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Flora, Structure and Carbon Sequestration of Vegetation in the Southeast of the Mono Biosphere Reserve in Togo Amidst Environmental Challenges

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Abstract

In most Sub-Saharan African countries such as Togo, people's heavy dependence on ecosystem services is a major factor in accelerating the degradation of natural resources, which are already suffering as a result of climatic factors. This study was initiated to contribute to the sustainable and rational management of forest resources in the south-east of the Mono Biosphere Reserve in Togo. It specifically aims to identify and characterize the flora of the residual forest ecosystems within the reserve through their specific diversity, demographic structure, and carbon sequestration potential. The study was carried out in the forest ecosystems of Avévé. The methodology used was based on the analysis of phytosociological, forestry, ecological, and regeneration inventory data. Overall, the study revealed that the RBMT still has floristically viable habitats, despite the anthropogenic pressures it is subject to revealed a floristic diversity of 160 plant species divided into 52 families and 135 genera. The most represented families are Rubiaceae (29.09%), followed by Fabaceae (27.94%). The most represented species are *Mitragyna inermis* (Willd.) Kuntze (24.38%), *Lecaniodiscus cupanioides* Planch. Ex Benth (X) and *Lonchocarpus sericeus* (Poir.) Kunth (10.93%). The high presence of *Mitragyna inermis* observed in all the ecological groups identified makes it the characteristic species of the flooded marshy areas of southeast Togo and contributes to the resilience of the ecosystems and populations in the study area. The Shannon index for the formation groups varies between (3.03 and 5.16) bits. Pielou's equitability varies between (0.43 and 0.63) bits. The overall average density is estimated at 210 stems/ha, with an average diameter of 25.57 ± 21.77 m and an average height of 7.93 ± 3.83 m. The adjustment of the diameter classes of the plant groups to the Weibull distribution gave an "inverted J" shape with coefficient values of less than 1 overall, reflecting the existence of multispecific or uneven-aged stands. Assessment of the horizontal and vertical structure shows a predominance of the shrub layer in all the groups identified. The carbon sequestration potential is 41.89 T/Ha. Despite ongoing anthropogenic pressures, the Mono Biosphere Reserve abounds in a relatively rich diversity of flora, the preservation of which is essential for the survival of biodiversity and even for the riparian population. The data provided by this study would form the basis for sustainable management planning of the forest islands in the biosphere reserve.

Keywords

Biodiversity, Demographic Structure, Carbon, Biosphere Reserve, Forest Patches, Togo

1. Introduction

Forests are renewable natural or planted resources made up of "woody plants living in balance with their environment". As a result, forest resources play three essential roles, namely economic, ecological, and social (cultural and recreational), which are interrelated and naturally lead all managers to direct their management strategy in such a way as to manage them sustainably to perpetuate the functions and products within the ecosystems that they provide for mankind (Gnrofoun, 2010). However, it has to be said that over the last few decades, forest resource management methods have not been compatible with the rate at which resources are renewed. Most landscapes have been modified by human activity (Rompré et al., 2010). In sub-Saharan Africa, and particularly in Togo, the main causes of damage to forest ecosystems are agricultural clearing, the uncontrolled exploitation of wood resources, uncontrolled wildfires, etc. (Kokou et al., 1999; Akpamou et al., 2021; Atakpama et al., 2021). The most noticeable cases of degradation observed in Togo are in the protected areas of the arid northern regions of the Oti-Kéran-Mandjour protected area complex (Kokou et al., 1999; Dimobe et al., 2012; Polo-Akpisso et al., 2020) on the one hand and the southern regions, in particular the North Togodo-South Togodo complex and the whole (Konko et al., 2018; Adjonou et al., 2020) on the other.

To counter the degradation of forest resources, the Togolese government has undertaken reforms that take account of the concerns of local populations by setting up Biosphere Reserves (MERF, 2017). These are natural areas that reconcile the needs of local communities with biodiversity conservation measures. Several projects carried out between 2013 and 2016 led to the Mono Biosphere Reserve being included on the UNESCO list of World Heritage Sites (MERF, 2017), with the aim of facilitating the protection and sustainable use of biodiversity and ecosystem services. Despite the pressure that exists on the biological resources of this heritage, the forest relics of the MBR still abound in viable biological potential and contribute to the resilience of local communities in the face of poverty and climate change. This study, which focuses on the marshland formations of the RBMT, is intended to contribute to the development and sustainable management of forest ecosystems in Togo. More specifically, it aims to assess 1) the floristic diversity, 2) the demographic structure of the stands and 3) the carbon sequestration potential of the Avévé forest patches.

2. Materials and Methods

2.1. Study Area

The study is being carried out on the forest islands of the Aveve terroir, which had not been investigated when the reserve was listed in 2017. Administratively, it is part of the Lacs 2 commune (Lacs Prefecture). The Aveve terroir is a group of swampy forest ecosystems covering an area of 3309.73 ha, within which a complex of six (6) community forests can be identified: Amevo (28.21 ha), Fontan (24.93 ha), Mamboui (81.01 ha), Dougbanave (72.77 ha), Zogbeve (26.47 ha) and Avelebe (147.92 ha) referred to as AFOMADZEAVE (Figure 1). This zone lies between latitudes 6˚25'59.485"N and 6˚22'35.331"N and longitudes 1˚43'46.77"E and 1˚46'38.464"E. According to the zoning established in 2017, this ensemble is part of the transition zone of the Mono Biosphere Reserve in Togo, which has an area of 203,224 ha.

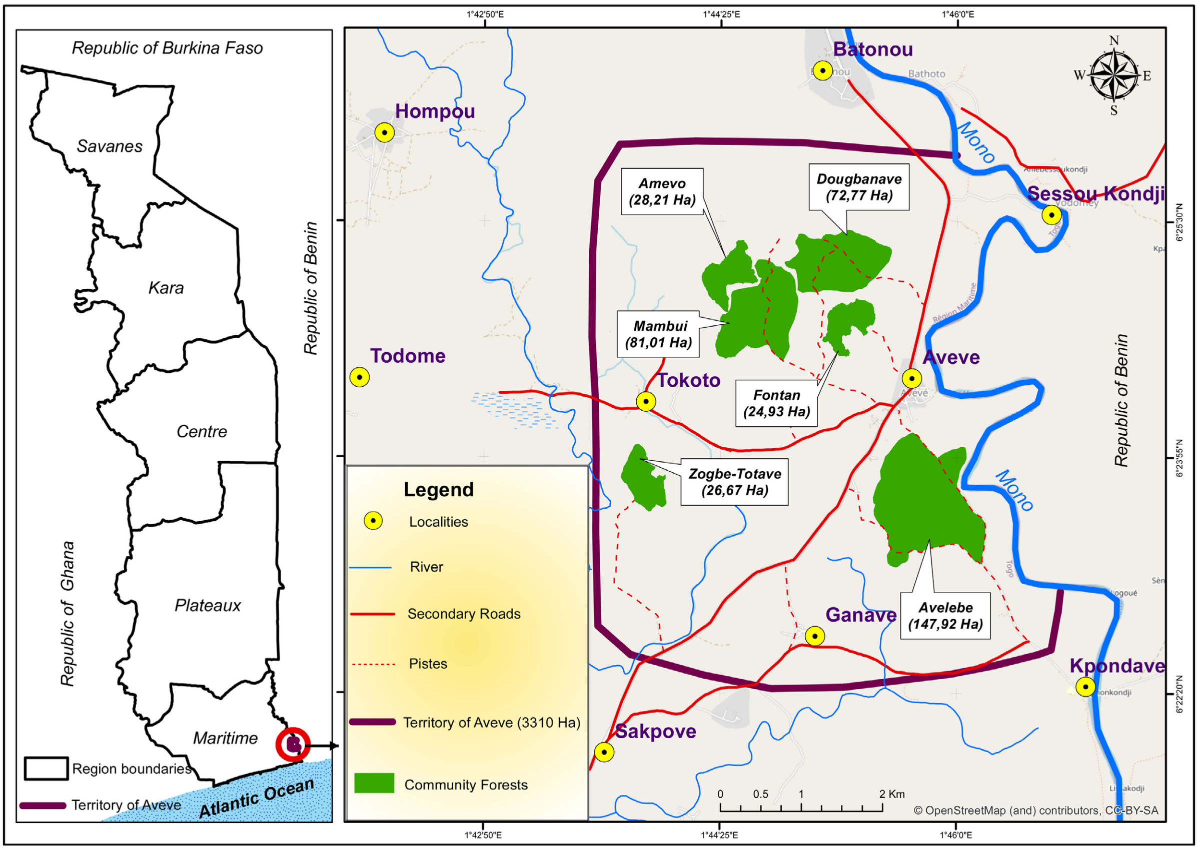


Figure 1. Map showing the location of the study area.

2.2. Data Collection

➢ **Sampling and plot sizes**

In order to collect statistically reliable qualitative and quantitative information for this study, the method of systematic sampling of the community forest blocks studied was applied. The choice of this method made it possible to take into account all the types of plant formations in each forest block of the AFOMADZEAVE complex. To do this, regular points equidistant by 200 m were applied to the study area (Figure 2). In total, 140 points covering the forest relics and covering a total area of 381.34 ha of community forest patches were inventoried, representing 11.5% of the swampy formations in the Avévé terroir to the south-east of the RBMT. This rate is related to the surface area of the reserve 203,224 ha and represents an overall sampling rate of 0.19%.

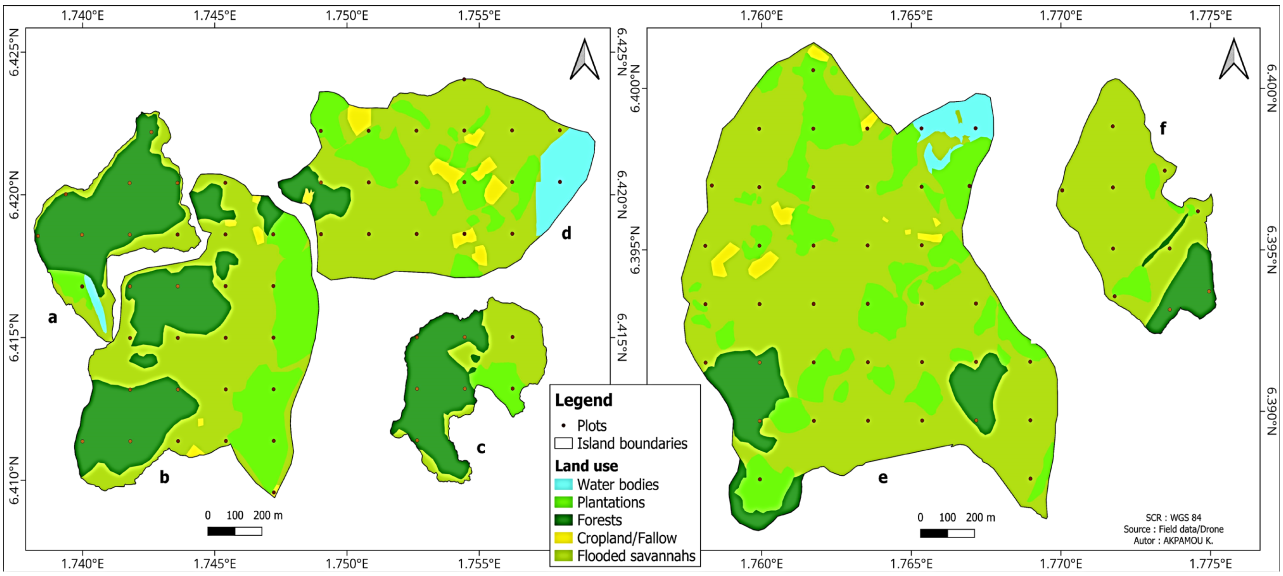


Figure 2. Systematic distribution of plots in forest patches. Community forest of Amevo (a), Mambui (b), Fontan (c), Dougbanave (d), Avelebe (e) and Zogbeve (f).

At each sampling point, a 30 m × 30 m plot (Figure 3) was set up for the floristic, forestry and ecological inventories. Square plots were chosen because they have been used successfully for inventories of dry forests, open forests, fallow land and savannah formations (Folega et al., 2014; Houeto et al., 2014; Glèlè Kakaï et al., 2016).

➢ **Floristic inventory**

Plant species were listed by scientific name (Kokou, 1998; Natta, 2003) within the ecosystem studied, taking into account their presence/absence in each 30 m x 30 m plot. The nomenclature of species and plant families is based on the analytical flora of Togo and Benin (Brunel et al., 1984; Akoègninou et al., 2006).
Species not identified in the field were collected and identified at the herbarium of the University of Lomé. The suprageneric classification of taxa is based entirely on that proposed by the Angiosperm Phylogeny Group (APG IV, 2016).

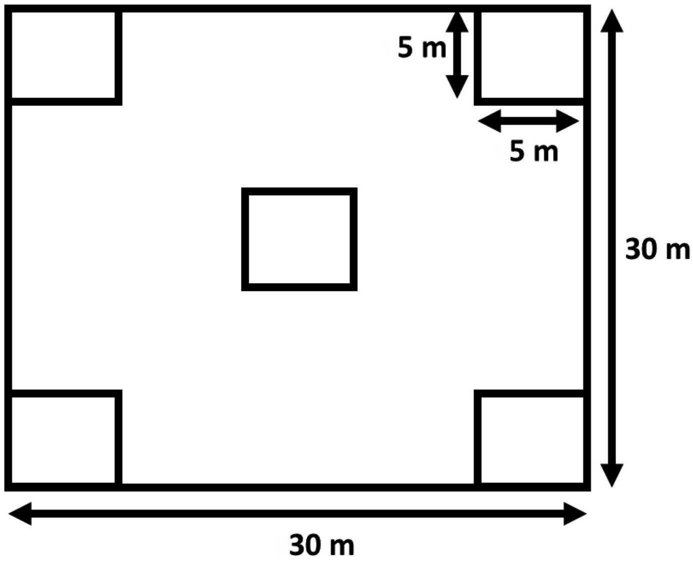


Figure 3. Plot layout for inventorying the main stand and natural regeneration.

➢ **Forest inventory**

The forest inventory was carried out on the same plots that had previously been subject to floristic inventories. Parameters such as the diameter at breast height (DBH) of woody plants with a diameter greater than or equal to 10 cm (DBH ≥ 10 cm) were measured using a tape measure. Visual scoring was used to define the bole height and total height of the woody plants (Kokou et al., 1999; Adjonou et al., 2009).

➢ **Ecological descriptors inventory**

In the same study plots, the ecological factors taken into account in this study are land use, poaching, grazing, vegetation fire and ground topography. To this end, a descriptor form designed for this purpose was filled in simultaneously with the floristic and forest inventory surveys. These data were useful for extracting the indirect gradients and ecological disturbances needed to establish species distribution and changes within the area's forest ecosystems.

➢ **Regeneration**

To carry out the regeneration inventory within each plot, five (5) small plots measuring 5 m × 5 m were installed (four were installed at the corners and the fifth in the center of the large plot). Species with a diameter at breast height (DBH) of less than 10 cm (DBH < 10 cm) using a tape measure were considered to be regenerating. All natural seedlings, stump sprouts and suckers were taken into account for regeneration (Sokpon et al., 2006). Regenerated species were counted in the five sub-plots.

2.3. Data Processing and Analysis

➢ **Floristic composition and diversity assessment**

The data collected was entered into a Microsoft Excel® spreadsheet. The list of species (herbaceous and woody) was drawn up and then completed by their family and genus. The biological types and phytogeographical affinity of each species were illustrated using raw spectra. The biological types (TB) used are those defined by Raunkiaer (1934) and adapted for the study of tropical plant formations by various authors (Mbayngone, 2014).

Vegetation gradients were determined using the ordination technique, by cross-referencing the matrix of surveys x species and environmental variables, then subjected to a multivariate principal component analysis (PCA) using CANOCO (Canonical Community Ordination) for Windows version 4.5 software. Axis interpretation was based on knowledge of the ecology of the species and environments surveyed. Each formation discriminated from the PCA was characterized by the most frequent species. The Shannon Index (ISh) and Piélou Equitability Index (Eq) were used to compare the discriminated formations with each other (Folega et al., 2017; Trekpo et al., 2023).

Species richness, the Shannon index (ISh) (Equation (1)) and the Piélou equitability index (Eq) (Equation (2)) were used as indicators of plant biodiversity.

The species richness N_0 corresponds to the total number of species found in each type of plant formation.

$$\text{ISh} = \sum\left(\left(\frac{N_i}{N}\right) * \log 2\left(\frac{N_i}{N}\right)\right) \quad (1)$$

where N_i: the sum of individuals of species i, N: the sum of individuals of all species.

$$\text{Ep} = \frac{\text{ISh}}{\log 2(N)} \quad (2)$$

where N = sum of individuals of all species

The ISh value is high when the number of species in the collection is large or the frequencies are not very different. The Eq value varies between 0 and 1. The more similar the frequencies of the species encountered, the closer this ratio is to zero. Conversely, a ratio that is very different from zero will correspond to a set of surveys with a few very dominant species or rare species (Magurran, 2004).

Anthropogenic formations such as plantations, fallow land and herbaceous species were not considered for further analysis. To determine the relationships between plant groupings, a "surveys x woody species" matrix of the natural formations selected was subjected to a Hierarchical Ascending Classification (HAC) following Ward's method (Cruz et al., 2010), using Community Analysis Parckage (CAP 2.15) software. This analysis made it possible to discriminate between the different woody plant groups associated with the formations studied.

- **Community structure analysis**

The analysis of the structure is based on the method of (Atakpama et al., 2014). The structural parameters assessed were: mean height, mean diameter, mean density and basal area. Statistical analyses were carried out using Microsoft Excel® spreadsheets and Minitab 16® software. The dendrometric parameters were calculated using the following formulae:

- Total density (D) of woody plants (Equation (3)):

$$D=\frac{n}{S}\times 0.001 \quad (3)$$

where n = number of plants per survey and S = survey area in hectares.

- Average tree diameter (D_m) (cm) (Equation (4)):

$$D_m=\left(\frac{1}{n}\sum_{i=1}^{n}d_i^2\right)^{\frac{1}{2}} \quad (4)$$

where n = number of trees; d_i = diameter at 1.30 m of tree i

- Land area (G) of ligneous plants (Equation (5)):

$$D_m=\frac{1}{n}\sum_{i=1}^{n}0.0001d^2 \quad (5)$$

where d_i = diameter in m at 1.30 m from the ground of tree i, S = survey area in hectare

- Natural regeneration rate is the ratio of the number of regenerated individuals to the number of non-regenerated individuals (Equation (6)).

$$\text{TR}=\frac{\text{Number of regenerating individuals}*100}{\text{Number of adult individuals}+\text{Number of regenerating individuals}} \quad (6)$$

If TR < 25%, regeneration is low;

25% < TR < 50%, regeneration is average;

TR > 50%, regeneration is abundant.

➢ **Carbon sequestration analysis**

The Aerial Biomass (AB) is calculated according to the classic allometric equations applicable to the study area (Chave et al., 2005). The calculation of underground biomass was based on the relationship between Cairns et al. (1997).

- The aerial biomass (BA) of each tree is assessed on the basis of its total height, diameter and specific density (Equation (7))

$$\text{BA}=\text{EXP}\left[-2187+0.916\,\text{LN}\left(\rho HD^2\right)\right] \quad (7)$$

where D = diameter at breast height (in m); ρ = specific density of the wood (in t/m^3 dried at 103˚C), H = total height of the tree (in m) and BA (in kg).

For species for which the specific density is not known, the average density P = 0.58 t/m^3 is assigned (Chave et al., 2005).

- The below-ground biomass (BS) of each tree is estimated from the above-ground biomass using the model developed by Cairns et al. (1997) (Equation (8)):

$$\text{BS}=\text{EXP}\left[-10587+0.916\,\text{LN}\left(\text{BA}\right)\right] \quad (8)$$

BS (in kg) = below-ground biomass and BA = above-ground biomass.

- The sum of the above-ground biomass (BA) and the below-ground biomass

(BS) gives the total biomass (BT in kg) (Equation (9)):

$$BT = BA + BS \quad (9)$$

The biomass is obtained by type of plant formation by adding together the biomasses of all the individual trees surveyed, followed by extrapolation to the hectare.

- The Carbon Stock (SC) is deduced using the following formula (Equation (10)):

$$SC = BT \times CF \quad (10)$$

CF = the default carbon ratio for all species equal to 0.47 (Folega et al., 2020).

- The equivalent of CO_2 (EqC) is determined by the relationship (Equation (11)):

$$EqC = 3.67 \times SC \quad \text{(Folega et al., 2020)} \quad (11)$$

The distribution of stems by height and diameter classes is fitted to the three (3) Weibull distribution parameters (Husch et al., 2002) of the Minitab software, according to the probability density function of Rondeux (2021) (Equation (12)):

$$f(x) = c/b\left((x-a)/b\right)^{c-1} \exp\left[-\left((x-a)/b\right)^{c}\right] \quad (12)$$

where, x = tree diameter; a = position parameter (zero if all tree categories are considered and non-zero if the trees considered have a diameter or height greater than or equal to a); b = scale or size parameter, it is linked to the central value of the diameters or heights of the trees in the cluster considered and c = shape parameter linked to the diameter or height of the structure considered.

3. Result

3.1. Specific Richness of All Plant Formations

A total of 182 species of flora were recorded in the study site (**Figure 4**), including 71 woody species. These species are divided into 153 genera and 54 families. The most represented families are Rubiaceae (29.09%) and Fabaceae (27.74%) (**Figure 4**). The most represented species are *Mitragyna inermis* (24.38%), *Lonchocarpus sericeus* (10.93%), *Acacia auriculiformis* (6.79%), *Diospyros mespiliformis* (4.69%) and *Lecaniodiscus cupanioides* (3.35%). The site is dominated by the following biological types: microphanerophytes (73.19%) followed by mesophanerophytes (14.24%). In terms of phytogeographical types, Guinean-Congolian species (29.22%) followed by transitional Guinean-Congolian/Sudanese-Zambézian species (27.68%) are the most represented. Species belonging to the Sudano-Zambézian zone and introduced species accounted for 26.77% and 16.33% respectively. The Shannon diversity index is equal to 5.02 bits and the Piélou equitability is 0.45 bits.

3.2. Vegetation Classification

Multivariate analysis using CANOCO software explains the variance in the richness of flora in the study area and the relationships between species distribu tion and environmental variables. The ordination results are shown in **Figure 5**.

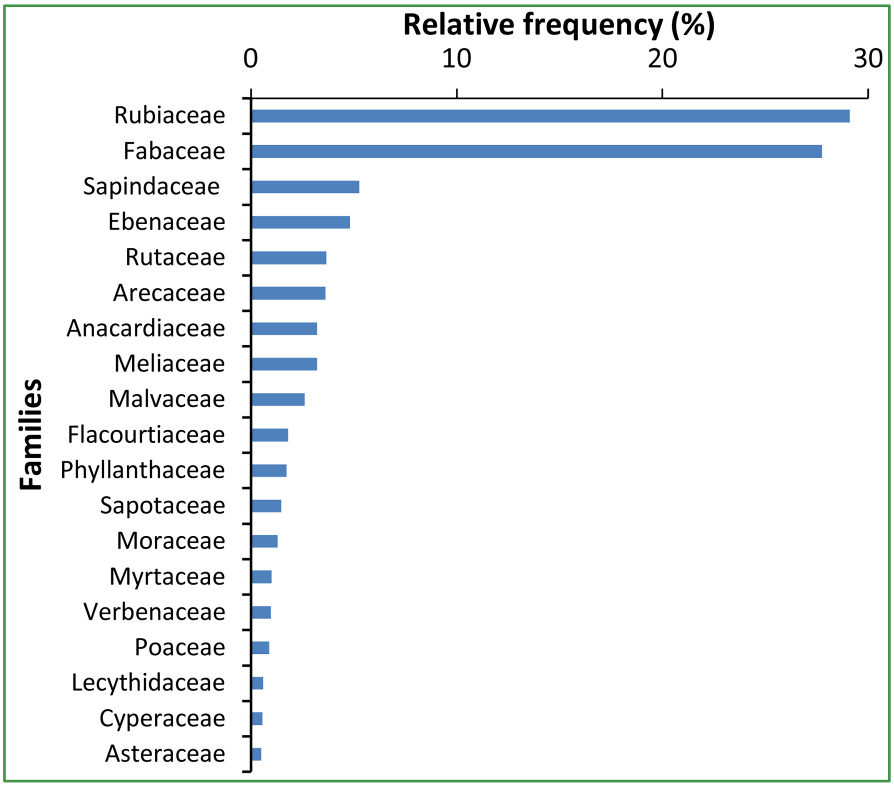


Figure 4. Distribution of floras by family.

The overall variance expressed by the axes is 34.7% for floristic richness and 65.3% for the relationship between species distribution and environmental variables. This clearly demonstrates that environmental gradients are the major determinants of the distribution or occurrence of plant species in the study site (**Table 1**).

Table 1. Eigenvalues and variances are explained by the first four PCA axes.

Axes	1	2	3	4	Total variance
Own values	0.145	0.088	0.058	0.056	1.000
Species-environment correlations	0.196	0.210	0.087	0.570	-
Cumulative percentage change in species data	14.5	23.3	29.1	34.7	-
Cumulative percentage change in the species-environment relationship	13.0	22.0	23.0	65.3	-
Sum of all eigenvalues	-	-	-	-	1.000
Sum of all canonical eigenvalues	-	-	-	-	0.043

It can be seen that the survey plots projected into the canonical space are perfectly grouped according to the different types of vegetation described in the zone, as shown in **Figure 5**. In other words, the four groups of surveys are perfectly individualised. The first group of formations characterises savannah vegetation; the second group of formations is characteristic of semi-deciduous dense forest vegetation; the third group of formations is plantations, while the last group of formations is a mixture of more anthropized vegetation made up of a crop-fallow mosaic.

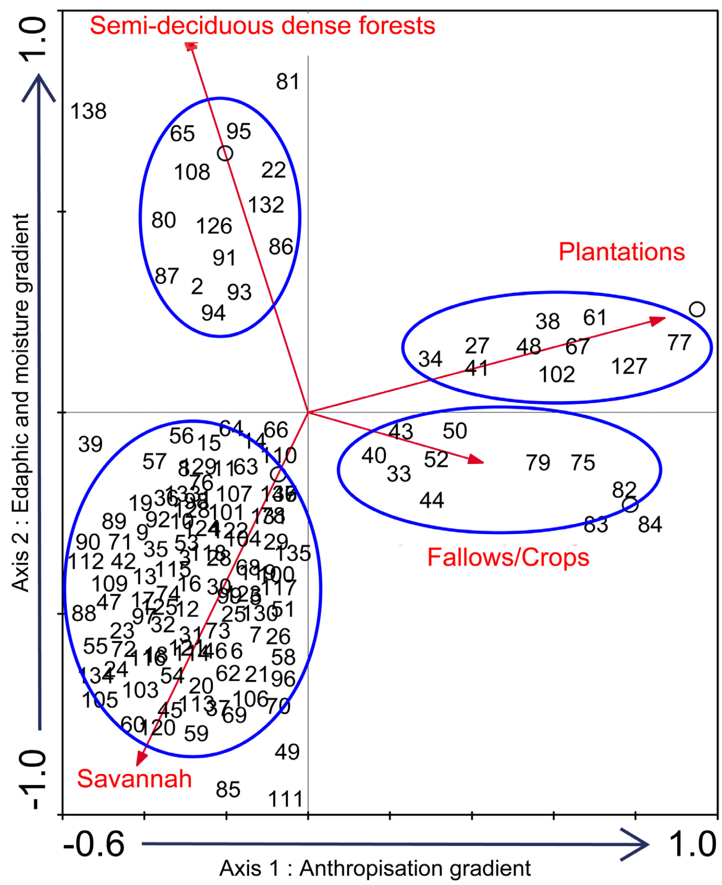


Figure 5. Ordination of the gradients of the multivariate analysis showing the types of plant formation according to groups of records and species.

The distribution of plant species and the grouping of plots in canonical space suggest the influence of ecological gradients on species distribution. Two ecological gradients in particular can be seen along axis 1 and axis 2 of the diagram.

Axis 1 expresses a variation from low-disturbance forests (semi-deciduous forests and savannahs) to high-disturbance, anthropised formations (plantations and fields/fallows). This indicates the influence of anthropogenic action, and therefore a gradient of increasing anthropisation. Axis 2 expresses a variation from more or less open plant formations (savannahs and fields/fallows) to denser, more closed formations (semi-deciduous forests and plantations). The latter axis would be controlled by a double gradient of both edaphic conditions and increasing humidity. Edaphic conditions improve as we move from open formations towards denser formations where the soil is better preserved and deeper. At the same time, humidity increases as you move from savannah to semi-deciduous forest.

- **Description of the types of plant formations identified**

➢ **Flooded savannah formation**

A total of 104 surveys were grouped together within this savannah formation (Figure 6). Most of these are flooded savannas. Grazing, wood cutting and animal dung were recorded in this group. In all, 161 plant species were recorded in 51 families and 140 genera. The most common species are *Mitragyna inermis* (31.17%), *Lonchocarpus sericeus* (10.57%) and *Acacia auriculiformis* (6.55%). Other species are poorly represented, with a frequency of less than 5%. The most represented families are Rubiaceae (34.88%) followed by Fabaceae (26.57%). Sudano Zambézian species are the most dominant (33.74%), followed by transitional species (GC-SZ; 26.28%) and Guinéo-Congolais species (GC; 24.90%). There were also introduced species (i; 15.07%). In total, there are twelve (12) biological types in the savannas. Microphanerophytes are the most represented (78.09%), followed by mesophanerophytes (5.25%). Nanophanerophytes and microphanerophyte lianas are poorly represented. The Shannon diversity index is equal to 4.68 bits and the Piélou equitability is 0.43 bits.

Figure 6. Flooded savannah with *Mitragyna inermis.*

➢ **Semi-deciduous dense forest formations**

A total of 15 surveys were grouped within the semi-deciduous dense forests (Figure 7) characterised by evidence of the presence of wild animals (footprints, droppings, calls, etc.). In all, 79 plant species were found, divided into 35 families and 70 genera. The most represented species are *Lecaniodiscus cupanioides* Planch. Ex Benth (10.70%), *Diospyros mespiliformis* (9.70%), *Dialium guinneense* (7.69%), *Zanthozylum zanthoziloides* (7.69%), *Acacia auriculiformis* (7.36%) and *Morinda lucida* (5.2%). Other species are poorly represented, with a frequency of less than 5%. The most common families are Fabaceae (27.03%), followed by Sapindaceae (12.84%), Ebenaceae (10.14%), Rubiaceae (8.78%) and Rutaceae (7.77%). Transitional species (GC-SZ; 45.89%) are followed by Guinéo-Congolese species (GC; 34.93%). There are also introduced species (i; 15.07%) followed by Sudano-Zambézian species (4.11%). In total, there are twelve (10) biological types in the dense deciduous forests. Microphanerophytes are the most represented (55.48%), followed by mesophanerophytes (25%). Nanophanerophytes (7.88%) and microphanerophyte lianas are poorly represented (5.14%). The Shannon diversity index is equal to 5.16 bits and the Piélou equitability is 0.63 bits.

Figure 7. Dense semi-deciduous forest.

➢ **Plantation formations**

A total of 10 surveys representing 40 species divided into 40 genera and 24 families were carried out in the plantation formations (**Figure 8**). Grazing, wood-cutting, charcoal-burning millstones, fields and vegetation fires were observed in this type of vegetation. The most common species are *Acacia auriculiformis* (21.25%), *Azadirachta indica* (14.38%), *Lonchocarpus sericeus* (13.75%), *Elaeis guineensis* (12.5%), *Albizzia Zygia* and *Eucalyptus camaldulensis* are poorly represented (5.63% and 5% respectively). The most represented families are Fabaceae (42.5%), followed by Meliaceae (14.38%), Arecaceae (12.5%) and Myrtaceae (5.63%). Introduced species dominate (i; 25.55%), followed by Guineo-Congolese species (23.36%) and transitional species (GC-SZ; 9.49%). There are ten (10) biological types within G3. Microphanerophytes (56.25%) followed by mesophanerophytes (29.38%) are the most represented. Nanophanerophytes (5.63%) and microphanerophyte lianas (2.5%) are poorly represented. The Shannon diversity index is equal to 3.96 bits and the Piélou equitability is 0.54 bits.

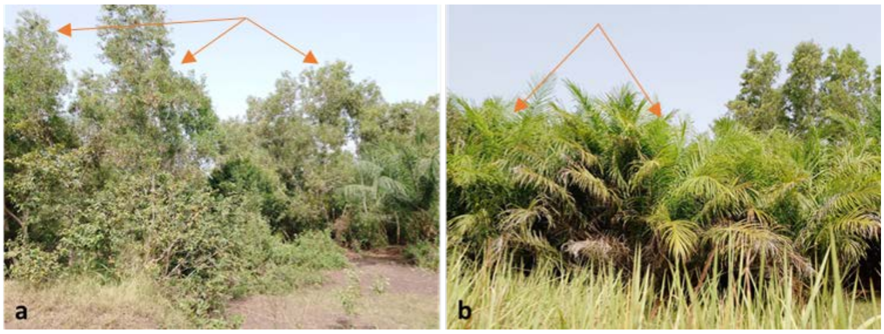


Figure 8. *Acacia auriculiformis* (a) and *Elaeis guineensis* (b) plantation.

➢ **Crops and fallow land formations**

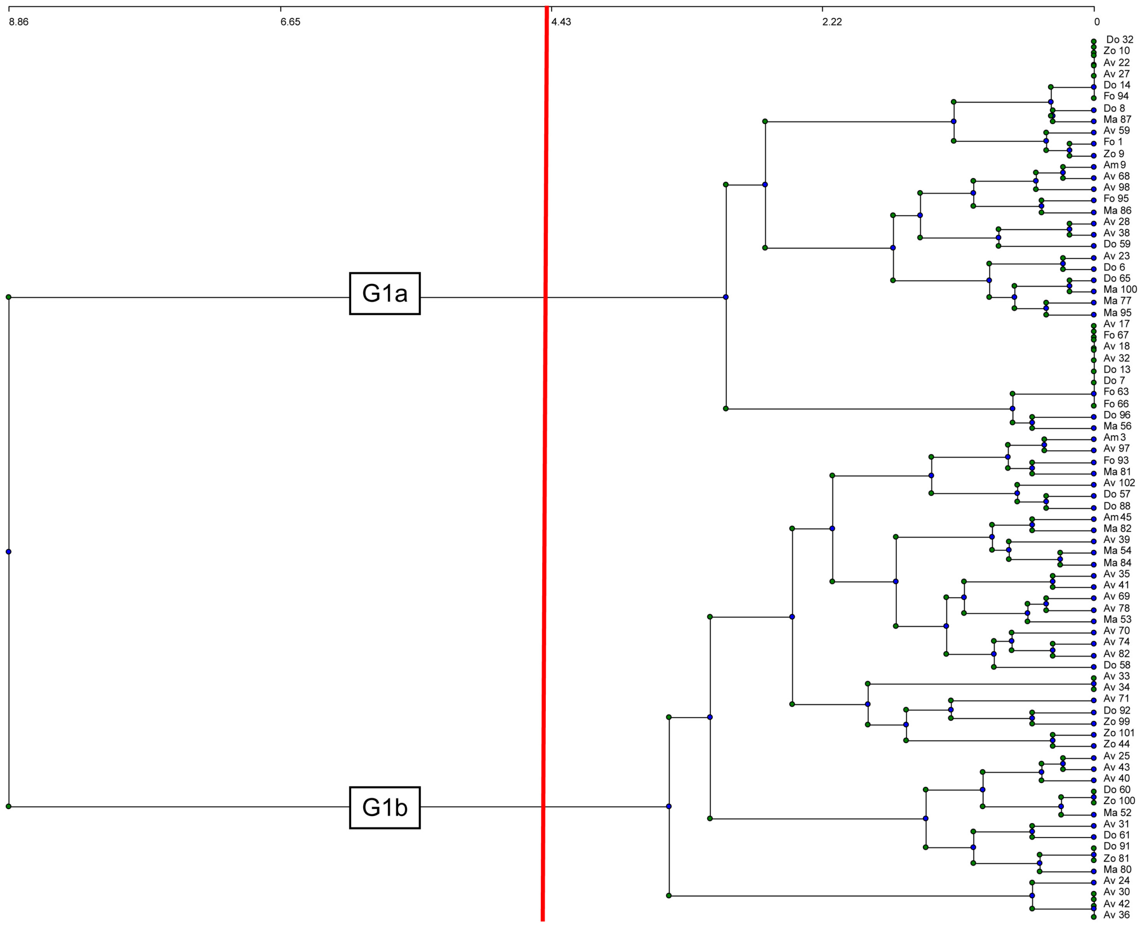
A total of 11 surveys were carried out for a total of 13 species divided into 12 genera and 10 families in the field/fallow land formations (**Figure 9**). Grazing, clearing, vegetation fires and charcoal millstones were observed in this group. The most common species are *Chromolaena odorata* (28.13%), followed by *Sarcocephalus latifolius* (25%), *Elaeis guineensis* (9.38%), *Citrus cinensis* (7.81%) and *Acacia auriculiformis* (6.25%). Species such as *Alchornea cordifolia* and *Ficus dicranostyla* are poorly represented (4.69%). The most represented families are the Asteraceae (28.13%) and Rubiaceae (26.56%). They are followed by Arecaceae (9.38%), Fabaceae (9.38%), Rutaceae (7.81%) and Moraceae (6.25%). Guineo-Congolese species are the most represented (GC; 67.19%), followed by introduced species (i; 20.31%) and transitional species (GC-SZ; 12.5%). There are four (04) biological types within G4. Mesophanerophytes (37.5%) followed by nanophanerophytes (32.81%) and microphanerophytes (28.13%). Megaphanerophytes are very low (1.56%). The Shannon diversity index is equal to 3.04 bits and the Piélou equitability is 0.51 bits.

Figure 9. Crops/Fallowland.

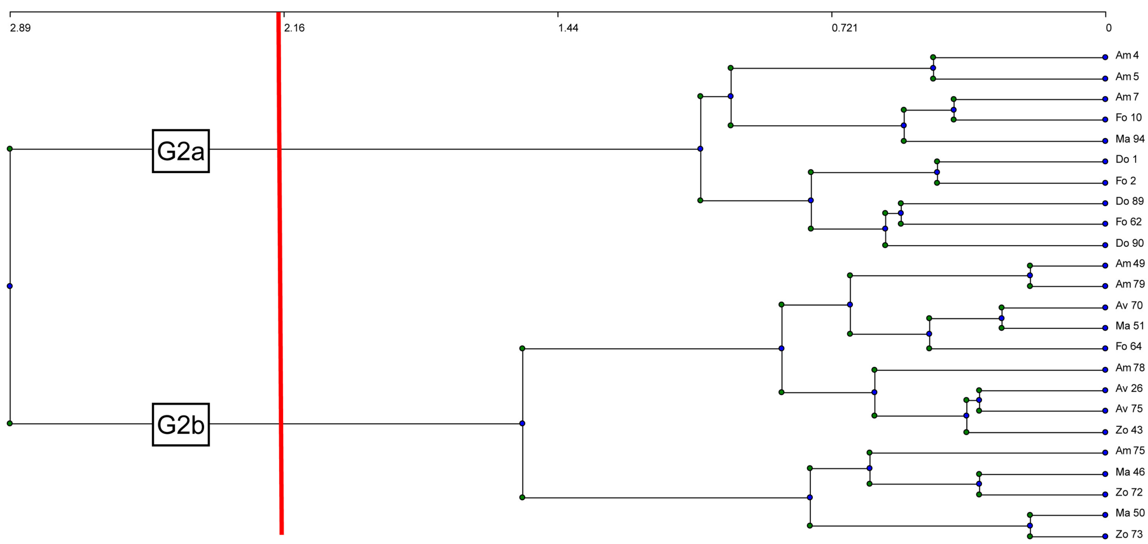
3.3. Structural Characteristics of Woody Plant Formations

- **Main woody plant groupings identified within plant formations**

Hierarchical Ascending Classification (HAC) applied to the two (2) types of plant formations (Savannahs and Semi-deciduous Dense Forests) using the Word's 1-Sorenson method made it possible to discriminate two plant groupings within each type of formation. Discrimination of savannahs at the 4.43 similarity threshold revealed the *Mitragyna inermis* (Willd.) Kuntze group (G1a) and the *Lonchocarpus sericeus* (Poir.) and *Mitragyna inermis* (Willd.) Kuntze group (G1b). The Semi-deciduous Dense Forest formation group, with a similarity threshold of 2.16%, is subdivided into two (2) plant groups. These are the *Lecaniodiscus cupanioides* Planch. Ex Benth and *Diospyros mespiliformis* Hochst. (G2a) and the grouping with *Mitragyna inermis* (Willd.) Kuntze and *Lonchocarpus sericeus* (Poir.) (G2b) (**Figure 10**).



(a)



(b)

Figure 10. Bottom-up hierarchical classification of surveys based on similarities in woody flora using Ward's method. Formation of savannahs (a) and patches of dense semi-deciduous forest (b). G1a: *Mitragyna inermis* (Willd.) Kuntze group. G1b: Group with *Lonchocarpus sericeus* (Poir.) and *Mitragyna inermis* (Willd.) Kuntze. G2a: Group with *Lecaniodiscus cupanioides* Planch. Ex Benth and *Diospyros mespiliformis* Hochst.; G2b: Group with *Mitragyna inermis* (Willd.) Kuntze and *Lonchocarpus sericeus* (Poir.)

- **Forest characteristics of the main plant groups**

1) *Mitragyna inermis* (Willd.) Kuntze group (G1a)

The density of trees in the G1a group was 145 stems/ha. The average diameter of the trees was 22.63 ± 17.91 cm. The average height of the trees was 7.99 ± 3.81 m. The basal area was 29.80 ± 0.15 m^2/ha (Table 2).

The regeneration rate is 58.53%, indicating that regeneration is moderately abundant. The species most represented in this regeneration are *Mitragyna inermis*, *Lonchocarpus sericeus* and *Bridelia ferruginea*. The distribution of stems by diameter class gives an "inverted J" appearance. This distribution reflects the predominance of small-diameter individuals (10 to 20 cm). The value of the Weibull shape coefficient c = 0.80, which is less than 1, thus characterises multispecific or uneven-aged stands. The density of large-diameter individuals is very low. The distribution of stems by height class shows a positive asymmetric distribution with a Weibull distribution shape coefficient c = 1.92, characteristic of stands with a predominance of young individuals. The most represented height class is 6 to 8 m (Figure 11).

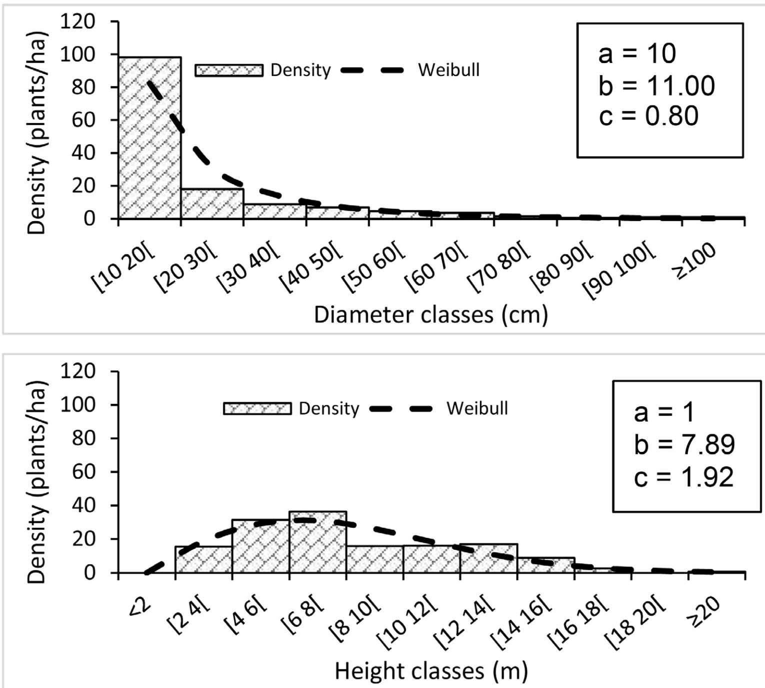


Figure 11. Diameter and height structure of *Mitragyna inermis* species.

2) Group with *Lonchocarpus sericeus* (Poir.) and *Mitragyna inermis* (Willd.) Kuntze (G1b)

The density of trees in this group was 133 stems/ha. The average diameter of the trees is estimated at 31.61 ± 25.45 cm. The average height of the trees is estimated at 8.45 ± 3.80 m. The basal area was 66.18 ± 0.29 m^2/ha (Table 2).

The regeneration rate is 70.12%, indicating that regeneration is abundant. *Bridelia ferruginea*, *Antidesma venosum* and *Mitragyna inermis* are the most represented species in the regeneration. The distribution of stems by diameter class gives an "inverted J" appearance. This distribution reflects the predominance of small-diameter individuals (10 to 20 cm). The value of the Weibull shape coefficient c = 0.91, which is less than 1, thus characterises multispecific or uneven-aged stands. The density of large-diameter individuals is very low. The distribution of stems by height class shows a positive asymmetric distribution with a Weibull distribution shape coefficient c = 2.09, characteristic of stands with a predominance of young individuals. The most represented height class is 4 to 6 m (Figure 12).

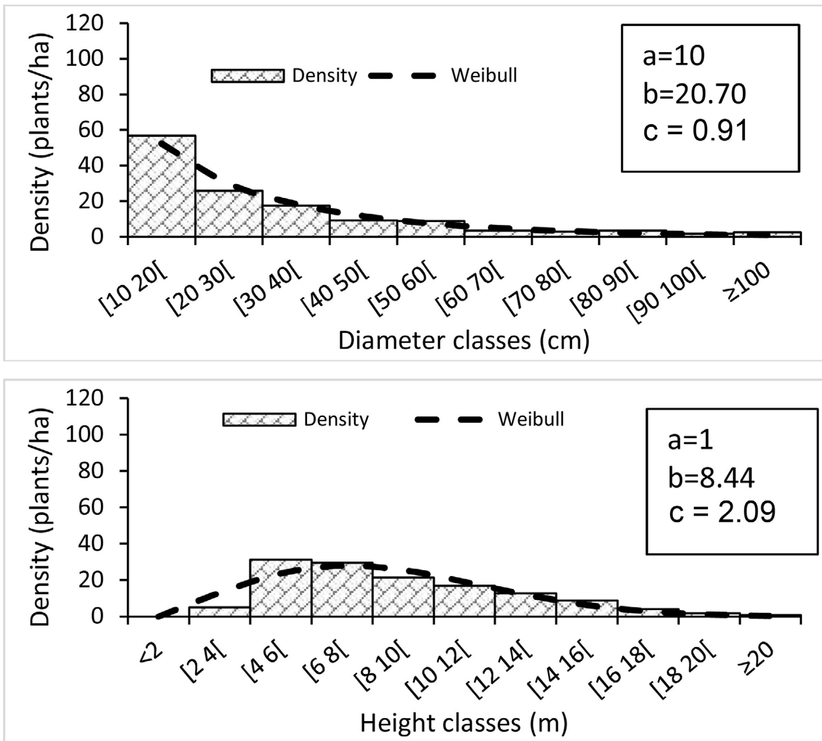


Figure 12. Diameter and height structure of species in the *Lonchocarpus sericeus* and *Mitragyna inermis* grouping.

3) Group with *Lecaniodiscus cupanioides* Planch. Ex Benth and *Diospyros mespiliformis* Hochst (G2a)

Tree density was 410 stems/ha in the *Lecaniodiscus cupanioides* and *Diospyros mespiliformis* group. The average diameter of the trees was 38.95 ± 34.46 cm. The average height of the trees was 7.95 ± 4.64 m. The basal area was 78.30 ± 0.39 m^2/ha (Table 2).

The regeneration rate was 65.38%. The species most represented in this regeneration are *Lecaniodiscus cupanioides*, *Mimusops kummel*, *Dialium guineense* and *Diospyros mespiliformis*. The distribution of stems by diameter class gives an "inverted J" appearance. This distribution reflects the predominance of small-diameter individuals (10 to 20 cm). There is also a high representation of individuals in the 30 to 40 cm diameter class and with a diameter greater than or equal to 100 m in this grouping. The value of the Weibull shape coefficient c = 0.88, which is less than 1, thus characterises multispecific or uneven-aged stands. The distribution of stems by height class shows a positive asymmetric distribution with a Weibull shape distribution coefficient c = 1.58, characteristic of stands with a predominance of young individuals. The most represented height class is 4 to 6 m, followed by 6 to 8 m. Individuals of 20 m or more in height are poorly represented (Figure 13).

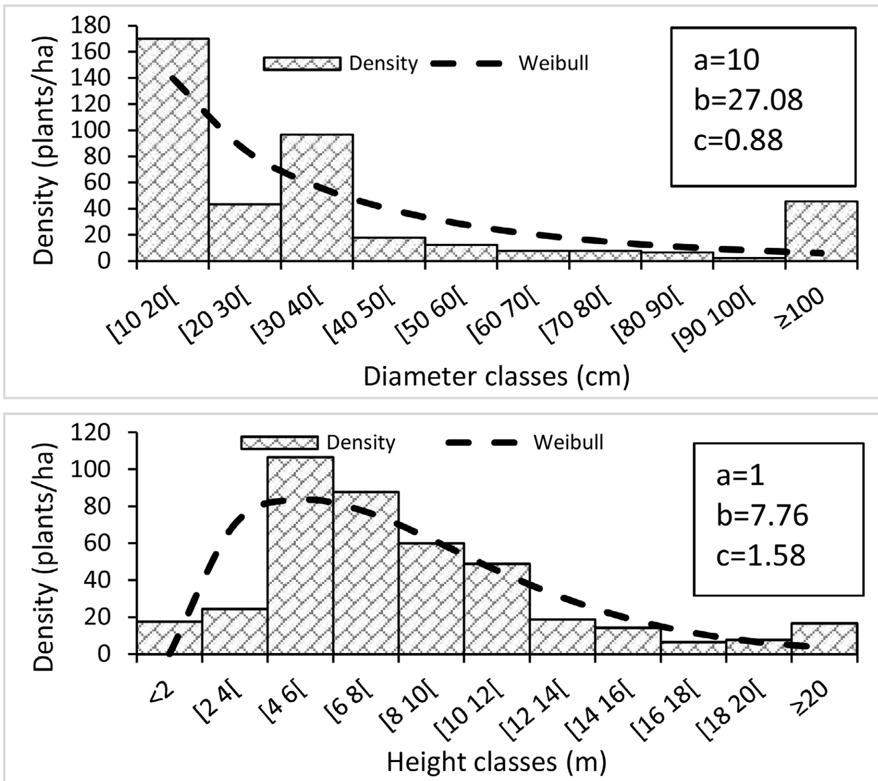


Figure 13. Diameter and height structure of species in the grouping with *Lecaniodiscus cupanioides* and *Diospyros mespiliformis.*

4) Group with *Mitragyna inermis* (Willd.) Kuntze and *Lonchocarpus sericeus* (Poir.) (G2b)

The density of trees in this group was 306 stems/ha. The average diameter of the trees is 28.94 ± 27.09 cm. The average height of the trees is estimated at 7.77 ± 3.49 m. The basal area was 37.67 ± 0.23 m^2/ha (Table 2).

The regeneration rate is 50%, indicating that regeneration is moderately abundant. *Lecaniodiscus cupanioides*, *Lonchocarpus sericeus* and *Mitragyna inermis* are the most represented species in the regeneration. The distribution of stems by diameter class gives an "inverted J" appearance. This distribution reflects the predominance of small-diameter individuals (10 to 20 cm). The value of the Weibull shape coefficient c = 0.80, which is less than 1, thus characterises multispecific or uneven-aged stands. The density of large-diameter individuals is very low (Figure 14). The distribution of stems by height class shows a positive asymmetric distribution with a Weibull distribution shape coefficient c = 2.07, characteristic of stands with a predominance of young individuals. The most represented height class is 4 to 6 m, followed by 8 to 10 m.

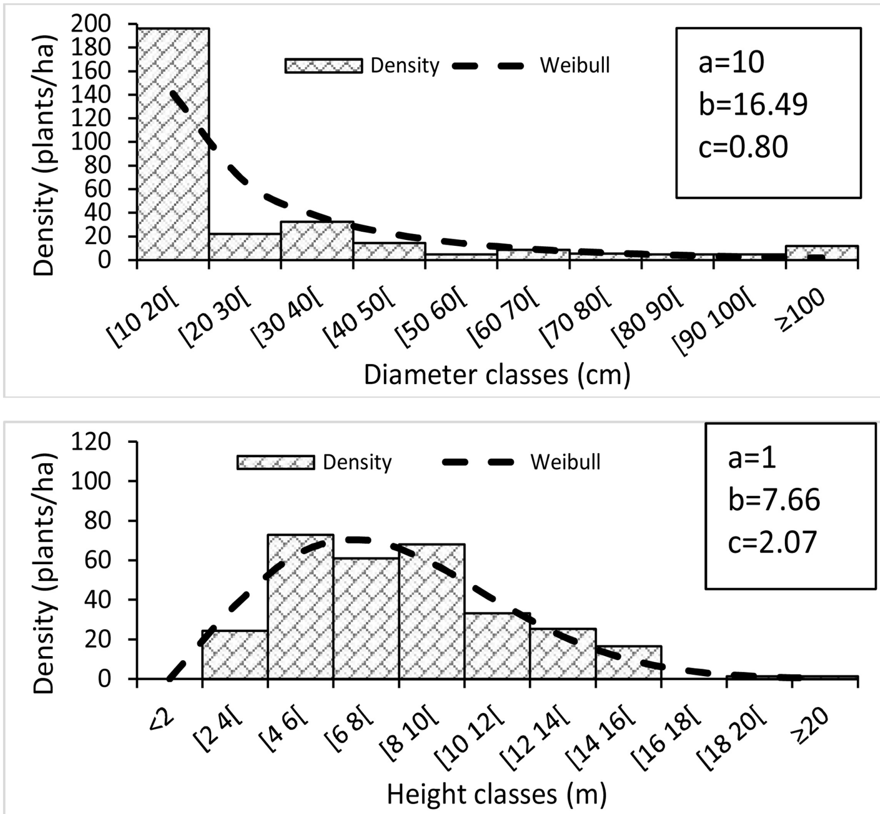


Figure 14. Diameter and height structure of species in the grouping with *Mitragyna inermis* and *Lonchocarpus sericeus.*

Table 2. Structural parameters of the main discriminated groups.

Parameters	G1 a	G1 b	G2 a	G2 b
Density (stem/ha)	145	133	410	306
Mean diameters (cm)	22.63 ± 17.91	31.61 ± 25.45	38.95 ± 34.46	28.94 ± 27.09
Mean heights (m)	7.99 ± 3.81	8.45 ± 3.80	7.95 ± 4.64	7.77 ± 3.49
Land surface area (m^2/ha)	29.80 ± 0.15	66.18 ± 0.29	78.30. ± 0.39	37.67 ± 0.23
Regeneration rate (%)	58.53	70.12	65.38	50

3.4. Biomass and Carbon Sequestration Potential of Residual Forest Patches

The total biomass is estimated at 89.13 T/Ha for all the surveys carried out. It is distributed as follows: 14.99 T/Ha for savannah formations, 43.04 T/Ha for semi-deciduous dense forests, 21.45 T/Ha for semi-deciduous dense forests and 9.64 T/Ha for fallow-crop mosaics. Above-ground biomass was estimated at 62.95 T/Ha and below-ground biomass at 26.18 T/Ha. The total carbon stock was estimated at 41.89 T/Ha for all 140 surveys, with a CO_2 equivalent of 153.75 tC/Ha. A CO_2 equivalent of 25.86 tC/Ha for savannah formations, 74.25 tC/Ha for semi-deciduous dense forests, 37.01 tC/Ha for plantation formations and 4.53 tC/Ha for fallow-crop mosaics was sequestered (Table 3).

Table 3. Biomass and carbon stock of plant formations.

Formations	Above-ground biomass (BA, T/Ha)	Underground biomass BS (T/Ha)	Total biomass (BT, T/Ha)	Carbon stock (SC, T/Ha)	Carbon equivalent (EqC, T/Ha)
Savannah formations	10.50 ± 2.05	4.48 ± 0.87	14.99 ± 2.92	7.04 ± 0.05	25.86 ± 0.17
Semi-deciduous dense forest formations	30.85 ± 0.53	12.18 ± 0.20	43.04 ± 0.73	20.23 ± 0.11	74.25 ± 0.4
Plantation	15.15 ± 0.76	6.30 ± 0.30	21.45 ± 1.06	10.08 ± 0.07	37.01 ± 0.24
Fallow-crop mosaics	6.43 ± 0.06	3.21 ± 0.02	9.64 ± 0.09	4.53 ± 0.01	16.64 ± 0.06
Total islands	62.95	26.18	89.13	41.89	153.75

4. Discussion

4.1. Specific Richness and Conservation of the Biodiversity of Formations

Species richness is one of the criteria frequently used to assess efforts to conserve and manage biodiversity and nature. This study assessed the floristic diversity of the marsh ecosystems in the transition zone of the biosphere reserve in south-east Togo. It provided the first exhaustive list of its vascular flora: 182 species in 54 families and 153 genera over a sampled area of 12.6 ha. This flora provides an excellent basis for further research.

The current results show that the forest islands to the south-east of the Mono Biosphere Reserve have a rich and varied flora. However, this richness is low compared with the 423 plant species and 188 plant species inventoried respectively by Kokou et al. (2005) and Folega et al. (2017) in the sacred forests of south-east Togo. These discrepancies can be explained by the differences between the areas inventoried, the low inclusion of herbaceous species in this study and also by the size of the study area, which is still smaller than in previous studies.

The forest patches in the south-east of the Mono Biosphere Reserve in Togo are dominated by Rubiaceae, Fabaceae (Kokou & Kokutse, 2010) and Sapindaceae. The high proportion of Rubiaceae in the study area could be explained by the fact that these taxa are extremely diverse in the tropics (Lachenaud & Jongkind, 2010; Lachenaud et al., 2013) and constitute one of the most important families in African rainforests (Akoègninou et al., 2006). They are mainly a group of plants in the tropics, with the greatest diversity in the low and mid-altitude zones of rainforests (Ntore, 2008; Davis et al., 2009). The result obtained is comparable to those of other authors who reveal that the forest formations observed in the Dahomey corridor ecoregion are dominated by the most ecologically important Angiosperm families, namely Rubiaceae, Leguminosae and Euphorbiaceae (Gentry, 1988; Kokou, 1998; Natta, 2003; Adomou, 2005; Adjonou et al., 2013). The study area is currently fragmented, dotted here and there with forest relicts or islands (Kokou et al., 2005; Adjonou et al., 2016). Several genera of the Rubiaceae family have also been recorded here, including Mitragyna, Sarcocephalus, Psychotria, Morinda, Chassalia, Morelia and others.

Phanerophytes represent the biological types found in the zone, with microphanerophytes followed by mesophanerophytes being the most dominant forms in savannah formations, semi-deciduous dense forests and plantations. On the other hand, for fallow/crop formations, mesophanerophytes followed by nanophanerophytes and microphanerophytes are the most dominant. The high representation of microphanerophytes and mesophanerophytes associated with few epiphytes, confirmed by the dominance of Rubiaceae, shows a preponderance of shrub or low forest formations (dense semi-deciduous) in the study environment since biological types are the parameters that best reflect the physiognomy of plant formations (Sinsin et al., 1996). The same results were reported by Aké-Assi (2001) in Côte d'Ivoire. These results also confirm the assertion by Schmidt et al. (2005) that biological types reflect not only the structural parameters in a vegetation but also the varied environmental conditions (river depressions, farmland, etc.) favourable to the development of woody species. Other authors indicate that the physiognomy and floristic composition of vegetation reflect the relationship between climate and vegetation (Adjossou, 2009). For Akpagana (1992) and Guelly (1994), the edaphic factor (soil type, depth, texture, humidity) and the degree of anthropisation of plant formations are factors that explain the distribution of plant formations.

The chorological distribution of the flora in the study area is generally marked by the representativeness of Guinean-Congolese (GC) species, followed by transitional Guinean-Congolese/Sudanese-Zambezian (GC/SZ) species. Sudano-Zambezian species and introduced species come third and fourth. This strong presence of Guineo-Congolese and Guineo-Congolese/Sudano-Zambezian species is due to the humid nature of the zone, which is conducive to the development of a relatively more hydrophilic flora. It also reflects the fact that the ecosystems of south-east Togo are part of a mosaic of global rainforests and savannah formations (Kokou & Kokutse, 2010). The presence of introduced species in a high proportion (16.33%) compared with 7.9% reported by Kokou and Kokutse (2010) confirms the risk of invasion and loss of biodiversity. Phytogeographical types are indicators of the state of ecosystems because they reflect the fidelity of species to their region of confinement (Toko Imorou, 2019). Floristic diversity indices are objective criteria for assessing the diversity of a plant community (Ramade, 1994). Examination of the Shannon-Weaver H' diversity index shows that dense semi-deciduous forest formations have a slightly higher diversity index (5.16 bits), followed by savannahs (4.68 bits), plantations (3.96 bits) and fallow/crops (3.04 bits). These results reflect the strong anthropisation of savannah formations, plantations and fallow land/crops as a result of the advance of the agricultural front within the Avévé forest island complex (Akpamou et al., 2021). In fact, the area is undergoing agricultural development through the establishment of planned agricultural development zones (ZAAP). The case of the Avévé ZAAP, which is one of the 20 ZAAPs of excellence, is palpable: around 100 ha of forest ecosystems in the Zogbétotavé block will have been converted by 2021.

According to Orth and Girard (1996), the Shannon index takes on high values in a phytocenosis when there is an equipartition of species and takes on low values when there is a dominance of certain species over others. The results show that semi-deciduous dense forests are floristically very diverse, with a set of records with similar species frequencies and a strong presence of rare species. This is confirmed by the analysis of Pielou's equitability, which shows high values in semi-deciduous dense forests = 0.63, plantations = 0.54 and fallow/crops = 0.51 (>0.5) and low values in savannahs = 0.43, where it is less than 0.5. The low equitability observed in the savannas indicates an irregular distribution between individuals of species with a strong dominance of certain species, in particular *Mitragyna inermis* and *Lonchocarpus sericeus*.

4.2. Demographic Structure and Renewal of Woody Stands

All four (4) plant groups (G1a, G1b, G2a, G2b) from the savannahs and dense semi-deciduous forests discriminated show an "inverted J" horizontal structure reflecting a stand in full reconstitution (Atakpama et al., 2022). The predominance of small-diameter individuals [10 to 20] is a structure that is often observed in undisturbed ecosystems under favourable ecological conditions such as humidity, soil, etc. Small-diameter individuals ensure the stability of the stand. Small-diameter trees ensure the future of natural formations, while large-diameter trees resulting from natural selection are seed trees that ensure the future of stands through the production of seeds or suckers (Morou, 2010; Folega et al., 2017).

The low representativeness or absence of individuals of other diameter classes in the G1a and G1b plant groups could be explained by the way in which individuals are exploited by clear-cutting or selective felling of certain woody species for energy and construction purposes, thus reducing the presence of large-diameter trees in the stands, or even the absence or disappearance of certain species with a high commercial value. These include species such as *Mitragyna inermis*, *Lonchocarpus sericeus*, *Mimusops andogensis*, *Mimusops Kummel*, *Diospyros mespiliformis*, *Dialium guinneense* and *Vitex doniana*. On the other hand, in the *Mitragyna inermis* plant group (G1a), the low values for average diameter, basal area and average density can be explained not only by the ecological conditions of the environment but also by the preferential use of the species characteristic of G1a (M. inermis) for various ecosystem uses (food, fodder, construction, screens, furniture, etc.). Generally speaking, this ecosystem is regularly cleared to create agricultural fields and plantations. This explains the average regeneration observed in the G1a and G2b groups, which are similar to savannahs.

In contrast, the regeneration rate is very high for the other plant groups G1b and G2a, which have been identified as being close to semi-deciduous dense forests. The high rate of regeneration is an opportunity to reconstitute and restore these groups (Atakpama et al., 2017). The distribution of stems by height class shows a bell-shaped pattern in the four (4) plant groups identified, reflecting the predominance of young individuals (Hounkpèvi et al., 2011; Kombate et al., 2023). The overall average density is estimated at 210 stems/ha with an average diameter of 25.57 ± 21.77 m and an average height of 7.93 ± 3.83 m. This density is low compared with that observed in the sacred forests of the Adja plateau (244 to 335 stems/ha) (Gbodjinou et al., 2022) and that of the Massi reserve (La Lama) in Benin (229 stems/ha) (Hounkpèvi et al., 2011). The low stem density (145 stems/ha and 133 stems/ha) observed in the G1a and G1b groups compared with the G2a and G2b groups (410 stems/ha and 306 stems/ha) certainly reflects the intense exploitation of timber resources by local populations (Adjakpa et al., 2011).

Mechanisms for reducing emissions from deforestation and degradation (REDD+) are defined through the assessment of carbon stocks in order to put in place viable mitigation strategies to combat climate change. Community forests now appear to be one of the best options for reducing greenhouse gas emissions, both worldwide and in Togo.

4.3. Biomass and Carbon Sequestration Potential of Residual Forest Patches

The results of the carbon stock assessment on all the sites inventoried in the marsh ecosystems of south-east Togo reveal an overall contribution of 41.89 T/Ha, i.e. 153.75 tC/Ha. This result is higher than those obtained by Kombate et al. (2019). They obtained a carbon sequestration potential of 35.47 T/Ha on the Akposso Plateaux in the sub-humid zone of Togo. However, the result obtained is lower than that found by Henry et al. (2011), which is 355 T. The high carbon stock in dense semi-deciduous forests (20.23 T C/ha) compared with savannah formations (7.04 T/Ha), plantations (10.08 T/Ha) and fallow-crop mosaics (4.53 T/Ha) is thought to be due to the low anthropogenic activity observed in dense semi-deciduous forests (Kombate et al., 2023).

5. Conclusion

The state of knowledge of the biodiversity of the ecosystems of the forest islands of the Mono Biosphere Reserve in south-east Togo revealed a floristic richness of

182 plant species divided into 153 genera and 54 families. Four main groups of woody plants were identified. These were G1a: *Mitragyna inermis* (Willd.) Kuntze group; G1b: *Lonchocarpus sericeus* (Poir.) and *Mitragyna inermis* (Willd.) Kuntze group; G2a: *Lecaniodiscus cupanioides* Planch. Ex Benth and *Diospyros mespiliformis*Hochst; G2b: group with *Mitragyna inermis* (Willd.) Kuntze and *Lonchocarpus sericeus* (Poir.). The G1a grouping with *Mitragyna inermis* is similar to the groupings of swamp formations generally observed in tropical regions, whereas the G2b grouping with *Mitragyna inermis* and *Lonchocarpus sericeus* is similar to the groupings of swamp forests widely distributed throughout tropical Africa. A total of 71 woody species were inventoried, including *Lonchocarpus sericeus*, *Mitragyna inermis*, *Lecaniodiscus cupanoides*, *Diospyros mespiliformis*, *Mimusops andogensis*, *Afania senegalensis*, *Afzelia africana*, *Vitex doniana* and *Acacia auriculiformis*. The distribution of biological types shows the dominance of microphanerophytes and mesophanerophytes, thus confirming the presence of savannah-forest mosaics and their belonging to the transition zone. Guinean-Congolese and Guinean-Congolese/Sudano-Zambézian species characterise the plant formations in the zone. The structural analysis of the plant groupings identified within the forest patches in the south-east of the Mono Biosphere Reserve has revealed the presence of a great potential for woody forest resources, despite the permanent pressures that prevail due to the precariousness observed in the area, the effects of recurrent flooding and the extension of the agricultural front. These forest groupings show a regular dynamic based on the abundance of young stems to ensure the renewal of the stand, the sign of the Mono Biosphere Reserve's ability to sustain itself over time. This is an indicator to a regular dynamic and balanced structure within the ecosystems studied indicating its resilience. An overall carbon stock of 41.89 T/Ha (153.75 tC/Ha) was obtained.

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Conflicts of Interest

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

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