

# Early Recovery of Dry Miombo Woodlands Following Selective Charcoal Harvesting in Morogoro, Tanzania

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## Abstract

Miombo woodlands provide essential ecological services and livelihoods in southern Africa but are increasingly threatened by charcoal production. This study assessed early recovery of dry Miombo woodlands following selective charcoal harvesting in three districts in Morogoro Region, Tanzania. A chronosequence approach was used with 106 plots across fallow ages of 1, 3.5, and 6 years and adjacent unharvested controls. Stand structural attributes, *i.e.*, stem density, basal area, volume, and above-ground biomass (AGB) were quantified, and growth rates were estimated using mean annual increment (MAI) and carbon sequestration. Results revealed that stand parameters increased with fallow age, with stem density rising from about 324 trees ha<sup>-1</sup> in one-year fallows to about 1302 trees ha<sup>-1</sup> in six-year fallows. Volume MAI ranged from 3.45 to 3.90 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>, while carbon sequestration ranged from 1.17 to 1.33 t ha<sup>-1</sup> yr<sup>-1</sup>. Although biomass and volume had not yet reached levels observed in unharvested stands, the results indicate strong early recovery and highlight the potential of selective, rotational charcoal harvesting systems to support sustainable woodland management.

## Keywords

Selective Harvesting, Charcoal Fallows, Mean Annual Increment, Volume and AGB, Carbon Sequestration

## 1. Introduction

Miombo woodlands are widely distributed across central and southern Africa covering a total of 2.7 mil km<sup>2</sup> [1]. These seasonally dry tropical forests are characterized by the dominance of *Brachystegia*, *Julbernardia*, and *Isoberlinia* species. In Tanzania, this ecosystem covers about 48.1 million ha representing about 54.4%

of the total land area of 88.3 million ha [2]. Miombo woodlands play a significant role in the adjacent communities. In addition, they provide direct benefits such as timber and poles, as well as non-timber forest products, including honey, mushrooms, and medicinal plants. In addition, they provide important ecosystem services, including mitigating climate change through carbon storage, biodiversity conservation, and watershed protection [3] [4].

Due to the heavy reliance of local communities on goods and services derived from miombo woodlands, there is growing concern about the integrity of this critical ecosystem. The primary drivers of degradation include unsustainable charcoal production, agricultural expansion, illegal logging, recurrent fires, and overgrazing [5] [6]. It is estimated that more than 80% of Tanzania's population relies on fuelwood, predominantly charcoal, as their primary source of energy [6]. This substantial demand has accelerated forest degradation, resulting in declining forest cover and increased habitat fragmentation. Given the sustained and growing reliance on wood-based energy, this demand is likely to persist for several decades [7]. This call for intervention is to enhance the sustainable use of miombo woodlands. One of the unique characteristics of miombo woodlands is their capacity to regenerate, which management efforts need to tap into.

Recovery in Miombo woodlands is driven by a combination of vegetative and seed-based regeneration processes that shape post-disturbance dynamics [8] [9]. Following charcoal production, timber harvesting, or cultivation, vegetative regeneration, particularly coppicing and resprouting from pre-existing root systems, often dominates, enabling rapid shoot growth due to established belowground resources. However, coppicing success varies by species, stump size, and time since cutting, and may decline with repeated harvesting [10]. Seed-based regeneration also plays a critical role, especially where fire or land clearing reduces stump viability, with recruitment influenced by disturbance intensity, light availability, and dispersal mechanisms, including animal-mediated seed dispersal in degraded sites. Nonetheless, regeneration capacity differs markedly among species, and some high-value timber species exhibit poor recruitment, implying that although structural recovery may occur within a few decades, full compositional recovery is slower and may result in long-term shifts in woodland structure and species composition [11] [12].

These regeneration dynamics directly inform forest management decisions. Accordingly, sustainable management and utilisation of miombo woodlands depend on a sound understanding of stand growth dynamics and post-disturbance recovery processes. A core principle of sustainable forest management is the determination of growth rates to ensure that the allowable cut does not exceed the periodic increment, thereby maintaining a balance between livelihood needs and ecosystem conservation [13]. However, tree growth in Miombo systems is shaped by multiple interacting factors. For example, stands at the climax stage typically exhibit lower increments compared to regrowth stands recovering after disturbance. In addition, regrowth performance is strongly influenced by the type and intensity of disturbance, including the degree of seed-bank disruption, fire-related mortality, and the capacity of residual stumps to regenerate via coppicing [14]. Consequently, the na-

ture of resource extraction practices becomes critical in shaping recovery outcomes.

Selective timber harvesting, for instance, creates canopy gaps, and has been shown not to consistently restore commercially valuable timber species [12]. As many target species are light-demanding and may fail to regenerate adequately under partial canopy cover, this potentially favours less valuable species. Conversely, evidence from central Mozambique indicates that logged stands may exhibit greater species diversity than areas recovering from agriculture or charcoal production, likely because logging often leaves residual vegetation and soil structure relatively intact, facilitating faster recovery [11]. In contrast, charcoal production, driven by rising urban energy demand and rural poverty, remains one of the most pervasive degradation drivers in Miombo systems [15]. It involves the selective removal of high-density species for carbonisation in traditional earth kilns, gradually altering stand structure and composition. Sustainability varies by ecological zone: dry Miombo in Zambia is considered unsustainable under current practices, requiring approximately 2.3 ha of regrowth to match the output of 1 ha of mature woodland, whereas wetter Miombo may sustain production under 50 - 55-year cutting cycles [15].

Within the context of diverse disturbance regimes and variable recovery trajectories, understanding how particular harvesting strategies shape regeneration outcomes is critical for informed management. This study, therefore, investigates the impact of selective cutting for charcoal production on the recovery of dry Miombo woodlands in selected sites in the Morogoro region, Tanzania. While most previous studies have examined intensive charcoal harvesting that results in extensive canopy opening [8] [12] [15], this research focuses on a more selective approach in which only species primarily preferred for charcoal are removed, while timber species of all size classes are deliberately retained for future timber production. Although timber species are technically suitable for charcoal, this study assesses the ecological implications of reserving them for higher-value uses. Using a chronosequence approach and data from different fallow ages (1 - 6 years), this study evaluated early recovery patterns and rates under this selective harvesting model for dry Miombo woodlands. Specifically, this study aimed to i) determine stand parameters (basal area, volume and aboveground biomass (AGB)) for each fallow age, and ii) to determine the effect of fallow age on the volume increment and carbon sequestration.

## 2. Material and Methods

### 2.1. Study Area and Charcoal Project Description

The study was carried out in villages where the project Transforming Tanzania Charcoal Sector (TTCS) has been implemented by the Tanzania Forest Conservation Group (TFCG) since 2015. The study was conducted in three districts within the Morogoro region of Tanzania, namely Kilosa (503,727 ha), Morogoro (132,620 ha), and Mvomero (336,480 ha), located in Morogoro region (**Figure 1**) [16]. The study was carried out in the miombo woodlands that are managed by the villages, namely Ihombwe, Ulaya Mbuyuni, and Kigunga in Kilosa District; Misengele and Maharaka villages (6.2864°S, 37.6667°E) in Mvomero District; and Matuli and Mlingwa

(6.9463°S, 37.7047°E) in Mvuha District. Agriculture is the primary economic activity, comprising both subsistence (93%) and commercial (7%) farming [17]. Livestock keeping is another significant activity, with cattle, goats, and sheep commonly reared. Free grazing is prevalent in lowland areas, particularly within village lands [18].

The project has developed a 24-year rotational harvesting model based on a checkerboard mapping system within each Forest Management Unit (FMU). In this system, the FMU were divided into harvesting blocks measuring 50 m × 50 m, and only 1/24 of the blocks are harvested each year, assuming that a harvested block will fully recover after 24 years. To promote adequate regeneration, adjacent blocks are not harvested for at least 10 years, thereby creating a mosaic landscape of woodland patches at different stages of regeneration. There was harvesting protocol that were followed in the selected blocks set for harvesting as follows: trees with a diameter at breast height (DBH) of 15 cm or less are not harvested, and at least three trees with DBH greater than 15 cm must be retained in each 50 m × 50 m harvesting block; minimum buffer distances must be maintained between harvesting areas and water sources; harvesting is restricted to slopes with gradients of less than 30%; and high-value timber species such as Mvule (*Milicia excelsa*), Mninga (*Pterocarpus angolensis*), *Julbernardia globiflora* and *Mpingo* (*Dalbergia melanoxylon*) are strictly protected. Additionally, individual trees with significant biodiversity value, such as those serving as nesting sites, are excluded from harvesting [10].

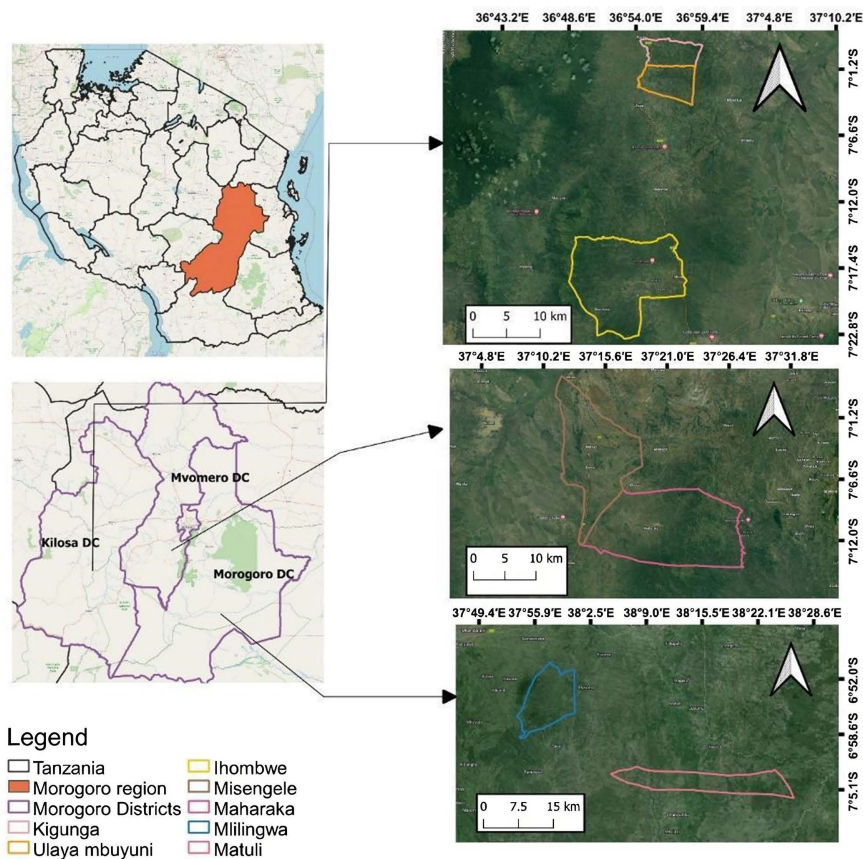


Figure 1. Locations of the study sites.

## 2.2. Sampling Design

The study site was divided into two main categories: 1) harvested coupes representing different fallow ages and 2) adjacent unharvested control blocks. Within each selected block, a random sampling approach was applied to establish study plots across Kilosa, Mvomero, and Morogoro district. Four treatment categories were defined based on time since charcoal harvesting (fallow age): 1) blocks harvested in 2015 (6-year fallow), 2) blocks harvested in 2018 (3.5-year fallow), 3) blocks harvested in 2021 (1-year fallow), and 4) unharvested control plots. The selected chronosequence sites were comparable in terms of soil characteristics, fire history, grazing pressure, and prior stand condition, minimizing the influence of confounding environmental factors on recovery patterns [19].

A total of 106 plots were established, comprising 79 plots in harvested coupes and 27 plots in unharvested control blocks. At the village level, Ihombwe had 38 plots, of which 30 were harvested and 8 were unharvested; Ulaya Mbuyuni had 28 plots, including 18 harvested and 10 unharvested; Kigunga had 12 plots, of which 3 were harvested and 9 were unharvested. Matuli and Mlilingwa each had 10 harvested plots, Misengele had 6 harvested plots, and Maharaka had 2 harvested plots. In harvested areas, plots were distributed in blocks arranged in a chessboard-like grid following the rotational harvesting system. Each sample plot followed a circular design with a radius of 15 m, with a nested central subplot of 1 m radius.

## 2.3. Data Collection

Within each plot (15 m radius), all trees with DBH  $\geq 1$  cm were identified and measured at 1.3 m above ground using a diameter tape for larger stems and a Vernier calliper for smaller individuals to ensure measurement accuracy. The measured individuals were subsequently categorized into diameter classes as follows: 1 = 1 - 9.9 cm, 2 = 10 - 19.9 cm, 3 = 20 - 29.9 cm, 4 = 30 - 39.9 cm, and 5 =  $\geq 40$  cm. Species identification was conducted in the field by a qualified botanist familiar with the local flora, and uncertain individuals were verified using field reference materials where necessary. In harvested areas, the fallow age (time since harvesting) of each plot was determined from official harvesting records, enabling analysis of post-harvest recovery patterns in relation to disturbance history.

## 2.4. Data Analysis

### 2.4.1. Stand Parameters

Stand parameters of interest included the number of stems (N), basal area (G), volume (V), above-ground biomass (AGB), and carbon stock. These parameters were first computed at the individual tree level and then aggregated to the plot level and converted to per-hectare values by dividing the plot-level totals by plot area for each fallow age and control plots. Tree volume was estimated using the DBH-based allometric equation (1) developed by [19] while above-ground biomass was estimated using equation (2) developed by [20]. These models were selected due to their strong empirical support in miombo woodlands and high pre-

dictive accuracy, as indicated by high coefficients of determination ( $R^2$ ) reported in their respective studies. Biomass was subsequently converted to carbon stock using a carbon fraction of 0.47 [21], as expressed in equation (3).

$$V = 0.00016 * DBH^{2.463} \quad (1)$$

$$AGB = 0.0674 * DBH^{2.472} \quad (2)$$

$$C = AGB * 0.47 \quad (3)$$

Where:  $V$  and  $AGB$  are the current volume in  $m^3$  and aboveground biomass in tons, respectively,  $C$  is the carbon, and  $DBH$  is the diameter at breast height.

#### 2.4.2. Growth Rate

Growth rates (GR) were estimated using a chronosequence-based approach by comparing mean stand parameters across fallow-age classes. Differences in stand parameters were calculated between successive fallow-age classes, specifically between 2015 - 2021 (6 years) and 2018 - 2021 (3.5 years). The mean difference for each variable was obtained by subtracting the mean value of the younger fallow age from that of the older fallow age. Annual growth rates were then derived by dividing these differences by the corresponding time interval, as expressed in equation (4):

$$GR = (Y_{C_{y_1}} - Y_{C_{y_2}}) / (y_2 - y_1) \quad (4)$$

Where: GR represents the annual increment of the stand variable;  $Y_{C_{y_1}}$  the current volume or carbon stock for the block harvested in year 1;  $Y_{C_{y_2}}$  is the mean current volume or carbon for the blocks harvested in year 2. Year 1 or 2 refers to the year the harvesting took place, *i.e.*, 2015, 2018, and 2021.

### 3. Results

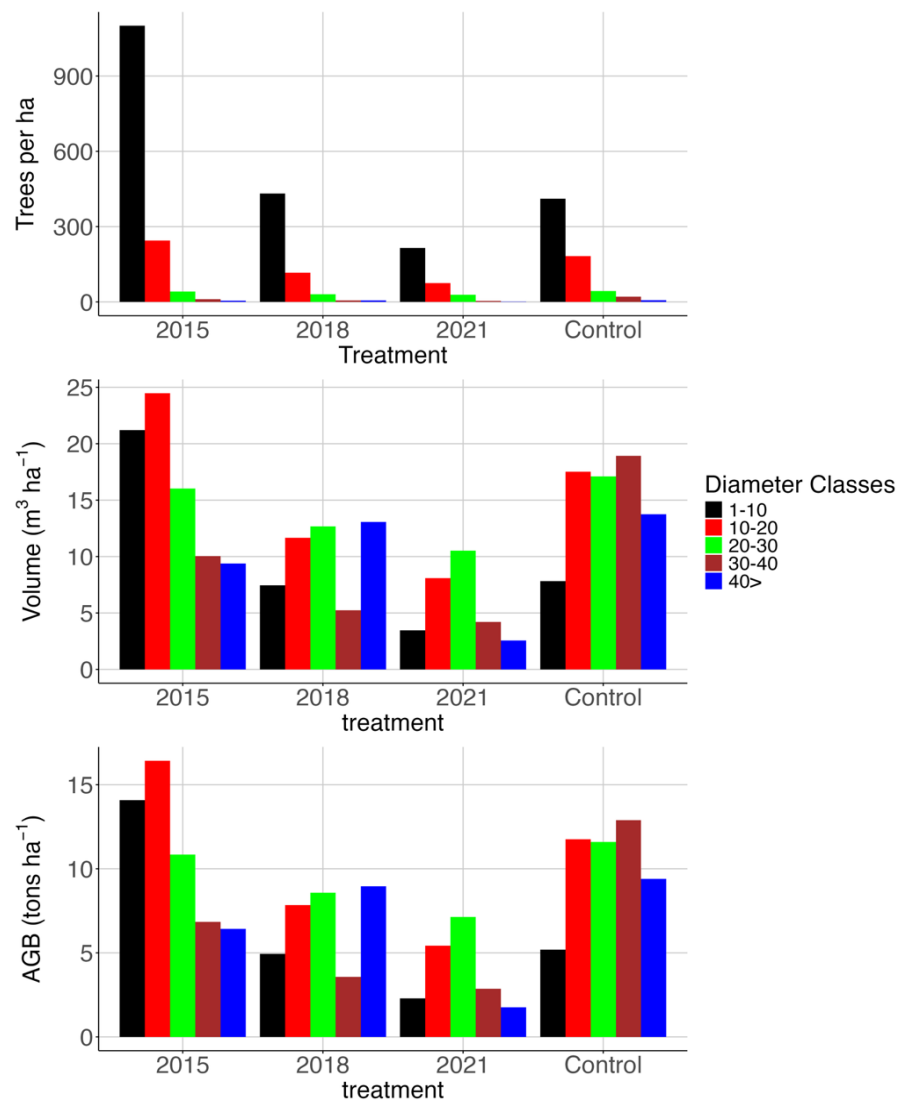
#### 3.1. Stand Parameters

Stem density, basal area, volume, and aboveground biomass varied across treatments. The findings indicate that the number of stems increases with the length of the fallow period, from 323 stems  $ha^{-1}$  in the reference year (1-year fallow age) to 1301 stems  $ha^{-1}$  for sites with a fallow age of 6 years (Table 1, Table 2). Basal area, volume, and aboveground biomass showed a similar trend, increasing from 4.67  $m^2 ha^{-1}$  to 9.16  $m^2 ha^{-1}$ , 42.87  $m^3 ha^{-1}$  to 66.28  $m^3 ha^{-1}$ , and 29.47 tons  $ha^{-1}$  to 54.62 tonnes  $ha^{-1}$ , respectively. The average stem density, basal area, volume and above-ground biomass for the control plots were found to be 664.91 stems  $ha^{-1}$ , 10.19  $m^2 ha^{-1}$ , 93.84  $m^3 ha^{-1}$ , and 63.76 tons  $ha^{-1}$ , respectively. The variation of stand parameters across plots, as indicated by the confidence interval, was large (>30%), particularly for AGB.

**Table 1.** Stand parameters across fallow periods.

Fallow age	N (stems $ha^{-1}$ )	G ( $m^2 ha^{-1}$ )	V ( $m^3 ha^{-1}$ )	AGB (tons $ha^{-1}$ )
6	1301.69 ± 219.66	9.16 ± 2.40	66.28 ± 20.68	44.98 ± 14.01
3.5	590.04 ± 86.43	6.60 ± 1.32	54.19 ± 14.22	36.78 ± 9.71
1	323.97 ± 91.33	4.67 ± 1.47	42.87 ± 14.18	29.03 ± 9.64
Control	664.91 ± 147.743	10.19 ± 1.97	93.84 ± 24.78	63.76 ± 17.03

The distribution of stem density, volume, and aboveground biomass (AGB) across diameter classes shows distinctive differences among fallow periods (**Figure 2**). The older fallow had a larger number of stems in the small diameter classes, *i.e.*, 1 - 10 and 10 - 20 compared to other fallow age treatment suggesting the increase in number of trees in these classes with the age of the fallow. Consequently, the number of stems in these classes influenced the increase in volume and biomass in the corresponding diameter classes. The fallow trees harvested in 2021 (short fallow) exhibited a reduction in the number of small-diameter trees. The control sites with no harvesting had large accumulations of volume and biomass contributed mainly by the medium and larger diameter classes (**Figure 2**).



**Figure 2.** Stand Structure across diameter classes by treatment year/fallow age (2015, 2018, 2021, and Control).

### 3.2 Growth Rate

The average differences in stand parameters between fallow age, MAI, and carbon

sequestration are presented in **Table 2**. The findings show that the increase in the fallow period increased the differences in stand parameters from the reference age, except for the number of trees. For example, the basal area at the fallow age of six years differed from the reference age by about  $4.47 \text{ m}^2 \text{ ha}^{-1}$ , while at the fallow age of 3.5, the difference was  $2.56 \text{ m}^2 \text{ ha}^{-1}$ . The basal area annual increment was found to be around  $0.74 \text{ m}^2 \text{ ha}^{-1}$ . The increase in the fallow period from 3.5 to 6 years led to pronounced increases in volume and AGB accumulations, from  $12.08 \text{ m}^3 \text{ ha}^{-1}$  to  $23.41 \text{ m}^3 \text{ ha}^{-1}$ , and from  $8.20 \text{ tonnes ha}^{-1}$  to  $15.95 \text{ tonnes ha}^{-1}$ , respectively. On average, the volume MAI and carbon sequestration ranged from  $3.45$  to  $3.90 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  and from  $1.17$  to  $1.33 \text{ t ha}^{-1} \text{ yr}^{-1}$ , with large confidence intervals around the means.

**Table 2.** Effect of fallow period on the stand parameters.

Stand variable	Difference (2015 - 2021)	Period (years)	Annual increment (2015 - 2021: <i>per year</i> )	Difference (2018 - 2021)	Period (years)	Annual increment (2018 - 2021: <i>per year</i> )
N (stems $\text{ha}^{-1}$ )	$977.72 \pm 143.2$	6	$162.95 \pm 31.67$	$711.65 \pm 92.21$	3.5	$203.33 \pm 60.21$
G ( $\text{m}^2 \text{ ha}^{-1}$ )	$4.49 \pm 3.01$	6	$0.75 \pm 0.15$	$2.56 \pm 0.82$	3.5	$0.73 \pm 0.37$
V ( $\text{m}^3 \text{ ha}^{-1}$ )	$23.41 \pm 26.74$	6	$3.90 \pm 2.31$	$12.08 \pm 6.12$	3.5	$3.45 \pm 1.54$
AGB (tons $\text{ha}^{-1}$ )	$15.95 \pm 26.74$	6	$2.66 \pm 1.78$	$8.20 \pm 5.23$	3.5	$2.34 \pm 0.98$
C (tons $\text{ha}^{-1}$ )	$7.975 \pm 18.13$	6	$1.33 \pm 0.89$	$4.10 \pm 2.11$	3.5	$1.17 \pm 0.49$

#### 4. Discuss

This study employed a chronosequence approach to assess structural changes in Miombo woodlands following charcoal harvesting. Unlike conventional charcoal production practices, harvesting at the selected site was conducted selectively, *i.e.*, timber species of all size classes were retained, while non-timber species were harvested only after attaining a minimum DBH of 15 cm. Furthermore, harvesting followed a checkerboard mapping system in which alternating coupes were left unharvested. This spatially structured approach maintains continuous forest cover across the landscape and supports biodiversity by preserving habitat availability and ecological connectivity [22]. This study presents early structural change in miombo woodlands, using a fallow age of 6 years max, utilising 79 plots laid out in charcoal-harvested blocks and 27 plots as controls in unharvested sites.

The findings indicate a progressive increase in tree density with advancing fallow age following selective charcoal harvesting. This pattern can be attributed to canopy opening created by the removal of selected stems, which reduced competition for light, moisture, and nutrients. The partial canopy disturbance enhanced light penetration to the forest floor, creating favorable conditions for the establishment and growth of light-demanding species [23]. The high stem density in the 1 - 10 cm diameter class, observed shortly after harvesting, is unlikely to result mainly from coppice regrowth. Instead, it reflects successful establishment and growth of seedlings and saplings that advanced into this size class under increased light availability following canopy opening [24] [25]. For example, it has been re-

ported that some light-demanding trees, such as *Brachystegia spiciformis* and *Julbernardia globiflora*, their coppice shoots could reach 5 cm DBH within 5 - 8 years under favourable conditions, while seedling-origin stems required 10 - 15 years to reach the same threshold [26] [27]. Nevertheless, comparing the number of trees in the 6-year fallow with the control treatment, the findings indicate that the fallow has more trees (1301 versus 665 trees ha<sup>-1</sup>). The relatively high stem count in the 6-year fallow likely reflects transient recruitment before density-dependent mortality and competitive thinning become pronounced. Studies indicate that tree density often continues to reorganise for decades after disturbance, with trends toward lower stem density and larger mean tree size as competition and natural mortality operate over 30 to 50+ years [9] [11] [12].

The AGB and stand volume increased progressively with fallow age, reflecting rapid tree recruitment and reduced competition in regenerating stands. In the fallows (3.5 and 6 years), small-sized trees significantly contributed to the rise in AGB and volume, underscoring the substantial influence of early regeneration dynamics. These characteristics have been reported elsewhere [12]. Conversely, as expected, the control plots were dominated by medium-to large-sized trees, which accounted for the majority of total biomass and volume (Figure 2). The 1-year-old fallows, despite having lower AGB and volume, displayed a pattern similar to the control, with medium-sized trees contributing more substantially, likely because insufficient time had elapsed for canopy opening to significantly stimulate small-tree recruitment. Despite the observed increase, biomass accumulation in fallows did not surpass that of the control plots, primarily due to the short recovery period. Consistent with previous studies, early successional stands (1 - 10 years post-clearing) are characterised by rapid stem recruitment but relatively low biomass accumulation due to the small size of trees. Biomass accumulation accelerates in intermediate stages (10 - 30 years) as trees grow into larger size classes, and declines in older stands (>30 years) as structural equilibrium is approached. Nevertheless, this trend demonstrates the promising development of miombo in the study site with the applied treatments.

Growth rates are a key determinant of sustainable levels of forest exploitation, as they indicate a stand's capacity to recover following disturbance [13] [28]. The results of this study demonstrate encouraging recovery trends in basal area, stand volume, and aboveground biomass (AGB). Few studies have reported the annual increment in basal area. It has been reported that the mean basal area ranges from 0.24 to 0.35 m<sup>2</sup> ha<sup>-1</sup> year<sup>-1</sup>, depending on the age of the fallow in Zambia [29]. The reported basal area increment in this study (0.74 m<sup>2</sup> ha<sup>-1</sup>) is higher than previously reported values, likely due to differences in harvesting intensity, which allowed the remaining trees to grow rapidly.

The MAI for volume, an important stand parameter for determining sustainable allowable cut, was estimated to range from 3.45 to 3.90 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> in this study. These values indicate relatively strong recovery and growth in the regenerating stands. Comparable MAI values have been reported in other studies, where volume and carbon accumulation rates ranged from 1 to 3 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> in mature

miombo stands and 3 to 6 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> in younger and actively regenerating stands [9] [30] [31]. The values observed in the present study, therefore, fall within the range typically associated with young, fast-growing stands, indicating that the harvested sites may return to their pre-harvested condition within 30 to 50 years.

Furthermore, carbon sequestration rates recorded in this study (1.17 to 1.33 t ha<sup>-1</sup> yr<sup>-1</sup>) are slightly higher than those reported elsewhere for miombo ecosystems. For example, [31] documented sequestration rates of 0.75 t ha<sup>-1</sup> yr<sup>-1</sup> in 50-year-old miombo woodlands and 0.9 t ha<sup>-1</sup> yr<sup>-1</sup> in 16-year-old miombo fallows, both originating from agricultural fallow systems. The comparatively lower values reported in those systems may be attributed to differences in disturbance history and stand structure. In the present study, the selective harvesting approach left a portion of trees standing, likely reducing competition and creating growing space that enhanced the growth of residual trees and regenerating individuals. In contrast, recovery in agricultural fallow systems typically occurs after more extensive clearing, where regeneration starts largely from seedlings and coppice, leading to slower biomass accumulation during the early stages of stand development.

## 5. Conclusion

The results indicate that dry Miombo woodlands demonstrate strong early recovery following selective charcoal harvesting. Structural attributes, including stem density, basal area, volume, and above-ground biomass, increased with fallow age, reflecting active regeneration and improving stand conditions over time. The estimated mean annual increment for volume (3.45 - 3.90 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>) and carbon sequestration (1.17 - 1.33 t ha<sup>-1</sup> yr<sup>-1</sup>) indicates relatively rapid growth typical of young regenerating stands. Although biomass and volume in the fallows had not yet reached the levels observed in unharvested stands within the six-year recovery period, the trends demonstrate the resilience of Miombo woodlands under controlled harvesting regimes. These findings support the potential of rotational and selective charcoal harvesting systems to sustain woodland productivity while maintaining ecosystem recovery and carbon storage.

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## Disclosure Statement

No potential conflict of interest was reported by the authors.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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