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IMPACT OF SITE PROTECTION MECHANISMS ON NATURAL REGENERATION POTENTIAL ALONG A DEGRADATION GRADIENT IN MIOMBO WOODLAND REGION OF THE DEMOCRATIC REPUBLIC OF THE CONGO

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ABSTRACT

For several decades, the Miombo woodland located in Lubumbashi plain in the Democratic Republic of the Congo (DRC), has experienced significant changes in its floristic composition due to increasing human activity on the landscape, which has greatly impacted its potential for natural regeneration. Various human interventions have been implemented to protect this ecosystem, including the adoption of set-aside mechanisms with varying levels of protection. The objective of this study was to assess the effects of site protection mechanisms on the regeneration potential of vegetation, along a disturbance gradient, in the Miombo woodland of the Democratic Republic of the Congo. A study was conducted at Upper Katanga region in the Miombo woodland in the Lubumbashi Plain, involving a total of 60, 10 m x 10 m plots with 20 plots per site established across three sites, namely Kibundu, Kiswishi and Mikembo. Each plot was subjected to different levels of protection that is conservation with fence, without fence and forest communities-based management. A total of 1,230 individual trees were inventoried, representing 65 species, 45 genera and 20 families. Vertical spatial structure analysis revealed that the understory harbours greater species diversity than the upper canopy. The most represented families in the strata were *Fabaceae*, *Apocynaceae*, *Phyllanthaceae* and *Ochnaceae*. Additionally, Coefficient of Variation (CV) across the sites indicated uneven spatial distribution of three crowns within strata. Kibundu, with a CV of 102.9% in the upper canopy against 73.6% in Kiswishi and 18.4% in Mikembo, was found to influence the absolute density of individuals in the understory (CV =32.4, 61.5, 72.3% for Kibundu, Kiswishi and Mikembo, respectively). Interestingly, there was a high correlation between site disturbance rate of the potential of landscape regeneration (r =0.85, 0.055 and 0.77 at Kibundu, Kiswishi and Mikembo, respectively). Despite human pressures, regeneration indices were greater than unity, indicating a state of equilibrium in the vegetation of the Miombo woodland.

Key Words: Disturbance gradient, Lubumbashi plain, strata, understory, upper canopy

RESUME

La plaine de Lubumbashi subit depuis plusieurs décennies des changements dans sa composition floristique dû à l'anthropisation du paysage, qui impactent fortement son potentiel de régénération. Diverses actions de l'homme ont déjà été entreprises dans le but de protéger cet écosystème, par l'adoption des mécanismes de mise en défens avec des degrés de protection différents. L'analyse de l'impact de ces mesures de protection sur le potentiel de régénération est nécessaire à l'aménagement et la conservation de cet écosystème. L'objectif de cette étude était d'évaluer les effets des mécanismes de protection des sites sur le potentiel de régénération naturelle de la végétation, le long d'un gradient de perturbation, dans la forêt de Miombo de la République démocratique du Congo. L'étude a été menée dans la région du Haut-Katanga, dans la forêt de Miombo de la plaine de Lubumbashi, impliquant un total de 60 parcelles de 10 m x 10 m, avec 20 parcelles par site, réparties sur trois sites, à savoir Kibundu, Kiswishi et Mikembo. Chaque parcelle a été soumise à différents niveaux de protection, à savoir la conservation avec clôture, sans clôture et la gestion par la foresterie communautaire. Un total de 1230 individus a été inventorié répartis dans 65 espèces, 45 genres et 20 familles. L'analyse de la structure spatiale verticale montre que le sous-bois renferme une diversité spécifique plus grande que la canopée supérieure. Les familles les plus représentées dans les strates sont les *Fabaceae*, les *Apocynaceae*, les *Phyllanthaceae* et les *Ochnaceae*. En outre, le coefficient de variation (CV) entre les sites a indiqué une distribution spatiale disproportionnelle de la canopée dans les strates. Kibundu, avec un CV de 102,9% dans la canopée supérieure contre 73,6% à Kiswishi et 18,4% à Mikembo, ce qui influence la densité absolue des individus dans le sous-bois (CV =32,4%, 61,5%, 72,3% pour Kibundu, Kiswishi et Mikembo, respectivement). Il est intéressant de noter qu'il existe une forte corrélation entre le taux de perturbation du site et le potentiel de régénération naturelle du paysage (r = 0,85; 0,055; 0,77 à Kibundu, Kiswishi et Mikembo, respectivement). Par ailleurs,.le site avec un taux de perturbation élevé montre aussi un potentiel de régénération naturelle plus grand. Malgré la pression anthropiques, les indices de régénération sont supérieurs à l'unité. Ceci traduit un état d'équilibre de la végétation de la plaine de Lubumbashi.

Mots Clés : Gradient de perturbation, plaine de Lubumbashi, strates, sous-bois, canopée supérieure

INTRODUCTION

For several decades, the Miombo woodland in the Lubumbashi plain has experienced significant changes in its floristic composition due to increasing human activity on the landscape, which has greatly impacted its potential for natural regeneration. Moreover, in this century, sustainable management of natural resources is one humanity's greatest challenges (FAO, 2020; Muteya *et al.*, 2023).

Among the threatened resources, forest ecosystems hold vital importance for both rural and international ecosystems (Aboubacar *et al.*, 2023). The Miombo woodland is one of the global 200 ecoregions recognised for its exceptional biodiversity (Olson and Dinerstein, 2002; Beaumont *et al.*, 2011). Its high level of endemism (Linder *et al.*, 2014) makes it a biodiversity hotspot and a priority for conservation (Kouadio *et al.*, 2021). The Miombo of the Lubumbashi plain, with a deforestation rate often quantified as 3 to 5%, higher than the national average of 0.2% (Muteya *et al*., 2023; Sikuzani *et al*., 2023) in the DRC, provides numerous ecosystem services to local communities (Marc *et al.*, 2021; Nghonda *et al.*, 2023). This ecosystem, directly or indirectly, meets the daily needs of over 80% of people in both urban and rural areas of Upper Katanga province (Frost, 1996). It is also a significant source of timber and non-timber forest products, for primary and secondary needs (Sikuzani *et al.*, 2024; Wa Ngoy Kashiki *et al.*, 2021) and plays a crucial role in stabilising the local and regional climate (Chidumayo, 2009).

In spite of its climatic importance, the Miombo of the Lubumbashi plain remains the forest formation most affected ecosystem by agricultural land expansion (Marc *et al.*, 2021), the intensification of mining activities (Cabala *et al*., 2018; Sikuzani e*t al*., 2020), the increasing demand for charcoal and firewood (Dubiez *et al*., 2020), repeated bush fires (Sikuzani *et al.*, 2023), uncontrolled urbanisation (Sikuzani *et al.*, 2017), and the underlying effects of demographic expansion (Pont, 2006). These factors are the primary drivers of deforestation and degradation of these forest ecosystems (Muteya *et al.*, 2023).

Deforestation has significantly reduced ecosystem services, due to the disappearance or scarcity of many plant species (Muledi *et al.*, 2016). These phenomena have a substantial impact on the natural management of biological diversity and the overall functioning of ecosystems (Bogaert *et al.*, 2018), while affecting the spatial structure and natural regeneration of trees (Ayessa *et al.*, 2022) Consequently, the restoration of ecosystems relying solely on natural regeneration, often disrupted by ongoing human harvesting, is unlikely to succeed. Miombo faces multiple threats from human activities (Cabala *et al*. 2018; Sikuzani *et al*., 2024) and tends to regenerate through generative means or sprouting from stumps (Ponge *et al*., 1994; Frederique *et al*., 2019).

Some human interventions to protect the Miombo have been implemented in the Lubumbashi plain (Sikuzani *et al*., 2020); Marc *et al*. 2021; Nkombe *et al*., 2023;), including land enclosure with or without fences (Sikuzani *et al*., 2020; Nkombe *et al*., 2023;); and community forestry (Murhula, 2021). However, there has been efforts to examine the impact of these conservation or protection mechanisms on regeneration in this ecosystem. The objective of this study was to assess the effects of site protection mechanisms on the regeneration potential of vegetation, along a disturbance gradient, in the Miombo woodland of the Democratic Republic of the Congo.

MATERIALS AND METHODS

Description of the study area. This study area covered three sites, namely the Mikembo sanctuary, the Kiswishi monastery and the Kibundu Forestry Community Based Management (FCBM). These sites are all part of the Miombo woodland in the Lubumbashi plain. They are all located along major axes, including the Likasi axis (Kiswishi Monastery) and the Kasenga axis (Mikembo sanctuary and Kibundu FCBM). The Kiswishi monastery is situated in the peri-urban zone (Sikuzani *et al*., 2020); while the Mikembo sanctuary and Kibundu FCBM are located 35 and 110 Km from Lubumbashi city, respectively (Fig. 1).

The Mikembo sanctuary (800 ha) has been protected by fencing since 2003 (Muledi *et al*., 2016; Nkombe *et al*., 2023); while the Kiswishi monastery (452 ha) has been protected for a long time without fencing (Sikuzani *et al.* 2020). Both sites are regarded by Bogaert *et al*. (2018) as key monitoring locations for Miombo restoration in the Lubumbashi region.

The Kibundu FCBM is managed by the local community of Kibundu village under the provisions of decree-law number 14/018 of August 2, 2014 (Baraka *et al*., 2022). It is classified as a permanent production forest.

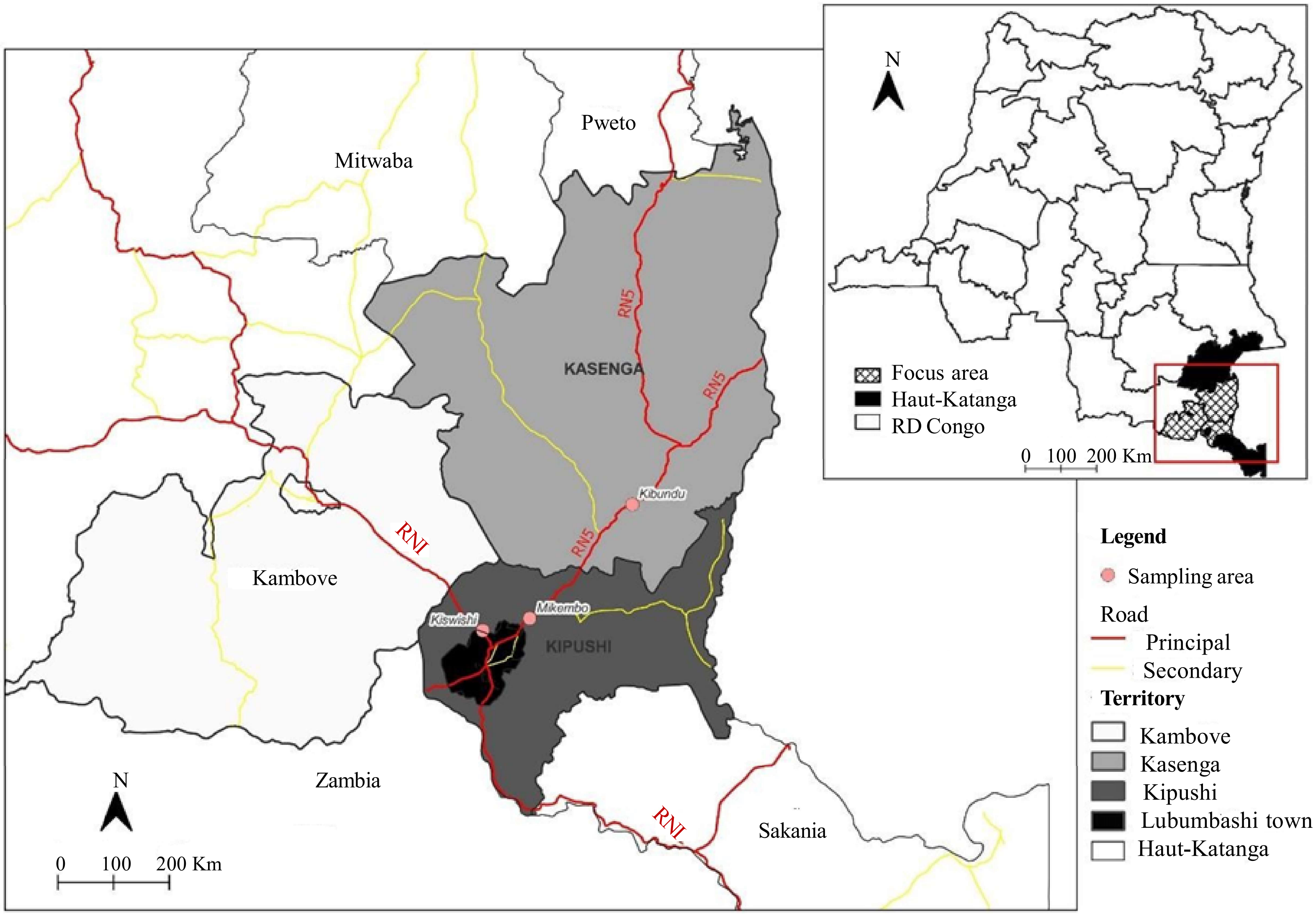

Figure 1. Location of the study sites on the map of the Community Forestry project area in the south-east of the Democratic Republic of the Congo. RN1: Likasi axis and RN5: Kasenga axis.

These different management conditions reflect varying conservation statuses.

The climate of the sites is characterised by two distinct seasons; namely a rainy season from November to March and a dry season from May to September, with April and October serving as transitional months. The mean rainfall is 1270 mm; while the mean temperature and relative humidity are 20 °C and 66%, respectively (Malaisse *et al*., 1978). The predominant vegetation type is open forest of the Miombo woodland, with scattered patches of vegetation, resulting from anthropogenic activities (Malaisse, 2018).

Sampling strategies. Data were collected from one hectare per site (a), which was subdivided into four 50 m x 50 m plots (b), each containing five systematically arranged 10 m x 10 m subplots (c) for observation (Fig. 2). The vegetation of the entire Lubumbashi Plain is essentially forest, except in situations where limiting edaphic factors prevent the establishment of a woody stand (dembos and outcrops of metalliferous rock). There are at least three types of forests in the Lubumbashi Plain, including Muhulu (dense dry forest), Mushitu (gallery forest) and Miombo (open forest), which form the matrix of the Lubumbashi Plain, not forgetting the vegetation of the high termite mounds (Muledi, 2017). All the sites studied are in the Miombo (open forest), whose flora is clearly dominated by the Zambezi. It is considered a form of degradation of dense dry forest by fire. All trees and shrubs were inventoried in 10 m x 10 m subplots. Data were collected in a stratified way based on the direction of the South-East cardinal orientation. The Pythagorean triangle formula was used to check the straightness of the sides of each plot (Fig. 3).

Dendrometry parameters were collected across the three locations, including diameter at breast height (DBH), crown diameter (CD), total height (H) and the Cartesian coordinates of each three. The diameter measurements were made using a forest tape, following the conventions of measuring a standing tree, according to its morphology (Rondeux, 2021, Equation 1).

$$\text{DBH} = \sqrt{D1^2 + D2^2} + D3^2 + \cdots + Dn^2 \qquad \text{Equation 1}$$

With: DBH = Diameter at breast height; D1, D2, D3, …, Dn: Diameter at 1.30 m from the ground of different branches.

The total height (H), which represents the distance between the base of the tree and its terminal bud, was measured using a Haga clinometer; and defined by Equation 2.

$$H = L(tg\alpha_1 + tg\alpha_2) \qquad \text{Equation 2}$$

Where:

L = distance and α_1 and α_2 = viewing angles at the top and bottom of the tree.

The basal area, which is the sum of the cross-sectional area of the trunks at a height of 1.30 m above the ground of the trees surveyed per hectare, was obtained using Equation 3:

$$G = \sum \frac{DHP^2\pi}{4} \qquad \text{Equation 3}$$

Where:

G = basal area in $m^2\ ha^{-1}$.

The mean absolute density in the strata, which is the ratio of the total number of individuals sampled in each state (N) to the area sampled (S) per hectare, was obtained using Equation 4:

$$D = \frac{N}{S} \qquad \text{Equation 4}$$

Where:

N = total number of individuals in the plots, and S = area surveyed.

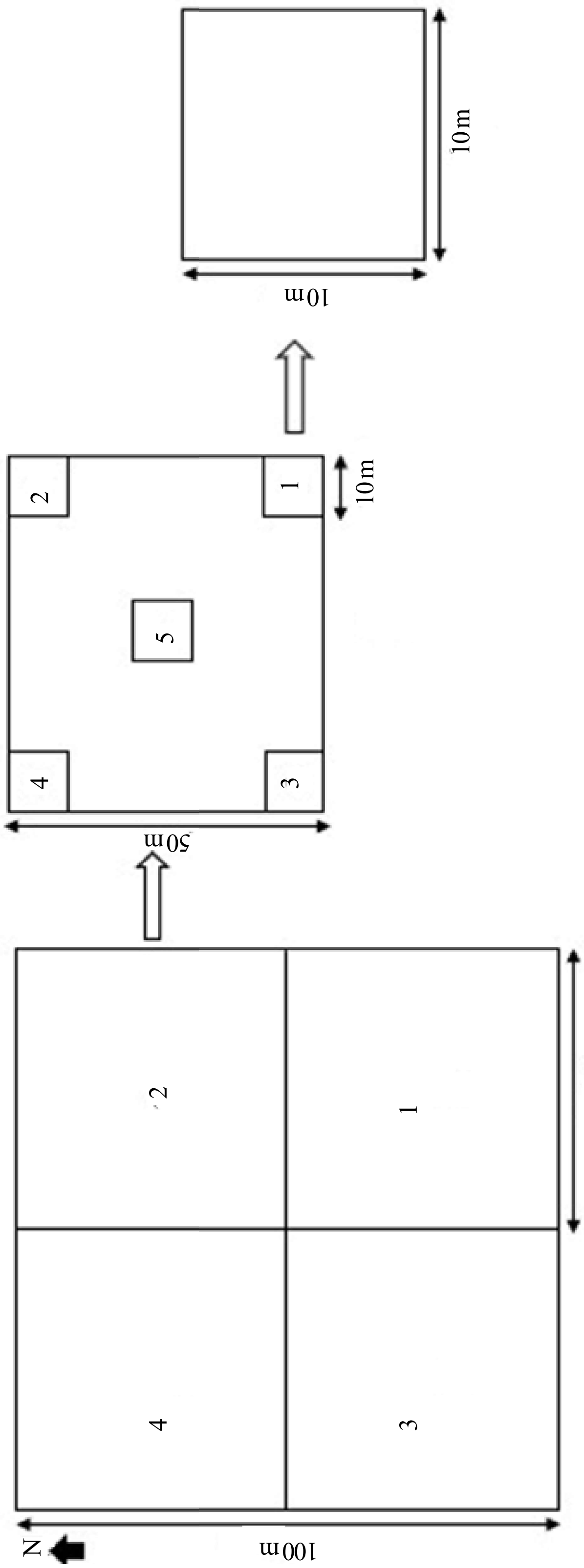

Figure 2. Visual representation of the materialisation of plots in the tree sites in the Miombo woodland in the Democratic Republic of the Congo.

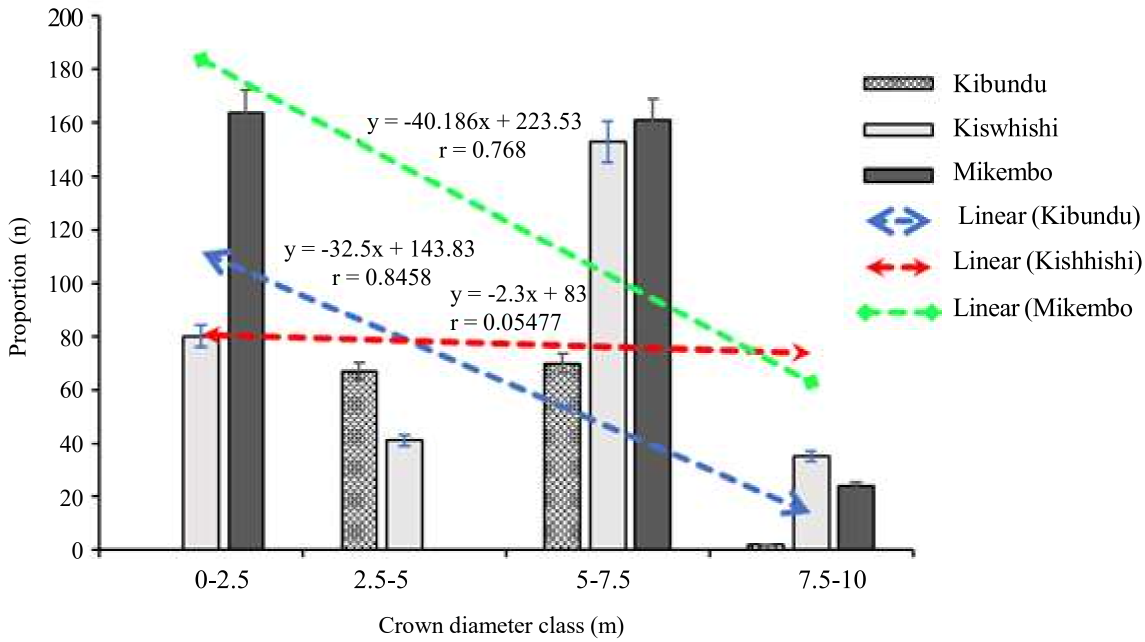

Figure 3. Correlations between individuals in the undergrow and crown diameter elongation in the upper canopy in Miombo woodland in the Democratic Republic of the Congo.

The variability of the spatial distribution of the longitudinal projection of trees on the ground in each stratum was obtained by determining the coefficient of variation using Equation 5 (Josoa *et al*., 2023), *viz*:

$$CV(G) = \frac{S(G)}{X} \times 100 \quad \text{................ Equation 5}$$

Where:

CV = percentage coefficient of variation;

$$S(G) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(G_i - X)^2}$$

Where:

G = basal area and S(G) = standard deviation of the basal areas plot's sum and X = mean of the basal areas plot's sum.

The natural regeneration index of the sites, which is a ratio between the number of regenerates in the understory and mature trees number in the upper canopy, was evaluated following Equation 6 (Hakizimana *et al*., 2011):

$$R_n = \frac{\text{Total number of regenerates in the undergrowth}}{\text{Total number of mature trees in the upper canopy}}$$

.... Equation 6

The impact of the anthropisation of the sites was assessed by determining the disturbance index. It was obtained using Equation 7:

$$DI = \frac{\text{Therophytes + Chamephytes}}{\text{Total number of species}} \times 100$$

.... Equation 7

Where therophytes are plants that complete their cycle in a few months and spend the unfavourable period as seeds (Sirvent, 2020a) and chamephytes are plants with perennial buds at or just above the soil surface, not exceeding 25 cm in height (Smith, 1913, as cited in Sirvent, 2020a). These two biological types are the first to become established when the canopy is less open, as they are ruderal heliophile species.

The effect of the upper canopy on the number of seedlings able to thrive as understory, was determined using Pearson's correlation coefficient *r*, which determines the strength of the correlation between two variables *x* and *y*, calculated using the Equation 8:

$$r = \frac{n\sum xy - (\sum x \sum y)}{\sqrt{n\sum x^2 - (\sum x)^2}\sqrt{n\sum y^2 - (\sum y)^2}}$$

.... Equation 8

Where:

n is the number of matched individuals from *x* and from *y*.

Moreover, the minimum diameter considered varied by stratum: DBH ≥10 cm for the upper canopy (Muledi *et al.*, 2016), compared with 1.5 to 10 cm for the understory (Hakizimana *et al.*, 2011). Species identification was conducted using field guides (Lomalisa *et al*, 2022); while species nomenclature was validated using the flora of Central Africa (Congo, Ruanda-Urundi) database at www.Floredafriquecentrale.be.

In addition, the composition and species richness of the herbaceous stratum were assessed using 21 circular quadrats of 1 m of diameter across four 25 m transects, starting from the centre of the 50 m x 50 m plot (b) in each site, according to SEOSAW protocol (Mograbi *et al.*, 2022); and the Global Grassy Group guide (Lehmann *et al.*, 2022). Knowledge of the biological types of the species inventoried, was based on the observations of bud's position as according to Sirvent (2020a, b).

Data analysis. Vegetation structure was analysed mainly at the level of floristic composition to assess the distribution of species richness in the strata of each site through relative frequency; and at the level of stand structure, using comparison of means by one-way analysis of variance (ANOVA) to evaluate the difference between ecological and dendrometric parameters in each site.

Analysis of the regeneration and disturbance indices was carried out primarily to compare sites and determine the level of disturbance. A correlation was done to highlight the increase in therophyte and chamaephyte species depending on the site.

The effect of the upper canopy on the number of seedlings able to develop in the understory was determined using Pearson's correlation coefficient. This test made it possible to compare bivariate data, in particular the number of individuals in the understory and the degree of upper canopy cover, by determining the direction and intensity of the linear correlation between the two variables at each site. In addition, the Kruskal-Wallis's test was used to confirm the effect at site level. R version 4.3.2 was used for all statistical analyses of the data.

RESULTS

Vegetation structure

Floristic composition. The *Fabaceae* family was the most represented in both strata across the assessed sites, with a representation of 55.6 and 41.5% at Kibundu, 41.5 and 53.3% at Kiswishi, and 64.4 and 55.0% at Mikembo (Table 1). The other three most represented families are *Phyllanthaceae, Apocynaceae* and *Ochnaceae*. Of these four families, only *Phyllanthaceae* showed a significant difference between sites (P = 0.0082). The dominant species in both strata were *Julbernardia paniculata* (10.7 and 6.3% at Kibundu, 15.3 and 1.2% at Kiswishi and 25.7 and 9.4% at Mikembo). The least represented species were *Phyllocosmus lemaireanus* (0 and 0.3%) at Kibundu, *Hexalobus* monopetalus (0 and 0.3%) at Kiswishi and *Antidesma venosum* (0 and 0.2%) at Mikembo. In addition, specific species were abundant in the understory at each site: *Terminalia brachystemma* (23.1%) at Kibundu, *Bridelia*

TABLE 1. Families of vegetation and their frequencies as represented at the different sites in Miombo woodland in the Democratic Republic of the Congo

Family	Sites					
	Kibundu		Kiswishi		Mikembo	
	UC	SB	UC	SB	UC	SB
Annonaceae	1.48	0.00	1.06	0.59	1.74	0.75
Apocynaceae	**8.87**	**7.64**	**6.38**	**1.95**	**11.30**	**3.38**
Chrysobalanaceae	0.00	0.00	10.64	2.34	0.00	0.75
Clusiaceae	0.00	0.00	0.00	0.39	0.00	0.00
Combretaceae	11.11	22.91	0.00	1.95	3.48	3.00
Dipterocarpaceae	0.00	0.48	15.96	3.13	6.09	0.00
Fabaceae	**55.56**	**41.53**	**41.49**	**53.32**	**64.35**	**54.97**
Hypericaceae	0.00	0.24	0.00	6.45	0.00	0.00
Ixonanthaceae	2.78	0.00	1.06	0.98	0.87	0.75
Lamiaceae	1.39	4.53	0.00	0.00	0.00	0.38
Loganiaceae	0.00	0.95	1.06	0.78	0.00	0.38
Malvaceae	0.00	0.00	0.00	0.98	0.00	0.75
Moraceae	0.00	0.00	1.06	0.39	0.00	0.56
Myrtaceae	0.00	0.72	7.45	0.20	0.00	0.00
Ochnaceae	**2.78**	**11.69**	**1.06**	**5.08**	**1.74**	**2.63**
Oleaceae	0.00	0.00	0.00	3.13	0.00	0.75
Phyllanthaceae	**13.89**	**6.21**	**8.51**	**15.63**	**9.57**	**30.02**
Rhizophoraceae	0.00	0.48	3.19	0.59	0.87	0.00
Rubiaceae	0.00	0.95	1.06	1.95	0.00	0.38
Sapindaceae	1.39	1.67	0.00	0.20	0.00	0.56

UC = Upper Canopy; SB = Understory. Families in bold represent those found in both strata in all the studied sites

duvigneaudii (16.9%) at Mikembo and *Dalbergia boehmii* (12.7%) at Kiswishi.

Stand structure. The structural characteristics of the sites are distinct (Table 1). The sylvigenetic parameters (DBH and H) at all sites show a significant difference between strata with P = 0.0067 in the upper canopy and P = 0.000001 in the understory, for diameter at breast height (DBH); P = 0.00001 in the upper canopy and P = 0.0127 in the understory for Height (H). Consequently, the coefficient of variation (CV) across the sites indicated uneven spatial distribution of tree crowns within strata. Kibundu, with a CV of 102.9%, showed a very widespread in the upper canopy,

The basal area in the understory was highly significant (P = 0.0001), depending on the site (Table 1). However, species richness did not vary significantly (P > 0.05) between strata or sites. The densities of woody species in the upper canopy and understory were, respectively, 140 and 1670 at Kibundu, 380 and 1735 at Kiswishi, and 350 and 2395 at Mikembo (Table 2).

Natural regeneration and site degradation gradient. With a regeneration index greater than unity, natural regeneration in the Lubumbashi plain reflects a state of equilibrium (Table 2). However, it varied from site to site, with Rn = 11.9 at Kibundu, Rn = 6.4 at Mikembo and Rn = 4.8 at Kiswishi (Table 2).

In addition, Kibundu had a higher regeneration index than the other two study sites. However, there were no significant differences (P> 0.05) between the study sites.

The mean disturbance index across study sites was 59% (Table 3). The number of therophytes and chamaephytes increased proportionally (r = 0.50). The highest index was found at Kibundu (74.2%), and the lowest at Mikembo (44.1%). (Table 2). Furthermore, the disproportionate density of individuals in the upper canopy was highly significant, with regards to the study sites.

Impact of the upper canopy on regeneration. For all the sites, the crown diameter classes in the 2.5 to 7.5 m range had the greatest number of regenerating individuals

TABLE 2. Structural characteristics of dendrometry parameters in strata, according to sites in Miombo woodland in the Democratic Republic of the Congo

Sites	Strata	DBH (cm)	H (m)	S. R	G ($m^2.ha^{-1}$)	da (n ha^{-1})	CV (G)%)
Kibundu	UC	24.2±12.9	10.3±4.5	9±2.9	5.8±5.3	140	102.9
	SB	2.9±2.7	1.6±1.2	34±15.2	1.1±0.9	1670	32.4
Kiswishi	UC	23.6±13.2	9.3±3.8	18±3.6	16.6±5.0	380	73.6
	SB	2.2±1.7	2.0±1.1	44±10.1	0.6±0.4	1735	61.5
Mikembo	UC	22.4±11.9	13.1±3.8	15±4.9	13.8±1.6	350	18.4
	SB	2.5±1.9	3.6±7.3	37±33.2	1.2±0.7	2395	72.3
P Value	UC	0.0067**	0.0000***	0.643	0.21	0.374	-
	SB	0.0000***	0.0127*	0.789	0.0001***	0.271	-

*, **, ***: Significance level at P=0.05, respectively; UC = upper canopy, SB = understory, DBH = Diameter at breast height, H = Total height, S.R = Specific richness, G = Basal area= Absolute density (number of individuals/ha), CV (G)% = Coefficient of variation as a function of basal area

TABLE 3. Regeneration and disturbance index values for the three study sites in Miombo woodland in the Democratic Republic of the Congo

Sites	Strata	N	Rn	Biological type	Number	DI (%)
Kibundu	UC	28	11.9	Th + Ch	23	74.2
	SB	334		Total species	31	
Kiswishi	UC	72	4.8	Th + Ch	31	59.6
	SB	347		Total species	52	
Mikembo	UC	70	6.8	Th + Ch	15	44.1
	SB	479		Total species	34	

CS = upper canopy; SB = understory; N = number of trees; Rn = natural regeneration index. Th = Therophytes; Ch = Chamephytes; DI (%) = Disturbance index in the understory, with a density of up to 3,420 stems per hectare (Fig. 1). However, the diameter of the crown of the upper canopy was positively correlated with the density of the understory (Kibundu r = 0.85, Kiswishi r = 0.055 and Mikembo r = 0.77). The intensity of the positive linear correlation was strong at Kibundu and Mikembo, with the correlation coefficient fairly close to 1; while at Kiswishi the correlation was positive, but with a weak linear intensity. There was a significant variation in crown diameter between sites.

DISCUSSION

Vegetation structure

Floristic composition. The dominant presence of the *Fabaceae* family in both strata across the study sites (Table 1), could be attributed to the fact that this family contains species with a wide ecological range, and contains species characteristic of the wet Miombo Woodland (Meerts, 2016). The vegetation structure comprising a total of 1,230 individuals recorded at the three sites, representing 65 species, 45 genera and 20 families (Table 4); imply that the Lubumbashi plain contains a wealth of species richness. These findings are consistent with those of Muledi *et al*., (2016) and Sikuzani *et al*., (2020), who despite observing a high number of individuals, reported relatively few genera and families at Mikembo and Kiswishi, respectively. This could be attributed to the species assemblage patterns in the Lubumbashi plain, as outlined by Muledi *et al*. (2016).

Differences in results from these authors may be due to differences in the methods used and sampling efforts, compared to the present study. However, applying different inventory methods at the same site can yield a richer flora list (Gnahoré *et al*., 2020). This is because the temporary plots are one-off plots and are marked out on the ground by judging the appearance of the vegetation. This method is slightly faster than an inventory based on permanent plots: the centre is not marked, and the position of each tree is not recorded (azimuth, distance). However, such an inventory does not allow certain variables such as growth, quality or the silvicultural treatment applied to be monitored over time.

Furthermore, a comparison of the number of individuals per stratum shows that Mikembo is the richest site in the understory compared to the other sites (Table 2). This could be explained by the fact that this site is subject to a protection mechanism with fencing and total absence of fire, which means that there is a consequent reduction in human activity following controlled access (Nkombe *et al.*, 2023). This favours the development of young shoots in the understory.

In the vegetation structure described above, the presence of 1060 individuals in the understory, distributed among 64 species, 43 genera and 20 families, compared with 170 individuals distributed among 21 species, 17 genera and 15 families in the upper canopy (Table 1); suggests that specific composition is not the same in the two strata. This could be explained by the light tolerance of the species because in addition to underground competition for nutrients, which limits the growth of pioneer species during vegetation succession, light is the second element that can nourish them. Competition for belowground resources is often considered to be symmetric with respect to size, based on the assumption that nutrient uptake is proportional to plant size (Shenkin *et al.*, 2020). In contrast, competition for light is assumed to be asymmetric with respect to size, with larger individuals preying on resources by shading their smaller neighbours and depriving them of light in a manner disproportionate to their size (Vincent and Harja, 2008).

Species diversity between the two strata varied from site to site, with Mikembo hosting more individuals in the understory, including the characteristic species *Triumfetta dekindtiana* and *Terminalia brachystemma* being prominent in Kibundu (Table 4). This can

TABLE 4. Species richness and abundance at the study sites in Miombo woodland in the Democratic Republic of the Congo

No.	Species	Family	Kibundu		Kiswishi		Mikembo	
			CS	SB	CS	SB	CS	SB
1	*Acacia goetzei* Harms subsp	*Fabaceae*	0	0	0	0.3	0	0
2	*Acacia polyacantha* subsp.	*Fabaceae*	0	0	0	2.9	0	0
3	*Afzelia quanzensis* Welw.	*Fabaceae*	0	0.3	0	0	0	0
4	*Albizia adianthifolia* (Schumach.)	*Fabaceae*	0	1.2	6.9	10.7	0	0.4
5	*Albizia antunesiana* Harms	*Fabaceae*	0	0.6	2.8	8.7	0	0
6	*Albizia versicolor* Welw. ex Oliv.	*Fabaceae*	0	5.4	0	0	0	0
7	*Allophylus africanus* P.Beauv.	*Sapindaceae*	0	2.4	0	0	0	0
8	*Anisophyllea boehmii* engl.	*Rhizophoraceae*	0	0.6	0	1.4	0	0.2
9	*Annona senegalensis* Pers.	*Annonaceae*	0	0	0	0.6	0	0
10	*Antidesma venosum* e.Mey. ex Tul.	*Phyllanthaceae*	0	0	0	0	0	0.2
11	*Baphia bequaertii* De Wild.	*Fabaceae*	0	0	4.2	0.3	0	0
12	*Bobgunnia madagascariensis* (Desv.)	*Fabaceae*	7.1	0.3	4.2	0.9	0	0
13	*Brachystegia boehmii* Taub.	*Fabaceae*	7.1	1.8	4.2	0.3	0	0
14	*Brachystegia gossweileri* Davy & Hutch.	*Fabaceae*	0	0	4.2	0	0	0
15	*Brachystegia microphylla* Harms	*Fabaceae*	0	0	0	0	0	0
16	*Brachystegia spiciformis* Benth	*Fabaceae*	35.7	0.3	2.8	1.4	0	4.8
17	*Brachystegia taxifolia* Harms	*Fabaceae*	0	0	0	0	0	5.4
19	*Bridelia duvigneaudii* J.Léonard	*Phyllanthaceae*	0	0.3	0	4.9	0	16.9
20	*Combretum collinum* Fresen. subsp.	*Combretaceae*	0	0	0	1.7	2.9	1
21	*Combretum molle* r.Br. ex G.Don	*Combretaceae*	0	0	0	0.3	0	2.1
22	*Dalbergia boehmii* Taub.	*Fabaceae*	0	5.1	1.4	12.7	2.9	11.7
23	*Diplorhynchus condylocarpon* (Müll.Arg.)	*Apocynaceae*	17.9	5.4	6.9	2.9	17.1	3.1
24	*Erythrophleum africanum* (Welw.) Harms	*Fabaceae*	0	0.3	0	0.6	0	0
25	*Ficus thonningii* Blume	*Moraceae*	0	0	0	0.9	1.4	0.4
26	*Garcinia huillensis* Welw. ex Oliv	*Clusiaceae*	0	0	0	0.6	0	0
27	*Haplocoelum foliolosum* (Hiern)	*Sapindaceae*	0	0	0	0	0	0.2

TABLE 4. Contd.

No.	Species	Family	Kibundu		Kiswishi		Mikembo	
			CS	SB	CS	SB	CS	SB
28	*Harungana madagascariensis* Lam.	*Hypericaceae*	0	0	0	3.2	0	0
29	*Hexalobus monopetalus* (A.rich.) engl.	*Annonaceae*	0	0	0	0.3	1.4	1
30	*Hymenocardia acida* Tul.	*Phyllanthaceae*	0	2.3	0	0	0	0
31	*Isoberlinia angolensis* (Welw. ex Benth.)	*Fabaceae*	0	9	0	0.3	0	0
32	*Julbernardia globiflora* (Benth.) Troupin	*Fabaceae*	7.1	0	0	0.3	8.6	27.4
33	*Julbernardia paniculata* (Benth.) Troupin	*Fabaceae*	10.7	6.3	15.3	1.2	25.7	9.4
34	*Maranthes floribunda* (Baker) F.White	*Chrysobalanaceae*	0	0	0	1.2	0	0
35	*Marquesia macroura* Gilg	*Dipterocarpaceae*	0	0	18.1	1.4	8.6	0
36	*Monotes katangensis* De Wild.	*Dipterocarpaceae*	0	0.6	2.8	3.2	0	0.2
37	*Multidentia crassa* (Hiern)	*Rubiaceae*	0	0	0	0.3	0	0
38	*Ochna afzelii* r.Br. ex Oliv	*Ochnaceae*	0	3.3	0	2.8	0	0
39	*Ochna puberula* N.robs	*Ochnaceae*	0	0	0	1.4	0	2.1
40	*Ochna schweinfurthiana* F.Hoffm.	*Ochnaceae*	0	4.2	0	2.3	1.4	0.2
41	*Parinari curatellifolia* Planch. ex Benth	*Chrysobalanaceae*	0	0	13.9	2	0	0.6
42	*Pericopsis angolensis* (Harms)	*Fabaceae*	0	0	0	2.6	2.9	0.8
43	*Philenoptera katangensis* (De Wild.)	*Fabaceae*	0	0	0	0	1.4	0
44	*Phyllocosmus lemaireanus* (De Wild. & T.Durand)	*Ixonanthaceae*	0	0.3	0	1.4	1.4	0.8
45	*Pseudolachnostylis maprouneifolia* Pax	*Phyllanthaceae*	3.6	3.3	2.8	10.4	4.2	1.5
46	*Psorospermum febrifugum* Spach.	*Hypericaceae*	0	0	0	1.7	0	0
47	*Pterocarpus angolensis* DC	*Fabaceae*	3.6	12.6	0	0	1.4	0
48	*Pterocarpus tinctorius* Welw.	*Fabaceae*	0	0	0	0	12.9	3.1
49	*Rothmannia engleriana* (K.Schum.)	*Rubiaceae*	0	0.9	1.4	1.4	0	0
50	*Rothmannia whitfieldii (*Lindl.) Dandy	*Rubiaceae*	0	0	0	0	0	0.4
51	*Schrebera trichoclada* Welw.	*Oleaceae*	0	0	0	1.7	0	0.6
52	*Senna petersiana* (Bolle) Lock	*Fabaceae*	0	0	0	0	0	0.6
53	*Strychnos cocculoides* Bak.	*Loganiaceae*	0	1.5	0	1.2	0	0.2

TABLE 4. Contd.

No.	Species	Family	Kibundu		Kiswishi		Mikembo	
			CS	SB	CS	SB	CS	SB
54	*Strychnos spinosa* Lam.	*Loganiaceae*	0	0	0	0.3	0	0
55	*Syzygium guineense* (Willd.) DC.	*Myrtaceae*	0	0.9	4.2	1.4	0	0
56	*Terminalia brachystemma* Welw.	*Combretaceae*	7.1	23.1	0	0	0	0
57	*Terminalia mollis* Laws.	*Combretaceae*	0	0.3	0	0	0	0
58	*Triumfetta dekindtiana Engl.*	*Malvaceae*	0	0	0	0	0	0.4
59	*Uapaca kirkiana* Müll.Arg.	*Phyllanthaceae*	0	0	1.4	4.3	0	0
60	*Uapaca nitida* Müll.Arg.	*Phyllanthaceae*	0	1.2	2.8	0.9	5.7	1.9
61	*Uapaca pilosa* Hutch.	*Phyllanthaceae*	0	0.3	0	0.9	0	0.6
62	*Uapaca robynsii* De Wild.	*Phyllanthaceae*	0	0	0	0	0	0
63	*Uvariastrum hexaloboides* (r.e.Fries)	*Phyllanthaceae*	0	1.2	0	0	0	0
64	*Vitex fischeri* Gürke	*Lamiaceae*	0	0	0	0	0	0.4
65	*Vitex madiensis* Oliv. *subsp.* madiensis	*Lamiaceae*	0	1.2	0	0	0	0
66	*Vitex mombassae* Vatke	*Lamiaceae*	0	2.4	0	0	0	0

The total number of individuals is respectively CS: 28, SB: 334 at Kibundu; CS: 72, SB: 347 at Kiswishi and CS: 70, SB: 479 at Mikembo. CS: upper canopy and SB: understory; abundance is expressed as a percentage be explained by the protection system at Mikembo, which, unlike other sites, is entirely fenced off, preventing human activities enchroachment. This observation comforms with that of Nkombe *et al.* (2023), who showed that site protection allows for forest class densification, which is desirable for the restoration of forest ecosystems in the Lubumbashi plain. In Kibundu, however, this may be influenced by differences in edaphic conditions, as *T. brachystemma* typically establishes itself on sandy soils, as confirmed by Meerts and Hasson (2017). Kiswishi had a slightly higher number of individuals in the upper canopy (Table 2), possibly because it is a more mature ecosystem than other sites (Sikuzani *et al.*, 2020).

The dominant families were *Fabaceae*, *Phyllanthaceae*, *Apocynaceae*, *Combretaceae, Chrysobalanaceae, Ochnaceae, Rubiaceae* and *Hypericaeae*; the structure of which suggests that Miombo of the Lubumbashi plain can restore itself only if human activities are reduced and regulated. Sikuzani *et al.* (2020) observed that even though the site is fenced off, it retains a high level of species richness in the open forest and wooded savannah, which is similar to the results found in the present study. This thus, testified to the importance of site protection mechanisms for its restoration and conservation. Across all sites, the *Fabaceae* family remained dominant, followed by *Phyllanthaceae* and *Apocynaceae*.

The dominance of these families is a common phenomenon in the Zambezi region, as reported by Malaisse (2010). Family and species diversity was higher in the understory than in the upper canopy, with *Julbernardia paniculata*, *Diplorhynchus condylocarpon*, *Pseudolachnostylis maprouneifolia* being generic species (Godlee *et al.*, 2020).

Kiswishi stood out with higher species richness in the understory, equaled by Mikembo in the upper canopy (Table 2). This can be attributed to the fact that these two ecosystems have been under threat of total degradation for over two decades (Sikuzani *et al.*, 2020); and are considered to be indicators for monitoring the restoration of the Lubumbashi plain (Bogaert *et al.*, 2018). On the other hand, Kibundu showed low species richness in both strata, due to its proximity to human dwellings and the continuous development of human activities, similar to observations advanced by Gnahoré e*t al.* (2020) at the Youpougon and Abobo sites near Banco National Park in Ivory Coast. Gnahoré e*t al.* (2020) also observed that the environments least subject to impacts are those that are not close to local communities. This shows that the mechanism used to protect a site has an impact on its restoration and composition; otherwise, it encourages its degradation.

Stand structure. The significant difference displayed by the sylvigenetic parameters of two strata, ranging from very significant in the upper canopy to highly significant in the understory for DBH, and the opposite trend for heights (Table 2); are evidence that the level of protection of the sites influences the sylvigenetic parameters within the strata. This could be due to stand of different ages and varying levels of anthropogenic influence across the sites. Several other reports showed that the site effects manifests in disproportionate distributions of structural characteristics (Hakizimana *et al.*, 2012; Adjonou *et al.*, 2016; Gansaonré, 2018).

The basal area was highly significant in the understory (Table 2), likely because density in the understory depends on light availability and management methods (Ducrey and Labbe, 1985; Issoufou *et al.*, 2013; Soulama *et al.*, 2015). The density and spatial distribution of individuals in the understory, expressed by the coefficient of variation, indicate that Mikembo and Kibundu have greater regeneration potential than Kiswishi. This can be attributed to Kibundu's lower upper canopy cover, and the degree of Mikembo degradation before being protected by a fence. Kiswishi has a larger basal area than the other sites because it has been protected for more than five decades, and only in the last two decades have communities encroached on its fringes and even illegally entered the area to harvest non-timber forest products because it is not fenced off. In addition, Kibundu has a lower basal area in the upper canopy due to sporadic logging for charcoal production. Mikembo, on the other hand, continues to densify because of the suppression of human activities within the forest. An observation consistent with Rollet (1983) in tropical forest gaps, where gap size plays a major role in individual establishment. Moreover, regeneration potential is related to individual density spatial distribution according to Hakizimana *et al.*, (2011).

The number of seedlings obtained at different sites confirms that they had balanced regeneration potential (Nghonda *et al.*, 2024). Therefore, the parameter influencing natural regeneration from one site to another remains the protection mechanism. Protection with fencing appears to be a good means of protection, since it allows the conservation of a large number of individual trees, because despite the fact that Kibundu indicates the presence of many young trees and seedlings that can grow in the forest, most of them die quickly, leaving a few trees with an average size of 24 cm (Table 2), and even fewer large and very large trees, as observed by White and Edwards (2000) in African rain forests. Thus, an increase in diameter at breast height has a negative influence on trees density in terms of individuals per unit area, which is the case at Kiswishi.

Natural regeneration and disturbance gradient. The high correlation of regeneration index and disturbance index in this study, was likely due to differing levels of Anthropization, which indicates a different disturbance gradient between the sites; testified by the higher presence of therophyte and chamaephyte species; proof of significant anthropisation of the sites depending on the level of protection (Aboubacar *et al.*, 2023; Gnahoré *et al.*, 2020).

These biological types are typically the first to establish after minimal anthropogenic disturbance (Sirvent, 2020a, b). The fenced site (Mikembo) shows a lower level of disturbance than the unfenced site (Kiswishi) and the site under the management of local communities (Kibundu). This means that Kibundu is very open compared with the others and has a higher degree of degradation through increased local community harvesting (Table 3).

Furthermore, differences in the regeneration index could be attributed to variations in site protection and exploitation methods. According to Aboubacar *et al*. (2023), regeneration index varies depending on the protection and maintenance system in place. Kibundu site, despite its status as a community forest under Decree-Law No 14/018 of August 2, 2014, concerning local community-based management, has a higher regeneration index compared to Mikembo and Kiswishi sites, which have been protected for over two decades (Nkombe *et al.*, 2023). This is likely due to the low density in Kibundu's upper canopy, resulting from the loss of mature trees used for charcoal production and other purposes. This reduces canopy cover and facilitates regenerate establishment (Lomalisa *et al.*, 2022; Aboubacar *et al.*, 2023). Moreover, Mikembo site had a higher regeneration index than Kiswishi, despite the lower disturbance rate of the former, as it was fully fenced with regulated access, unlike Kiswishi site, which had free access, without fencing.

The proximity of Kiswishi to settlements increases the number of therophytes and chamaephytes, while these species are systematically suppressed in the Mikembo reserve; noting a 23% reduction in therophytes in the Mikembo site between 2017 and 2023. Gnahoré *et al.* (2020) observed a similar pattern in Ivory Coast, He found that the Youpougon and Abobo sites had a high disturbance index, more so than the Adjamé and Attécoubé sites, because the former remain very open areas, easily accessible to local communities who infiltrate them with illegal activities, while the latter are well protected and far from incursions by local communities. This shows that there is a causal relationship between the regeneration potential of a site and the degree to which it has been disturbed; and suggests that fencing is the best method for densifying forest ecosystems on the Lubumbashi plain and for promoting natural regeneration, as colloborated earlier by Muledi *et al*. (2016) and later by Nkombe *et al*. (2023). This could facilitate the return of ecosystem services that were previously suppressed but remain essential for local communities.

Impact of the upper canopy on regeneration. The observation that the upper canopy significantly influences the density of regenerating plants in the understory, primarily through the crown diameter (Fig. 2), revealed the fact that regenerates tend to cluster in areas where the crown is narrower, suggesting that these plants in the Lubumbashi plain are highly tolerant to light. Similar findings were observed by Hakizimana *et al*. (2011) in the open forest of Rumonge in Burundi, where the concentration of individuals decreased as crown diameter increased with tree height.

Across all the study sites, the density of regenerates was highest in areas with intermediate crown diameters (Fig. 2), indicating a moderate degree of canopy openings for successful establishment. However, it should be noted that the influence of crown diameter on understory density varied proportionally, with the total height of the trees, which suggests that the upper canopy has a significant influence on regeneration in the understory. Indeed, the diameter classes of the upper canopy crown showed a highly significant difference between the sites and demonstrated a positive correlation ($r = 0.751$) with the average total heights of the trees in each site ($P = 0.0157$). This corroborates the results found earlier by Hakizimana *et al*, (2011) and later by Lomalisa *et al*, (2022), showing that the structure of a forest and the degree of canopy openness influence the species' richness and density of trees growing in the understory. Mikembo and Kibundu show a better correlation between crown diameter and density of regenerates in the understory than Kiswishi; this could be explained by the fact that Kiswishi has an ageing physiognomy than the other two sites. This also refers to the fact that Mikembo would have had a very advanced level of disturbance before being protected by a fence and away from any harvesting as reported by Nkombe *et al*. (2023). Furthermore, this demonstrates the influence of site protection mechanisms on the development of crown diameters and, in turn, that of the level of disturbance on the density of regenerates in the understory.

CONCLUSION

This study has provided insights into the characteristics of plant regeneration in miombo woodland of the Democratic Republique of Congo. Clearly, protection mechanisms influence regeneration, in this ecosystem. The fencing at Mikembo has allowed the re-growth of vegetation and the removal of evidence of human disturbance; at Kiswishi, protection without fencing has allowed the vegetation to move towards a climatic state, but continued access by riverine communities is undermining these efforts by increasing the level of disturbance.

On the other hand, at Kibundu, continued harvesting by local communities is limiting the vegetation's tendency to mature and increasing the level of disturbance; as a result, much of the vegetation is regenerating. However, human activity acts as a limiting factor, causing imbalances in the floristic composition of the different vegetation strata. Protecting a site with fencing appears to be a highly effective strategy for restoring the Lubumbashi plain, as it promotes natural regeneration by minimising anthropogenic disturbances, although this puts the economic cost of the process contestable. Conversely, unrestricted access to sites leads to sporadic wood cutting, which significantly reduces the number of trees in the upper canopy, thereby benefiting regeneration in the understory.

The gradual loss of mature trees reduces species diversity in the upper canopy and, consequently, hinders seminal regeneration in the understory. Across all the sites evaluated, only the *Apocynaceae, Fabaceae*, *Ochnaceae*, and *Phyllanthaceae* families were found to regenerate well in both the upper canopy and understory. Other families were unevenly represented and sometimes entirely absent in one of the strata. Overall, the regeneration index exceeded unity at each site, suggesting a state of equilibrium. However, this was counterbalanced by an increase in the disturbance index, which reflects degradation of the plant cover and a shift from forest formations to more degraded states. The observed disturbance rates also indicated that Kibundu and Kiswishi sites were the most open sites, making them more susceptible to ongoing human pressure.

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REFERENCES

Aboubacar, A., Baggenian, I., Laouvali, A., et Guimbo, I. D. 2023. Caractéristiques de la régénération naturelle de la végétation contractée des plateaux de l ' ouest du Niger suivant les gradients pluviométrique et d'anthropisation regeneration characteristics of contracted vegetation in Western Niger. *Eruropean Scientific Journal* 19(5):74-93. https://doi.org/10.19044/esj.2023.v19n30p74.

Adjonou, K., Radji, A.R. and Kokutse, A.D. 2016. Considération des caractéristiques structurales comme indicateurs écologiques d'aménagement forestier au Togo (Afrique de l'Ouest). *VertigO* 16(2): 1-16.

Ayessa, L., Koubouana, F., Ndzai, S. F., Mbete, P., Foly Mpela, G., Mikoungui Gomo, M.-S., Mboukou, M. et Douh, C. 2022. Etude floristique et structurale d'une forêt mixte a l'Ile M'bamou, République du Congo. *European Scientific Journal* 18(17):50-67 https://doi.org/10.19044/esj.2022.v18n17p50.

Baraka, P., Dhital, N., Asselin, H., Kibambe, J., Semeki, J. and Khasa, D.P. 2022. Local citizen group dynamics in the implementation of community forest concessions in the Democratic Republic of Congo. *Forest Policy and Economics* 136:1-11. https://doi.org/. https://doi.org/10.1016/j.forpol.2021.102680.

Beaumont, L.J., Pitman, A., Perkins, S., Zimmermann, N.E., Yoccoz, N. G. and Thuiller, W. 2011. Impacts of climate change on the world's most exceptional ecoregions. *Proceedings of the National Academy of Sciences of the United States of America*, 108(6):2306-2311. https://doi.org/10.1073/pnas.1007217108.

Bogaert, J., Colinet, G. and Mahy, G. 2018. Anthropisation des paysages katangais. Edited by Presse Universitaires de Liège. Gembloux: Presses universitaires de Liège-Agronomie-Gembloux. https://doi.org/D/2018/1665/147.

Cabala, K.S., Sikuzani, Y.U. and Munyemba Kankumbi, F. 2018). Activités anthropiques et dynamique spatiotemporelle de la forêt claire dans la Plaine de Lubumbashi.In: Bogaert, J., Mahy, G. and Colinet, G (Eds.). *Anthropisation des paysages katangais*. Presse Uni. Gembloux: Presses universitaires de Liège-Agronomie-Gembloux. pp. 253-266. https://doi.org/D/2018/1665/147.

Cabala, K.S., Sikuzani, Y.U. and Mwana, Y.A. 2018. Analyse structurale de la dynamique forestière dans la région de l 'Arc Cuprifère Katangais en République Démocratique du Congo/ : II . Analyse complémentaire de la fragmentation forestière. *Tropicultura* 36(4):621-630.

Chidumayo, E.N. 2009. Climate and phenology of savanna vegetation in southern Africa. *Journal of Vegetation Science* 12(3): 347-354.

Dubiez, E., Gazull, L., Okwe, A.N., Nkulu, J. et Péroches, A. 2020. Rapport d'étude de la consommation en énergies de production des usagers productifs de la ville de Lubumbashi, Cirad, Paris, France. 44pp.

Ducrey, M. et Labbe, P. 1985. Etude de la régénération naturelle controlée en forêt tropicale humide de Guadeloupe. *Annales Des Sciences Forestières* 42(3):297-322.

FAO. 2020. Global Forest Resources Assessment, Key findings. Edited by FAO. Rome, Italy. https://doi.org/https://doi.org/10.4060/ca8753en.

Frederique, M., Nourtier, M., Grinand, C. et Mercier, C. 2019. Miombo woodland regeneration dynamics after slash and burn agriculture in Mozambique', *XXV IUFRO Wold Congress*. 15pp.

Frost, P. 1996. The ecology of Miombo Woodlands. *The Miombo in Transition: Woodlands and Welfare in Africa*, (January 1996). 266pp. http://books.google.com/books?hl=nl&lr=&id=rpildJJVdU4C&pgis=1.

Gansaonré, R.N. 2018. Dynamique du couvert végétal et implications socio-environnementales à la périphérie du parc W/Burkina Faso. *VertigO* [Preprint], (Volume 18 numéro 1). https://doi.org/10.4000/vertigo.20249.

Gnahoré, E., Koné, M., Soro, Y., N'guessan, Y. J. et Bakayoko, A. 2020. Effets de l'anthropisation sur la diversité floristique à la périphérie du Parc National du Banco , Abidjan , Côte d ' Ivoire Résumé', *Afrique SCIENCE* 16:167-180.

Godlee, J.L., Gonçalves, F.M., Tchamba, J.J., Chisingui, A.V., Muledi, J.I., Shutcha, M.N., Ryan, C.M., Brade, T.K. and Dexter, K.G. 2020. Diversity and structure of an arid woodland in Southwest Angola, with comparison to the wider miombo ecoregion. *Diversity* 12(4):1-20. https://doi.org/10.3390/D12040140.

Hakizimana, P., Bangirinama, F. et Havyarimana, F. 2011. Analyse de l'effet de la structure spatiale des arbres sur la régénération naturelle de la forêt claire de Rumonge au Burundi. *Bulletin Scientifique de l'institut National Pour l'environnement et Conservation de La Nature* 6973(9):46-52.

Hakizimana, P., Bangirinama, F., Masharabu, T., Habonimana, B., De Cannière, C. et Bogaert, J. 2012. Caractérisation de la végétation de la forêt dense de Kigwena et de la forêt claire de Rumonge au Burundi. *Bois & Forets Des Tropiques* 312(312):43. https://doi.org/10.19182/bft2012.312.a20502.

Issoufou, B., Moustapha, A. M., Toudou, A., et Ali, M. 2013. Impact des modes de gestion de la Régénération Naturelle Assistée des ligneux (RNA) sur la résilience des écosystèmes dans le Centre-Sud du Niger. *Journal of Applied Biosciences* 71(11):5742-5752. https://doi.org/https://dx.doi.org/10.4314/jab.v71i1.98819.

Kaleba, S.C., Sikuzani, Y.U., Sambieni, K.R., Bogaert, J. et Kankumbi, F.M. 2017. Dynamique des écosystémes forestiers de I'Arc Cuprifére Katangais en République Démocratique du Congo. I. Causes, transformations spatiales et ampleur. *Tropicultura* 35(3):192-202.

Kouadio, C.K.N., Koulibaly, A., Coulibaly, S., Boko, B.B., Dramane, K.B., Diomande, V.A. et Kouadio, Y.J. 2021. Potentiel de régénératio naturelle des espèces ligneuses associées dans les agrosystèmes Cacaoyers traditionnels de la zonne rurale de Djekro (Dalao, Côte d'ivoire. *Agronomie Africaine* 33(1):97-108.

Lehmann, C.E.R., Archibald, S., Vorontsova, M.S., Hempson, G.P. and Wieczorkowski, J.D. 2022. Global Grassy Group guide to understanding and measuring the functional and taxonomic composition of ground layer plants. 22pp.

Linder, H.P., Harris, D.J. and Botanic, R. 2014. The evolution of African plant diversity. *Frontiers* 2:1-14. https://doi.org/10.3389/fevo.2014.00038.

Lomalisa, R.K., Malale, H.N. seya wa, Lofumbo, G.L. et Mokoso, J. de D.M. 2022. Analyse de la régénération naturelle dans le Bassin du Congo/ : cas de Guarea cedrata (A . Chev .) Pellegr . dans les massifs forestiers de la Cuvette centrale de Yoko et de Yangambi. *Geo-Eco-Trop* 46(3):389-401.

Malaisse, F., Malaisse-Mousset, M. and Schorochoff, G. 1978. Analyse de la pluviosité à Lubumbasshi et dans ses environs immédiats/ : Contribution à l'écosystème forêt claire (Miombo). *Geo-Eco-Trop* 2(3):301-315.

Malaisse, F. 2010. 'L ' homme dans la forêt claire zambezienne. Contribution à l'étude de l'écosystème forêt claire (Miombo). *African Studies Program at the University of Wisconsin-Madison* 7:38-64.

Malaisse, F. 2018. Le Katanga , une mosaïque d ' écosystèmes en mutation/ : une approche globale. In: *Anthropisation des paysages Katangais*. pp. 1-82.

Marc, J., Kyalamakasa, K., Mpundu, M., Mulambi, M., Kasongo, E., Mukonzo, L., Shutcha, M. N., Tekeu, H., Nkombe, A. K., and Khasa, D. 2021. Early selection of tree species for regeneration in degraded woodland of Southeastern Congo Basin. *MDPI Forests* 12:1-17. https://doi.org/https://doi.org/10.3390/f12020117.

Meerts, P. 2016. An annotated checklist to the trees and shrubs of the upper Katanga (D.R. Congo). *Phytotaxa* 258(3):201-250. https://doi.org/10.11646/phytotaxa.258.3.1.

Meerts, P. and Hasson, M. 2017. Arbres et arbustes du Haut-Katanga. Editions Jardin Botanique de Meise. 386pp.

Mograbi, P., Godlee, J., Ryan, C., Archibald, S., Ang, R., Benitez, L., Buluma, M., Elifuraha, E., Kathambi, V., Kalugasha, J., Lissu, N. M., Maina, W., Mogonong, B., and Nyamugadza, E. 2022. SEOSAW herbaceous sampling protocol. 28pp. https://doi.org/https://globalgrassygroup.github.io/protocol/.

Muledi, I. J., Bauman, D., Drouet, T., Vleminckx, J., Jacobs, A., Lejoly, J., Meerts, P. and Shutcha, M.N. 2016. Fine-scale habitats influence tree species assemblage in a miombo forest. *Journal of Plant Ecology* 4:1-12. https://doi.org/10.1093/jpe/rtw104.

Muledi, J.I. 2017. Ecologie fonctionnelle et dendroécologie d ' une forêt claire de la plaine de Lubumbashi (Haut-Katanga/ ; République démocratique du Congo), PhD Thesis. University de Lubumbashi, DR Congo. 399pp.

Murhula, S.I. 2021. Dynamique paysagère et caractérisation des peuplements forestiers dans les concessions forestières des communautés locales du Haut-Katanga en République Démocratique du Congo, M.Sc. Thesis Université de Lubumbashi, DR Congo. 81pp.

Muteya, H.K., Nghonda, D.N., Kalenda, F.M., Strammer, H., Kankumbi, F.M., Malaisse, F., Bastin, J.-F., Sikuzani, Y. U. and Bogaert, J. 2023. Mapping and quantification of Miombo deforestation in the extent and changes between 1990 and 2022. *Land* 12:2-23. https://doi.org/10.3390/land12101852.

Nghonda, D.N. 2023. Socio-economic value and availability of plant-based non-timber forest products (NTFPs) within the charcoal production basin of the city of Lubumbashi (DR Congo). *Preprints*

Volume? 1-20. https://doi.org/10.20944/preprints202309.1127.v1.

Nghonda, D.N., Muteya, H.K., Salomon, W., Mushagalusa, F.C., Malaisse, F., Ponette, Q., Sikuzani, Y.U., Kalenga, W.M. and Bogaert, J. 2024. Floristic diversity and natural regeneration of Miombo Woodlands in the rural area of Lubumbashi, D.R. Congo. *MDPI Diversity* 16(405):19. https://doi.org/10.3390/d16070405.

Nkombe, A.K., Simeon, K.M., Urbain, M.T., and Joel, L.L. 2023. Dynamics of the forest landscape in the Mikembo sanctuary/ : 20 years after it's creation as a flora and fauna conservation reserve, Upper-Katanga, DR Congo. *Environment & Ecosystem Science* 7:54-60. https://doi.org/10.26480/ees.02.2023.54.60.

Olson, D.M. and Dinerstein, E. 2002. The global 200: Priority ecoregions for global conservation. *Annals of the Missouri Botanical Garden* 89(2):199-224. https://doi.org/10.2307/3298564.

Ouédraogo, A., Thiombiano, A., Hahn-Hadjali, K. et Guinko, S. 2006. Diagnostic de l ' état de dégradation des peuplements de quatre espèces ligneuses en zone soudanienne du Burkina Faso. *Secheresse* 17:485-491. https://doi.org/10.1684/sec.2006.0058.

Ponge, J.-F., André, J., Bernier, N. et Gallet, C. 1994. La régénération naturelle: connaissances actuelles. Le cas de l'épicéa en forêt de Macot (Savoie). *Revue Forestière Française* 1:25-45. https://doi.org/10.4267/2042/26510

Pont, D. 2006. Conséquences du changement global sur la distribution et la démographie du Chabot (Cottus gobio)/ : une aproche intégrative. In: *Biodiversité Et Changement Global*. Paris: IFB-GICC. pp. 28-36.

Rollet, B. 1983. La régénération naturelle dans les trouées/ : un processus général de la dynamique des forêts tropicales humides. *Bois et Forêts des Tropiques* 201(3): 1-30.

Rondeux, J. 2021. La mesure des arbres et des peuplements forestiers. Liège: Presses Agronomiques de Gembloux. 738pp.

Shenkin, A., Bentley, L.P., Oliveras, I., Salinas, N., Adu-Bredu, S., Marimon-Junior, B.H., Marimon, B.S., Peprah, T., Choque, E.L., Trujillo Rodriguez, L., Clemente Arenas, E.R., Adonteng, C., Seidu, J., Passos, F.B., Reis, S.M., Blonder, B., Silman, M., Enquist, B. J., Asner, G.P. and Malhi, Y. 2020. The influence of ecosystem and phylogeny on tropical tree crown size and shape. *Frontiers in Forests and Global Change* 3:1-19. https://doi.org/10.3389/ffgc.2020.501757.

Sikuzani, Y.U., Malaisse, F., Kaleba, S.C., Kankumbi, F.M., et Bogaert, J. 2017. Le rayon de déforestation autour de la ville de Lubumbashi (Haut-Katanga, R.D. Congo): Synthèse. *Tropicultura* 35(3):215-221.

Sikuzani, Y.U., Boisson, S., Kaleba, S.C., Khonde, C.N., Malaisse, F., Halleux, J.-M., Bogaert, J. et Kankumbi, F.M. 2019. Dynamique de l'occupation du sol autour des sites miniers le long du gradient urbain-rural de la ville de Lubumbashi, RD Congo. *Base* 24(1):14-27. https://doi.org/10.25518/1780-4507.18306.

Sikuzani, Y.U., Muteya, K., Langunu, S., Alipade, E. et Kankumbi, M. 2020. Strucure des peuplements des formations végétales d'un paysage protégé en zone périurbaine de la ville de Lubumbashi (RD Congo). *Geo-Eco-Trop* 44(1):1-13.

Sikuzani, Y.U., Mukenza, M., Malaisse, F. and Kaseya, P.K. 2023. The spatiotemporal changing dynamics of Miombo deforestation and illegal human activities for forest fire in Kundelungu National Park, Democratic Republic of the Congo. *MDPI fire* 6:2-21. https://doi.org/10.3390/fire6050174.

Sikuzani, Y.U., Muteya, K., Mleci, J.Y. and Mukenza, M. 2024. Ecologies the restoration of degraded landscapes along the urban - rural gradient of Lubumbashi

City (Democratic Republic of the Congo) by Acacia auriculiformis plantations: Their spatial dynamics and impact on plant diversity. *MDPI Ecologies*. 5:25-41. https://doi.org/10.3390/ecologies 5010002.

Sirvent, L. 2020a. L'essentiel des types biologiques/ : Clé de détermination et glossaire', *Concervatoire botanique national méditerranéen de Poquerolles*. HYERES. 11pp. https://doi.org/10.13140/RG.2.2.12996.17281.

Sirvent, L. 2020b. Les types biologiques/ : Etat de l'art, actualisation des définitions et mise en place d'un référentiel. Concervatoire botanique national méditerranéen de Poquerolles. *HYERES*. 64pp. https://doi.org/10.13140/RG.2.2.14673.89440.

Soulama, S., Kadeba, A., Nacoulma, B., Traore, S., Bachmann, Y. et Thiombiano, A. 2015. Impact des activités anthropiques sur la dynamique de la végétation de la réserve partielle de faune de Pama et de ses périphéries (sud-est du Burkina Faso) dans un contexte de variabilité climatique. *Journal of Applied Biosciences* 87(1): 8047-8064. https://doi.org/10.4314/jab.v87i1.6.

Vincent, G. and Harja, D. 2008. Exploring ecological significance of tree crown plasticity through three-dimensional modelling. *Annals of Botany* 101(8): 1221-1231. https://doi.org/10.1093/aob/mcm189.

Wa Ngoy Kashiki, B.K., De Kesel, A., Kabange Mukala, E., Bostoen, K. and Degreef, J. 2021. Edible fungi consumed by the lamba and bemba people of haut-Katanga (DR Congo). *European Journal of Agriculture and Food Sciences* 3(3):41-46. https://doi.org/10.24018/ejfood.2021. 3.3.289.

White, L. and Edwards, A. 2000. Conservation research in the African rain forests: A technical handbook. Wildlife Conservation Society. Edited by L.W.& A. Edwards. New York, USA. 444pp.