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Assessing Floristic Diversity, Stand Structures, and Carbon Stocks in Sacred Forests of West Cameroon: Insights from Bandrefam and Batoufam

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Abstract

Sacred forests play a valuable role in the conservation of local biodiversity and provide numerous ecosystem services in Cameroon. The aim of this study was to estimate floristic diversity, stand structures and carbon stocks in the sacred forests of Bandrefam and Batoufam (western Cameroon). The floristic inventory and the stand structures were carried out in 25 m × 25 m plots for individuals with diameters greater than 10 cm; 5 m × 5 m for individuals with diameters less than 10 cm. Carbon stocks were estimated using the non-destructive method and allometric equations. The floristic inventory identified 65 species divided into 57 genera and 30 families in the Bandrefam sacred forest and 45 species divided into 42 genera and 27 families in the Batoufam sacred forest. In the Bandrefam, the most important families are Phyllanthaceae (53.98%), Moraceae (21.69%), Lamiaceae (20.15%). At Batoufam, the most important families are Phyllanthaceae (39.73%), Fabaceae (28.47%), Araliaceae (23.77%). *Malacantha alnifolia* (55.14%), *Vitex grandifolia* (18.43%), *Bosqueia angolensis* (15.06%) were the most important species in Bandrefam. Otherwise, *Malacantha alnifolia* (28%), *Polyscias fulva* (22.73%), *Psychotria* sp. (21.28%) were the most important in Batoufam. The Bandrefam sacred forest has the highest tree density (2669 stems/ha). Total carbon stock is 484.88 ± 2.28 tC/ha at Batoufam and 313.95 ± 0.93 tC/ha at

Bandrefam. The economic value varies between 5858.04 ± 27.62 USD/ha in Batoufam sacred forest and 3788.51 ± 11.26 USD/ha in Bandrefam sacred forest. The number of individuals and small-diameter trees has little influence on the carbon stocks in the trees. Medium-diameter trees store the most carbon, and very large-diameter trees, which are very poorly represented, store less carbon. In another way, wood density and the basal areas influence the carbon storage of the trees.

Keywords

Sacred Forests, Stand Structures, Carbon Stocks, West-Cameroon

1. Introduction

Tropical forests serve as invaluable reservoirs of carbon and biodiversity, playing a critical role in the fight against climate change (COMIFAC, 2015). The Congo Basin's forests represent the world's second-largest expanse of dense tropical rainforest, following the Amazon, covering approximately 200 million hectares and accounting for 90% of Africa's dense tropical forests (Megevand et al., 2013). Their degradation results not only in the loss of forest cover but also diminishes their ability to provide essential goods and services, including carbon storage, climate regulation, and biodiversity conservation (Berenguer et al., 2014).

In Cameroon, forests span over 19.09 million hectares, accounting for 11% of the Congo Basin's forests and 41.3% of the country's total land area (UNFCCC, 2008). These forests are crucial, providing essential goods and services to more than 1.2 billion people worldwide (CDB, 2004). They also host over 8000 plant species across 220 families and 1800 genera, making Cameroon one of Africa's most biodiverse nations in terms of plant life (Letouzey, 1985; Onana, 2011). Recognizing the significance of these forests, the country has implemented the Forestry Law of January 20, 1994, which regulates the management of forests, wildlife, and fisheries in pursuit of sustainable development. However, this law does not address the status of Sacred Forests (SF), creating a legal gap that is exacerbated by the numerous threats these areas face (Ngounou, 2023).

SF are not only regarded as the last refuges of biodiversity, but also as unique relics of significant socio-cultural and ecological value. These forests harbor distinct ecosystems and serve as important spiritual and religious sites. Typically, they consist of unharvested patches of vegetation, are generally better protected than other forested areas, and contribute to both biodiversity conservation and the livelihoods of local communities (Tiokeng et al., 2019; Talukdar & Gupta, 2018; Tura et al., 2013). Research has shown that the biodiversity within these forests exhibits a high degree of endemism (Ngounou, 2023). Indigenous communities preserve these areas in accordance with their religious beliefs and taboos (Abdullah et al., 2022). While Sacred Forests play a vital role in conserving many economically and ecologically important tree species, their integrity is increasingly threatened by various anthropogenic pressures (Mequanint et al., 2020).

Furthermore, SF play a crucial role in mitigating the global threat of climate change by storing carbon and providing essential regulating ecosystem services (Pala et al., 2013). Consequently, their conservation and sustainable management are vital not only for meeting the needs of local populations but also for addressing global challenges. This has led to increasing interest from researchers and conservation organizations, including the Commission des Forêts d'Afrique Centrale (COMIFAC), the United Nations Educational, Scientific and Cultural Organization (UNESCO), the Convention on Biological Diversity (CBD), and the United Nations Framework Convention on Climate Change (UNFCCC) through its REDD+ (Reducing Emissions from Deforestation and Degradation) initiative (Agbani et al., 2018). The study of floristic composition, species diversity and structural analysis are crucial for supplying necessary information on species richness and diversity of the forests, and the vegetation types are useful for forest management purposes and help in understanding forest ecology and ecosystem functions (Giriraj et al., 2008; Siraj et al., 2017; Sewale & Mammo, 2022). Furthermore, the Knowledge of floristic composition and structure of the forest is also useful in identifying ecologically and economically important plants and their diversities, protecting threatened and economically important plant species (Addo-Fordjour et al., 2009; Sewale & Mammo, 2022).

The West Cameroon Region is notable for its relatively well-preserved traditions, even as it experiences high human density where traditional systems remain prevalent (Tiokeng et al., 2019). This high population density correlates with intensified agricultural and agro-pastoral activities, leading to significant land degradation. For decades, the SF in this area has faced increasing urbanization and anthropogenic pressures, including land pressure, population growth, agricultural practices, illegal logging, and vegetation fires (Sinthumule, 2024). These factors pose major ecological concerns for these SFs, threatening their biodiversity, ecological integrity, and essential ecosystem functions (Lounang et al., 2018; Cardelús et al., 2019; Ngounou, 2023). The SF of Bandrefam and Batoufam are particularly vulnerable to these challenges. Given their unique floristic composition and potential for carbon sequestration, it is crucial to include these forest relics in REDD$^+$ and carbon credit policies.

Several authors have conducted research on the SF of western Cameroon. Ngounou (2023) examined floristic diversity and carbon storage in the SF of the Commune of Bazou. Tiokeng et al. (2020) performed a comprehensive study on the significance of the SF in Mbing Mekoup, Bamendjinda, and Bamendjo, detailing their floristic composition and the conservation status of the recorded species. Lounang et al. (2018) inventoried tree species and estimated carbon stocks in the Konoghap SF, comparing these with hedgerows and Eucalyptus plantations. Nkongmeneck et al. (2010) conducted mapping and diagnostic studies of SF in Cameroon. However, there is a notable lack of data regarding the floristic diversity and carbon storage potential of the SF in Batoufam and Bandrefam. Therefore, it is essential to continue research in these areas, as such studies would not only enhance local management systems but also contribute to our understanding of floristic diversity and carbon sequestration potential, ultimately supporting Cameroon's REDD⁺ objectives and enriching its biodiversity database.

This area was selected for several compelling reasons: SF often hosts a rich diversity of plant species. Studying these ecosystems allows us to assess the impact of degradation on local biodiversity and understand how their protection helps maintain ecological balance; there is a lack of research focused on floristic diversity, degradation factors, and carbon sequestration potential in these SF.

Thus, the main question guiding this study is: what are the floristic composition and current carbon sequestration potential of the SF in Bandrefam and Batoufam, both located in the West Cameroon region?

The hypotheses to be tested during this study include: human activities in the SF of Batoufam and Bandrefam negatively impact the distribution, floristic diversity, and carbon sequestration potential of these areas; the potential plant diversity in the SF of Batoufam and Bandrefam is under constant threat from urbanization and anthropogenic activities, leading to the scarcity and disappearance of several plant species.

The aim of this study was to estimate floristic diversity, stand structures and carbon stocks in the sacred forests of Batoufam and Bandrefam. More specifically, the objectives were to: inventory the wood diversity in the SF of Batoufam and Bandrefam; determine the structural characteristics of these SF, and estimate the carbon stocks present in these forests.

2. Materiel and Methods

2.1. Study Area

This study was conducted in the rural localities of Batoufam and Bandrefam, located in the Koung-khi Division and Bayangam Subdivision of the West Region of Cameroon (**Figure 1**). The two SF (Bandrefam, covering an area of 79.24 hectares, and Batoufam, spanning 12.89 hectares) were selected for this research due to their unique contributions to the conservation of natural forest ecosystems in western Cameroon (see **Figure 1**). These sacred forests are designated areas aimed at the protection, conservation, and promotion of Cameroon's native species.

Bandrefam, located at 5˚13'53"N and 10˚29'10"E, is a village grouping and a second-degree chiefdom within the Bayangam commune. It is bordered to the west and southwest by Bangoua, to the north by Batoufam, and to the east by Bagang-Fokam, covering an area of approximately 17 km^2. The terrain features a mix of plateaus (such as Lô'oshitô, Tchî, and Sinkouô) and mountains (including Kouofiog and Kouomenang), interspersed with fertile valleys rich in fine sand. The main rivers flowing through the village are Panchêh and Wooze. The climate is tropical, characterized by a long dry season and a short rainy season.

Batoufam (referred to as *Tswefap* in the local language) is situated at 5˚15'03"N and 10˚28'54"E and also serves as the seat of a second-degree traditional chieftaincy. Now part of the Bayangam arrondissement in the Koung-Khi department of Cameroon's West Region, Batoufam hosts the largest sacred forest in West Cameroon, covering 12.89 hectares. This forest is notable for its rare and protected flora and has been designated as a national natural heritage site by the Ministry of the Environment of the Republic of Cameroon. The estimated resident population of Batoufam is around 30,000 (Lounang, 2006).

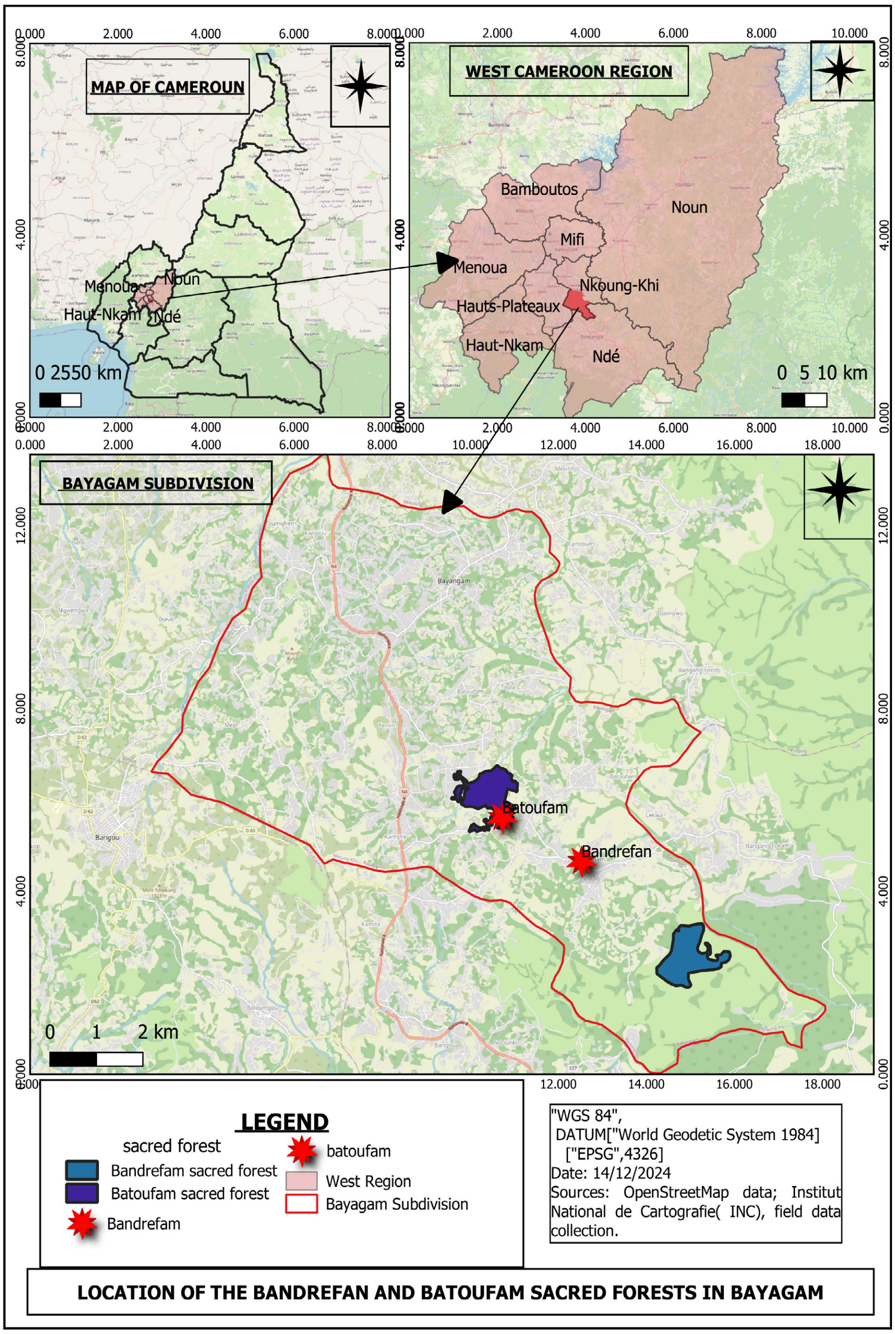

Figure 1. Location of the studied sacred forests in Batoufam and Bandrefam, West Region-Cameroon.

Climatological data recorded by the meteorological station of the Koung-khi Divisional Delegation of Agriculture and Rural Development in Bandjoun indicate that the climate in this zone is tropical, characterized by two distinct seasons: a dry season from November to February and a rainy season from March to October. The average annual precipitation is 1.518 mm, and the average temperature is 20.9˚C. The primary vegetation in this locality has largely been replaced by other land use types. However, following the processing of field data and the use of mapping tools, the Kouoghap sacred forest, currently spanning 110 hectares, has managed to retain its primitive character. This forest is dominated by tree species such as *Syncepalum cerasiferum*, *Tricalysia macrophylla*, *Trilepisium madagascariense*, *Markhamia tomentosa*, *Funtumia africana*, and *Vitex grandifolia* (Noumi, 2012).

Morphostructurally, Batoufam and Bandrefam are situated within the Western Highlands of Cameroon (Lounang, 2006; Guiffo, 2003; Letouzey, 1985), classified under the Guinean-Congolese sub-mountain area (Kayo, 2004). These localities lie at the foot of the eastern slope of Bangou Mountain. The region features ferruginous, ferralitic, and hydromorphic soils, primarily derived from volcanic rocks. Elevations can exceed 2000 meters, with an average ranging from 1400 to 1800 meters, compared to the heights of the Yom and Tougopou hills in Bayangam (Noumi, 2012; Lounang, 2006).

2.2. Data Collection

Floristic diversity was assessed to evaluate the availability and representativeness of plant species in the study area. Data collection occurred in the sacred forests of Batoufam and Bandrefam, which were chosen for their accessibility. Prior to the study, permission was obtained from traditional authorities in each village or district.

After identifying the collection sites, the first step was to delineate the sample plots. The experimental setup, based on the non-permanent plot method, was inspired by the works of Tiokeng et al. (2020) and Tiokeng et al. (2019). Scattered plots measuring 25 m × 25 m were established in the various SF, recording and measuring all individuals with a Diameter at Breast Height (DBH) of 10 cm or greater, taken 1.30 m above the ground (**Figure 2**). For trees with defects such as buttresses or stilt roots, measurements were made 30 cm above the irregularities. Trees with diameters less than 10 cm were counted in two 5 m × 5 m sub-plots located at the north-west and south-east corners of each main plot (**Figure 2**). The number of plots established was proportional to the size of the sites. Despite the relatively small size of these forest remnants, the plots were designed to capture the various types of plant formations present. In total, 20 sample plots covering 625 m^2 were established, with 13 located in the Bandrefam sacred forest and 7 in Batoufam. These plots represent 0.01% and 0.03% of the total forest area of Bandrefam and Batoufam, respectively.

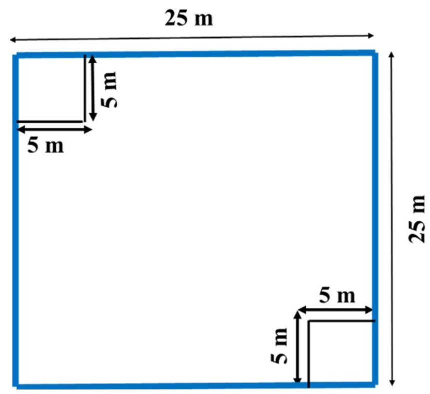

Figure 2. Sampling design used for the documentation of trees.

2.3. Measurement of Dendrometric Parameters

For each identified tree, parameters such as diameter and both scientific and common names were recorded. Trees with diameters greater than 10 cm were measured at 1.30 m from the ground, with additional measurements taken 30 cm above any defects. For individuals with diameters less than 10 cm, measurements were made 50 cm above the ground. During the inventory process, all counted individuals were marked to prevent double counting. Correspondences between local, commercial, and scientific names were established using botanical lexicons (Wilks & Issembé, 2000). The geographical coordinates of each plot were recorded using GPS. Samples of species that could not be identified in the field were collected, pressed, and preserved in 70% alcohol for later identification at the National Herbarium of Cameroon. The taxonomic nomenclature adopted followed the phylogenetic classification of angiosperms as outlined in the APG IV system (The Angiosperm Phylogeny Group et al., 2016).

2.4. Floristic Data Analysis and Statistical Processing

Data Analysis Focused Floristic Parameters

The data collected in the field were analyzed to characterize the flora of the Batoufam and Bandrefam SF. The floristic parameters below were determined in order to carry out a qualitative and quantitative analysis of the flora studied.

Floristic Composition and Species Richness (S): This metric, based on Ramade (2003), quantifies the number of different species present in the forests.

Shannon-Weaver Index: This index accounts for both the abundance and evenness of the species present, providing insights into the diversity of woody species in each SF. The Shannon-Weaver Index ranges from 0 (indicating only one species is present) to Ln (indicating all species are equally abundant) (Shannon & Weaver, 1949). It can be calculated using the following equation:

$$H' = -\sum_{i=1}^{S} \left(pi \, Lnpi \right) \tag{1}$$

where H' is the Shannon-Weaver Index, S is the total number of species, and pi is the proportion of individuals of species i relative to the total number of individuals.

- **Evenness Index (E) or Pielou Equitability Index (EQ)** was calculated to estimate the uniformity of tree species distribution in each sacred forest. This index approaches 0 when most individuals belong to a single species and equals 1 when all species are equally abundant (Pielou, 1969).

The formula for the Evenness Index is as follows:

$$E = \frac{H'}{LnS} \tag{2}$$

where H' = Shannon-Weaver diversity index, S is the total number of species in a site; Ln = natural logarithm.

- **The Simpson Diversity Index (D)**, also known as the concentration of dominance, measures the probability that two randomly selected individuals from a population belong to the same species. This index provides insight into the level of dominance by particular species within a community. It can be calculated using the following formula:

$$D = 1 - \sum_{i=1}^{s} p_i^2 \tag{3}$$

with p_i: the number of individuals of species i; S: the total number of individuals of all species. D varies from 0 to 1. It tends towards a value of 0 to indicate minimum diversity, and a value of 1 to indicate maximum diversity (Simpson, 1949).

- The **Fisher-alpha index (α)** quantifies the expected increase in species richness as sample size increases. It provides a measure of biodiversity that accounts for both the number of species and their relative abundances (Fisher et al., 1943). The formula for calculating the Fisher-alpha index is as follows:

$$\alpha = \frac{S-1}{\sum_{i=1}^{S} \frac{1}{ni} - 1} \tag{4}$$

where α is the Fisher-alpha index; S is the total number of species observed; ni is the number of individuals of species i.

The **Sorensen Similarity Coefficient (Ks)** is used to compare the floristic composition of two sites by indicating the percentage of common species shared between them. This coefficient helps assess how similar the biodiversity of the two sacred forests is (Sorensen, 1948). The formula for calculating the Sorensen Similarity Coefficient is:

$$Ks = \frac{2\mathrm{C}}{\mathrm{A}+\mathrm{B}} \times 100 \tag{5}$$

where Ks is Sorensen's coefficient of similarity; A, the number of species in a list belonging to one site; B, the number of species in a list belonging to site B; C, the total number of species common to the two sites to be compared. We assumed that if $Ks \geq 50\%$, the two sacred forests are floristically similar.

2.5. Stand Structures of the Studied Forests

The stand structures and composition of the studied forests were analyzed using the following parameters:

(i) **Density (D)**: This parameter refers to the number of individual woody species within a specified area, expressed as the number of stems counted per hectare (Fournier & Sasson, 1983). Density was calculated using the following formula:

$$\text{D (stems/ha)} = \frac{\text{Total number of all trees}}{\text{sample size in hectare}} = \frac{\text{number of individuals belonging to species i}}{\text{area in hectares}} \quad (6)$$

(ii) **Basal Area (BA)**: This parameter represents the cross-sectional area of a timber trunk at breast height (1.30 m from the ground) and is an important metric for assessing forest stand density and productivity (Sonké, 2004). Basal area is calculated per hectare and expressed in square meters per hectare (m^2/ha) using the following formula:

$$\text{BA} = (\pi\ (D_i)^2)/4 \quad (7)$$

where D_i is the diameter of the individual at breast height (cm); $\pi = 3.14$.

(iii) **Distribution of Individuals by Diameter Classes**: This parameter reflects the distribution of trees within specific diameter classes and is crucial for assessing the ecological status and conservation of the biotope. It provides insights into the degree of disturbance or conservation of the forest environment.

In this study, the trees inventoried in the plots were grouped into 10 cm diameter classes to create a diametric structure. This classification allows for the visualization of tree distribution across various size categories, aiding in the assessment of the forest's age structure and health. The diameter classes are distributed as follows: [10 - 20[, [20 - 30[, [30 - 40[, [40 - 50[, [50 - 60[, [60 -70[, [70 - 80[, [80 - 90[, [100 - + ∞[.

Species Composition

The species composition was described using the following parameters:

(i) **Relative Frequency (RFr)**: This metric serves as an indicator of the homogeneity and heterogeneity of a given vegetation type. A higher number of woody species in the upper frequency classes indicates greater homogeneity within the forest, while lower numbers suggest heterogeneity (Daget, 1976). To compute the relative frequency, the number of occurrences of each woody species in the sample area was counted and recorded. The relative frequency for each species was calculated using the following equation:

$$\text{RFr} = \frac{\text{Number of plot in which species occur}}{\text{Total number of plots sampled}} \times 100 \quad (8)$$

(ii) **Relative Dominance (RDo)**: This parameter indicates the contribution of a specific species to the overall basal area within a population. It helps assess the ecological importance and influence of individual species in the forest community (Reitsma, 1988). Relative dominance for each species can be calculated using the following formula:

$$\text{RDo} = \frac{\text{Basal area of species}}{\text{Basal area of all species}} = \times 100 \quad (9)$$

(iii) **Relative Density (RDe)**: This parameter quantifies the contribution of a specific species to the total density of all species within the sampled area. It helps in understanding the abundance of individual species relative to the overall population (Kent & Coker, 2003). Relative density for each species is calculated according to this formula:

$$\text{RDe} = \frac{\text{Number of indivduals belonged to taxon i}}{\text{Total number of individuals of all sampled plots}} \times 100 \tag{10}$$

The Important Value Index (IVI) and the Family Important Value (FIV) were calculated for species and families according to the formulas of Cottam & Curtis (1956) and Mori et al. (1983). That index highlights the ecological importance of species and families.

(iv) **Important Value Index (IVI)**: The IVI provides a comprehensive measure of the ecological significance of each taxonomic group within a plant community. This composite index integrates relative measures of species density, frequency, and dominance, offering insights into the structural role and ecological success of each species in the forest (Mori et al., 1983; Senterre, 2005). The IVI is given by the equation:

$$\text{IVI} = \text{relative density} + \text{relative frequency} + \text{relative dominance} \tag{11}$$

(v) **Family Important Value (FIV)**: The family importance value (FIV) is the sum of the relative diversity, relative dominance and relative frequency of each family.

2.6. Biomass and Carbon Stocks Estimation in the Sacred Forests Studied

Biomass and carbon stocks of woody vegetation were assessed using a non-destructive method, with allometric equations varying according to tree diameter (Brown, 1997). The computed variables such as tree density, species richness, basal area, and biomass were compared among the three forest types using ANOVA.

Three allometric models were employed to estimate the aboveground biomass (AGB) of trees based on species and tree diameters, utilizing the following allometric equations:

$D \geq 10$ cm GBH (Adult tree species)

$$\text{AGB} = \text{Exp}\left(-2.3027 + 1.1599\ln(\rho) + 3.0484\ln(D) + 0.0807(\ln(D))^2 + 0.3197E\right)$$

$$\text{(Fayolle et al., 2018)} \tag{12}$$

$5 \text{ cm} \leq D < 10 \text{ cm}$ (Juvenile tree species)

$$\text{AGB} = \text{Exp}\left(-1.803 - 0.9761\text{E} + 0.976\ln(\rho) + 2.673\ln(D) - 0.0299(\ln(D))^2\right)$$

$$\text{(Chave et al., 2014)} \tag{13}$$

$$\begin{aligned} &D < 5 \text{ cm (Herbaceous)} \\ &\text{Exp}\left(-2.145 + 2.451\ln(D) + 1.120\ln(\rho) \times \text{CF}\right) \end{aligned} \quad \text{(Ntomen, 2020)} \tag{14}$$

with ρ: specific density of a species expressed (g/cm^3); E: climatic index; D: diameter (cm); ρ: specific density of a species; CF: expansion factor (CF = 0.09).

2.6.1. Wood Density Estimation

Species-specific wood density was obtained from the global wood density database (Zanne et al., 2009). For species with several densities from different authors for the same system, the average density was considered. Furthermore, for species that lacked species-level wood density values, genus-level averages were used instead. For species for which there is no available literature on density, the default value ($\rho_{default}$ = 0.58 g/cm^3) for African tropical forests was used (Chave et al., 2009).

2.6.2. Below-Ground Biomass (BGB) Estimation

Below-ground biomass (BGB) of trees was calculated using the methodology proposed by IPCC (2003), which is the application of a root-to-shoot ratio method. The equation used to calculate the belowground biomass is given below:

$$BGB = AGB * 0.24 \tag{15}$$

where BGB is below-ground biomass; AGB is aboveground biomass, and 0.24 is the conversion factor (or 24 % of AGB), because we were in a tropical forest (Zapfack et al., 2013).

2.6.3. Total Woody Carbon (TWC)

Total woody carbon (TWC) was determined by following the equation:

$$TWC = (AGB + BGB) \times 0.47 \tag{16}$$

where AGB = Aboveground biomass (t/ha), BGB is Belowground biomass (t/ha); 0.47 is the conversion factor, which represents that the Carbon content is assumed as 47% of the total biomass for tropical and subtropical forests (Eggleston et al., 2006; Winrock International, 2005; Zapfack et al., 2013).

2.6.4. Estimation of Equivalent CO_2

Equivalent CO_2 was determined by following the equation: $CO_2eq = 3.67 \times$ Carbon stock values, where 3.67 represents the molar mass ratio between CO_2 (44) and C (12).

2.6.5. Monetary Value of Carbon Stocks Potential of Studied Sacred Forests

Carbon pricing may involve a combination of taxes on emissions and payments for emission reductions in tropical forest countries, allowing for potential external funding from international carbon markets or public funds (Busch & Engelmann, 2017). The following conversion, as outlined in the REDD$^+$ framework, was utilized: 1 t CO_2eq = 3.3 USD (Donofrio et al., 2020; Cédric et al., 2022).

2.7. Statistical Analysis

All statistical analyses were performed using R version 3.3.0, PAST 3.0.0.0, and the Statistical Package for the Social Sciences (SPSS) version 23 for the analysis of variance (ANOVA). R version 4.1.2 was employed for analyses beyond ANOVA. Multiple comparison tests (MCT) were conducted to assess carbon stocks across different systems, and the average species richness of various sacred forests was determined and compared using the 5% Kruskal-Wallis test. ArcGIS software was utilized to generate the maps.

Correlations were established to assess the relationships and linearity among the different variables, with a significance level set at 5% ($p < 0.05$). The Spearman rank coefficient (r) was calculated to evaluate the degree of association between distributions, where values closer to −1 or +1 indicate a stronger relationship. The Kolmogorov-Smirnov test was employed to assess the level of dependence and significance between variables at the 95% confidence level.

3. Results and Discussion

3.1. Results

3.1.1. Species Richness and Diversity

In total, 1028 individuals were recorded across two sacred forests, encompassing 83 species, 73 genera, and 36 families. Among these, 704 individuals, representing 76 species, 66 genera, and 35 families, had a diameter of 10 cm or greater, while 324 individuals, classified into 48 species, 45 genera, and 31 families, had a diameter of less than 10 cm.

An analysis of the data presented in **Table 1** reveals that the Bandrefam sacred forest is home to 65 species across 57 genera and 30 families. Among the individuals with a diameter of 10 cm or greater, there are 61 species distributed among 53 genera and 30 families. Conversely, those with a diameter of less than 10 cm comprise 30 species in 29 genera and 21 families.

The flora of the Batoufam Sacred Forest consists of 45 species belonging to 42 genera and 27 families. Of these, 41 species are represented among individuals with a diameter of 10 cm or greater, spread across 39 genera and 25 families, while individuals with a diameter of less than 10 cm include 30 species in 29 genera and 24 families. So, the Bandrefam sacred forest is the richest in species, genera and families. In both forests, the most diverse genera, ranked in descending order by the number of species, are as follows: *Trichillia*, *Ficus*, and *Albizia*, each with three species, followed by *Cola*, *Diospyros*, *Strombosia*, *Tetrorchidium*, *Vitex*, and *Macaranga*, each represented by two species. The remaining 63 genera contain either one or two species. The most represented genera in Bandrefam's SF were distributed in descending order as follows: *Ficus* (3 species), *Albizia*, *Cola*, *Diospyros*, *Strombosia*, *Tretrorchidium*, *Trichillia* and *Vitex* (2 species each) and 48 genera each had a single species. In the Batoufam SF, genera were distributed in descending order as follows: *Albizia* (3 species), *Macaranga* and *Trichillia* (2 species each) and 39 genera had a single species (**Table 1**).

The Shannon diversity index is estimated at 3.4 for the Bandrefam sacred forest and 3.2 for the Batoufam sacred forest, while the Piélou equitability index is 0.81 and 0.83, respectively. The Fischer-Alpha index is calculated at 19.21 for Bandrefam and 15.63 for Batoufam. These values indicate that both sacred forests exhibit good biodiversity, with a relatively equitable distribution of species within each forest.

Additionally, Simpson's index is 0.93 for Bandrefam and 0.94 for Batoufam, both values being close to 1, which suggests a high probability that two randomly selected individuals from these sites belong to different species (Table 1).

The calculation of floristic similarity yielded a value of 83%, suggesting a very high degree of similarity between the two sites.

Table 1. Species richness and diversity index.

		Ni	Ne	Ng	Nf	Density (Stems/ha)	H' (Bit)	Eq	D'	α	ST: basal area (m²/ha)
Bandrefam	D ≥ 10 cm	368	61	53	30		3.3	0.80	0.91	20.85	
	D < 10 cm	179	30	29	21		2.9	0.85	0.92	10.31	
	Total	547	65	57	30	2669	3.38	0.81	0.93	19.21	58.08
Batoufam	D ≥ 10 cm	336	41	39	25		3.2	0.86	0.94	12.25	
	D < 10 cm	145	30	29	24		2.9	0.85	0.91	11.49	
	Total	481	45	42	27	1918	3.17	0.83	0.94	12.15	76.15
Total	D ≥ 10 cm	704	76	66	35		3.44	0.80	0.94	21.64	
	D < 10 cm	324	48	45	31		3.29	0.85	0.95	15.57	
	Total	1028	83	73	36	4588	3.51	0.79	0.95	21.3	

Ni: number of individuals; Ne: number of species; Ng: number of genera; H': Shannon index; Eq: Pielou index; D': Simpson index; α: Alpha-Fisher Index

3.1.2. Structural Parameters

1) Vertical structure

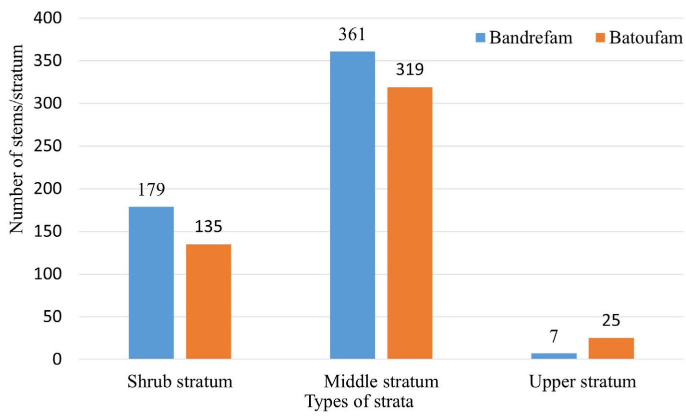

Figure 3. Vertical structure of the sacred forests studied.

The middle stratum, comprising trees with diameters ranging from 10 cm to 70 cm, is the most prevalent, with 361 species recorded in the Bandrefam sacred forest and 319 species in the Batoufam sacred forest. The upper stratum, which includes trees with diameters greater than 70 cm, is denser in the Batoufam site, with 25 species represented. The significant presence of the middle stratum in both sites suggests that these ecosystems are approaching maturity. This phenomenon is attributed to a scarcity of large stems exceeding 70 cm in diameter. The absence of these larger trees facilitates greater light penetration through the canopy, thereby increasing the number of individuals within the middle stratum. Conversely, the shrub stratum is notably dominant at the Bandrefam site, featuring 179 species (**Figure 3**).

2) Basal areas

Basal areas vary across the sites studied, with a lower value recorded in the Batoufam sacred forest (76.15 m^2/ha) compared to a higher value in the Bandrefam sacred forest (58.08 m^2/ha) (**Table 1**). In the Bandrefam sacred forest, the species with the highest basal area include *Malacantha alnifolia* (17.19 m^2/ha), *Vitex grandifolia* (4.70 m^2/ha), and *Sapium ellipticum* (3.25 m^2/ha). Conversely, the species with the lowest basal area values are *Thomandersia hensii* (0.39 m^2/ha), *Ficus* sp. (0.43 m^2/ha), and *Phyllanthus discoideus* (0.41 m^2/ha). In the Batoufam sacred forest, the highest basal area values are attributed to *Malacantha alnifolia* (10.00 m^2/ha), *Vitex grandifolia* (8.34 m^2/ha), *Bosqueia angolensis* (5.66 m^2/ha), *Amphimas pterocarpoides* (4.93 m^2/ha), *Polyscias fulva* (4.89 m^2/ha), *Canarium schweinfurthii* (4.85 m^2/ha), *Phyllanthus discoideus* (4.34 m^2/ha), *Pseudospondias microcarpa* (3.86 m^2/ha), *Trichilia welwitschii* (3.56 m^2/ha), and *Sterculia tragacantha* (3.38 m^2/ha). These species represent the highest basal area values in this forest.

3) Tree density on the studied sites

The distribution of tree density reveals that the Bandrefam sacred forest has a higher density (2669 stems/ha) compared to the Batoufam sacred forest (1918 stems/ha). Within Bandrefam, *Thomandersia hensii* is the most abundant species, with a remarkable density of 572 stems/ha. It is followed by *Sorindeia grandifolia* (234 stems/ha), *Malacantha alnifolia* (214 stems/ha), *Hannoa klaineana* (212 stems/ha), *Sterculia tragacantha* (189 stems/ha), *Strombosia pustulata* (187 stems/ha), and *Psychotria* sp. (112 stems/ha). In the Batoufam sacred forest, the species with the highest densities include *Polyscias fulva* (332 stems/ha), *Psychotria* sp. (326 stems/ha), *Funtumia elastica* (155 stems/ha), *Markhamia tomentosa* (137 stems/ha), *Sterculia tragacantha* (122 stems/ha), and *Malacantha alnifolia* (102 stems/ha).

4) Stand diameter structures

The distribution of stems by diameter class in the two sacred forests demonstrates a clear dominance of the diameter class below 10 cm, with 2015 stems/ha in Bandrefam and 1300 stems/ha in Batoufam. This distribution exhibits a decreasing exponential pattern, characteristic of a reverse J-shaped curve, indicative of ecological vigor and a strong potential for sustainability, as young individuals are poised to replace those that have died. Notably, the number of individuals in the large-diameter class (over 80 cm) is very low. In contrast, small-sized trees (less than 10 cm DBH) account for the majority of total tree density, contributing 75.49% in Bandrefam and 67.79% in Batoufam. Medium-sized trees (10 - 59.9 cm DBH) represent 23.04% in Bandrefam and 27.39% in Batoufam. Large-sized trees (≥60.1 cm DBH) contribute only 1.94% in Bandrefam and 4.82% in Batoufam (**Figure 4**).

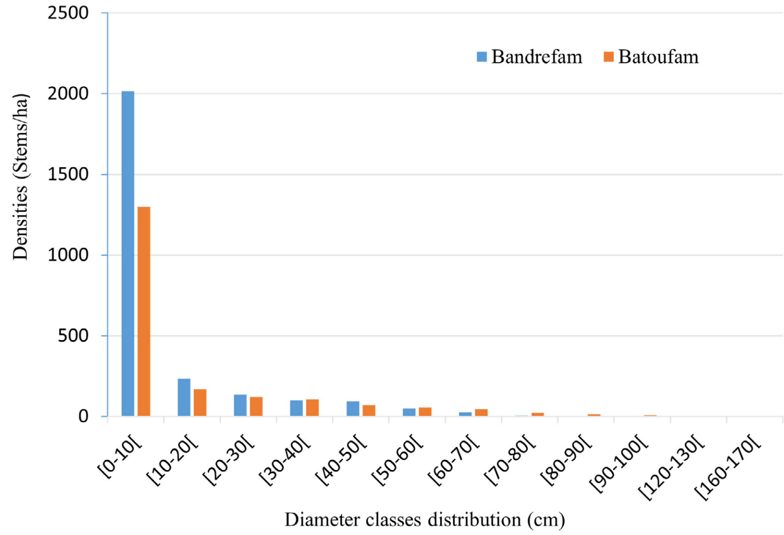

Figure 4. Total diameter classes at studied sites.

5) Most important families

Based on the Family Importance Value (FIV), 12 families in the Bandrefam sacred forest and 13 families in the Batoufam sacred forest are classified as significant (FIV ≥ 10%).

In the Bandrefam sacred forest, the top five families are as follows: Phyllanthaceae (53.98%), Moraceae (21.69%), Lamiaceae (20.15%), Simaroubaceae (19.50%), and Fabaceae (18.86%).

In the Batoufam sacred forest, the leading families include Phyllanthaceae (39.73%), Fabaceae (28.47%), Araliaceae (23.77%), Moraceae (23.43%), and Rubiaceae (22.45%) (Table 2).

Table 2. Most important families in the two forests (FIV ≥ 10 %).

Locations	Families	Fr	Dr	Do	FIV
Bandrefram	Phyllanthaceae	6.87	20.66	26.45	53.98
	Moraceae	6.87	7.31	7.50	21.69
	Lamiaceae	6.11	6.76	7.28	20.15
	Simaroubaceae	5.34	7.68	6.48	19.50
	Fabaceae	6.11	5.30	7.45	18.86
	Malvaceae	5.34	6.03	4.88	16.26
	Euphorbiaceae	6.11	3.66	4.81	14.57
	Anacardiaceae	2.29	6.58	5.28	14.15
	Meliaceae	5.34	3.47	3.91	12.73
	Olacaceae	6.11	4.02	2.30	12.43
	Sapindaceae	5.34	2.38	4.11	11.83
	Rubiaceae	4.58	3.47	2.23	10.29
Batoufam	Phyllanthaceae	6.98	14.14	18.61	39.73
	Fabaceae	6.98	8.52	12.97	28.47
	Araliaceae	6.20	10.19	7.38	23.77
	Moraceae	6.20	7.90	9.31	23.41
	Rubiaceae	6.98	11.85	3.62	22.45

Continued

Lamiaceae	6.98	4.78	10.25	22.01
Malvaceae	6.20	7.07	4.84	18.11
Meliaceae	6.20	5.61	4.67	16.49
Bignoniaceae	4.65	6.44	2.84	13.93
Anacardiaceae	5.43	1.87	4.72	12.02
Apocynaceae	4.65	3.95	2.63	11.23
Sapindaceae	3.88	4.99	1.72	10.58
Burseraceae	3.10	1.46	5.98	10.54

Fr: relative frequency; Dr: relative density; Do: Relative Dominance; FIV: Family importance value Index

6) Most important species

Malacantha alnifolia (55.14%), *Vitex grandifolia* (18.43%), *Bosqueia angolensis* (15.06%), *Hannoa klaineana* (11.81%), *Sapium ellipticum* (10.92%), *Sterculia tragacantha* (10.64%), *Trichillia welwitschii* (10.12 %) were the most important species in Bandrefam.

Otherwise, species like *Malacantha alnifolia* (28%), *Polyscias fulva* (22.73%), *Psychotria* sp. (21.28%), *Vitex grandifolia* (20.84%), *Bosqueia angolensis* (17.97%), *Sterculia tragacantha* (17.07%), *Trichillia welwitschii* (14.26%), *Markhamia tomentosa* (13.15%), *Phyllanthus discoideus* (13.14%), *Pseudospondias microcarpa* (11.11%), *Funtumia elastica* (10.17%), *Canarium schweinfurthii* (10, 02%), were the most important in Batoufam (FIV ≥ 10 %) (Table 3).

Table 3. The most important species in the studied sacred forests.

	Species	Fr	Dr	Do	FIV
Bandrefram	*Malacantha alnifolia*	5.08	19.93	30.12	55.14
	Bosqueia angolensis	5.08	5.67	4.31	15.06
	Vitex grandifolia	4.52	5.67	8.24	18.43
	Trichilia welwitschii	3.95	2.93	3.24	10.12
	Strombosia pustulata	3.95	2.38	0.07	6.40
	Hannoa klaineana	3.39	7.13	1.29	11.81
	Sterculia tragacantha	3.39	4.75	2.50	10.64
	Sapium ellipticum	3.39	1.83	5.71	10.92
	Psychotria sp.	2.82	3.11	0.87	6.80
	Piptadeniastrum africanum	2.82	2.38	2.71	7.91
	Heisteria parvifolia	2.82	1.46	1.15	5.43
	Blighia welwitschii	2.82	1.46	0.94	5.23
	Polyscias fulva	2.82	0.91	3.60	7.34
	Canarium schweinfurthii	2.26	0.91	1.90	5.08
Batoufam	*Malacantha alnifolia*	5.16	9.56	13.27	28.00
	Polyscias fulva	5.16	10.19	7.38	22.73
	Psychotria sp.	5.81	11.85	3.62	21.28
	Vitex grandifolia	5.81	4.78	10.25	20.84
	Bosqueia angolensis	5.16	5.61	7.20	17.97
	Sterculia tragacantha	5.16	7.07	4.84	17.07
	Trichilia welwitschii	4.52	5.20	4.55	14.26
	Markhamia tomentosa	3.87	6.44	2.84	13.15

Continued

Phyllanthus discoideus	3.23	4.57	5.34	13.14
Pseudospondias microcarpa	4.52	1.87	4.72	11.11
Funtumia elastica	3.87	3.74	2.56	10.17
Canarium schweinfurthii	2.58	1.46	5.98	10.02
Blighia welwitschii	3.23	4.99	1.72	9.93
Amphimas pterocarpoides	1.94	0.62	5.94	8.50
Piptadeniastrum africanum	3.23	2.91	1.93	8.06
Ficus exasperata	2.58	2.29	2.11	6.98
Pentaclethra macrophylla	2.58	2.08	1.41	6.07
Pycnanthus angolensis	2.58	1.66	1.22	5.46

7) Comparison between the two sacred forests

The calculation of Sorensen's Coefficient of Similarity yielded a value greater than 50% (Sorensen = 83%), leading to the conclusion that there is a very high degree of floristic similarity between the two sites. So, the families common to both sacred forests are as follows: Phyllanthaceae, Fabaceae, Moraceae, Lamiaceae, Malvaceae, Rubiaceae, Meliaceae, Anacardiaceae, Sapindaceae. Three genera are present in both SF. These are: *Albizia*, *Macaranga*, *Trichillia.* In addition, there are 27 species in common between the two sites.

3.1.3. Carbon Stock Estimation

1) Aboveground carbon

Overall, aboveground carbon stocks were estimated at a total of 643.34 ± 1.38 tC/ha distributed as follows: 252.72 ± 0.75 tC/ha and 390,6231 ± 1.84 tC/ha in Bandrefam and Batoufam SF respectively (Table 4). Kruskal-Wallis test for equal medians showed that there was a significant difference between sample medians (p-value = 0.001433) ($p < 0.05$). The Bandrefam SF has the highest aerial carbon stock compared to the Batoufam SF.

2) Underground carbon

Overall, underground carbon stocks are estimated at a total of 154.61 ± 0.33 tC/ha, distributed as follows: 60.76 ± 0.18 tC/ha in the Bandrefam sacred forest and 93.85 ± 0.44 tC/ha in the Batoufam sacred forest (Table 4). Kruskal-Wallis test for equal medians showed that there was a significant difference between sample medians (p-value = 0.00257) ($p < 0.05$).

3) Total carbon stocks

Analysis of the results for total carbon stocks (Table 4) indicates that the two sacred forests collectively store 798.83 ± 1.72 tC/ha, distributed as follows: 484.88 ± 2.28 tC/ha in the Batoufam sacred forest and 313.95 ± 0.93 tC/ha in the Bandrefam sacred forest. Kruskal-Wallis test for equal medians showed that there was a significant difference between sample medians, p-value = 0.00658 ($p < 0.05$).

For individuals with a diameter (D) of 10 cm or more, the Batoufam sacred forest has a higher carbon stock value of 467.90 ± 2.61 tC/ha, compared to 289.45 ± 1.07 tC/ha in the Bandrefam sacred forest, resulting in a combined total of 757.35 tC/ha (Table 4).

For individuals with a diameter between 5 cm and 10 cm, the Bandrefam sacred forest shows a higher carbon stock of 23.33 ± 0.12 tC/ha, while the Batoufam sacred forest has 15.96 ± 0.12 tC/ha, yielding a total of 39.28 tC/ha (Table 4).

Lastly, for individuals with a diameter of less than 5 cm, the Bandrefam sacred forest again has a higher value of 1.17 ± 0.011 tC/ha compared to 1.02 ± 0.012 tC/ha in the Batoufam sacred forest, resulting in a total of 2.19 tC/ha (Table 4).

According to different tree diameters species, the Kruskal-Wallis test for equal medians shows that there was a highly significant difference between the mean carbon stocks found in the Bandrefam and Batoufam SF (p-value = 0.011).

Table 4. Carbon stock estimation.

Tree diameters (cm)	Total carbon (tC/ha)								
	Aboveground carbon AGB (tC/ha)			Belowground carbon BGB (tC/ha)			Total carbon (tC/ha)		
	BDFam	BTFam	Total	BDFam	BTFam	Total	BDFam	BTFam	Total
D ≥ 10	233.43 ± 0.86	377.34 ± 2.11	610.77 ± 1.61	56.02 ± 2.21	90.56 ± 0.51	146.58 ± .085	289.45 ± 1.07	467.90 ± 2.61	757.35 ± 1.99
5 ≤ D < 10	18.81 ± 0.1	12.87 ± 0.1	31.68 ± 0.1	4.52 ± 0.02	3.09 ± 0.02	7.60 ± 0.02	23.33 ± 0.12	15.96 ± 0.12	39.28 ± 0.12
D < 5	0.48 ± 0.005	0.42 ± 0.005	0.89 ± 0.005	0.23 ± 0.002	0.20 ± 0.002	0.42 ± 0.002	1.17 ± 0.011	1.02 ± 0.012	2.19 ± 0.012
Total	252.72 ± 0.75	390.62 ± 1.84	643.34 ± 1.38	60.76 ± 0.18	93.85 ± 0.44	154.61 ± 0.33	313.95 ± 0.93	484.88 ± 2.28	798.83 ± 1.72

BDFam = Bandrefam; BTFam = Batoufam.

4) Assessment of ecological and economic values of carbon stocks

Data analysis of ecological values yielded a total of 2929.04 ± 6.29 t CO_2eq/ha, distributed as 1151.16 ± 3.41 t CO_2/ha in Bandrefam SF and 1777.88 ± 3.41 t CO_2/ha in Batoufam SF (Table 5).

Economic values increase with carbon stocks. Thus, the economic value varies between 5858.04 ± 27.62 USD/ha in Batoufam SF and 3788.51 ± 11.26 USD/ha in Bandrefam SF. It should be noted that the Batoufam SF has a higher economic value than the Bandrefam SF. For the two sites as a whole, it is 9646.55 ± 20.77 USD/ha.

Table 5. Ecological and economic value of different sacred forests.

Study sites	BT (t/ha)	C (tC/ha)	CO_2eq (t CO_2eq/ha)	Monetary value (USD/ha)
Bandrefam	660.95 ± 1.96	313.95 ± 0.93	1151.16 ± 3.41	3788.51 ± 11.26
Batoufam	1020.80 ± 4.81	484.88 ± 2.28	1777.88 ± 8.37	5858.04 ± 27.62
Total	1681.75 ± 3.61	798.83 ± 1.72	2929.04 ± 6.29	9646.55 ± 20.77

3.1.4. Correlations between Carbon Stocks, Basal Area, Wood Density and the Number of Individuals of Plant Species

- Bandrefam case

The analysis of the PCA of carbon stocks, basal area, and plant species (including wood density and number of individuals) at Bandrefam demonstrated that carbon stocks, the number of individuals, and wood density are all positively and strongly correlated with the F1 axis, with correlation coefficients of 0.56, 0.71, and 0.41, respectively. Basal area showed a weak positive correlation with the F1 axis (0.10). Conversely, the F2 axis had a strong positive correlation with carbon stocks (0.81) but was weakly correlated with basal area (0.12) and negatively correlated with the number of individuals (−0.48) and wood density (−0.30) (**Figure 5**).

Notably, *Malacantha alnifolia*, with the highest number of trees (109) and total density (18.37), exhibited the largest basal area (18.37 m²/ha) and stored the most carbon (100.06 tC/ha). Following this species was *Hannoa klaineana*, which, while having fewer trees (39) and a total density of 22.62, still had a notable basal area of 2.55 m²/ha and a carbon stock of 7.41 tC/ha (**Figure 5**).

Other species, such as *Piptadeniastrum africanum*, *Sapium ellipticum*, *Allophyllus africanus*, and *Polyscias fulva*, despite low individual counts (13, 10, 5, and 5, respectively), demonstrated significant carbon stocks (11.35, 17.97, 11.86, and 7.93 tC/ha) due to their high wood densities (7.86, 5.51, 2.25, and 1.185, respectively).

In contrast, species like *Thomandersia hensii*, *Sorindeia grandifolia*, *Strombosia pustulata*, *Psychotria sp.*, *Markhamia tomentosa*, and *Phoenix reclinata*, despite having high individual counts (34, 28, 13, 17, 19, and 13), recorded low carbon stocks (≤5 tC/ha), attributable to their low wood densities (<1.5 m²/ha) (**Figure 5**).

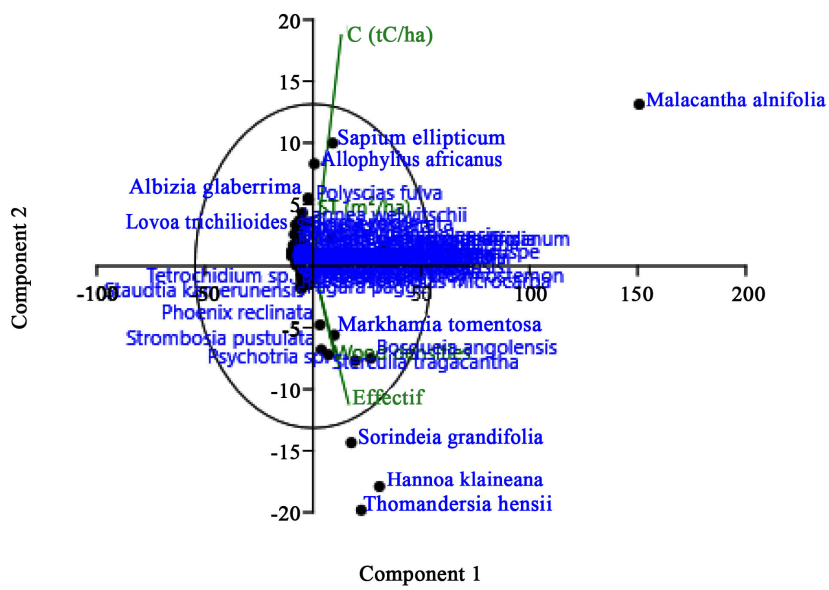

Figure 5. Principal component analysis of the relationships between carbon stocks, basal area, wood density and the number of individuals of plant species in the Bandrefam sacred forest.

- Batoufam Case

The analysis of the PCA conducted at Batoufam indicated that carbon stocks, the number of individuals, and wood density were positively and strongly correlated with the F1 axis, with correlation coefficients of 0.71, 0.61, and 0.33, respectively. Basal area had a weak positive correlation with the F1 axis (0.12). On the F2 axis, the number of individuals was strongly and positively correlated (0.65), while carbon stocks (−0.12) and basal area (−0.05) were negatively correlated.

In Batoufam, *Malacantha alnifolia* again emerged as a key species, having the highest number of trees (46) and total density (26.68), with the highest basal area (11.03 m^2/ha) and carbon stock (72.02 tC/ha). *Vitex grandifolia* followed, with a notable number of trees (23) and total density (13.34), alongside a basal area of 8.52 m^2/ha and a carbon stock of 47.90 tC/ha (**Figure 6**).

Species like *Amphimas pterocarpoides*, *Pseudospondias microcarpa*, and *Canarium schweinfurthii*, despite their low individual counts (3, 9, and 7, respectively), maintained significant carbon stocks (47.90, 27.84, and 26.16 tC/ha), attributed to their relatively high wood densities (4.93, 3.92, and 4.97, respectively) (**Figure 6**).

Conversely, species such as *Markhamia tomentosa*, *Blighia welwitschii*, and *Piptadeniastrum africanum*, despite having high individual counts (31, 24, and 14), recorded low carbon stocks (8.30, 6.87, and 8.77 tC/ha), which can be explained by their lower basal areas (2.36, 1.43, and 1.60 m^2/ha).

Overall, we can conclude that wood density and the basal areas influence the carbon storage of the trees. The higher these parameters are, the higher the carbon stock values are (**Figure 6**).

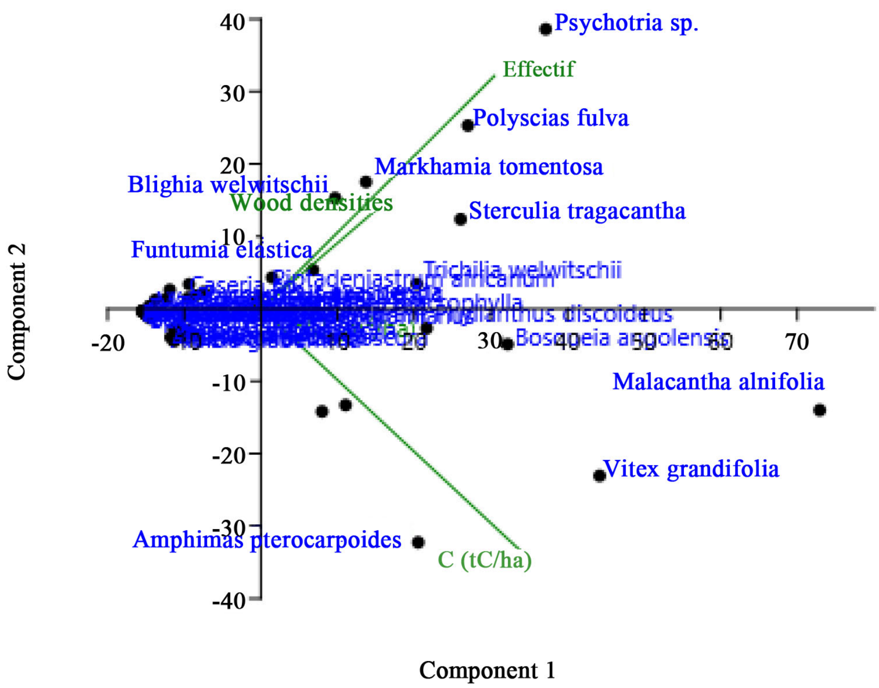

Figure 6. Principal component analysis of the relationships between carbon stocks, basal area, wood density and the number of individuals of plant species in the Batoufam sacred forest.

3.2. Discussion

3.2.1. Floristic Inventory

In general, sacred forests play a significant role in the regional conservation of original potential vegetation types. The floristic inventory revealed a total of 83 species, categorized into 72 genera and 30 families. This finding is lower than that reported by Ngounou (2023), who identified 151 species across 94 genera and 38 families in the sacred forests of Bazou (West Cameroon). Additionally, it falls short of the results obtained by Dar et al. (2022) in the sacred forests of India, where 109 species were documented, belonging to 90 genera and 40 families. Furthermore, Dar et al. (2019) conducted a survey of tree diversity, biomass, and carbon storage in the sacred forests of Central India, identifying 103 tree species across 81 genera and 37 families. The discrepancy in species richness can be attributed to differences in sampling methodologies and surveyed areas (41 sacred forests in India, as noted by Dar et al. (2019)). Similarly, Dar et al. (2019) used three 20 m × 20 m plots in each sacred forest, which were subdivided into four 10 m × 10 m quadrats.

Ecologically, the most represented families include Phyllanthaceae (47.64%), Fabaceae (24.08%), Moraceae (22.69%), and Lamiaceae (21.70%). These findings contrast with those of Ngounou (2023), who found that the dominant families in the sacred forests of Bazou were Clusiaceae, Fabaceae, Burseraceae, and Phyllanthaceae. Such differences may be explained by the various changes affecting these forests due to climate change and human activities (Guenodjo, 2021).

The high Shannon index values reflect favorable environmental conditions conducive to a diverse array of species (Sonké, 1998). In this study, the Shannon index ranged from 3.38 to 3.17 bits at Bandrefam and Batoufam, indicating a high level of specific diversity within the sacred forests investigated. According to Kent and Cooker (2003), a community is considered rich when its Shannon diversity index is greater than or equal to 3.5 bits. The values recorded in this study are consistent with those found by Lounang et al. (2018), who reported that the Batoufam sacred forest exhibited considerable woody diversity with a Shannon index of 3.51 bits. Simpson's index, calculated at 0.9489 bits, suggests average site diversity (Tiokeng et al., 2020). The Piélou equitability index and Fisher alpha index derived from the inventory analysis were 0.79 bits and 21.3 bits, respectively. Nonetheless, the values of the Piélou equitability and Simpson indices imply that the flora is represented by a limited number of species in terms of abundance (Sonké, 2004).

3.2.2. Structural Parameters

The basal area measurements at both sites ranged from 34.4 m^2/ha to 83.06 m^2/ha, all of which are lower than those recorded by Noumi (2012) in the Koughap sacred forest and Noumi & Tiam (2016) in the Mont Oku sacred forest (205.02 m^2/ha). These figures, however, exceed those reported by Ngounou (2023) in the Bazou sacred forest (30.35 m^2/ha and 77.64 m^2/ha). These results indicate a notable abundance of small-diameter individuals, as well as species represented by very few individuals (Tiokeng et al., 2020).

The diameter structure of the trees in these forests demonstrates a consistent regeneration density. Notably, the [0 - 10 cm] diameter class exhibited the highest number of individuals at both sites. The presence of a substantial population of young trees, coupled with a progressive decrease in diameter, suggests that these forests provide favorable conditions for tree survival in the absence of disturbances (Ngounou, 2023). Furthermore, this distribution pattern contrasts with that reported by Tiokeng et al. (2020) in the highland sacred forests of West Cameroon, where the largest number of individuals was found in the [10 - 20 cm] diameter class.

3.2.3. Carbon Stock Estimation

The assessment of carbon stocks in tropical forests has emerged as a global priority in the context of implementing the REDD+ mechanism (Panzou et al., 2016). Carbon stock analysis reveals that the Batoufam sacred forest stores significantly more carbon (469.26 tC/ha) compared to the Bandrefam sacred forest (291.41 tC/ha), with a total carbon sequestration of 760.57 tC/ha. This finding contrasts with those reported by Ngounou (2023) for the Bazou sacred forest (1709.26 tC/ha), Lounang et al. (2018) for the Koughap sacred forest (128 tC/ha), and Dar et al. (2022) across 59 sacred forests in central India (92.4 tC/ha). The observed differences may be attributed to the choice of allometric equations used and the size of the sacred forests studied. Indeed, variations in carbon stock estimates in tropical regions can often be explained by the sampling methodologies and the specific allometric equations employed (Chave et al., 2014; Lounang et al., 2018; Ngounou, 2023).

Subterranean biomass was assessed using a conversion factor, in contrast to Dar et al. (2019), who utilized the root ratio from Mokany et al. (2006) (0.563 or 0.275) based on the size of subterranean biomass. Additionally, carbon sequestration tends to be greater when biomass is substantial, increasing with tree diameter class (Ngounou, 2023). These observations align with the findings of Tsoumou et al. (2016).

The total economic value of the two sites is estimated at 9,204,129 USD, exceeding the figure reported by Cédric et al. (2022) for bamboo carbon stocks in the Western Highlands of Cameroon (1503 ± 624 USD/ha). This discrepancy is largely attributed to the size of the sacred forests analyzed. Although economic value varies from one sacred forest to another, it has the potential not only to enhance the living conditions of riparian communities but also to bolster forest management efforts. The economic valuation, combined with the number of species protected on the IUCN Red List and the biodiversity of these sites, underscores the necessity of preserving these forests. Therefore, integrating their value and harmonizing the cost of carbon equivalent (tCO_2), given its variability in the market, represents a viable approach to combat deforestation and the degradation of tropical forests (Ngounou, 2023).

These findings emphasize the importance of bamboo within the REDD+ strategy and its role in payment for ecosystem services programs.

4. Conclusion

The increasing population in Cameroon has led to significant forest loss, as these areas are either directly exploited for energy and income or converted to alternative land uses to satisfy growing demands for food, housing, urbanization, and infrastructure. This study aimed to estimate floristic diversity, stand structures and carbon stocks and sequestration in the sacred forests of Bandrefam and Batoufam in western Cameroon. It involved a comprehensive inventory of their wood diversity, stand structure, carbon stocks and sequestration. The floristic inventory identified 65 species belonging to 57 genera and 30 families in the Bandrefam sacred forest, and 45 species across 42 genera and 27 families in the Batoufam sacred forest. In Bandrefam, the most represented families were Moraceae and Phyllanthaceae (9 species each), followed by Fabaceae, Lamiaceae, and Olacaceae (8 species each). In contrast, the Batoufam forest was dominated by Fabaceae, Lamiaceae, Phyllanthaceae, and Rubiaceae (9 species each), with Araliaceae, Malvaceae, Meliaceae, and Moraceae contributing 8 species each. Total carbon stocks were measured at 469.26 tC/ha for Batoufam and 291.41 tC/ha for Bandrefam. The economic value of these forests varies, with Batoufam valued at 5,678,013 USD/ha and Bandrefam at 3,526,083 USD/ha. Notably, the highest tree density was found in the Bandrefam sacred forest, while Batoufam exhibited the greatest basal area. Moreover, the sacred forests of Bandrefam and Batoufam sequester substantial amounts of carbon but are also confronted with degradation factors that necessitate sustainable management. Therefore, it is essential to incorporate these forests into REDD+ policies to enhance their role in combating climate change. Strengthened protection measures could transform these forest areas into vital refuges for diverse flora and fauna.

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Conflicts of Interest

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

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