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Drivers and biodiversity indicators of Miombo degradation in the Lubumbashi charcoal production basin (Upper Katanga, DR Congo)

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Abstract

Miombo woodlands of the Lubumbashi Charcoal Production Basin (LCPB) are crucial for biodiversity and ecosystem services, yet are threatened by anthropogenic pressures, including rising energy demand. This study analyzes key degradation drivers and biodiversity indicators across three recovery stages—advanced, intermediate, and early recovery—using plot-based surveys. The results identified wood harvesting for charcoal production as the main driver of Miombo woodland degradation, which increases with distance from settlements. In contrast, invasive species, bark stripping, and artisanal mining have comparatively minor effects. In terms of ecosystem condition, the early recovery stage showed low diversity (Shannon–Weiner index = 1.14). This ecosystem is dominated by *Isoberlinia angolensis* (IVI = 18.37; abundance = 22 individuals), *Julbernardia paniculata* (IVI = 11.17; 18 individuals), and *Brachystegia wangermeeana* (IVI = 8.53; 6 individuals), with weak structural attributes (51 trees/ha, mean DBH = 11.56 cm, mean height = 4.47 m). The intermediate recovery stage showed greater diversity (Shannon–Weiner index = 2.13), dominated by *B. wangermeeana* (IVI = 13.69; 83 individuals), *B. spiciformis* (IVI = 12.04; 56 individuals), and *Albizia adianthifolia* (IVI = 8.90; 48 individuals), with improved structure (285 trees/ha, DBH = 18.83 cm, height = 6.31 m). The advanced recovery stage exhibited the greater diversity (Shannon–Weiner index = 2.11), dominated by *Marquesia macroura* (IVI = 23.09; 88 individuals), *Diplorhynchus condylocarpon* (IVI = 11.27; 64 individuals), and *J. globiflora* (IVI = 9.10; 71 individuals), with the most developed structure (323 trees/ha, DBH = 24.20 cm, height = 9.64 m). The findings support policy reforms such as regulating destructive practices and expanding private protected areas to enhance forest management amid increasing anthropogenic pressures.

Keywords Ecosystem disturbance, Floristic composition, Ecological succession, Woodlands

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1 Introduction

Forests sustain biodiversity, regulate climate, and support environmental balance through essential ecosystem services for humans [1]. However, increasing anthropogenic pressures—particularly deforestation and forest degradation—pose major threats to their ecological integrity [2]. Forest degradation refers to the alteration of a forest's structure, composition, and function, resulting in a reduced capacity to deliver ecosystem services [3]. This phenomenon is especially pronounced in tropical biodiversity hotspots, with region-specific drivers such as wildfires in the Amazon and logging in Southeast Asia [4].

In sub-Saharan Africa, forests cover approximately 16% of the land area and support the livelihoods of over two-thirds of the population [5]. The region's forest degradation is driven by land-use change, agricultural expansion, and fragmentation, contributing to biodiversity loss, soil erosion, and altered hydrological cycles—factors that increase food insecurity [6]. These pressures are particularly severe in Miombo woodlands, which span roughly 2 million km^2 across central and southern Africa, representing nearly 10% of the continent's forest cover [7, 8]. Miombo ecosystems extend across Angola, Malawi, Mozambique, southeastern DRC, Tanzania, Zambia, Zimbabwe [6] and Burundi [9], and support essential ecosystem services for rural communities [10]. Dominated by the genera *Brachystegia*, *Julbernardia*, and *Isoberlinia*, Miombo ecosystems are characterized by ecological traits such as strong coppicing ability and fire tolerance, which enable regeneration after disturbance [11, 12]. These processes shape the resilience of Miombo woodlands to human pressures while influencing their long-term degradation trajectories [13]. The DRC hosts approximately 145 million hectares of forests, comprising dense humid forests, montane forests, savanna-forest mosaics and Miombo woodlands [14]. Miombo ecosystems cover 11% of the national territory and are predominant in the southeastern Katanga region, where mining and agriculture have intensified degradation [15]. Mining activities, largely focused on copper and cobalt extraction, include both licensed industrial operations and widespread artisanal practices, which generate soil contamination and water pollution [16]. Agricultural expansion is mainly based on slash-and-burn systems, with maize and cassava as the dominant crops [13]. These shifting cultivation practices drive forest clearance, soil nutrient depletion, and recurrent fire disturbance, thereby accelerating ecosystem degradation [17].

In Lubumbashi, rapid urban growth and energy demands have accelerated deforestation through charcoal production and agricultural expansion [13, 18]. Between 1990 and 2022, Miombo cover in the Lubumbashi Charcoal Production Basin (LCPB) declined from 77.98 to 40.01%, largely replaced by savanna [19]. Beyond these direct drivers, weak forest governance, widespread poverty [13, 20], and the absence of affordable and reliable energy alternatives have entrenched charcoal as the primary energy source for households [18]. This reliance reflects both limited policy effectiveness and socio-economic vulnerability, which reinforce communities' dependence on Miombo woodlands [20]. The resulting transformation has severe ecological and socio-economic implications, including diminished charcoal supply, increased energy costs, soil degradation, and disrupted water cycles [18, 21].

In this context, a comprehensive assessment of anthropogenic drivers and degradation indicators is urgently needed, especially in peri-urban areas experiencing rapid transformation. Despite numerous studies analyzing land-cover change using

medium-resolution remote sensing [19, 22] or floristic structure via field plots [23–25], few have integrated direct field-based assessments of both disturbance drivers and degradation indicators. Yet, field inventories provide robust, spatially explicit insights into ecosystem dynamics [26]. In Madagascar, plot-based surveys were successfully used [27, 28] to link disturbance types with indicators of structural degradation, similar approaches can complement remote sensing in African woodlands.

This study aims to identify the primary anthropogenic drivers of Miombo woodland degradation and assess floristic and dendrometric changes across three recovery stages—advanced, intermediate, and early recovery —within the Lubumbashi Charcoal Production Basin (LCPB). The advanced recovery ecosystem has been free from human activities for over 21 years, allowing the development of a mature successional Miombo stage [29]. The intermediate recovery ecosystem has been undisturbed for about 14 years, whereas the early recovery ecosystem has only been protected from anthropogenic pressures for 7 years. These abandonment periods likely influence regeneration and structural recovery within Miombo formations. Given the region's heavy reliance on charcoal, driven by limited electricity access [30], we hypothesize that wood harvesting for charcoal production is the primary degradation driver. Furthermore, we hypothesize that logging intensity decreases with distance from villages, reflecting reduced accessibility and exploitation pressure. Finaly, ecological theories such as the Intermediate Disturbance Hypothesis suggest that species diversity may peak at intermediate successional stages due to moderate disturbance [31, 32]. In the context of Miombo woodlands, this implies that intermediate recovery stands could harbor relatively higher diversity than early recovery or long-undisturbed stands. However, empirical studies in the region also emphasize that the mature Miombo tends to maintain higher diversity, structural complexity and tree density [6, 33, 34]. Based on this dual perspective, we hypothesis that species diversity may not follow a strictly linear decline with degradation, and that intermediate recovery stands could exhibit diversity levels comparable to or higher than mature stands, while early recovery stands are expected to show the lowest structural and floristic attributes.

2 Materials and methods

2.1 Study area

The LCPB (Fig. 1) covers 26,603.4 km^2 in southeastern DRC, within the Upper Katanga province, between latitudes 10° 39′ 7.47″-12° 26′ 37.61″ S and longitudes 26° 20′ 54.95″–28° 40′ 13.55″ E [19]. This area, delimited by Ref. [19], encompasses the network of villages that supply charcoal to the city of Lubumbashi, hence its designation as the Lubumbashi charcoal production basin (LCPB). The region has an average elevation of 1,200 m and experiences a Cw climate according to Köppen's classification, which corresponds to a subtropical climate characterized by distinct wet and dry seasons [35]. Rainfall occurs mainly between November and March, with an annual average rainfall exceeding 1200 mm, and the dry season from Mai to September, separated by a two transitional months [36]. The mean annual temperature was 20 °C in the second half of the twentieth century, but recent studies have documented a warming trend [36].

The vegetation is dominated by open Miombo woodlands, interspersed with natural savannas. However, increasing anthropogenic activities have triggered a progressive conversion of Miombo woodlands into wooded savanna, followed by shrub savanna,

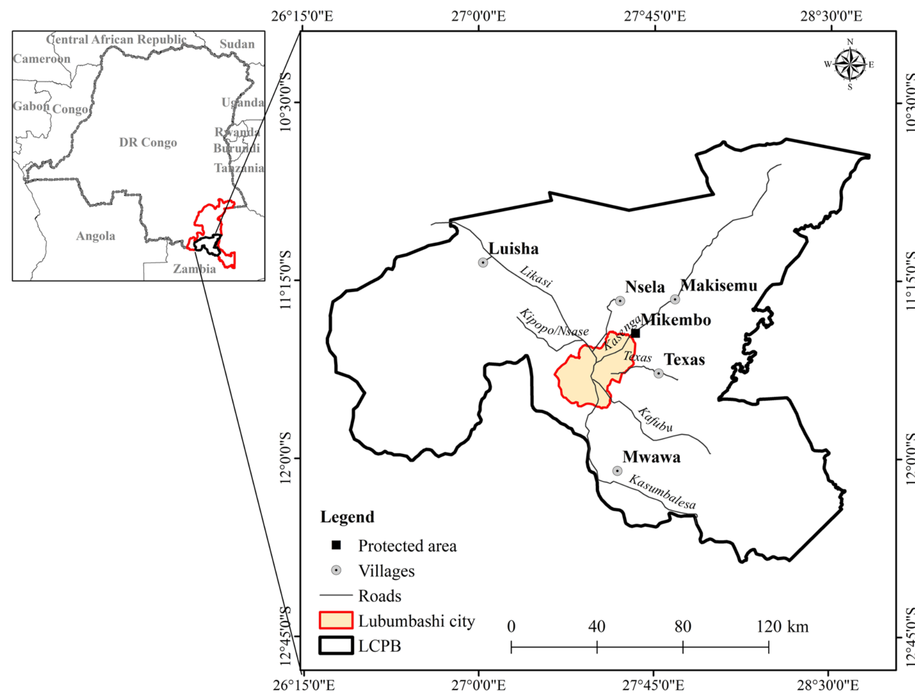

Fig. 1 Geographic location of the LCPB in the Haut-Katanga province, DRC, showing the selected charcoal-producing villages and the main charcoal transportation routes

and ultimately grassland savanna [15]. The region's population, experiencing continuous growth, primarily engages in agriculture, residential livestock farming, charcoal production, trade, and artisanal mining [13, 18, 21, 37].

2.2 Study sites selection

The selection of study sites followed a structured and rigorous approach to ensure representativity and relevance in the analysis. Among 63 villages identified as charcoal supply sources in the LCPB, five key villages (Luisha, Makisemu, Mwawa, Nsela, and Texas) were selected based on explicit criteria, including supply frequency, advanced degradation levels, and connectivity with other localities within the LCPB (Table 1). Furthermore, villages were selected in areas previously identified as having undergone conversion from intact Miombo to degraded Miombo or savanna between 2015 and 2022 according to Ref. [19]. These villages are strategically distributed across the north, northwest, east, and south, ensuring comprehensive geographic coverage of affected areas (Fig. 1).

The selection method was based on semi-structured surveys conducted between February and July 2023 at 14 charcoal sales depots in Lubumbashi. To ensure representativeness, two major depots were randomly chosen in each of the seven communes of the city, allowing for the identification of the most frequently exploited villages [19]. Additionally, to provide a reference site free from direct anthropogenic pressures, the Mikembo protected area was included in the study.

For floristic and dendrometric indicators, the sites were classified into three recovery stages based on ecosystem age, determined through local knowledge and land cover analysis (Table 1). The Makisemu forest, free from major anthropogenic disturbances since 2015, represents the early recovery stage, with approximately 7 years of natural

Table 1 Geographic coordinates, number of households, degradation level, distance from Lubumbashi, road conditions connecting the village to Lubumbashi, and main activities in the selected villages within the LCPB

Villages	Geographic coordinates	Households	Recovery level	Distance from Lubumbashi	Road condition	Main activities	ADF	ADI	Age (year)
Luisha	11°10′ S; 27°01′ E	2760	ER	86 km	VG	1, 2, 3, 4	X		7
Makisemu	11°19′ S; 27°50′ E	356	ER	72 km	VG	1, 2, 3	X	X	7
Mwawa 1	12°03′ S; 27°35′ E	115	ER	60 km	G	1, 2, 3	X		7
Mwawa 2	12°03′ S; 27°35′ E	115	IR	60 km	G	–		X	14
Nsela	11°20′ S; 27°36′ E	129	ER	30 km	PC	1, 2, 3, 4	X		7
Texas	11°39′ S; 27°46′ E	179	ER	30 km	PC	1, 2, 3	X		7
Mikembo	11°28′ S; 27°40′ E	0	M	30 km	VG	–	–	X	21

With M: mature; IR: intermediate recovery; ER: early recovery; VG: very good; G: good; PC: poorcondition; 1: agriculture; 2: charcoal production; 3: small-scale trade; 4: artisanal mining; ADF:analysis of disturbance factors; ADI: analysis of disturbance indicators

Table 2 Disturbance factors and indicators recorded in the LCPB of Lubumbashi, based on informal surveys conducted in five villages: Luisha, Makisemu, Mwawa, Nsela, and Texas

No	Degradation factor	Indicator
1	Wood harvesting	Presence of tree stumps or trunks with resprouts, signs of charcoal production activities, including the presence of kilns
2	Bark stripping	Presence of bark harvesting marks on a tree trunk, reflecting its use in traditional pharmacopoeia
3	Invasion of exotic species	Observation of exotic species presence, including *Eucalyptus sp.*, *Pinus sp.*, *Acacia sp.*, and others
4	Artisanal mining activities	Presence of small-scale mining sites and artisanal miner camps

regeneration. The Mwawa forest, abandoned since 2008, corresponds to the intermediate recovery stage, with about 14 years of regeneration. In Makisemu and Mwawa, the forests regenerated naturally following their abandonment. In contrast, the Mikembo forest, under formal protection since 2002, represents the advanced/mature recovery, with more than 21 years of ecological recovery [38]. In this ecosystem, the forests have naturally regenerated following their protection from major human disturbances.

2.3 Sampling and data collection

2.3.1 Identification of disturbance factors in the LCPB

The methodological approach was based on field inventories of disturbance indicators in Miombo woodlands, adapted from Rakotondrasoa et al. [27, 28]. A typology of potential disturbance indicators (Table 2, Fig. 2) was developed based on literature [13, 14], and refined through informal interviews with key stakeholders from five selected villages in the LCPB. Stakeholder selection was based on 10 resource persons per village, randomly chosen according to their residence time in the village (more than 10 years) and their direct involvement in the Miombo woodlands use, particularly as famers, charcoal producers, and hunters, which constitute the main livelihood activities in the study area.

Fig. 2 Illustrations of vegetation degradation factors in the LCPB. With **1**: charcoal kilns and a cut tree trunk. **2**: bark stripping, **3**: an *Eucalyptus grandis* individual in the degraded *miombo* woodlands, **4**: an abandoned site after artisanal mining activities (
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Field inventories were carried out in 160 sampling plots in total, each measuring 10 m × 500 m, a layout chosen to effectively capture spatial gradients of disturbance across extended distances. In each village, 32 plots were systematically distributed along four 4-km transects radiating in cardinal directions (north, south, east, west) from the village center. Plots were established at 500-m intervals along each transect (]0–500],]500–1000],]1000–1500],]1500–2000],]2000–2500],]2500–3000],]3000–3500] and]3500–4000] m). The 4000-m threshold was determined through preliminary consultations with local stakeholders and corroborated by literature indicating that anthropogenic pressure is most intense within a 3000–5000 m radius of rural settlements [39]. The protocol was adapted from Ref. [27] due to ecological and contextual similarities.

Fieldwork was conducted between May and September 2023. In the field, disturbance indicators were recorded in binary (presence/absence) format, including charcoal kilns, cut stumps, debarked trees, presence of exotic species, and artisanal mining activity (Fig. 2). Geolocation was captured using a handheld GPS device.

2.3.2 Floristic and dendrometric data collection

Data were collected between April and June 2023 across three Miombo woodland study sites, following the protocol recommended by Ref. [40]. Floristic inventories were carried out in 16 systematically distributed rectangular plots (20 m × 50 m; 1000 m^2 each) per degradation level, resulting in a total of 48 plots (16 for each of the three recovery stages). The choice of using the same number of plots was preferred because the selected sites have relatively comparable area, each covering approximately 500 ha. The rectangular design was chosen to optimize species detectability [41]. Plots were spaced 100 m apart and arranged along two perpendicular transects (20 m wide and 500 m long),

oriented north–south and east–west, to effectively capture spatial variability in vegetation while accounting for logistical constraints [40].

Within each plot, diameter at breast height (DBH) was measured at 1.3 m above ground using a diameter tape, and tree height was recorded using a Forest PRO II laser rangefinder [42]. A minimum DBH threshold of 10 cm was applied to exclude juvenile trees and shrubs, focusing on established individuals contributing meaningfully to forest structure and dynamics [23, 24]. For multi-stemmed trees, each stem with a DBH ≥ 10 cm was measured separately at 1.3 m. This approach allowed the inclusion of multi-stemmed individuals in quadratic mean DBH calculation without overcounting or biasing stand structure estimates [23]. Measurement instruments were calibrated through repeated trials to ensure data accuracy and reliability.

2.4 Data analysis

2.4.1 Analysis of disturbance factors data

Villages were treated as replicates to identify the most influential factors contributing to the degradation of Miombo woodlands within the LCPB. The present of each factor was recorded as binary data (1 = present, 0 = absent), and their occurrence frequency was calculated. Statistically significant differences in factor occurrence were evaluated using the generalized Fisher's exact test for count data, with Holm's correction applied to account for multiple pairwise comparisons [43]. This approach enabled the identification of the most dominant driver of forest degradation and the establishment of a hierarchy among the observed factors.

Associations among disturbance factors were then examined using Fisher's exact test to account for small, expected counts (some as low as 4), ensuring robust results [44].

Finally, the influence of distance on the presence or absence of disturbance factors was analyzed using binary logistic regression [45], a method specifically suited for binary response variables in relation to a continuous predictor (distance). This approach allows for the estimation of the probability of disturbance factor occurrence as a function of distance from villages, providing a more precise assessment of spatial patterns.

2.4.2 Analysis of floristic and dendrometric parameters data

Floristic inventories were conducted to determine species richness and individual abundance at each site. Diversity was assessed using the Shannon–Wiener index (H, Eq. 1), which accounts for both species abundance and evenness, while species distribution was evaluated using Pielou's evenness index (E, Eq. 2) [46]. The influence of recovery stage age on various parameters—, species richness, diversity (H), and evenness (E)—was tested using analysis of variance (ANOVA). When normality assumptions were not met, the Kruskal–Wallis test was applied [40]. A significance level of $P = 0.05$ was used for all statistical tests. Data normality was assessed using the Shapiro–Wilk test, guiding the selection between parametric and non-parametric methods. For significant results, post hoc comparisons were conducted using Tukey's HSD (for ANOVA) or Dunn's test (for Kruskal–Wallis) [33].

Species composition was analyzed using the Importance Value Index (IVI, Eq. 3), which integrates relative dominance, density, and frequency [41]. Relative dominance corresponds to the proportion of total basal area represented by each species. Relative density reflects the number of individuals of species i relative to the total number of

sampled individuals, while relative frequency represents the proportion of plots in which a species occurs [33].

Stand horizontal structure was characterized by tree density (Eq. 4), expressed as the number of individuals per hectare [47]. The quadratic mean DBH (DBH_m), in centimeters, was calculated using Eq. 5, accounting for multi-stemmed individuals measured at 1.30 m above ground [42]. Basal area (BA), in m^2/ha, representing the total cross-sectional area of tree stems at breast height, was computed using Eqs. 6 and 7 [42]. The effects of ecosystem type on structural parameters—DBH, height, density, and basal area—were tested using ANOVA; when assumptions of normality were not met, the non-parametric Kruskal–Wallis's test was applied. The DBH–height relationship was modeled using an asymptotic nonlinear regression, incorporating biological limits to height growth [48]. Structural distribution was assessed using DBH and height classes defined at 5 cm intervals. All statistical analyses were performed in R (version 4.3.1).

$$H' = -\sum_{i=1}^{n} p_i \ln (p_i) \tag{1}$$

where H' is the Shannon diversity index, n represents the number of species, and p_i is the proportion of individuals of a given species within a plot, calculated as the number of individuals of that species divided by the total number of individuals in the plot.

$$E = \frac{H}{H_{max}} = \frac{H}{lnS} \tag{2}$$

where E is Pielou's equitability index, H_{max} is the maximum Shannon diversity index, and S represents the total number of species identified in the study area.

$$IVI = \frac{(RDo + RDe + RF)}{3} \tag{3}$$

where IVI is the Importance Value Index, RDo represents relative dominance, RDe is relative density, and RF is relative frequency.

$$D = \frac{N}{S} \tag{4}$$

where D is the tree density per hectare, N is the number of trees per plot, and S is the plot area expressed in hectares.

$$DBH_m = \sqrt{\frac{1}{n}\sum_{i=n}^{n} d_i^2} \tag{5}$$

where d_i represents the DBH of each stem or branch, measured at 1.30 m above the ground, and n corresponds to the total number of stems or branches measured.

$$BA = EF\sum_{i=1}^{n} \frac{\pi d_i^2}{4} \tag{6}$$

where EF is the expansion factor, defined as the inverse of the plot area (in hectares) and calculated using Eq. 7. It is used to extrapolate basal area to a per-hectare scale [42].

$$EF = {}^{A_R}/_{(A_{SE})_i} \tag{7}$$

where A_R is the reference area (one hectare = 10.000 m^2), and $(A_{SE})_i$ is the sampling unit area containing tree *i*.

3 Results

3.1 Drivers of Miombo degradation in the LCPB

Wood harvesting is the primary source of disturbance in the sampling units, as reflected by its high occurrence rate (Table 3). In contrast, the invasion of exotic species, bark stripping, and artisanal mining activities are the least frequently observed disturbance factors.

The analysis of the generalized Fisher's exact test revealed significant differences among the observed degradation factors ($p < 0.001$). Pairwise comparisons showed that wood harvesting was the most frequently observed factor, significantly more common than invasion of exotic species ($p = 6.2 \times 10^{-11}$), artisanal mining activities ($p < 2 \times 10^{-16}$), and bark stripping ($p < 2 \times 10^{-16}$). Invasion of exotic species occurred more frequently than artisanal mining ($p = 4.1 \times 10^{-6}$) and bark stripping ($p = 0.037$), while bark stripping was observed more often than artisanal mining ($p = 0.009$).

However, interaction analysis among these factors did not reveal any significant associations ($p > 0.05$), indicating that they operate independently (Fig. 3).

Regarding the analysis of the effect of distance from the village on the spatial distribution of degradation factors, the results of the binary logistic regression are presented in Table 4. The findings show that wood harvesting ($\beta = 0.902$, $p < 0.01$) exhibits positive and significant coefficients, indicating that the likelihood of his occurrence increases with distance from the village. Conversely, the presence of invasive exotic species is associated with a significant negative coefficient ($\beta = -0.749$, $p < 0.01$), suggesting a higher concentration of this factor near villages. In contrast, neither bark stripping ($\beta = 0.030$, $p = 0.903$) nor artisanal mining activities ($\beta = -0.213$, $p = 0.648$) show a significant relationship with distance. This suggests that these forms of degradation are less influenced by proximity to human settlements. Overall, these results highlight a clear spatial pattern for certain degradation drivers (wood harvesting, invasive species), while others appear more diffuse or spatially independent of village proximity.

3.2 Floristic composition and diversity

A total of 1.065 individuals were recorded across the three study sites, representing 63 species, 40 genera, and 23 families. The Fabaceae family was the most diverse, accounting for 34.92% of all species, while *Brachystegia* was the most represented genus (9.52% of recorded species). Analysis of the three ecosystem types—advanced, intermediate, and early recovery—revealed significant differences in floristic richness and forest

Table 3 Presence-absence of disturbance factors in vegetation surrounding charcoal-producing villages within the LCPB of Lubumbashi (DR Congo)

Degradation factor	Presence–absence (%)
Wood harvesting	90,00
Fires	90,00
Invasion of exotic species	37,50
Bark stripping	21,25
Artisanal mining activities	5,00

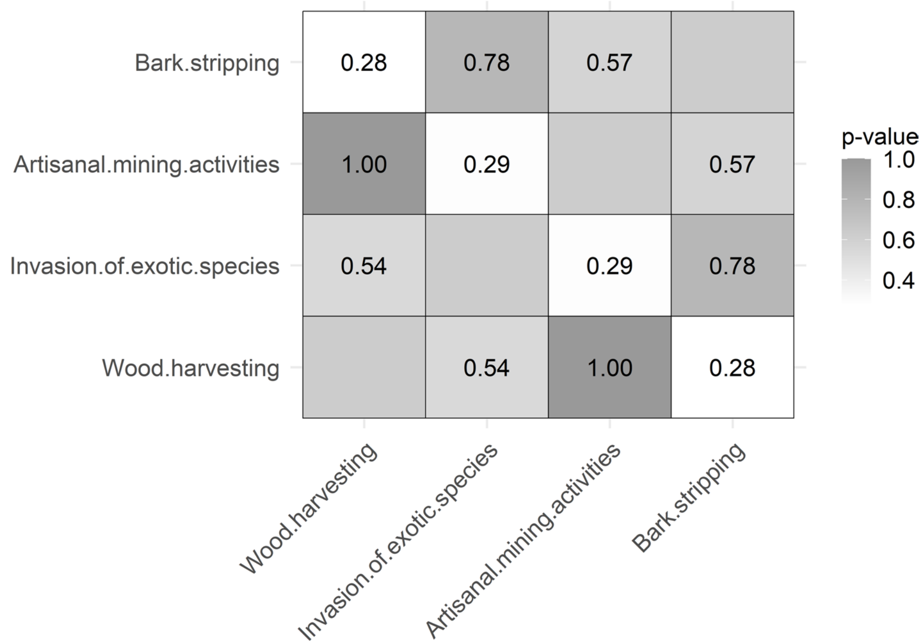

Fig. 3 Heatmap of *p* values from pairwise statistical tests between degradation factors in the LCPB, using the generalized Fisher's exact test based on presence-absence data. No combination showed a significant association

Table 4 Results of the binary logistic regression examining the effect of distance to the village on the distribution of disturbance factors

Factor	Estimate	Standard error	z-value	*p* value	Significance
Wood harvesting	0.902	0.343	2.626	0.009	**
Invasion of exotic species	− 0.749	0.238	− 3.152	0.002	**
Artisanal mining activities	− 0.213	0.467	0.456	0.648	ns
Bark stripping	0.030	0.245	1.122	0.903	ns

** =*p*< 0,01, * =*p*< 0,05, ns: non-significant

structure. The advanced recovery ecosystem contained a total of 519 individuals, distributed among 36 species, 25 genera, and 15 families, with *Brachystegia* as the dominant genus and a tree density of 323 trees/ha. The intermediate recovery ecosystem hosted 456 individuals, representing 48 species, 33 genera, and 20 families, also dominated by *Brachystegia*, with a tree density of 285 trees/ha. In contrast, the early recovery ecosystem exhibited a markedly different structure, with only 90 individuals across 23 species, 15 genera, and 7 families. In this site, *Uapaca* and *Vitex* were dominant, and the tree density was significantly lower, at 51 trees/ha.

Statistical analysis showed highly significant differences in species richness among the three ecosystems ($F = 41.61$, $p < 0.001$). The Tukey HSD test revealed no significant difference between the advanced and intermediate recovery ecosystems, whereas both differed significantly from the early recovery site (Fig. 5).

Floristic diversity, as measured by the Shannon–Wiener index, was high and comparable in the advanced and intermediate recovery ecosystems, with mean values of 2.11 and 2.13, respectively (Fig. 4). In contrast, the early recovery ecosystem showed significantly lower diversity (mean = 1.14; $F = 41.97$, $p < 0.001$). Species evenness, measured using Pielou's index, showed values of 0.74, 0.73, and 0.81 in the advanced, intermediate

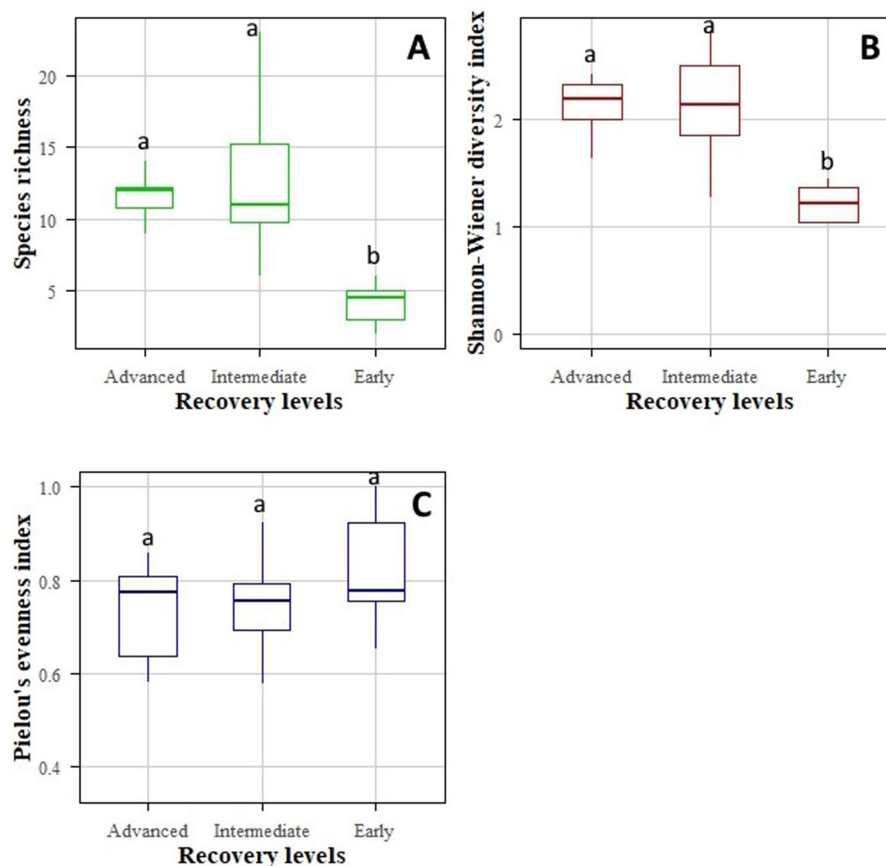

Fig. 4 The variation of ecological factors according to the disturbance level. **A**: species richness, **B**: Shannon–Weaver diversity index, and **C**: Pielou's evenness index

recovery, and early recovery ecosystems, respectively (Fig. 4), with no statistically significant differences ($p > 0.05$).

Structural analysis revealed notable differences among the three ecosystems, particularly in species abundance and Importance Value Index (IVI), as detailed in Tables S1 and S2, available in the supplementary materials. In the advanced recovery, the species with the highest IVI values were *Marquesia macroura* (IVI = 23.09; abundance = 88), *Diplorhynchus condylocarpon* (IVI = 11.27; abundance = 64), and *Julbernardia globiflora* (IVI = 9.10; abundance = 71). In the intermediate recovery ecosystem, *Brachystegia wangermeeana* (IVI = 13.69; abundance = 83), *Brachystegia spiciformis* (IVI = 12.04; abundance = 56), and *Albizia adianthifolia* (IVI = 8.90; abundance = 48) were the most dominant. In the early recovery ecosystem, dominant species included *Isoberlinia angolensis* (IVI = 18.37; abundance = 22), *Julbernardia paniculata* (IVI = 11.17; abundance = 18), and *Brachystegia wangermeeana* (IVI = 8.53; abundance = 6).

3.3 Dendrometric parameters

The structural analysis of tree stands revealed significant variation in key dendrometric parameters across recovery stages. Tree density remained high (> 300 trees/ha) in both advanced and intermediate recovery sites but dropped below 100 trees/ha in early recovery ecosystem. Statistical analysis confirmed high that tree density differed significantly among ecosystems ($\chi^2 = 28.99$, $p < 0.001$), with post hoc tests indicating no significant

difference between the advanced and intermediate recovery sites, both of which contrasted markedly with the severely degraded ecosystem (Fig. 5).

Similarly, DBH and tree height varied significantly with recovery stages ($F = 41.61$, $p < 0.001$), with mean DBH values of 24.21 ± 3.41 cm (advanced recovery), 18.83 ± 3.21 cm (intermediate recovery), and 11.56 ± 3.25 cm (early recovery) (Fig. 5). DBH class distributions followed an inverse J-shape typical of regenerating forests. Young trees (10–15 cm DBH) dominated the early recovery (82.71%) and intermediate recovery ecosystems (49.12%), while their proportion was lower in the advanced recovery ecosystem (39.80%), where they remained the dominant class. In contrast, larger diameter classes were more frequent in the advanced recovery ecosystem, indicating mature stand development (Fig. 6).

Tree height also exhibited significant differences ($\chi^2 = 35.25$, $p < 0.001$). Mean height declined from 9.64 ± 2.24 m in advanced recoverystands to 6.31 ± 0.74 m (intermediate recovery) and 4.47 ± 1.5 m (early recovery) (Fig. 5). In the early recovery site, 65% of individuals were under 5 m, whereas taller trees (> 15 m) were present only in the advanced recovery ecosystem (10%), highlighting its structural maturity (Fig. 6).

Basal area further emphasized these differences: 13.42 ± 5.21 m^2/ha in the advanced recovery ecosystem, compared to 0.65 ± 0.44 and 0.73 ± 0.44 m^2/ha in intermediate and early recovery ecosystems, respectively ($\chi^2 = 39.97$, $p < 0.001$; Fig. 5).

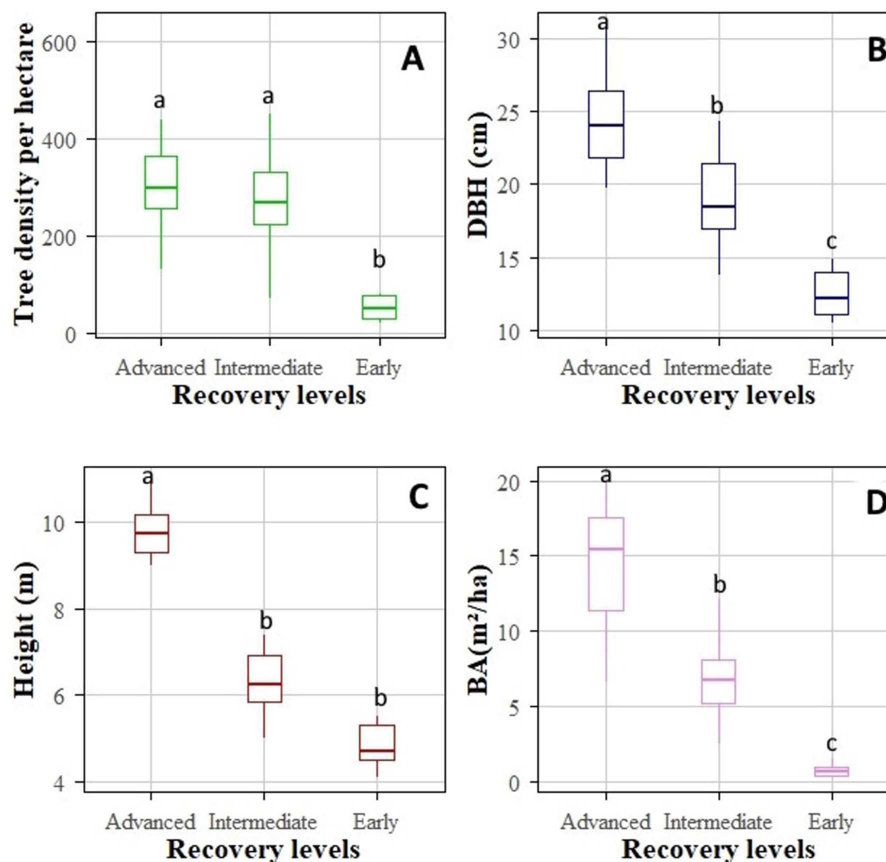

Fig. 5 The variation of ecological factors according to the disturbance level. **A**: mean tree density per hectare, **B**: mean DBH, **C**: mean tree height, and **D**: mean basal area (BA)

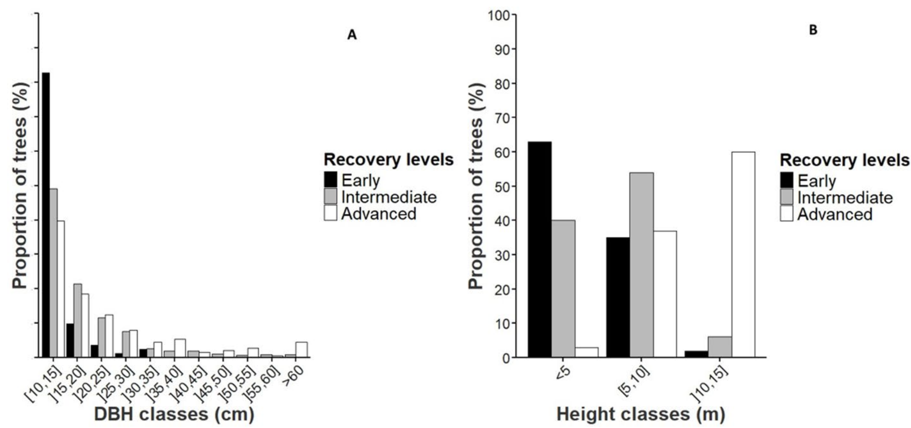

Fig. 6 Distribution of tree diameter (cm, **A**) and height (m, **B**) in advanced, intermediate, and early recovery ecosystems

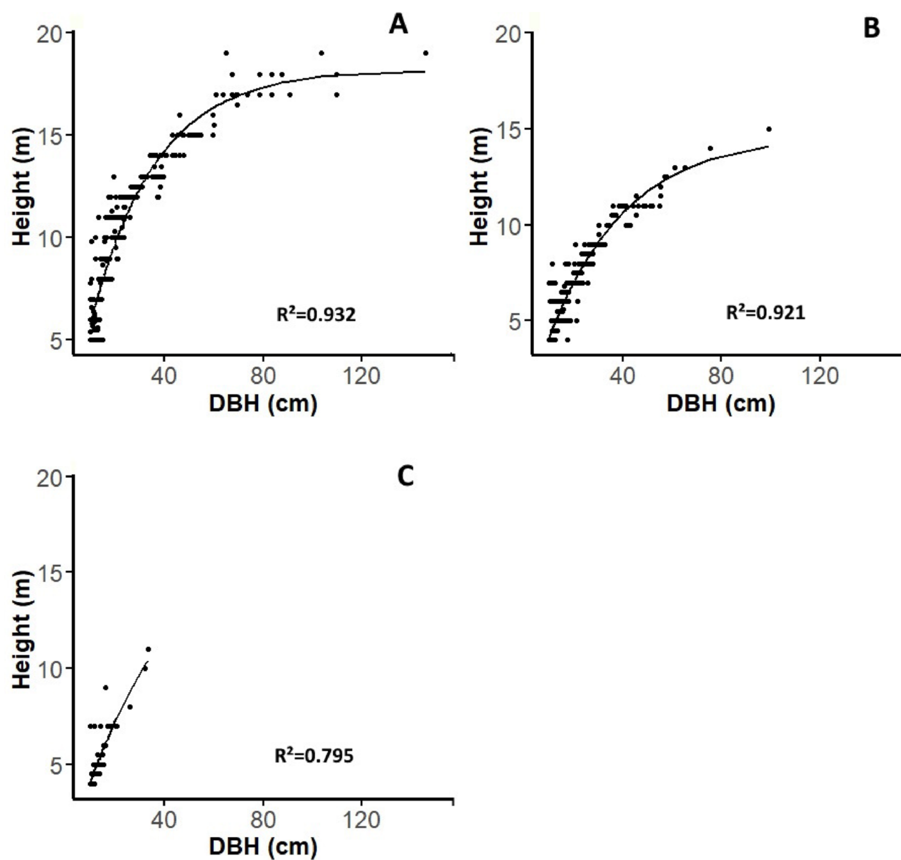

Fig. 7 Asymptotic regression illustrating the diameter-height relationship of trees in in advanced, intermediate, and early recovery ecosystems

The diameter-height relationship, analyzed through asymptotic regression, also varied with recovery stage. In the advanced recoveryecosystem, the asymptotic model explains 93.2% of the variability in height as a function of diameter (Fig. 7). In the intermediate recovery ecosystem, 92.1% of the variability in tree height as a function of diameter is described by the asymptotic model (Fig. 7). In the early recovery ecosystem, the asymptotic model accounts for 79.5% of the observed variation in tree height in relation to

diameter within this advanced recoveryecosystem (Fig. 7). These results indicate that the model perform best in the advanced recoveryecosystem, capturing most of the variability in tree height relative to diameter, while its explanatory power decrease progressively in intermediate and early recovery ecosystems.

4 Discussion

4.1 Underlying drivers and immediate pressures behind Miombo woodland degradation in the LCPB

Our findings identify wood harvesting for charcoal as the primary driver of Miombo degradation in the LCPB. The rapid growth of urban populations in sub-Saharan Africa, particularly in the Democratic Republic of Congo (DRC), is driven by rural–urban migration and high urban fertility rates [37]. In the DRC, this trend is especially pronounced in mining towns, which act as economic magnets. In the Katanga region, the mining boom since 2002 has further intensified this dynamic [49]. Lubumbashi, the country's second-largest city, exemplifies this growth, with its population increasing from 1.6 million in the early 2000s [50] to over 3 million by 2020 [37]. This demographic pressure has led to a dramatic rise in demand for wood energy, especially charcoal used for cooking [18]. More than 72% of households in Lubumbashi and surrounding areas rely on charcoal [51], largely due to inadequate electricity access [30], thus increasing dependency on Miombo woodlands [13]. Our rusults are consistent with national report [14], and echo broader regional patterns in Angola [52] and Zambia [53].

Other drivers such as invasion of exotic species, bark stripping, and artisanal mining were also observed but with lower frequency. Invasive of exotic species, facilitated by frequent disturbance, compete with native flora and alter habitat conditions [54]. These species are dominated by *Tithonia diversifolia*, *Imperata cylindrica*, *Leucaena leucocephala*, *Lantana camara*, and *Ricinus communis* [55]. Their presence is most notable near settlements, consistent with findings in Zambia [56]. Despite these pressure, Miombo woodland ecosystems exhibit notable resilience due to traits such as coppicing, fire tolerance, and rapid regeneration after disturbance [11, 29, 57]. These characteristics allow native species to persist and maintain ecosystem structure and function even in the presence of invasive plants, although continued disturbance may eventually erode this resilience. Bark stripping, often for medicinal or utilitarian purposes, weakens trees and increases their susceptibility to pests and disease [58], as also noted in Zambian Miombo forests [59]. Artisanal mining contributes to land clearing, erosion, and forest fragmentation, a pattern also seen in Zimbabwe's Mzingwane District [60].

The results did not reveal any significant association among the Miombo degradation factors, suggesting that the presence or intensity of one degradation factor does not directly influence the occurrence of others, and each factor can contribute separately to forest degradation. For some associations, our findings align with those of Ref. [61], who did not observe a link between wood harvesting and the invasion of exotic species in the northwestern part of Virunga National Park, DR Congo. This similarity may be explained by comparable socio-economic conditions between the two areas.

Spatial analysis shows that wood harvest increase with distance from villages, likely due to resource depletion near settlements, pushing exploitation further afield [19]. Conversely, exotic species are more prevalent near villages, where disturbances are common. Bark stripping and artisanal mining show no clear spatial correlation, as they depend

more on the availability of specific tree species or mineral deposits than on proximity to settlements.

4.2 Assessment of forest ecosystem condition and the influence of human pressures on floristic degradation indicators in the LCPB

Floristic analysis revealed a consistent dominance of Fabaceae across all three ecosystems studied. This pattern, previously observed in the Katangan Miombo [23] and more broadly across the Miombo ecoregion [62], is largely attributed to their nitrogen-fixing capacity—a key adaptive trait in nutrient-poor tropical soils [63]. Their ecological plasticity and tolerance to recurring disturbances, including frequent fires and human exploitation, reinforce their persistence in these highly anthropized landscapes [64].

Species richness peaked in the intermediate recovery ecosystem, likely due to the intermediate disturbance effect, which favors the coexistence of heliophilous and shade-tolerant species. In contrast, the early recovery site exhibited reduced species richness, reflecting more intense and recent anthropogenic pressures. The Shannon–Wiener diversity index in both the advanced and intermediate recovery ecosystems indicates moderate to high floristic diversity [46]. However, the early recovery ecosystem has a much lower diversity, characteristic of an early regeneration stage dominated by pioneer species. These findings are consistent with patterns reported in Zambia [65] and central-southern Angola [33].

Despite variations in species richness, evenness remained relatively stable across ecosystems, suggesting that competitive exclusion has not yet led to dominance by a few taxa. This aligns with Ref. [29], who argue that full species richness recovery in Miombo ecosystems requires over two decades of abandonment. Furthermore, evenness did not differ significantly between studied ecosystems. This is likely because disturbances can eliminate rare species without substantially affecting the abundance patterns of the remaining species [66].

The Importance Value Index (IVI) analysis highlights differences in species composition across the studied ecosystems, all characteristic of Zambezian humid Miombo woodlands [65]. The advanced recovery ecosystem was dominated by *M. macroura* and *D. condylocarpon*, species known for their fire resistance and low commercial value [24], indicating historical disturbance followed by a prolonged recovery phase [38]. The presence of *J. globiflora*, a key Miombo indicator, further supports the hypothesis of post-disturbance regeneration.

In the intermediate recovery ecosystem, *B. wangermeeana* and *B. spiciformis*, core Miombo species [8], co-occurred with *A. adianthifolia*, a disturbance-tolerant pioneer species [67]. This composition suggests an ongoing secondary succession, where floristic diversity is maintained by regeneration processes.

Early recovery site was dominated by species from genera such as *Uapaca* and *Vitex*, characterized by rapid growth and adaptability to open, high-light environments. Their dominance indicates recent and intense disturbance [65]. The economic and nutritional value of these species likely contributes to their selective retention by local communities. Similar patterns were found in Mozambique, where *U. kirkiana* is considered a degradation indicator [68]. Low IVI values suggest reduced species dominance and high floristic heterogeneity, indicating active recruitment and confirming IVI as a useful indicator of forest degradation and regeneration [69].

Tree density was highest in the advanced recovery ecosystem, consistent with protected sites like Mikembo [24] and Kiswishi [25], a quasi-protected ecosystem. These results underscore the role of conservation in maintaining structural integrity. However, the lack of significant difference between the advanced and intermediate recovery ecosystems may reflect increased pioneer recruitment in recovering stands [70]. Early recovery ecosystem showed much lower tree density, consistent with early-stage regeneration dynamics [29, 63].

Dendrometric analysis revealed a higher proportion of mature trees—taller individuals with larger DBH—in the advanced recovery ecosystem, reflecting longer uninterrupted growth periods [29]. In contrast, earlier recovery stages were dominated by smaller, younger trees, indicating that recent disturbances constrained the development of large-diameter individuals [40]. The observed DBH structure has important implications for ecosystem health: mature trees contribute to canopy closure, carbon storage, and habitat complexity, which are critical for biodiversity maintenance and ecosystem resilience [71]. Conversely, the dominance of small trees in earlier recovery stages suggests reduced structural complexity, lower biomass, and diminished capacity to buffer further disturbances, highlighting the vulnerability of these ecosystems to ongoing anthropogenic pressures [72].

Regarding the diameter–height relationship, the results showed an excellent fit for the advanced recovery ecosystem, indicating that in mature stands this relationship is highly stable and predictable [73]. Similarly, the intermediate recovery ecosystem also exhibited a strong fit, reflecting a well-defined diameter–height relationship. In contrast, the early recovery stand displayed greater variability and lower predictability [74]. These findings confirm that the asymptotic model adequately describes the height–diameter relationship and that stability increases with stand age [75].

Finally, basal area values were highest in the advanced recovery ecosystem, reflecting greater biomass accumulation. Lower basal areas in earlier recovery ecosystems indicate younger, regenerating stands. These findings confirm the strong influence of recovery stage and forest age on biomass structure, aligning with trends observed in Zambia [65].

4.3 Implications for forest management

The degradation of Miombo woodlands in the Lubumbashi Charcoal Production Basin (LCPB) is primarily driven by anthropogenic activities such as wood harvesting for charcoal. Exotic species invasion, bark stripping, and artisanal mining activities playing a second role. This combined pressure leads to declines in species richness, floristic diversity, tree density, mean DBH, height, and basal area—key indicators of forest health.

These findings highlight the need for targeted forest policies adapted to Miombo ecosystems. In the DRC, the national forestry code—designed for dense tropical forests—requires revision to address Miombo-specific dynamics, such as regulating charcoal production, controlling species exploitation, and banning destructive practices. Tanzania has taken steps in this direction by criminalizing unsustainable uses [76].

In Lubumbashi, strengthening provincial reforestation services and wildfire management capacity is vital. Lessons from Tanzania's Miombo regions—such as firebreaks, legal enforcement, and community involvement—could guide action [77].

In the face of rapid urban growth, expanding both public and private protected areas and implementing integrated land-use planning are key. The Mikembo Sanctuary near

Lubumbashi illustrates the success of long-term protection, where 21 years of conservation have enabled natural Miombo regeneration [38]. Similarly, Gabon's Lopé National Park has demonstrated the value of protected areas in forest conservation [78].

Finally, the situation observed in the intermediate recovery stage suggests the need to regulate human activities through protective measures, strengthened law enforcement, and the establishment of protected areas, including private reserves. For early recovery site, however, large-scale active reforestation remains necessary, as shown by Ref [79]. in the Sahel.

5 Conclusions

This study identified the main anthropogenic drivers of Miombo woodland degradation and examined the floristic and dendrometric responses across varying recovery stages in the LCPB. The results confirm that wood harvesting for charcoal is the main degradation driver. Contrary to our initial hypothesis, the intensity of these pressures increases with distance from villages, reflecting resource depletion near settlements. Results also revealed that degradation significantly alters floristic composition and stand structure. Early recovery ecosystem is characterized by reduced species richness, low tree density, and a dominance of small-diameter individuals, while advanced and intermediate recovery sites exhibit higher diversity, greater densities, and structural attributes typical of advanced successional stages, supporting our second hypothesis.

Although limited in spatial and temporal scope, this study provides essential insights for forest management in Miombo systems. Findings support the need for policy reforms addressing destructive practices, promoting sustainable agriculture, and expanding protected areas. Future research should expand both the spatial and temporal coverage of surveys, integrate socio-economic data, and conduct in-depht analyses of context-specific barriers such as corruption, weak governance, and lack of enforcement. Combining long-term monitoring will with remote sensing and participatory approaches will be critical to refine degradation assessments and inform adaptive strategies for preserving Miombo woodlands under increasing anthropogenic pressure. Furthermore, future studies should investigate the influence of environmental factors, such as precipitation and soil characteristics, on woodlands degradation and recovery, to better understand their interactions with anthropogenic pressures.

Supplementary Information

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Supplementary Material 1

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Author contributions

Conceptualization: HKM, YUS & JB; Data curation: HKM, DNN, JYM, YUS & JB; Formal analysis: HKM, JYM; Funding acquisition: JB; Investigation: HKM; Methodology: HKM, JYM, OLR, QP, YUS & JB; Project administration: YUS & JB; Resources: HKM & YUS; Software: HKM, JYM; Supervision: YUS & JB; Validation: HKM, YUS & JB; Writing—original draft: HKM & YUS; Writing—review & editing: HKM, FM, OLR, YUS, & JB.

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Data availability
The data presented in this study are available on request from the corresponding author.

Declarations

Ethics approval and consent to participate
All experimental procedures and preliminary surveys conducted for the selection of study sites were reviewed and approved by the Ethics Committee of the Cooperation Office of the University of Lubumbashi, reference number EC/COOP/UNILU/126/2025, ensuring that all procedures were carried out in full accordance with the relevant ethical guidelines and regulations governing research involving human participants. Prior to participation in the surveys, all individuals were fully informed of the study's objectives and voluntary nature, and provided their informed consent. No participants under the age of 18 were involved, ensuring compliance with ethical standards for minors. Consent was obtained in accordance with the guidelines set by the Ethics Committee of the University of Lubumbashi.

Consent for publication
The images in this study depict forest degradation factors in village community areas. To comply with ethical standards, prior informed consent was obtained from the relevant village chiefs. Furthermore, the informed consent of the landowners was secured for the specific use and publication of these images for scientific purposes related to this study.

Generative AI statement
The authors declare that Gen AI was only used to enhance text readability and correct language usage.

Competing interests
The authors declare no competing interests.

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