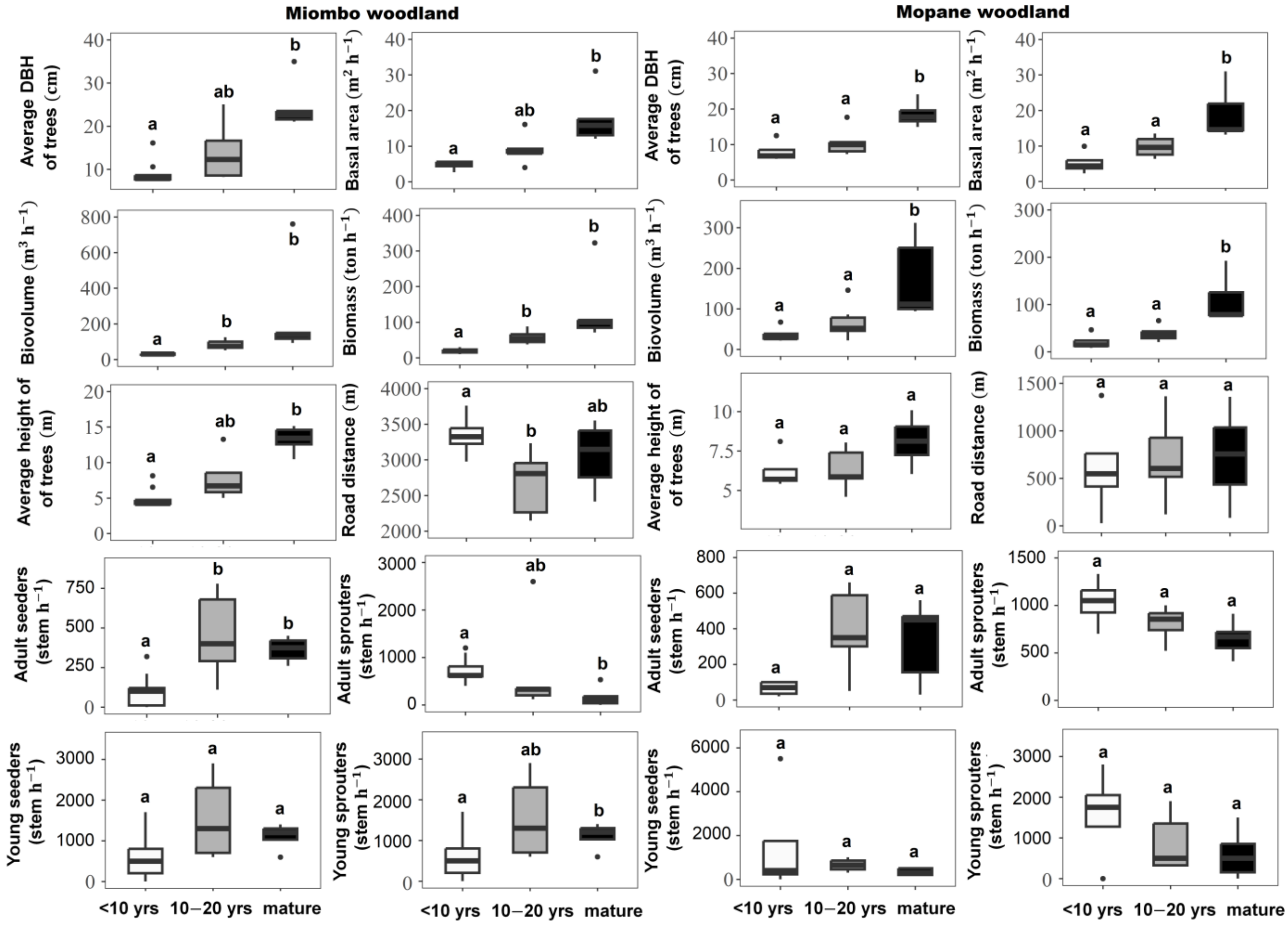

Figure 3. Boxplots resulting from the Pairwise Wilcoxon test using the Bonferroni correction for *p*-value adjustment, recording the principal differences between recent (<10 yrs), intermediate (10–20 yrs), and mature plots, using important variables namely, average DBH of trees, basal area, average height of trees, Biomass, Biovolume, Distance of the plot to road (Road distance), and density of seeders and sprouters, into Miombo and Mopane woodlands. Different letters indicate statistically significant differences.

Table 4. Indicator species and probabilities, regeneration type, combined groups of fallows stages as observed in the Miombo and Mopane area. 1 (recent fallow), 2 (intermediate fallow), and 3 (mature fallow).

Woodland Type	Tree Age	Specie	Acron.	Regen. Type	Denomin.	Fallow Age	Ind. Value	Prob. ($p < 0.05$)
Mopane	Young	*Spirostachys africana*	PafrT	Stump	Young sprouter	1	0.50	0.043
		Spirostachys africana	SafrJ	Seed	Young seeders	2	0.58	0.033
		Spirostachys africana	SafrP	Seed	Seedling	2	0.50	0.04
		Combretum molle	CmolP	Seed	Seedling	3	0.57	0.041
	Adult	*Colophospermum mopane*	CmopTA	Stump	Adult sprouters	1	0.50	0.037
		Acacia senegal	AsenTA	Stump	Adult sprouters	2	0.72	0.002
Miombo	Young	*Brachystegia spiciformis*	BspiT	Stump	Young sprouters	1	0.55	0.045
	Adult	*Julbernardia paniculata*	JpanA	Seed	Adult seeders	2	0.62	0.022
		Brachystegia spiciformis	BspiA	Seed	Adult seeders	3	0.54	0.042

4. Discussion

Overall, findings suggest that selective removal of woody species as a result of selective cutting for charcoal production has a significant impact on the structure and dynamics of Mopane and Miombo tree communities, despite having no direct effect on their diversity. As expected, size-related variables such as the diameter at breast height (DBH), basal area, biomass, and biovolume of trees increased as the age of the fallow increased. Nevertheless, there were no significant differences in the richness, diversity, or dominance of trees between the adult and young classes or between recent and older fallow lands. The height of trees in Mopane was more variable in all fallows than in Miombo, probably because it contained fewer charcoal-bearing species.

Regardless of the impact on the tree communities, the selective logging of species for charcoal production is very important for rural communities, as many species in addition to charcoal, provide medicinal, food, pasture, and shade uses. Most of Angola's forest resources arise from the dry tropical forests and woodlands, known as Mopane and Miombo, which constitute more than half of the country's total forest area [71]. The extensive use and exploitation of wood forest resources involves environmental, social, and economic impacts [35,41]. In this context, considering the results obtained, essential considerations were presented that can contribute to explaining how charcoal production can affect the structure and composition of these woodlands.

It was found that most species regenerate from stumps after cutting, as demonstrated by Chidumayo [72]. Immediately after felling, the capacity of regeneration of individuals by stumps increased. Moreover, as soon as the canopy opens and the precipitation increases, the specific competition between individuals regenerated by seeds and by stumps increases. Both vegetation types, Miombo and Mopane, had more multi-stemmed trees in recent and intermediate fallows (Table S1), corroborating the results obtained in Bicuar National Park by Godlee et al. [73] In the plots, it was found a significant difference between the number of sprouter and seeder trees in Miombo, but not in Mopane (Table S3).

It was also found that Mopane fallows seem to take longer to regenerate than Miombo, probably because Mopane vegetation is more affected by environmental and anthropogenic factors. For instance, the climate in the Mopane region, with its high temperatures and low rainfall, may not facilitate vegetation recovery after cutting. Moreover, soil poverty, low water storage capacity, and poor infiltration in Mopane are important characteristics to consider [2]. Populations have a great scarcity of resources, which causes a greater trend towards charcoal production to generate family income and to do dry farming just for household consumption. Moreover, the rise in cattle breeding and hunting practices has resulted in an increase in the practice of fire for hunting and creating new pastures, as recorded in Zigelski et al. [74]. However, in both regions, there is a wealth of non-timber forest resources, particularly fruits and seeds, roots, leaves, and mushrooms [75–78]. However, the residents in the Mopane zone seem to invest scarcely in selling these products to replace their source of income, especially during the most difficult periods. Therefore, the fear is that with this intensity, Mopane's fallow land will probably not reach the mature stage. Additionally, the new Miombo kilns are increasingly distant from villages and roads. As rural families are poor, charcoal production is the basis of family subsistence for almost all of them, and they are, therefore, exempt from taxes. On the other hand, the sale of charcoal by the producing families is controlled by the authorities. If they sell large quantities, they must pay taxes just as they are levied on companies [79,80]. Probably this is the reason why most families, particularly in the Miombo region, try to produce charcoal away from the eyes of the inspectorate, as there is a shortage of means and human resources to control such acts. Therefore, it makes sense for the new fallows to be far from the road and closer to the mature forest. It is evident that to produce large quantities of charcoal for profit, it is necessary to find areas with more biomass to burn while allowing those areas adjacent to roadways and under the supervision of inspectors to regenerate freely. Moreover, the conversion of woody biomass is affected by a number of factors, including the type of kiln, the experience of the charcoal producer, and the quality of the wood..

Chiteculo et al. (2018) [42] refer to a conversion factor of 0.19 for biomass and Miapia et al. 2021 [24] indicate a conversion factor of 0.23 for volume; however, in a recently submitted work [81], we estimated an efficiency of only 0.14 comparable to the value referred to in [35], implying an even higher environmental risk of this practice.

In addition to socio-economic and edaphoclimatic reasons, data confirmed that the indicator species in Mopane are those considered sun-tolerant and drought-tolerant, namely *Colophospermum mopane*, *Spirostachys africana*, and *Acacia senegal*. While in Miombo, the indicator species are those considered shade semi-tolerant or shade-tolerant and are also considered as no fire-tolerant at a young age, namely *Brachystegia spiciformis* and *Julbernadia paniculata*. However, other species such as *Burkea africana*, *Diplorhynchus condylocarpon*, *Pericopsis angolensis*, *Combretum* spp., and *Strychnos* spp. are described by many authors as species growing in disturbed areas and being fire-resistant [27,82–86]. Gonçalves et al. [87] showed similar results confirming that *J. paniculata* is an indicator species of medium and old fallow lands in Miombo. Furthermore, they observed that *B. spiciformis* was quite frequent even though it was not selected as an indicator species. Furthermore, the study area overlaps with the region previously investigated by Chisingui et al. [88]. These authors defined a set of characteristic plant communities, with Miombo and Mopane woodlands corresponding to the *Brachystegia spiciformis-Julbernardia paniculata* and *Colophospermum mopane-Spirostachys africana*, respectively.

Regarding the different impacts that agriculture and charcoal production have on the recovery of forests in Africa, the selective removal of tree species for the production of charcoal permits a comparatively quick regeneration by sprouting [25], with the unfortunate exception of the detrimental effect that kiln construction has on soil biodiversity [89]. In contrast, agriculture results in the removal of almost all trees. In Zambia, it was observed that stem densities were significantly higher in charcoal than in agriculture fallows, despite that the difference decreased with fallow age [27]. However, cultural production practices and poor post-harvest management of charcoal, including kiln efficiency and the short production cycle, increase the negative environmental impacts of charcoal production [90,91]. Also in Zambia, the Miombo production rate is approximately 2.49 tons per hectare per year [92–94], meaning that it could take six to 29 years to reach maturity. As a result, the current level of Miombo exploration could be excessive, compromising the future of this woodland. Still, the production and consumption of forest products in many African countries, which are generally rudimentary, could be more efficient [95]. Strategies that contribute to the sustainability of charcoal production should be developed and implemented. Replacing charcoal with other sources of energy, particularly for cooking in cities, should be promoted to reduce the appetite of the rural community that uses charcoal as its main source of income [22,27,91]. The reuse of the gases resulting from charcoal production, or the use of a low-cost retort kiln or eco-charcoal are already additional proposals [96,97]. More protective measures are also important. For example, *B. spiciformis* is an abundant species in Angola, but a recent study reported that about 47% of its distribution includes areas with "High" and "Very High" threat levels, and only 4.2% are in protected areas [98], reinforcing the concern of Shumba et al. [99] and Romeiras et al. [100], about the importance of increasing conservation areas for the most vulnerable forest species. The production rates of Miombo wood in regrowth require long cutting cycles for maturation, which conditions the sustainable production of charcoal [26]. However, a greater diversification of rural populations' sources of income, particularly through the valorization of non-timber forest products such as mushrooms, edible wild fruits and leaves, beekeeping, etc. could be an alternative for the sustainable management of forest resources.

5. Conclusions

Ecosystem services obtained from Miombo and Mopane woodlands are important to the livelihoods of millions of people in Central and Southern Africa. In southern Angola, many species of trees are used as firewood and to make charcoal, with a growing trend in recent decades. If this trend continues, the use of Miombo and Mopane resources may become unsustainable. This study demonstrated that the two types of woods have distinct recovery tendencies following their felling for charcoal production and that the tree community structure takes a lot longer to regenerate. It is also shown that the species assemblage seems to change only slightly after the cutting of charcoal-bearing species. This could be possible since species that are used to make charcoal sprout instead of dying after being cut, allowing the species composition to basically remain unchanged. Moreover, many of the tree species here reported are key species with significant socioeconomic significance in Angola and the way these resources are managed is an important concern. Overexploitation can affect not only the composition and structure of the vegetation but also the way of life for those living in rural areas.

Finally, in the present study, first-hand data was obtained, particularly in southern Angola, regarding the impact of charcoal exploitation in Miombo and Mopane woodlands. Hopefully, this methodology might be replicated in other regions of Angola, allowing for improved forest monitoring and management strategies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15010078/s1. Kissanga_et_al_Row_data.xls (contains the Supplementary Tables: S1, S2, S3, and S4: Species names and acronyms of the surveyed trees; Table S1A Adult individuals in Miombo woodland plots; Table S1B Young individuals in Miombo woodland plots; Table S1C Adult individuals in Mopane woodland plots; Table S1D Young individuals in Mopane woodland plots; Table S2A Environmental and response variables in Miombo woodland; Table S2B Environmental and response variables in Mopane woodland; Table S2C Diversity variables in Miombo woodlands; Table S2D Diversity variables in Mopane woodlands; Table S3 Statistics and pair-wise Wilcoxon test summaries; Table S4 Spearman correlation coefficients between environmental and functional variables).

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