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Floristic Diversity, Forest Structure and Above-ground Carbon Stocks of the Mbamba Forest, Kwilu Province, Democratic Republic of the Congo

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Graphical Abstract

This study characterizes the floristic diversity, forest structure and above-ground carbon stocks of the Mbamba forest. The results reveal high floristic diversity and structural heterogeneity, with distinct floristic groups and a strong contribution of dominant species to forest structure. The forest also stores substantial above-ground biomass and carbon, highlighting its ecological importance and the need to conserve floristic diversity, structurally important species and large trees.



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Abstract: This study characterizes the floristic diversity, forest structure and above-ground carbon stocks of the forest within the Sisters of Mary concession in Mbamba, Kwilu Province, Democratic Republic of the Congo. The inventory was conducted in 18 plots of 25 × 25 m, covering 1.125 ha. It recorded 536 woody individuals belonging to 101 taxa and 32 families, with high floristic diversity (H' = 3.701; Simpson = 0.942; Pielou = 0.802). *Staudtia kamerunensis*, *Dichostemma glaucescens* and *Brachystegia laurentii* accounted for 34.70% of individuals, and stems of 10–30 cm diameter represented 75.1%. Multivariate analyses distinguished two floristic groups, with differences in composition (PERMANOVA: pseudo-$F_{1,16}$ = 4.216; R^2 = 0.209; p < 0.001) and dispersion (PERMDISP: $F_{1,16}$ = 8.501; p = 0.010). Mean above-ground biomass was 423.24 ± 77.50 Mg ha^{-1}, corresponding to 198.92 ± 36.43 Mg C ha^{-1}. These results highlight a floristically diverse forest with substantial above-ground biomass and carbon stocks, supporting its conservation and temporal monitoring.

Keywords: *Floristic diversity, Forest structure, Above-ground carbon stocks*

Introduction

African tropical forests are major reservoirs of biodiversity and carbon. Congo Basin forests store considerable carbon, but their net sink function is increasingly threatened by socio-economic and climatic pressures [1].

The Democratic Republic of the Congo (DRC) contains the largest share of Congo Basin forests, yet data on diversity, structure and carbon stocks remain geographically uneven. Forest–savannah transition zones are particularly under-documented despite agriculture, fuelwood use, fires and fragmentation [2,3].

Kwilu forests occur in this transitional context, where floristic composition and structure influence biomass [4]. In African tropical forests, biomass may be concentrated in a few dominant species or large trees [5,6], depending on tree size, density, basal area, wood density and species composition [7].

The Mbamba forest in the Sisters of Mary concession retains well-developed woody vegetation, but its floristic composition, structure and above-ground carbon stocks remain poorly quantified.

This study characterizes floristic diversity, forest structure and above-ground carbon stocks, identifies floristic groups and characteristic species, and quantifies biomass and carbon.

Materials and Methods

Study Area

The study was conducted in the Sisters of Mary concession forest at Mbamba, Imbongo Sector, Bulungu Territory, Kwilu Province, DRC (Figure 1).

The region has a tropical climate, with a rainy season mainly from August to May and a dry season from May to August. Annual rainfall is about 1,600 mm and mean relative humidity 78% [4]. Soils are mainly sandy to sandy-clayey over sandstone substrates [8,9].

The site belongs to the Guineo-Congolian domain within a forest–savannah mosaic. Masens *et al.* [4] reported terra firme forests dominated by *Brachystegia laurentii.*

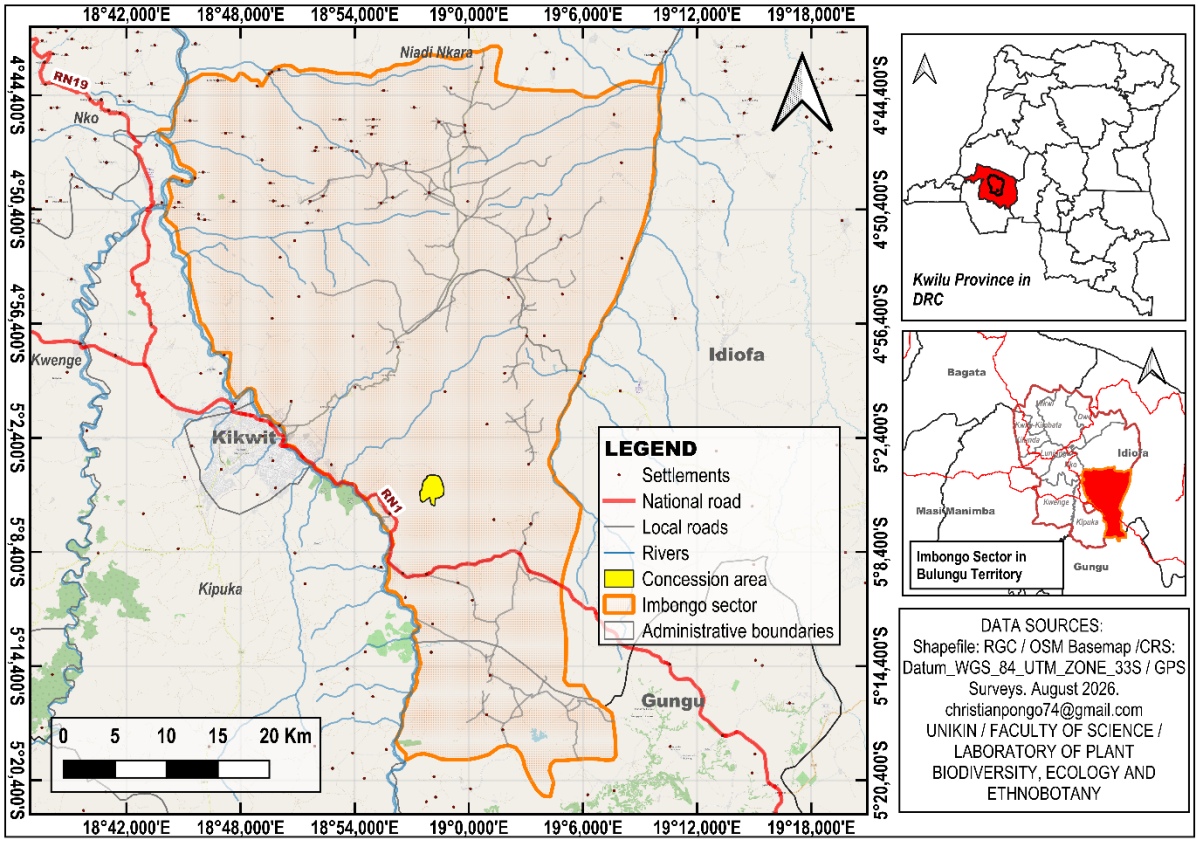


Figure 1. Location of the forest within the Sisters of Mary concession in Mbamba, Kwilu Province, Democratic Republic of the Congo.

Sampling Design and Data Collection

Following a preliminary survey, 18 purposively selected 25 × 25 m plots (625 m²) were established across forest sectors representing physiognomic variability, but avoiding edges, tracks, savannahs and recently disturbed areas. All woody individuals with DBH ≥ 10 cm were inventoried and identified to species level when possible using botanical expertise and taxonomic references.

Trunk circumference was measured at 1.30 m above ground, or immediately above buttresses, swellings or deformities, following tropical forest inventory recommendations [10,11]. Diameter at breast height (DBH) was then calculated from circumference using the following formula (1)

$$DHP = \frac{C}{\pi} \quad (1)$$

where **C** represents the trunk circumference (cm) and $\boldsymbol{\pi}$ **= 3.1416**

Floristic Diversity and Structural Parameters

Species richness was the number of taxa recorded at site and plot levels. Floristic diversity was quantified using Shannon–Wiener, Simpson and Pielou indices [12]. The Shannon–Wiener index (H') was calculated as follows (2) :

$$H' = -\sum_{i=1}^{S} p_i \, ln(p_i) \quad (2)$$

where S represents the total number of species and p_i the proportion of individuals belonging to species i. Simpson's diversity index ($1-D$) was expressed as follows (3):

$$1 - D = 1 - \sum_{i=1}^{S} p_i^2 \quad (3)$$

Pielou's evenness (J') was obtained as follows (4):

$$J' = \frac{H'}{ln(S)} \quad (4)$$

These indices described diversity and evenness. Sampling representativeness was examined with a species accumulation curve based on cumulative richness across plots. Because each plot covered 0.0625 ha, richness was expressed against the cumulative sampled area.

Stand structure was described using density, diameter distribution and basal area [10]. Density (D) was calculated as follows (5):

$$D = N/S \quad (5)$$

where N corresponds to the number of trees recorded and S to the sampled area in hectares. The individual basal area (ST_i) was calculated from DBH as follows (6):

$$ST_i = \frac{\pi \, DHP^2}{4} \quad (6)$$

with DBH expressed in metres. The basal area of the stand (ST) was then obtained by summing the individual basal areas and expressing the result per hectare (7):

$$ST = \frac{\sum \quad ST_i}{S} \quad (7)$$

and expressed in $m^2\ ha^{-1}$. Diameter-class distributions described horizontal stand structure.

The structural role of species was assessed through relative density, relative dominance, relative frequency and the Importance Value Index [13]. Relative density (DR_i) was calculated as follows (8):

$$DR_i = \frac{N_i}{N} \, x \, 100 \quad (8)$$

Relative dominance (DoR_i) was obtained from basal area (9):

$$DoR_i = \frac{ST_i}{ST_{total}} \, x \, 100 \quad (9)$$

Relative frequency (FR_i) was calculated as follows (10):

$$FR_i = \frac{F_i}{\sum \quad F_i} \, x \, 100 \quad (10)$$

The Importance Value Index was then obtained by adding these three components (11):

$$IVI_i = DR_i + DoR_i + FR_i \quad (11)$$

This index made it possible to identify the species playing the most important role in the structure of the stand.

Analysis of Floristic Structure

The floristic structure of the plots was explored using hierarchical cluster analysis (HCA) based on Bray–Curtis dissimilarities calculated from species abundances [14]. A second classification based on the Jaccard index, after transforming abundance data into presence–absence data, was performed to assess the stability of the groupings when only species occurrence was considered.

Variation in floristic composition among plots was examined using NMDS (Non-metric Multidimensional Scaling) based on Bray–Curtis dissimilarities [15,16]. A DCA (Detrended Correspondence Analysis) was used as a complementary approach to characterize the main gradients of floristic variation.

Differences in floristic composition between groups were tested using PERMANOVA, based on Bray–Curtis dissimilarities and 9,999 permutations [17]. Homogeneity of multivariate dispersions was assessed in parallel using PERMDISP, based on the distances of plots from the centroid of their respective group [18].

Species characteristic of the floristic groups were identified using IndVal analysis, which combines species specificity and fidelity to groups **[19].** A SIMPER (Similarity Percentage) analysis, based on Bray–Curtis dissimilarities, was then used to identify the species contributing most to the differentiation between groups.

Estimation of Biomass and Carbon Stock

Individual above-ground biomass was estimated using an allometric equation developed by Fayolle *et al.* [20] for trees in African tropical forests, incorporating diameter and wood density:

$$\mathbf{AGB_p = \exp\left[0.046 + 1.156 \log(\rho) + 1.123 \log(DHP) + 0.436 (\log(DHP))^2 - 0.045 (\log(DHP))^3\right]} \quad (12)$$

where ***AGBp*** represents the above-ground biomass of the tree (kg), ***DBH*** the diameter at breast height (cm), $\boldsymbol{\rho}$ the wood density (g cm^{-3}), ***log*** the natural logarithm, and ***exp*** the exponential function. Wood density (ρ, g cm^{-3}) was assigned to each taxon using the `getWoodDensity()` function of the R package BIOMASS, based on the Global Wood Density Database v.2 [21,22]. Total above-ground biomass was obtained by summing the individual biomass values of all trees recorded in the plots and was then converted into tonnes per hectare (t/ha) [4].

Above-ground carbon stock (*C*) was estimated from above-ground biomass (*AGB*), considering a carbon fraction of 0.47 (13).

$$\mathbf{C = AGB \times 0{,}47} \quad (13)$$

where *C* represents the above-ground carbon stock (Mg C ha^{-1}) and *AGB* the above-ground biomass (Mg ha^{-1}). Total carbon stock was obtained by summing the individual carbon stocks of all trees recorded in the plots. The CO_2 equivalent was then calculated from the ratio of the molecular masses of CO_2 and carbon (14):

$$CO_{2eq} = C \; x \; 3{,}667 \quad (14)$$

The results were expressed in Mg ha^{-1} for above-ground biomass, Mg C ha^{-1} for carbon stock and Mg CO_2 ha^{-1} for CO_2 equivalent.

Statistical Analyses

Analyses were performed in R 4.6.1. Quantitative variables were summarized by mean, standard deviation, median, range and coefficient of variation. Vegan [23] was used for multivariate analyses; indicspecies for IndVal; car for Levene's test; effectsize for Hedges' g; stats for UPGMA; dendextend [24] for dendrograms; and ggplot2/ggrepel for graphics. Floristic groups were compared for richness, density, basal area and AGB.

Results

Floristic Composition and Diversity

A total of 536 woody individuals belonging to 101 taxa and 32 families were recorded in the 1.125 ha sampled area. *Staudtia kamerunensis* was the most abundant species, with 90 individuals (16.79%), followed by *Dichostemma glaucescens* with 73 individuals (13.62%) and *Brachystegia laurentii* with 23 individuals (4.29%). Together, these three species represented 34.70% of the recorded individuals. Seventy taxa were represented by fewer than five individuals and together accounted for 21.08% of the total abundance (Table 1).

Table 1. Relative abundance and density of the main woody species

Species	No. of individuals	Relative abundance (%)	Density (individuals ha^{-1})
Staudtia kamerunensis Warb.	90	16.79	80.00
Dichostemma glaucescens Pierre	73	13.62	64.89
Brachystegia laurentii (De Wild.) Hoyle	23	4.29	20.44
Anisophyllea polyneura Engl.	16	2.99	14.22
Mammea africana Sabine	15	2.80	13.33
Parinari excelsa Sabine	15	2.80	13.33
Pentadesma butyracea Sabine	13	2.43	11.56
Scorodophloeus zenkeri Harms	13	2.43	11.56
Xylopia staudtii Engl. & Diels	13	2.43	11.56
Sacoglottis gabonensis (Baill.) Urb.	12	2.24	10.67
Tessmannia africana Harms	12	2.24	10.67
Lophira alata Banks ex C.F.Gaertn.	9	1.68	8.00
Maranthes chrysophylla (Oliv.) Prance	9	1.68	8.00
Symphonia globulifera L.f.	9	1.68	8.00
Distemonanthus benthamianus Baill.	8	1.49	7.11
Scyphocephalium mannii (Benth.) Warb.	8	1.49	7.11
Strombosia pustulata Oliv.	8	1.49	7.11
Xylopia hypolampra Mildbr.	8	1.49	7.11
Detarium macrocarpum Harms	6	1.12	5.33
Hannoa klaineana Pierre & Engl.	6	1.12	5.33
Prioria balsamifera (Vermoesen) Breteler	6	1.12	5.33

Pterocarpus mildbraedii Harms	6	1.12	5.33
Annonidium mannii (Oliv.) Engl. & Diels	5	0.93	4.44
Anthrocaryon klaineanum Pierre	5	0.93	4.44
Dacryodes klaineana (Pierre) H.J.Lam	5	0.93	4.44
Entandrophragma angolense (Welw.) C.DC.	5	0.93	4.44
Entandrophragma candollei Harms	5	0.93	4.44
Lebruniodendron leptanthum (Harms) J.Léonard	5	0.93	4.44
Nesogordonia papaverifera (A.Chev.) Capuron	5	0.93	4.44
Pentaclethra macrophylla Benth.	5	0.93	4.44
Trichilia welwitschii C.DC.	5	0.93	4.44
Other taxa (70)	**113**	**21.08**	**100.44**
Total	**536**	**100.00**	**476.44**

At the taxonomic level, the 101 taxa were distributed among 32 families. Fabales was the most species-rich order, with 22 species (21.78%), followed by Malpighiales and Sapindales, each with 21 species (20.79%). In terms of abundance, Malpighiales was dominant, with 180 individuals (33.58%), followed by Magnoliales with 133 individuals (24.81%) and Fabales with 106 individuals (19.78%) (Table 2)

Table 2. Taxonomic composition and abundance of recorded orders

Order	No. of families	No. of species	Species (%)	No. of individuals	Density (individuals ha^{-1})	Relative abundance (%)
Malpighiales	11	21	20.79	180	160.00	33.58
Magnoliales	2	11	10.89	133	118.22	24.81
Fabales	1	22	21.78	106	94.22	19.78
Sapindales	5	21	20.79	57	50.67	10.63
Cucurbitales	1	1	0.99	16	14.22	2.99
Santalales	1	3	2.97	11	9.78	2.05
Gentianales	2	7	6.93	10	8.89	1.87
Ericales	3	6	5.94	8	7.11	1.49
Malvales	1	2	1.98	6	5.33	1.12
Rosales	2	3	2.97	5	4.44	0.93
Apiales	1	1	0.99	1	0.89	0.19
Arecales	1	1	0.99	1	0.89	0.19
Lamiales	1	1	0.99	1	0.89	0.19
Ranunculales	1	1	0.99	1	0.89	0.19
Total	**32**	**101**	**100.00**	**536**	**476.44**	**100.00**

Fabaceae was the most species-rich family, with 22 species (21.78%), followed by Meliaceae with 10 species (9.90%), Annonaceae with seven species (6.93%), Apocynaceae with six species (5.94%) and Burseraceae with five species (4.95%) (Table 3; Figure 2). Myristicaceae, although

represented by only four species, accounted for 91 individuals (16.98%). Euphorbiaceae comprised 73 individuals (13.62%).

Table 3. Species richness, abundance and density of the main botanical families

Family	No. of species	Species (%)	No. of individuals	Relative abundance (%)	Density (individuals ha^{-1})
Fabaceae	22	21.78	106	19.78	94.22
Myristicaceae	4	3.96	91	16.98	80.89
Euphorbiaceae	2	1.98	73	13.62	64.89
Calophyllaceae	2	1.98	28	5.22	24.89
Chrysobalanaceae	3	2.97	28	5.22	24.89
Meliaceae	10	9.90	28	5.22	24.89
Annonaceae	7	6.93	27	5.04	24.00
Burseraceae	5	4.95	17	3.17	15.11
Anisophylleaceae	1	0.99	16	2.99	14.22
Humiriaceae	1	0.99	12	2.24	10.67
Irvingiaceae	4	3.96	11	2.05	9.78
Olacaceae	3	2.97	11	2.05	9.78
Ochnaceae	1	0.99	9	1.68	8.00
Clusiaceae	1	0.99	9	1.68	8.00
Apocynaceae	6	5.94	8	1.49	7.11
Other families (17)	**29**	**28.71**	**72**	**13.43**	**64.00**
Overall total	**101**	**100.00**	**536**	**100.00**	**476.44**

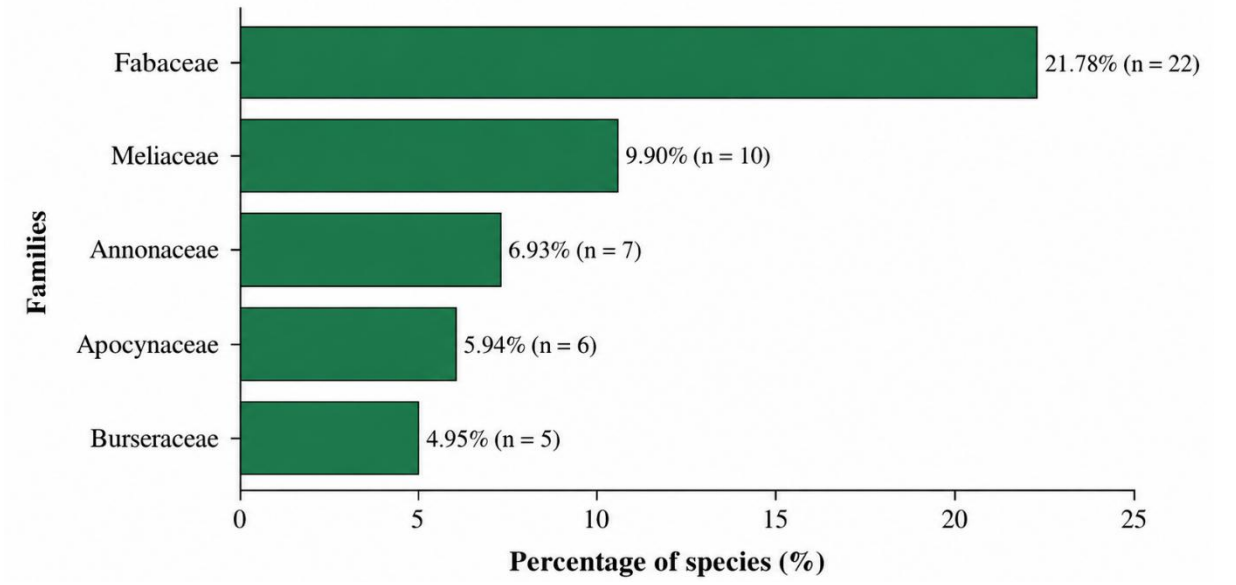


Figure 2. Distribution of the five most species-rich families.

The species accumulation curve increased progressively with sampled area, with a gradual slowing towards the end of sampling (Figure 3). Mean cumulative richness reached 95.77 species at 1.00 ha, 98.45 species at 1.0625 ha and 101 species at the total sampled area of 1.125 ha (Table 4).

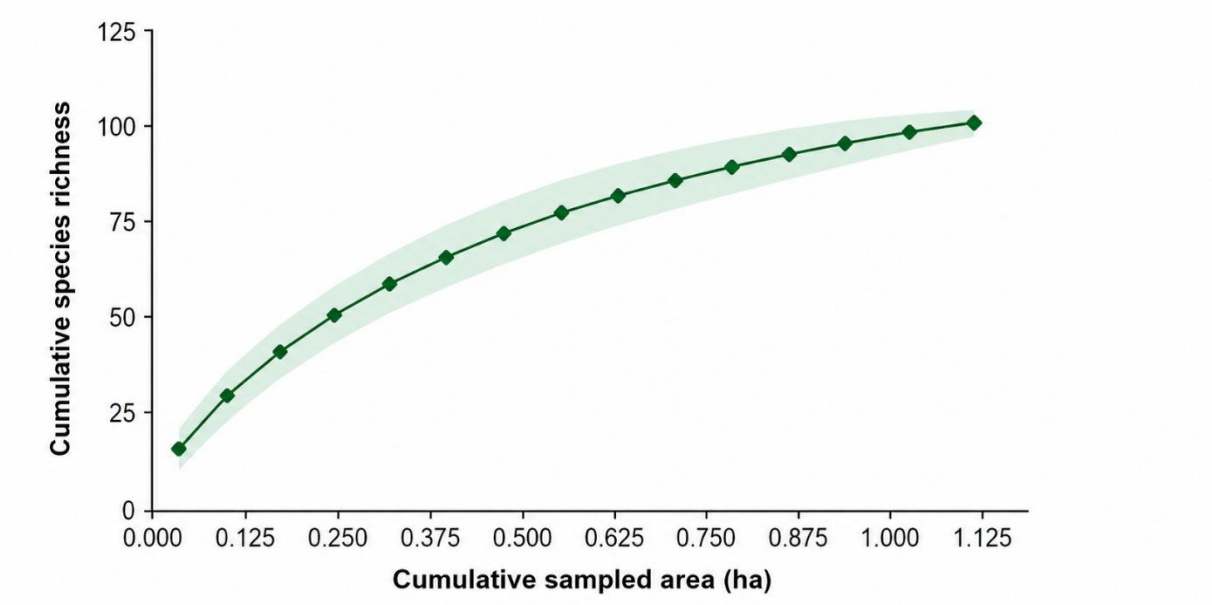


Figure 3. Species accumulation curve as a function of cumulative sampled area.

Table 4. Mean cumulative species richness and associated variability according to sampled area

No. of plots	Sampled area (ha)	Mean species richness	Standard deviation	Lower limit	Upper limit
1	0.0625	15.37	4.02	11.35	19.39
2	0.1250	26.68	4.87	21.81	31.55
3	0.1875	35.95	5.41	30.54	41.36
4	0.2500	43.96	5.52	38.45	49.48
5	0.3125	50.93	5.48	45.45	56.41
6	0.3750	57.06	5.37	51.70	62.43
7	0.4375	62.53	5.23	57.30	67.76
8	0.5000	67.41	5.06	62.35	72.47
9	0.5625	71.87	4.83	67.03	76.70
10	0.6250	76.03	4.57	71.46	80.60
11	0.6875	79.83	4.32	75.50	84.15
12	0.7500	83.42	4.16	79.27	87.58
13	0.8125	86.78	3.80	82.99	90.58
14	0.8750	90.01	3.57	86.44	93.58
15	0.9375	93.01	3.20	89.81	96.22

16	1.0000	95.77	2.73	93.03	98.50
17	1.0625	98.45	1.98	96.47	100.43
18	1.1250	101.00	0.00	101.00	101.00

The ecological spectra showed a predominance of mesophyllous species, which represented 83.96% of individuals. Sarcochores were the dominant dispersal type (51.49%), followed by ballochores (32.46%) and barochores (11.01%). Guineo-Congolian and Lower Guineo-Congolian elements together represented most of the recorded individuals (Figure 4).

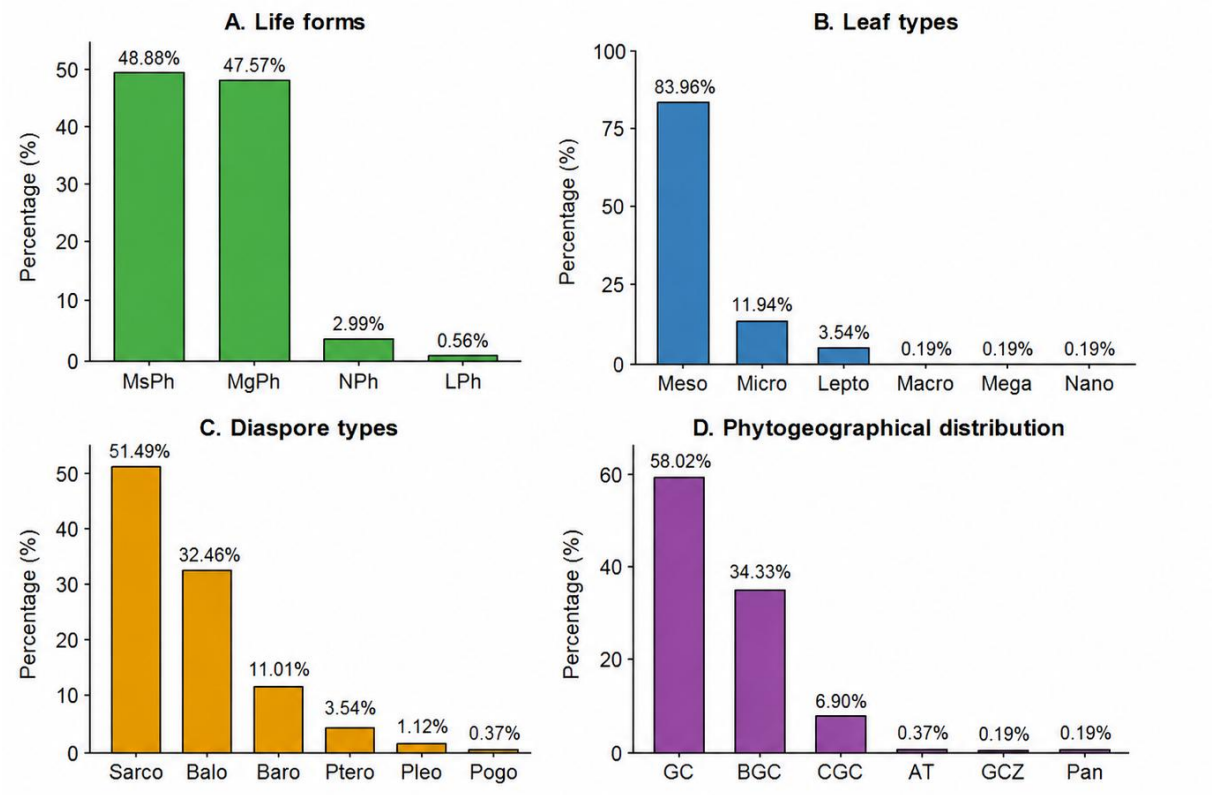


Figure 4. Ecological and phytogeographical spectra of the woody flora studied.

Overall floristic diversity was high, with a Shannon index (H') of 3.701, Simpson index ($1-D$) of 0.942 and Pielou evenness (J') of 0.802 (Table 5). Diversity varied among plots. Species richness ranged from six species in P8 to 23 species in P10. Shannon diversity ranged from 1.090 in P8 to 2.822 in P10. Pielou evenness ranged from 0.608 in P8 to 0.951 in P16 (Table 6).

Table 5. Overall floristic diversity indices

Level	Area (ha)	Abundance (N)	Richness (S)	Shannon (H′)	Simpson (1−D)	Pielou (J′)
Overall	1.125	536	101	3.701	0.942	0.802

Table 6. Floristic diversity indices calculated for the different 625 m² (0.0625 ha) plots

Plot	Abundance (N)	Richness (S)	Shannon (H′)	Simpson (1−D)	Pielou (J′)
P1	28	13	2.296	0.875	0.895
P2	26	17	2.578	0.896	0.910
P3	32	15	2.471	0.895	0.913
P4	31	19	2.729	0.916	0.927
P5	30	18	2.656	0.909	0.919
P6	27	10	1.886	0.796	0.819
P7	27	12	2.073	0.823	0.834
P8	28	6	1.090	0.536	0.608
P9	23	13	2.279	0.858	0.889
P10	40	23	2.822	0.913	0.900
P11	22	12	2.220	0.851	0.893
P12	28	16	2.481	0.885	0.895
P13	30	14	2.375	0.882	0.900
P14	37	20	2.711	0.904	0.905
P15	28	18	2.698	0.916	0.934
P16	30	18	2.748	0.927	0.951
P17	31	14	2.380	0.885	0.902
P18	38	19	2.728	0.920	0.926

Forest Structure and Ecological Importance of Species

Tree density varied among the 18 inventory plots (Figure 5a). Mean density was 476.4 stems ha^{-1}, with values ranging from 352 stems ha^{-1} in P11 to 640 stems ha^{-1} in P10 (Table 7). The mean number of individuals per plot was 29.8 ± 4.7, with the highest numbers recorded in P10 (40 individuals), P18 (38 individuals) and P14 (37 individuals) (Figure 5b).

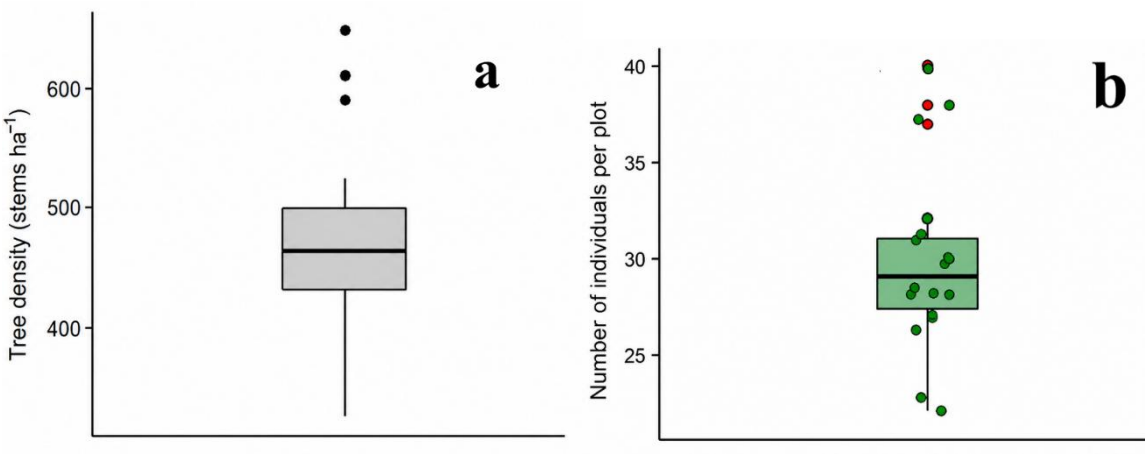


Figure 5. Distribution of (a) tree density (stems ha^{-1}) and (b) number of individuals per plot across the 18 inventory plots.

The diameter distribution was characterized by a predominance of individuals in the smaller diameter classes (Figure 6). The [10–20 cm[and [20–30 cm[classes represented 45.8% and 29.3% of individuals, respectively. Together, these two classes accounted for 75.1% of the recorded stems. From the [30–40 cm[class onwards, relative frequency decreased markedly, reaching 9.2%, then 6.5% in the [50–60 cm[class.

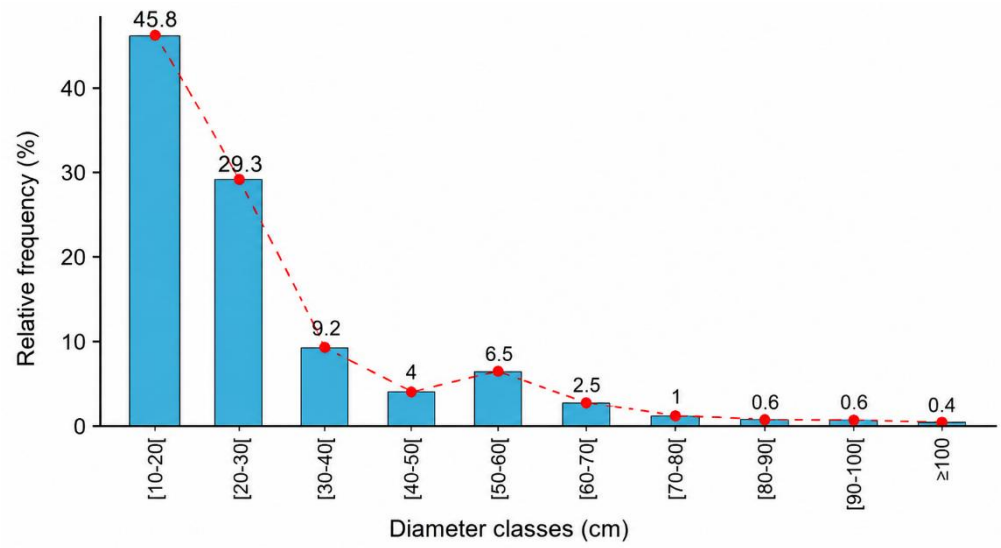


Figure 6. Distribution of individuals according to diameter classes.

Basal area also varied among plots, with a mean value of 36.37 m² ha^{-1}. The highest basal area was recorded in P8 (83.50 m² ha^{-1}), followed by P1 (56.83 m² ha^{-1}) and P2 (56.41 m² ha^{-1}), whereas the lowest value was recorded in P6 (19.63 m² ha^{-1}).

Table 7. Number of individuals, density and basal area of the inventoried stands

Plot	Number of individuals	Density (individuals ha^{-1})	Basal area (m^2)	Basal area (m^2 ha^{-1})
P1	28	448	3.55	56.83
P2	26	416	3.53	56.41
P3	32	512	1.28	20.54
P4	31	496	2.80	44.76
P5	30	480	1.96	31.30
P6	27	432	1.23	19.63
P7	27	432	1.42	22.64
P8	28	448	5.22	83.50
P9	23	368	1.81	28.96
P10	40	640	1.29	20.68
P11	22	352	1.94	31.12
P12	28	448	2.17	34.76
P13	30	480	1.83	29.29
P14	37	592	2.67	42.68
P15	28	448	1.85	29.62
P16	30	480	1.31	21.04
P17	31	496	2.05	32.84
P18	38	608	3.00	48.06
Mean ± SD	**29.8 ± 4.7**	**476.4 ± 75.8**	**2.27 ± 1.02**	**36.37 ± 16.39**

The Importance Value Index (IVI) showed differences in the structural importance of species. *Staudtia kamerunensis* had the highest IVI (32.81), with a relative density of 16.79%, relative dominance of 9.52% and relative frequency of 6.50%. *Brachystegia laurentii* ranked second (IVI = 24.46), with the highest relative dominance (18.37%), followed by *Dichostemma glaucescens* (IVI = 23.21). The remaining species had lower IVI values (Table 8).

Table 8. Structural parameters and Importance Value Index (IVI) of the main species

Species	Density (individuals ha^{-1})	BA (m^2 ha^{-1})	RD (%)	RDo (%)	RF (%)	IVI
Staudtia kamerunensis Warb.	80.00	3.46	16.79	9.52	6.50	32.81
Brachystegia laurentii (De Wild.) Hoyle	20.44	6.68	4.29	18.37	1.81	24.46
Dichostemma glaucescens Pierre	64.89	1.65	13.62	4.54	5.05	23.21
Mammea africana Sabine	13.33	1.11	2.80	3.06	3.25	9.10
Parinari excelsa Sabine	13.33	0.84	2.80	2.30	3.97	9.07
Xylopia staudtii Engl. & Diels	11.56	1.03	2.43	2.83	2.89	8.15
Tessmannia africana Harms	10.67	0.80	2.24	2.21	2.53	6.97
Scorodophloeus zenkeri Harms	11.56	0.97	2.43	2.66	1.81	6.89
Prioria balsamifera (Vermoesen) Breteler	5.33	1.48	1.12	4.06	1.44	6.63
Distemonanthus benthamianus Baill.	7.11	0.97	1.49	2.68	2.17	6.34
Pentadesma butyracea Sabine	11.56	0.62	2.43	1.70	2.17	6.29

Anisophyllea polyneura Engl.	14.22	0.50	2.99	1.37	1.81	6.16
Pterocarpus mildbraedii Harms	5.33	1.42	1.12	3.90	1.08	6.10
Symphonia globulifera L.f.	8.00	0.84	1.68	2.30	1.81	5.78
Sacoglottis gabonensis (Baill.) Urb.	10.67	0.43	2.24	1.19	2.17	5.59
Lophira alata Banks ex C.F.Gaertn.	8.00	0.62	1.68	1.71	1.81	5.19
Detarium macrocarpum Harms	5.33	0.95	1.12	2.61	1.08	4.81
Piptadeniastrum africanum (Hook.f.) Brenan	3.56	0.94	0.75	2.58	1.44	4.77
Hannoa klaineana Pierre & Engl.	5.33	0.51	1.12	1.39	2.17	4.68
Maranthes chrysophylla (Oliv.) Prance	8.00	0.28	1.68	0.77	2.17	4.62
Scyphocephalium mannii (Benth.) Warb.	7.11	0.53	1.49	1.46	1.44	4.40
Xylopia hypolampra Mildbr.	7.11	0.40	1.49	1.10	1.44	4.04
Anthrocaryon klaineanum Pierre	4.44	0.48	0.93	1.33	1.44	3.71
Klainedoxa gabonensis Pierre ex Engl.	3.56	0.53	0.75	1.47	1.44	3.66
Strombosia pustulata Oliv.	7.11	0.31	1.49	0.86	1.08	3.44
Lebruniodendron leptanthum (Harms) J.Léonard	4.44	0.49	0.93	1.34	1.08	3.35
Entandrophragma candollei Harms	4.44	0.29	0.93	0.80	1.44	3.17
E. cylindricum (Sprague) Sprague	2.67	0.54	0.56	1.49	1.08	3.13
Pentaclethra macrophylla Benth.	4.44	0.38	0.93	1.04	1.08	3.05
Annonidium mannii (Oliv.) Engl. & Diels	4.44	0.09	0.93	0.24	1.81	2.98
Other species (71 species)	108.44	6.23	22.76	17.13	37.54	77.44
Total	**476.44**	**36.37**	**100.00**	**100.00**	**100.00**	**300.00**

Floristic Differentiation and Characteristic Species

Hierarchical cluster analysis based on Bray–Curtis dissimilarities distinguished two floristic groups (Figure 7a). Group 1 comprised 11 plots, whereas Group 2 comprised seven plots. The classification based on Jaccard dissimilarity, using presence–absence data, was also examined to assess the grouping of plots when only species occurrence was considered (Figure 7b).

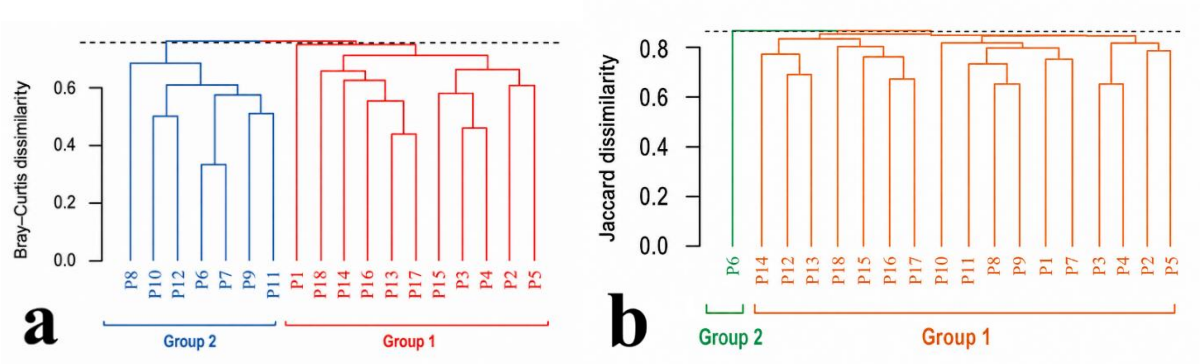


Figure 7. Hierarchical cluster analysis of the plots based on (a) Bray–Curtis dissimilarity using the unweighted pair group method with arithmetic mean (UPGMA), and (b) Jaccard dissimilarity calculated from presence–absence data.

NMDS ordination showed the distribution of the plots according to the two floristic groups derived from the Bray–Curtis hierarchical classification (Figure 8a). The Shepard diagram showed the relationship between observed Bray–Curtis dissimilarities and the distances represented by the NMDS ordination (Figure 8b). DCA provided a complementary representation of the floristic differentiation between plots and groups (Figure 8c).

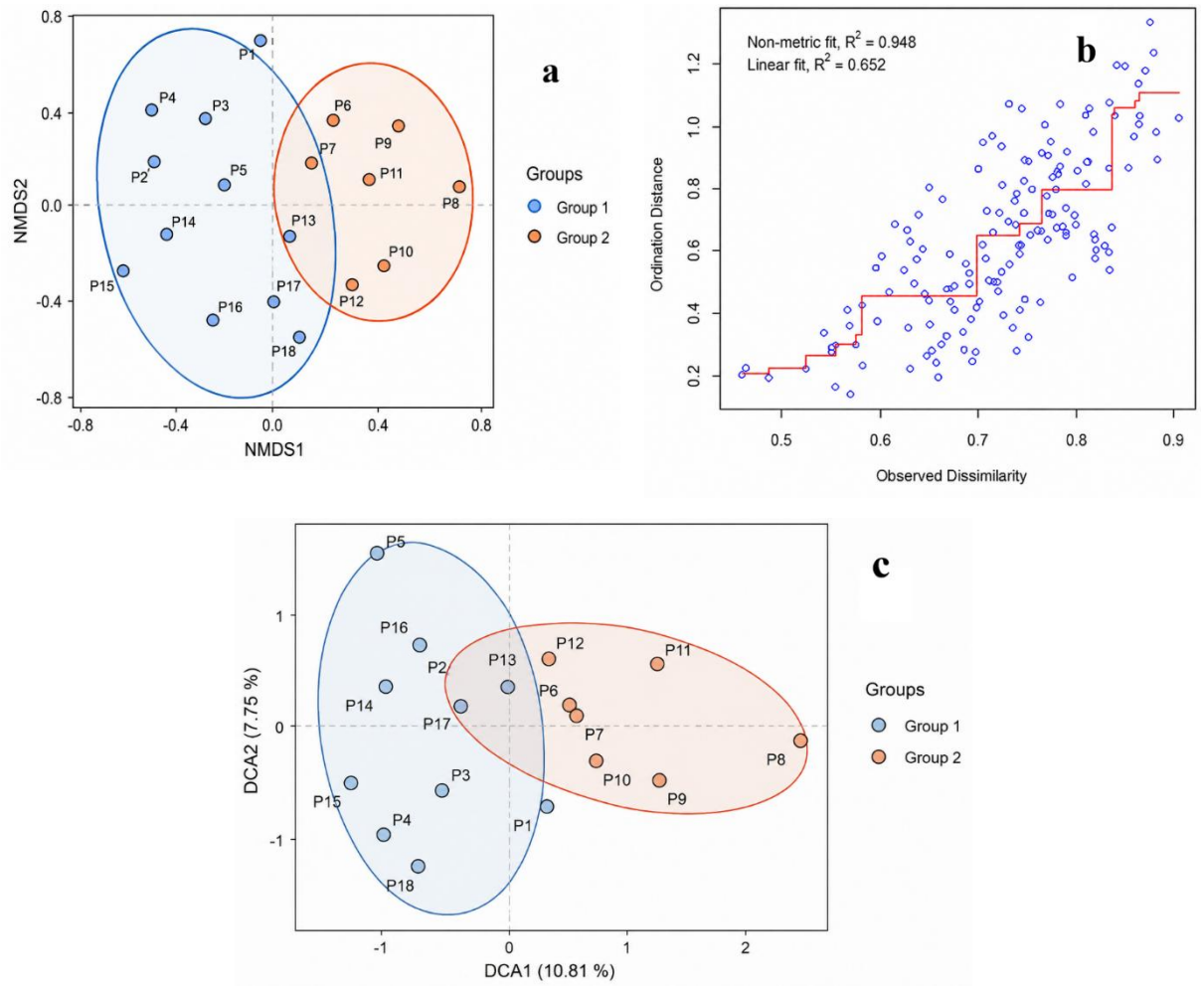


Figure 8. Floristic ordination of the plots: (a) NMDS ordination showing the floristic groups derived from the Bray–Curtis hierarchical classification; (b) Shepard diagram showing the relationship between observed Bray–Curtis dissimilarities and distances represented by the NMDS ordination; and (c) DCA ordination showing the floristic groups derived from the Bray–Curtis hierarchical classification.

PERMANOVA indicated a significant difference in floristic composition between the two groups (pseudo-$F_{1,16}$ = 4.216; R^2 = 0.209; p < 0.001). The PERMDISP test also indicated a significant difference in dispersion between the two groups ($F_{1,16}$ = 8.501; p = 0.010; 9,999 permutations), with mean distances to the centroid of 0.4607 for Group 1 and 0.3939 for Group 2 (Table 9; Figure 9).

Table 9. Effect of group on floristic composition and multivariate dispersion based on Bray–Curtis dissimilarities.

Analysis	Source of variation	df	Sum of squares	R^2	F	p	Distance to centroid
PERMANOVA	Group	1	0.9107	0.2085	4.2157	< **0.001**	–
	Residuals	16	3.4565	0.7915	–	–	–
PERMDISP	Group	1	0.0191	–	8.5014	**0.010**	–
	Residuals	16	0.0359	–	–	–	–
Dispersion	Group 1	–	–	–	–	–	0.4607
	Group 2	–	–	–	–	–	0.3939

Note. n = 18 plots. Differences in floristic composition were assessed using PERMANOVA, and the homogeneity of multivariate dispersions was assessed using PERMDISP. A p-value < 0.05 was considered statistically significant

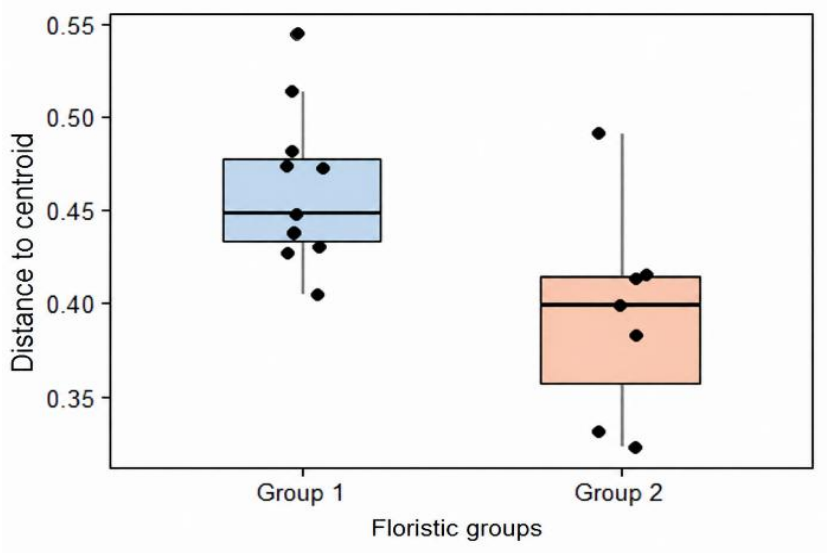


Figure 9. Distribution of distances to the centroid for the two floristic groups defined by the Bray–Curtis classification.

Indicator species analysis identified three species significantly associated with the floristic groups. *Dichostemma glaucescens* was associated with Group 2 (IndVal = 80.64%; $p = 0.0013$), whereas *Staudtia kamerunensis* was associated with Group 1 (IndVal = 66.30%; $p = 0.0087$). *Brachystegia laurentii* was also associated with Group 2 (IndVal = 55.54%; $p = 0.0284$). No other species showed a statistically significant association with either group at the 5% significance level (Table 10).

Table 10. Significant indicator species of the floristic groups identified by the Bray–Curtis classification.

Species	Indicator group	Abundance G1	Abundance G2	Frequency G1 (%)	Frequency G2 (%)	IndVal (%)	*p*
Dichostemma glaucescens	Group 2	20	53	63.64	100.00	80.64	0.0013
Staudtia kamerunensis	Group 1	68	22	100.00	100.00	66.30	0.0087
Brachystegia laurentii	Group 2	1	22	9.09	57.14	55.54	0.0284

Note. Only species with $p < 0.05$ are reported.

The first three species identified by SIMPER also corresponded to the three significant indicator species identified by the IndVal analysis, although the two methods do not measure the same aspect of floristic structure. *Dichostemma glaucescens* contributed 13.05% to the dissimilarity between groups, followed by *Staudtia kamerunensis* (8.20%) and *Brachystegia laurentii* (7.08%). Together, these three species accounted for 28.32% of the floristic dissimilarity between Groups 1 and 2 (Table 11).

Table 11. Contribution of the main species to floristic dissimilarity between Groups 1 and 2 according to the SIMPER analysis.

Species	Mean G1	Mean G2	Mean contribution	SD	Ratio	Contribution (%)	Cumulative (%)	*p*
Dichostemma glaucescens	1.82	7.57	0.0988	0.035	2.827	13.05	13.05	0.0001
Staudtia kamerunensis	6.18	3.14	0.0621	0.037	1.663	8.20	21.24	0.0064
Brachystegia laurentii	0.09	3.14	0.0536	0.104	0.515	7.08	28.32	0.0280
Anisophyllea polyneura	0.73	1.14	0.0238	0.028	0.842	3.15	31.47	0.3258
Scorodophloeus zenkeri	1.18	0.00	0.0204	0.028	0.727	2.69	34.16	0.3318
Mammea africana	1.18	0.29	0.0189	0.018	1.070	2.50	36.66	0.2719
Xylopia staudtii	0.64	0.86	0.0179	0.018	0.987	2.36	39.02	0.4774
Pentadesma butyracea	0.91	0.43	0.0176	0.019	0.918	2.32	41.34	0.7973
Sacoglottis gabonensis	0.55	0.86	0.0172	0.018	0.936	2.27	43.61	0.3157
Tessmannia africana	0.55	0.86	0.0171	0.017	0.992	2.26	45.86	0.2773
Parinari excelsa	0.73	1.00	0.0156	0.012	1.254	2.06	47.92	0.3539
Symphonia globulifera	0.82	0.00	0.0144	0.021	0.682	1.91	49.83	0.4151
Maranthes chrysophylla	0.45	0.57	0.0140	0.018	0.799	1.85	51.68	0.3432
Lophira alata	0.82	0.00	0.0137	0.019	0.736	1.81	53.49	0.2977

Strombosia pustulata	0.55	0.29	0.0134	0.026	0.515	1.77	55.26	0.4914
Xylopia hypolampra	0.55	0.29	0.0129	0.020	0.637	1.70	56.96	0.5258
Scyphocephalium mannii	0.36	0.57	0.0128	0.019	0.666	1.69	58.65	0.3297
Distemonanthus benthamianus	0.55	0.29	0.0109	0.012	0.883	1.44	60.09	0.8403
Pterocarpus mildbraedii	0.45	0.14	0.0098	0.021	0.462	1.29	61.38	0.5276
Anthrocaryon klaineanum	0.18	0.43	0.0093	0.013	0.714	1.23	62.61	0.2304
Prioria balsamifera	0.55	0.00	0.0092	0.013	0.697	1.21	63.82	0.4569
Detarium macrocarpum	0.55	0.00	0.0089	0.016	0.561	1.18	65.00	0.6683
Dacryodes klaineana	0.36	0.14	0.0081	0.019	0.424	1.07	66.07	0.4127
Hannoa klaineana	0.45	0.14	0.0078	0.009	0.923	1.03	67.10	0.2553
Annonidium mannii	0.45	0.00	0.0078	0.009	0.898	1.03	68.14	0.0577
Lebruniodendron leptanthum	0.45	0.00	0.0078	0.014	0.580	1.03	69.17	0.6306
Nesogordonia papaverifera	0.45	0.00	0.0077	0.011	0.681	1.02	70.18	0.4313

Aboveground Biomass and Carbon Stocks

Mean above-ground biomass was 423.24 ± 77.50 Mg ha^{-1}, with values ranging from 313.44 to 564.96 Mg ha^{-1} and a coefficient of variation of 18.31%. Mean carbon stock was 198.92 ± 36.43 Mg C ha^{-1}, ranging from 147.32 to 265.53 Mg C ha^{-1}. The corresponding mean CO_2 equivalent was 729.38 ± 133.57 Mg CO_2 ha^{-1}, with values ranging from 540.17 to 973.62 Mg CO_2 ha^{-1} (Table 12).

Table 12. Descriptive statistics of above-ground biomass, carbon stock and CO_2 equivalent of the inventoried woody stands

Variable	Mean ± SD	Median	Min	Max	CV (%)
Above-ground biomass (Mg ha^{-1})	423.24 ± 77.50	413.04	313.44	564.96	18.31
Carbon stock (Mg C ha^{-1})	198.92 ± 36.43	194.13	147.32	265.53	18.31
CO_2 equivalent (Mg CO_2 ha^{-1})	729.38 ± 133.57	711.81	540.17	973.62	18.31

Above-ground biomass, carbon stock and CO_2 equivalent differed in their mean values between the two floristic groups. Group 1 had a mean above-ground biomass of 451.08 ± 66.71 Mg ha^{-1}, corresponding to 212.01 ± 31.35 Mg C ha^{-1} and 777.37 ± 114.96 Mg CO_2 ha^{-1}. Group 2 had lower mean values, with 379.50 ± 77.12 Mg ha^{-1} of above-ground biomass, 178.36 ± 36.25 Mg C ha^{-1} of carbon and 653.99 ± 132.91 Mg CO_2 ha^{-1} (Table 13).

Table 13. Above-ground biomass, carbon stock and CO_2 equivalent by vegetation group

Vegetation group	*n*	Above-ground biomass (Mg ha^{-1})	Carbon stock (Mg C ha^{-1})	CO_2 equivalent (Mg CO_2 ha^{-1})
Entire study site	18	423.24 ± 77.50	198.92 ± 36.43	729.38 ± 133.57
Group 1	11	451.08 ± 66.71	212.01 ± 31.35	777.37 ± 114.96
Group 2	7	379.50 ± 77.12	178.36 ± 36.25	653.99 ± 132.91

The contribution to above-ground biomass varied among species. *Staudtia kamerunensis* had the highest contribution, with 66.12 Mg ha^{-1}, representing 15.62% of total AGB, followed by *Dichostemma glaucescens* with 38.95 Mg ha^{-1} (9.20%) and *Brachystegia laurentii* with 33.22 Mg ha^{-1} (7.85%). Together, these three species accounted for 32.67% of total above-ground biomass. The 30 main woody species accounted for 80.22% of total AGB, whereas the remaining 71 species contributed 19.78%. The total values for the inventoried stands were 423.24 Mg ha^{-1} for AGB, 198.92 Mg C ha^{-1} for carbon stock and 729.38 Mg CO_2 ha^{-1} for CO_2 equivalent (Table 14).

Table 14. Contribution of the 30 main woody species to above-ground biomass, carbon stock and CO_2 equivalent.

Species	AGB (Mg ha^{-1})	Contribution (%)	C (Mg C ha^{-1})	CO_2 eq. (Mg CO_2 ha^{-1})
Staudtia kamerunensis Warb.	66.12	15.62	31.08	113.95
Dichostemma glaucescens Pierre	38.95	9.20	18.31	67.12
Brachystegia laurentii (De Wild.) Hoyle	33.22	7.85	15.61	57.25
Mammea africana Sabine	12.97	3.06	6.10	22.35
Scorodophloeus zenkeri Harms	11.95	2.82	5.62	20.59
Parinari excelsa Sabine	11.79	2.79	5.54	20.32
Tessmannia africana Harms	10.94	2.59	5.14	18.85
Symphonia globulifera L.f.	10.46	2.47	4.92	18.03
Anisophyllea polyneura Engl.	9.96	2.35	4.68	17.16
Pterocarpus mildbraedii Harms	9.16	2.16	4.31	15.79
Xylopia staudtii Engl. & Diels	8.94	2.11	4.20	15.41
Pentadesma butyracea Sabine	8.86	2.09	4.16	15.27
Sacoglottis gabonensis (Baill.) Urb.	8.72	2.06	4.10	15.03
Lophira alata Banks ex C.F.Gaertn.	8.68	2.05	4.08	14.96
Distemonanthus benthamianus Baill.	8.19	1.94	3.85	14.11

Prioria balsamifera (Vermoesen) Breteler	7.98	1.89	3.75	13.75
Detarium macrocarpum Harms	7.24	1.71	3.40	12.48
Strombosia pustulata Oliv.	6.31	1.49	2.97	10.87
Piptadeniastrum africanum (Hook.f.) Brenan	6.02	1.42	2.83	10.37
Maranthes chrysophylla (Oliv.) Prance	5.90	1.39	2.77	10.17
Scyphocephalium mannii (Benth.) Warb.	5.88	1.39	2.76	10.13
Xylopia hypolampra Mildbr.	5.43	1.28	2.55	9.36
Klainedoxa gabonensis Pierre ex Engl.	5.16	1.22	2.43	8.89
Lebruniodendron leptanthum (Harms) J.Léonard	5.04	1.19	2.37	8.69
Hannoa klaineana Pierre & Engl.	4.84	1.14	2.27	8.34
Anthrocaryon klaineanum Pierre	4.81	1.14	2.26	8.29
Pentaclethra macrophylla Benth.	4.66	1.10	2.19	8.03
Entandrophragma candollei Harms	3.95	0.93	1.86	6.81
Entandrophragma cylindricum (Sprague) Sprague	3.85	0.91	1.81	6.63
Guarea thompsonii Sprague & Hutch.	3.56	0.84	1.67	6.14
Other species (71 species)	**83.70**	**19.78**	**39.34**	**144.24**
Total	**423.24**	**100.00**	**198.92**	**729.38**

Comparison of the two floristic groups showed higher mean values in Group 1 for species richness, density, basal area and AGB (Figure 10). Mean species richness was 16.82 ± 2.40 species plot^{-1} in Group 1 and 13.14 ± 5.30 in Group 2. Density was 496.00 ± 58.13 and 445.71 ± 93.95 individuals ha^{-1}, respectively.

Table 15. Comparison of species richness, forest structure and above-ground biomass between floristic groups

Variable	Group 1 (n = 11), mean ± SD	Group 2 (n = 7), mean ± SD	Welch (*t*, df)	Welch *p*	Wilcoxon (*W*)	Wilcoxon *p*	Hedges' *g*
Species richness (species plot^{-1})	16.82 ± 2.40	13.14 ± 5.30	1.724 (7.59)	0.125	61.5	**0.041**	—
Density (individuals ha^{-1})	496.00 ± 58.13	445.71 ± 93.95	1.270 (8.96)	0.236	60.0	0.055	0.65
Basal area (m² ha^{-1})	37.57 ± 12.95	34.47 ± 22.35	0.333 (8.60)	0.747	51.0	0.277	0.17
AGB (Mg ha^{-1})	451.08 ± 66.71	379.50 ± 77.12	2.022 (11.51)	0.067	60.5	**0.047**	0.96

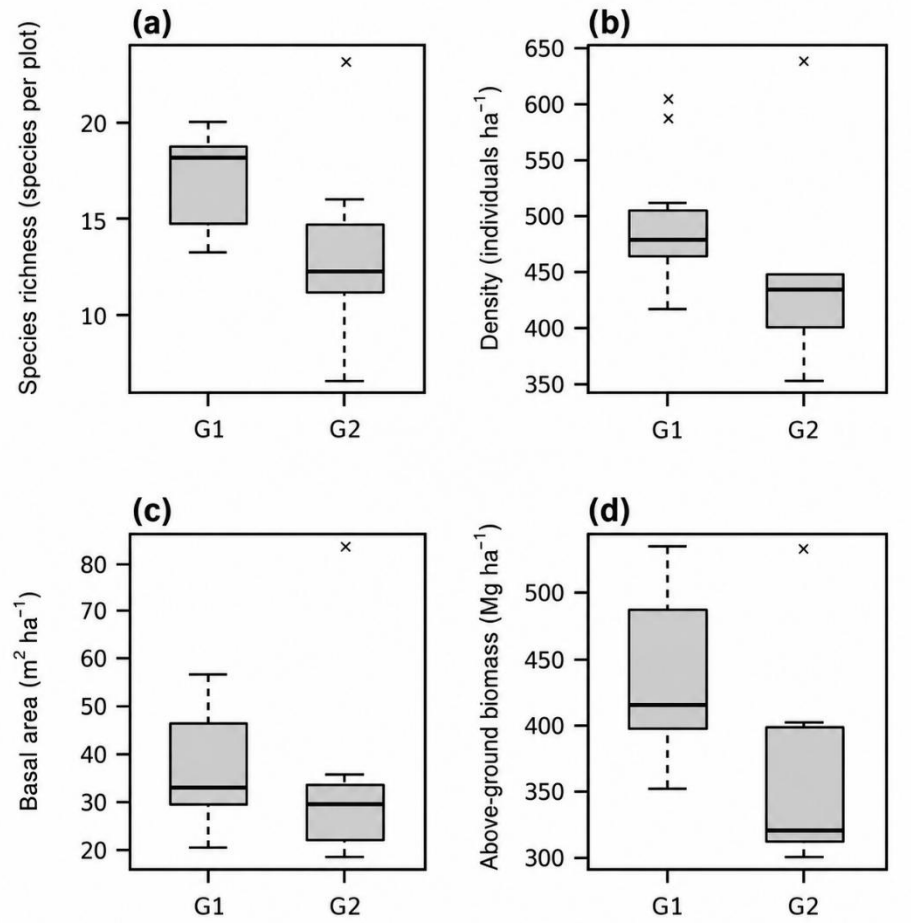


Figure 10. Distribution of above-ground biomass (AGB), basal area, density and species richness between the two floristic groups. The boxplots represent the median, interquartile range and values extending up to 1.5 times the interquartile range.

Welch's test showed no significant differences between groups for species richness (p = 0.125), density (p = 0.236), basal area (p = 0.747) or AGB (p = 0.067) (Table 15).

Discussion

The 536 individuals represented 101 taxa but were unevenly distributed: *Staudtia kamerunensis*, *Dichostemma glaucescens* and *Brachystegia laurentii* comprised 34.70% of stems, whereas 70 taxa with fewer than five individuals comprised 21.08%. Such coexistence of high richness and dominance is typical of tropical forests [6]. *Staudtia kamerunensis* accounted for 16.79% of stems and had the highest IVI (32.81), making it a major structural species. *Brachystegia laurentii* represented only 4.29% of stems but 18.37% of relative dominance and had the second-highest IVI (24.47), illustrating the structural influence of large individuals [25].

Overall Shannon (3.701), Simpson (0.942) and Pielou (0.802) indices indicate high diversity despite species dominance; interpretation should also consider richness and sampling completeness

[24]. Plot richness ranged from 6 to 23 species and Shannon diversity from 1.090 to 2.822, showing marked spatial heterogeneity. The accumulation curve slowed progressively, reaching a mean of 95.77 species at 1 ha versus 101 observed. This suggests good coverage but not exhaustiveness; formal assessment would require coverage and richness extrapolation [26].

Mesophylls predominated (83.96%), consistent with relatively humid conditions, although leaf size also reflects canopy position and species traits. Sarcochores comprised 51.49% of individuals, followed by ballochores (32.46%) and barochores (11.01%), suggesting an important role for animal-mediated dispersal that requires direct confirmation. Guineo-Congolian and Lower Guineo-Congolian elements comprised 92.35% of individuals, confirming the forest-domain affinity reported by Masens *et al.* [4].

Mean density was 476.4 stems ha^{-1}, close to 426 ± 11 stems ha^{-1} reported for African tropical forests by Lewis *et al.* [5]. Mean basal area was 36.37 m^2 ha^{-1} (19.63–83.50), showing that density alone does not explain structure. Contrasts between P10 and P8 highlight the importance of large trees, which can contribute disproportionately to biomass [6].

Bray–Curtis classification distinguished two floristic groups, and PERMANOVA confirmed differentiation (pseudo-$F_{1,16}$ = 4.216, R^2 = 0.209, $p < .001$). PERMDISP also differed between groups ($F_{1,16}$ = 8.501, p = .010), with greater dispersion in Group 1; PERMANOVA must therefore be interpreted in light of dispersion heterogeneity [18]. Environmental conditions or disturbance history may contribute to this heterogeneity, but these hypotheses require environmental data. *Dichostemma glaucescens* was associated with Group 2 (IndVal 80.64%, p = .0013; SIMPER 13.05%), as was *B. laurentii* (55.54%, p = .0284; 7.08%). These three species explained 28.32% of dissimilarity, but 27 species were needed to reach about 70%, indicating a broader multispecies contribution.

Mean AGB was 423.24 ± 77.50 Mg ha^{-1}, near the upper range for African tropical forests and close to 395.7 Mg ha^{-1} reported by Lewis *et al.* [5], consistent with high basal area and large trees. Mean carbon stock was 198.92 ± 36.43 Mg C ha^{-1} versus 162 ± 20 Mg C ha^{-1} reported for old-growth Yangambi forest [27]. AGB ranged from 313.44 to 564.96 Mg ha^{-1} (CV 18.31%), partly reflecting the distribution of large trees [6].

Group 1 had higher means for richness, density, basal area and AGB, but Welch's tests detected no significant differences; compositional differentiation was therefore clearer than structural differentiation. Density and basal area did not differ significantly (p = 0.236 and 0.747). The AGB

contrast may partly reflect composition because the three main differentiating species account for 32.67% of total AGB, but biomass also depends on size, abundance and wood density.

IVI ranked *Staudtia kamerunensis* (32.81), *Brachystegia laurentii* (24.46) and *Dichostemma glaucescens* (23.21) highest. The 30 leading species accounted for 80.22% of AGB, and *Staudtia kamerunensis, Dichostemma glaucescens* and *Brachystegia laurentii* for 32.67%, consistent with disproportionate biomass concentration in tropical forests [6,25]. *Staudtia kamerunensis* contributed 15.62% of AGB and had the highest abundance and IVI; *B. laurentii* contributed 7.85% of AGB despite only 4.29% of stems. Biomass contribution therefore depends on size and structure as well as abundance [6,25].

Conservation should jointly protect floristic diversity, large trees and dominant biomass-contributing species; the three leading species alone account for 32.67% of AGB [6]. The two floristic groups also demonstrate internal heterogeneity, which should be incorporated into management rather than treating the forest as uniform.

Conclusion

The Mbamba forest is floristically diverse and internally heterogeneous: 536 woody individuals in 1.125 ha represented 101 taxa, with a few dominant species and many poorly represented taxa. Two floristic assemblages were distinguished, notably associated with *Staudtia kamerunensis*, *Dichostemma glaucescens* and *Brachystegia laurentii*. Compositional differences were clearer than structural differences. Richness and AGB comparisons were method-sensitive. These values represent standing carbon, not sequestration rates, and exclude some estimation uncertainty. Repeated inventories with environmental and disturbance data are needed to assess carbon dynamics and explain heterogeneity.

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Ethical considerations

The study used floristic inventories and non-destructive dendrometric measurements, with no human participants or animal experimentation; ethics committee approval was therefore not

applicable. Fieldwork was authorized by the Sisters of Mary concession managers and followed applicable site-access and plant-resource rules.

Patience Loso Alik: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft; **Pisco Menga Munkolo:** Methodology, Formal analysis, Data curation, Writing – review & editing; **Jean-Paul Ngbolua:** Methodology, Formal analysis, Data curation, Writing – review & editing; **Crispin Balo Ilunga:** Formal analysis, Validation. **Godefroid Yaya:** Investigation, Data curation; **Félicien Lukoki Luyeye:** Validation, Writing – review & editing; **Bonaventure Masens Da Musa Yung:** Investigation, Validation, Supervision; All authors read, reviewed and approved the final version of the manuscript.

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