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Comparative analysis of carbon sequestration in cocoa-based agroforestry systems in Bonon (Central-Western Côte d'Ivoire)

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Abstract

This study investigates the ecological role of cocoa-based agroforestry systems (AFS) in Bonon. located in the Central-Western region of Côte d'Ivoire. Floristic inventories were conducted in 72 plots (25 m × 25 m) established across 52 cocoa plantations. To identify structurally homogeneous agroforestry systems. a hierarchical cluster analysis based on the coordinates of factorial axes derived from Multiple Factor Analysis was applied. resulting in the classification of three distinct AFS groups. Group 1 (61.53%) is characterized by a high density of productive cocoa trees (734.4 stems ha^{-1}) and a low abundance of associated shade trees. Group 2 (26.53%) comprises cocoa plantations with a moderate density of associated trees (651.5 stems ha^{-1}) and an average species richness of 8.6 species per plantation. Group 3 (11.54%) includes cocoa plantations integrating perennial crops such as coffee and cashew in active production. The mean aboveground biomass of cocoa trees and associated shade trees across the three AFS groups was estimated at 23.08 t DM ha^{-1}. Biomass was highest in Group 2 (30.48 t DM ha^{-1}). followed by Group 1 (22.71 t DM ha^{-1}). whereas Group 3 exhibited the lowest biomass (16.06 t DM ha^{-1}). The average carbon stock across AFS groups was 11.54 t C ha^{-1}. with Group 2 showing the highest carbon stock (15.24 t C ha^{-1}). consistent with its greater biomass accumulation. Overall. carbon sequestration and storage capacity in cocoa agroforestry systems are strongly influenced by farmers' management practices and structural attributes. including tree density. species diversity. tree height. and diameter.

Keywords: Agroforestry systems; Plant diversity; Carbon sequestration; Climate change; Côte d'Ivoire

1. Introduction

Like most countries in West and Central Africa. Côte d'Ivoire inherited from the colonial period the role of exporter of tropical agricultural commodities. particularly cocoa. of which it is the world's leading producer with an output exceeding 2 million tonnes (Assiri et al.. 2012). Indeed. the expansion of cocoa and coffee cultivation has occurred at the expense of primary forests. whose area declined from approximately 16 million hectares in 1960 to less than 2 million hectares today (Ruf and Agkpo. 2008 ;Maxime., 2012).). leading to the disappearance of numerous animal and plant species that are essential to local livelihoods. Consequently. in the search for ecologically sustainable. socially acceptable. and economically profitable alternatives to conventional agriculture. several researchers have advocated agroforestry systems (Adou Yao et al.. 2016). This approach corresponds to a complex agricultural activity integrating trees with crops and livestock production (Nair. 1993). Agroforestry can represent a sustainable alternative to deforestation and shifting cultivation by offsetting the ecological footprint associated with cocoa farming. while durably reconciling agricultural production with environmental protection (Vroh et al.. 2017). Cocoa cultivation requires the association of various plant species and trees. which. according to several studies. may play a significant role in carbon sequestration. The preservation of woody vegetation in cocoa-based agrosystems would thus contribute to their sustainability (Jagoret. 2011). However. the diversity of plant species associated with cocoa varies according to several factors. including cocoa variety. cultural background. farmers' age. and management objectives (Adja et al.. 2005;

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Kpangui et al.. 2015; Koulibaly et al.. 2017). Thus. although these associated species provide multiple ecosystem services—such as biodiversity conservation. maintenance of soil fertility. and additional income for local populations (Seghieri and Harmand. 2019) several knowledge gaps remain regarding their ecological benefits. particularly in terms of carbon sequestration. Therefore. obtaining an accurate estimate of carbon stocks in cocoa-based agroforestry systems (AFS) is essential to better understand their ecological impact on climate regulation. This will help to enhance the value of this land-use system and assess its potential socioeconomic benefits. particularly in the context of payments for ecosystem services schemes. The present study is thus essential to contribute to the quantification of sequestered carbon and to highlight the role and environmental importance of cocoa-based agroforestry systems in the locality of Bonon. It is based on the central hypothesis that carbon storage in cocoa-based AFS depends on the typology and floristic characteristics of these agrosystems. The general objective of this study is to assess the ecological role of cocoa-based agroforestry systems by estimating carbon sequestration rates in the locality of Bonon. To achieve this overall objective. four specific objectives were defined: (i) to establish a typology of cocoa-based agroforestry systems in the study area; (ii) to analyze floristic diversity according to agroforestry system types; (iii) to estimate carbon sequestration rates and their monetary value across cocoa-based agroforestry systems; and (iv) to determine the relationship between the structural diversity of cocoa-based agroforestry systems and carbon sequestration rates.

2. Methodology

2.1. Study area

The Department of Bonon is located in the Central-Western region of Côte d'Ivoire. within the Marahoué Region (Figure 1). It is bordered to the north by the city of Zuénoula. to the south by the sub-prefecture of Zaguiéta. to the east by the city of Bouaflé. and to the west by the sub-prefectures of Gonaté and Gadouan. Bonon is situated approximately 85 km west of Yamoussoukro and 324 km from Abidjan. This study was conducted in five villages of the study area. namely Dabouzra. Ouarèbota. Blaisekro 2. N'guatakouzkoukro. and Koffikro. The topography consists mainly of low plateaus with an average altitude of about 250 m. interspersed with small lowlands that are rarely encountered. Soils are predominantly ferralitic. moderately weathered. with a sandy-clay texture (Kouakou et al.. 2018). The main livelihood of the local population is agriculture. based primarily on cocoa and coffee production. as well as food crops such as plantain banana. rice. yam. and maize.

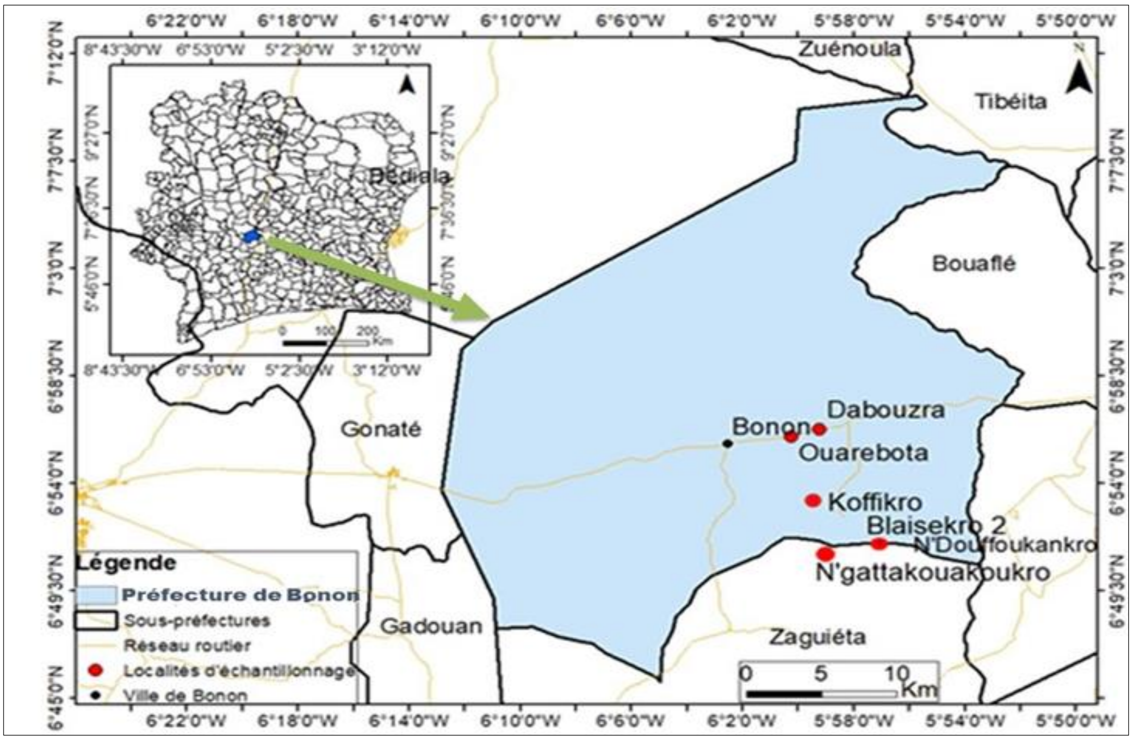

Figure 1 Location and description of the study area in the Bonon Sub-Prefecture

2.2. Selection of study sites

The locality of Bonon hosts numerous cocoa-based agroforestry systems. Plantation selection was based on field surveys and interviews conducted with farmers across the different villages of the study area. Information was collected on cropping systems. the main tree species conserved within plantations. and plantation size. Among the interviewed farmers. 50 were randomly selected and involved in the study. However. when a farmer owned several cocoa plantations. all plantations were considered in the analysis.

2.3. Sampling design

The sampling design consisted of 25 m × 25 m plots established in 52 cocoa plantations using a 100-m measuring tape. In total, 72 plots were installed. The number and spatial arrangement of inventory plots were primarily determined by topography, plot size (area), and plantation age. Once plots were delineated, their geographic coordinates were recorded using a GPS receiver prior to data collection. For the present study, a minimum of three (3) plots per hectare was established to ensure the representativeness of the data collected within each plantation.

2.4. Data collection

A plot-based inventory survey was conducted**.** Sampling plots of 625 m^2 were established within cocoa plantations. where all woody and non-woody plant species were identified. The following parameters were recorded: scientific name of each tree species. height. and circumference. Diameter at breast height (DBH ≥ 2.5 cm) was measured at 1.30 m above ground level for shade trees and at 30 cm above ground level for cocoa trees. using a measuring tape. These dendrometric variables were used to estimate aboveground biomass and carbon sequestration rates. Furthermore. multi-stemmed woody individuals were considered as single individuals during data analysis. Non-woody species and woody individuals with DBH < 2.5 cm were only counted and included to complete the floristic checklist.

2.5. Data analysis

2.5.1. Floristic analysis

Floristic richness refers to the total number of species recorded within a given area (Ake-Assi. 1984). It involves listing all species present in each plot. regardless of their abundance. to compile a comprehensive species checklist. The nomenclature of inventoried species followed the classification of Cronquist (1998). Species diversity was assessed using the Shannon diversity index (Shannon. 1948) and Pielou's evenness index (Pielou. 1966). The Shannon index measures the species composition of a community by considering both species richness and their relative abundances. It is calculated using the following formula:

$$H' = -\sum_{i=1}^{s}\left(\frac{ni}{N} * ln\left(\frac{ni}{N}\right)\right)$$

In this formula. H′ represents the Shannon index. n_i is the number of individuals of species *i*. and N is the total number of individuals of all species. The values of this index range from 0 to ln S. which represents the maximum diversity (where S is the total number of species in the community). When the community consists of a single species. H′ equals 0. whereas in a highly diverse community. it approaches ln S.

Piélou's evenness index (E) describes the distribution of individuals among the different species in a community (Wala et al.. 2005). E represents the evenness index. H is the Shannon diversity index. and S denotes the total number of species. It is calculated using the following formula:

$$E = \frac{H'}{ln(S)}$$

This index. which varies from 0 to 1. is used to assess the distribution of individuals among species in the environment. Thus. when it tends towards 0. one speaks of the dominance of one species over others. If E tends towards 1. the distribution of individuals among species is equitable (Wala et al.. 2005; Chave et al., 2014).

$$AGB = 0.0673 * (\rho * DHP * H)\,0.976$$

ρ = Specific density of the species (g/cm3); DHP = Diameter at 130 cm above ground level for other woody plants and at 30 cm above ground level for cocoa trees; H = Total height of a tree (m).

Belowground biomass (BGB) was estimated following the method adopted by the GIEC (2003). Specifically. belowground biomass was derived by multiplying the aboveground biomass (AGB) by a root-to-shoot ratio (R). which was set at 0.24 (Gibbs. 2007).

$$BGB = 0{,}24 * ABG$$

Total biomass (TB) was calculated by summing aboveground biomass (AGB) and belowground biomass (BGB) (Gueulou et al.. 2020). The unit of measurement is kilograms (kg).

$$BT = AGB + BGB$$

By convention. a value of 0.5 is used for wood carbon content (GIEC. 2006a; 2006b, 2007). Thus. above-ground biomass (AGB). below-ground biomass (BGB) and total biomass (BT) are converted into above-ground carbon (Ca). below-ground carbon (Cs) and total carbon (CT) sequestered by multiplying them by 0.5. This method has already been used by Ouédraogo et al. (2019).

- Ca = AGB ∗ 0.5
- Cs = BGB ∗ 0.5
- CT = BT* 0.5

After estimating the total carbon content of each tree. the corresponding amount of CO_2 was calculated. Sequestered CO_2 was obtained by applying the ratio of the molar masses of carbon and CO_2. Let M_mCO_2 = M_C + 2 × M_O = 12 + 2 × 16 = 44 g/mol.

where M_mCO_2 is the molar mass of CO_2. M_C is the molar mass of carbon. and M_O is the molar mass of oxygen. The carbon-to-oxygen combination ratio was then calculated as M_mCO_2 / M_C. which gives 44/12 ≈ 3.67. The amount of atmospheric CO_2 sequestered by the total biomass within the different agroforestry systems (AFS) was estimated by multiplying the carbon stock derived from biomass by 3.67 (Somarriba et al.. 2013).

$$CO2 = Ct * 3.67$$

2.5.2. Statistical analysis

To identify homogeneous groups for classifying cocoa-based agroforestry systems (AFS). three complementary statistical methods were employed: Multiple Factor Analysis (MFA). Hierarchical Ascending Classification (HAC). and Analysis of Variance (ANOVA). For the MFA. two categories of variables were used: active variables and supplementary (illustrative) variables (Pagès. 2002). The twelve active variables included: floristic richness. morphological types. average cocoa tree height. density of productive cocoa trees. average age of cocoa trees. density of banana trees. density of palm trees. density of productive cashew trees. density of productive coffee trees. density of young cocoa trees. density of young cashew trees. density of young coffee trees. density of other associated trees. and vegetation strata. Classification is a data analysis method that generates nested subsets through successive grouping of variables (Jain et al.. 1999). ANOVA was used to compare the means of calculated parameters among the different AFS groups. The purpose of the analysis was to determine whether the means of measured values across different groups differed significantly. Whenever the calculated probability was significant. Tukey's post-hoc test was performed to compare means pairwise and assess significant differences. The significance level for these analyses was set at 5% (P = 0.05). All analyses were conducted using the FactoMineR package in R software.

3. Results

3.1. Typology of cocoa-based agroforestry systems in the Bonon locality

3.1.1. Relationship among variables

To describe the relationships among the variables used to distinguish groups of cocoa-based agroforestry systems based on existing agricultural practices in cocoa cultivation. a Multiple Factor Analysis (MFA) was performed (Figure 2). The first two axes of the MFA applied to the inventoried plots accounted for 36.23% of the variance in the relationships among floristic characteristics of the plantations. After examining the factorial plane of floristic characteristics. the plots were distinguished and classified according to their positions along the positive and negative sides of the axes.

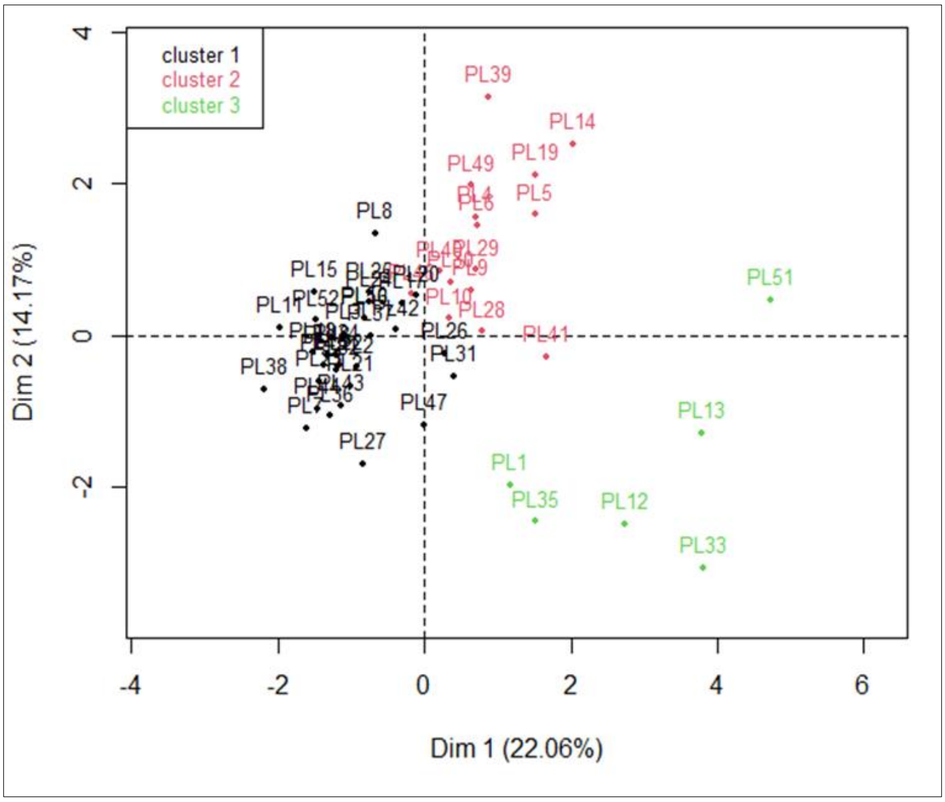

Figure 2 Factorial map of the plantations

Analysis of the first factorial plane of the variables highlighted Axis 1. which is characterized by variable groups such as morphological type (27.83). density of associated species (28.79). and vegetation strata (27.98). Axis 2 is characterized by plantations according to morphological types (20.69). density of associated species (29.53). vegetation strata (20.72). and floristic richness (25.35) (Table I).

Table 1 Eigenvalues and contribution of variable groups

	Axis_1	Axis_2	Axis_3	Axis_4	Axis_5
eigenvalue	2.28	2.08	1.62	1.23	1.14
percentage of inertia	24.24	13.14	10.92	8.27	7.7
Cumulative percentage of inertia	24.24	37.38	48.3	56.57	64.27
	Contribution of variable groups used				
Floristic richness	7.69	25.35	2.87	0.19	0.53
Morphological type	27.83	20.69	5.74	28.88	8.83
Density of associated species	28.79	29.53	26.81	36.6	1.74
Density of cacoa trees	7.65	2.32	18.96	4.25	16.75
Average height of cocoa trees	0	0.85	24.02	13.03	0.33
Stratum	27.98	20.72	7.02	14.76	31.52
Average age of cocoa trees	0.06	0.53	14.56	2.29	40.31

3.1.2. Plot clustering

The Hierarchical Ascending Classification (HAC) performed on the factorial axis coordinates from the MFA allowed the identification of three (3) groups of cocoa-based agroforestry systems (AFS) from the 52 analyzed plantations (Figure 3). Of the 19 variables used in the analyses. eleven (11) were significant in describing the different AFS groups. The remaining eight (8) variables did not significantly influence the clustering of plantations. These variables include: geophytes. average age of cocoa trees. the 16–32 m strata. average cocoa tree height. density of palms. density of non-productive (young) cashew trees. density of banana trees. and density of non-productive (young) cocoa trees.

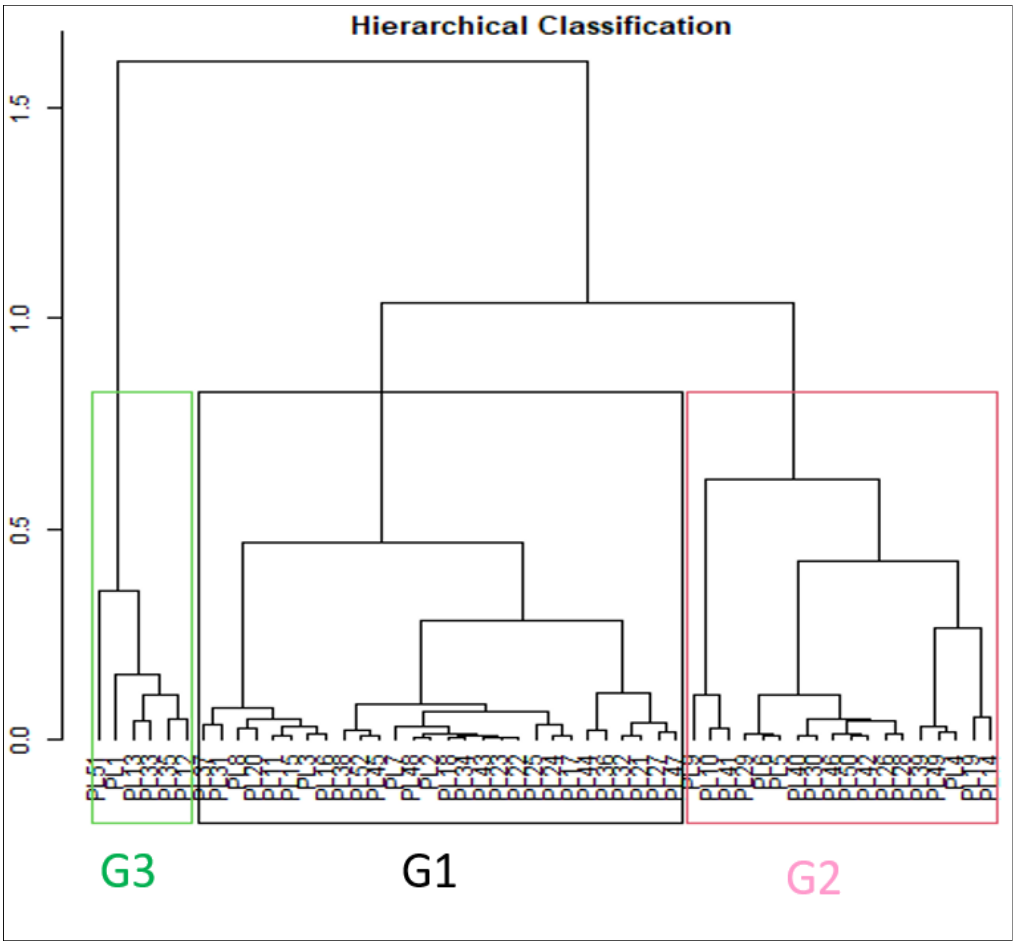

Figure 3 Hierarchical Ascending Classification of cocoa plantations in the study area G 3 = Group 3. G 1 = Group 1. G 2 = Group 2

3.1.3. Description of cocoa-based agroforestry system groups

Group 1 (Agroforestry System 1) represents 61.53% of the surveyed plantations. It comprises plantations with a high density of productive cocoa trees (734.4 stems/ha) and a low number of trees associated with the cocoa (Table II). The average floristic richness is 4.6 species. The average age of cocoa trees in this group is 17.4 years. with an average height of 5.3 m. Group 2 (Agroforestry System 2) represents 26.53% of the plantations. It consists of cocoa plantations associated with a few mostly large-sized trees. The average density of productive cocoa trees is 651.5 stems/ha. with an average floristic richness of 8.6 species per plantation (Table II). The average age of cocoa trees is 24.5 years. and their average height is 6.6 m. Group 3 (Agroforestry System 3) accounts for 11.54% of all plantations. These plantations include. in addition to cocoa. mostly perennial crops such as productive coffee and cashew trees. The average density of productive cocoa trees is 401.9 stems/ha. Among the associated perennial crops. coffee trees dominate with an average of 160 stems/ha. followed by cashew trees with 117 stems/ha. The average floristic richness is 6.8 species per plantation. The average age of cocoa trees in this group is 12 years. with an average height of 6.7 m

Table 2 Mean values of floristic indices and structural parameters of plot groups derived from Hierarchical Ascending Classification

Group	Variable	G1	G2	G3	Statistical test
floristic diversity	richness	4.6^{a}	8.6^{b}	6.8^{b}	29.2***
Cocoa trees	d_cocoa_yield (ind/ha)	734.4^{b}	651.5^{ab}	401.9^{a}	4.4*
	d_cocoa_non-productive (ind/ha)	154.9^{a}	231.7^{a}	214.5^{a}	0.7NS
	Age_cocoa	17.4^{a}	24.5^{a}	12.0^{a}	2.5NS
	Average_height_cocoa(m)	5.3^{a}	6.6^{a}	6.7^{a}	2.8NS
Density of perennial crops (plants/ha)	d_cashew tree_non-productive	16.5^{a}	50.3^{a}	14.5^{a}	1.6NS
	d_cashew tree_productive	19.3^{a}	35.4^{a}	117.8^{b}	13.3***
	d_coffee tree_productive	7.4^{a}	30.3^{a}	160.3^{b}	29.4***
	d_coffee_non-productive	4.0^{a}	11.4^{a}	120.5^{b}	24.4***
Density of other plants (plants/ha)	d_Palm tree	2.1^{a}	5.6^{a}	7.2^{a}	4.1NS
	d_Banana tree	27.9^{a}	33.5^{a}	31.3^{a}	0.4NS
	d_forest species	19.1^{a}	48.9^{b}	16.8^{a}	16.7***
Morphological type	Geophyte	5.0^{a}	6.1^{a}	10.0^{a}	0.2NS
	Tree	1.5^{a}	5.1^{b}	3.2^{ab}	16.7***
	Shrub	8.4^{a}	18.5^{a}	87.7^{b}	60.9***
Strates	H < 4	2.7^{a}	8.6^{a}	31.5^{b}	11.2***
	H (4 à 8 m)	3.1^{a}	5.1^{a}	40.0^{b}	36.8***
	H (8 à16 m)	1.9^{a}	5.6^{b}	8.0^{b}	14.9***
	H (16 à 32 m)	0.03^{a}	0.2^{a}	0.0^{a}	2.7NS
Origine	Native	10	6	5	
	Non-native	19	6	1	
	Foreign	3	2	0	

NS: not significant. For each row. values followed by the same letter are not significantly different at the 5% level. Significance levels of statistical tests: * < 0.05. ** < 0.01. *** < 0.001. d: density; d_cacoa_pro: density of productive cocoa; Hmoy_cacoa: average cocoa height; d_ana_prod: density of productive cashew; d_ana_non_pro: density of non-productive cashew; d_café_prod: density of productive coffee; d_café_non_prod: density of non-productive coffee.

3.2. Floristic diversity of cocoa-based agroforestry systems

3.2.1. Floristic richness of cocoa-based agroforestry systems

The inventories recorded a total of 8.886 individuals within the agroforestry systems. including 7.386 cocoa trees and 1.500 associated trees. These 1.500 individuals were distributed among 41 species. 34 genera. and 24 families (Table III). A low variation was observed in the number of species associated with cocoa across the AFS groups. Group 1 recorded the highest number of plant species (30 species) distributed among 24 genera and 19 families. Cocoa plantations in Group 2 had the lowest species richness. with 24 species distributed among 25 genera and 16 families.

Table 3 Species richness according to agroforestry systems

Group	Nbr ind	P.ind (%)	Nbr species	P.species (%)	NbrG	P.G (%)	Nbr.F	P.F (%)
G1	696	46.4	30	37.5	24	35.3	19	36.5
G2	408	27.2	24	30	25	36.8	16	30.8
G3	396	26.4	26	32.5	19	27.9	17	32.7

G 1 = Group 1; G 2 = Group 2; G 3 = Group 3; Nbr ind = number of individuals; Nbr species : number species; P.ind = proportion of individuals; P.species= proportion of species; NbrG = number of genera; P.G = proportion of genera; Nbr.F = number of families; P.F = proportion of families

3.2.2. Species diversity

Diversity parameters varied among the different agroforestry systems (Table IV). Shannon diversity index values ranged from 0.71 to 1.08. while Pielou's evenness index values ranged from 0.20 to 0.33. The Shannon index indicates that Group 3 is the most diverse (1.08). Regarding Pielou's evenness. species were not evenly distributed in any of the groups. However. when comparing groups. species in Group 3 were the most evenly distributed (0.33). In contrast. the evenness indices observed in Group 1 (0.20) and Group 2 (0.24) indicate that these groups are characterized by the dominance of certain species.

Table 4 Diversity indices calculated for different types of agroforestry systems

Agroforestry system	Shannon index	Evenness index
Groupe 1	0.71	0.20
Groupe 2	0.81	0.24
Groupe 3	1.08	0.33

3.2.3. Diameter structure

The stems of cocoa trees in the plots are characterized by medium diameters. which vary according to farmers' management practices (Figure 4). Only the diameter classes [2.5–10 cm] and [10–20 cm] recorded the highest number of cocoa stems across the groups. However. Groups 2 and 3 recorded more cocoa trees in the [2.5–10 cm] class. with respective values of 61.4% (Group 2) and 71.5% (Group 3). compared to 47.3% for Group 1. In the [10–20 cm] interval. Group 1 predominates with 30.8% of stems. followed by Group 2 (24.8%) and Group 3 (21.4%). Higher diameter classes contained fewer cocoa trees. representing individuals maintained during the regeneration phase. Regarding the species associated with cocoa. the histogram of their diameter distribution exhibits an "inverted J" shape (Figure 5). As one moves from one diameter class to the next. the proportion of trees gradually decreases. Most trees in Group 3 have diameters between 2.5 and 10 cm. representing 67.6% of stems. In contrast. Groups 1 and 2 contain more individuals in the 10–20 cm range. with 57.9% for Group 2 and 49.4% for Group 1. For larger diameter classes. the proportion of individuals is very low. especially for those with diameters >50 cm.

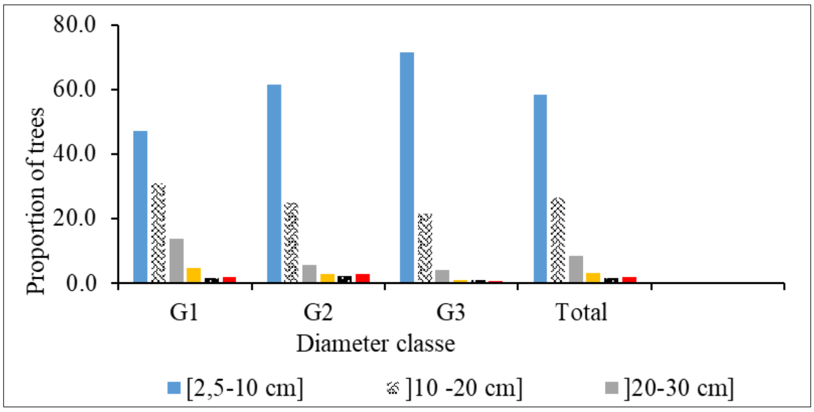

Figure 4 Diameter class distribution of trees associated with cocoa trees across agroforestry systems

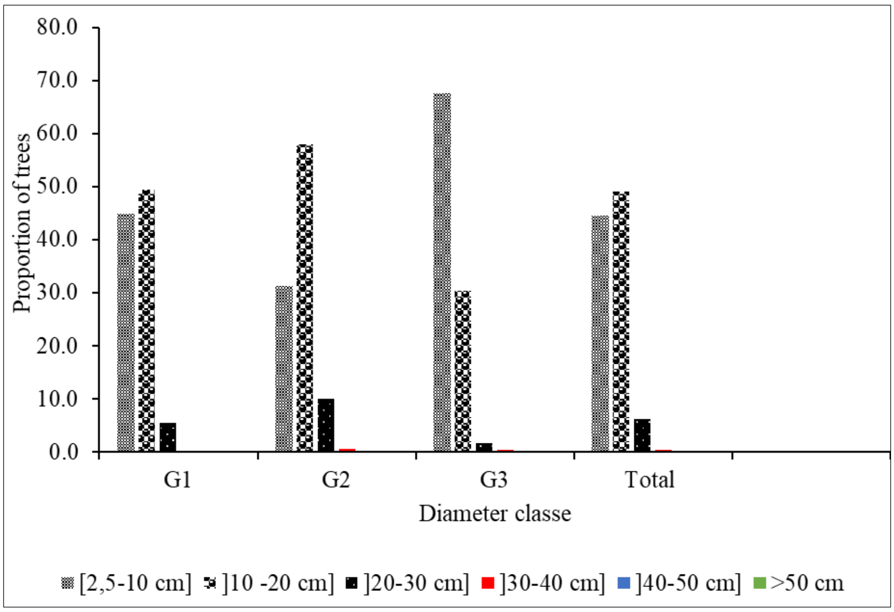

Figure 5 Diameter class distribution of cocoa trees across agroforestry systems

3.3. Biomass and carbon sequestration according to cocoa-based agroforestry systems

3.3.1. Biomass and total carbon sequestration

The mean biomass of cocoa trees and associated trees across the three-agroforestry system (AFS) groups was estimated at 23.08 t DM ha^{-1} (Table VII). Group 2 exhibited the highest biomass. with 30.48 t DM ha^{-1}**.** followed by Group 1 with 22.71 t DM ha^{-1}**.** Group 3 recorded the lowest biomass. with a value of 16.06 t DM ha^{-1}**.** Regarding carbon sequestration. the mean carbon stock across the different AFS groups was 11.54 t C ha^{-1}**.** Plots in Group 2 showed the highest carbon stock (15.24 t C ha^{-1}**).** reflecting their higher biomass. These were followed by Group 1 plots (11.36 t C ha^{-1}**).** Group 3 plantations sequestered the lowest amount of carbon. with a value of 8.03 t C ha^{-1}**.** Significant differences were observed among the AFS groups in terms of mean biomass values (F = 13.106; p-value = 0.00000213).

Table 5 Biomass and Total Carbon Stock According to Agroforestry Systems

Groups	Individual	BT (t DM ha^{-1})	CT (t C ha^{-1})
G1	4642	22.71^{b}	11.36^{b}
G2	2163	30.48^{c}	15.24^{a}
G3	1268	16.06^{a}	8.03^{c}
Total	8073	69.25	34.63

On the same line, values followed by the same letter are not significantly different (p < 0.05).. test de Tukey Within the same row. values followed by the same letter are not significantly different (p < 0.05. Tukey's HSD test). BT = total biomass; TC = total carbon; G1 = Group 1; G2 = Group 2; G3 = Group 3 (HSD)) BT= biomasse totale ; CT = carbone totale ; G 1 = Groupe 1 ; G 2= Groupe 2 ; G 3= Groupe 3

3.3.2. Biomass and Carbon Stock of Cocoa Trees According to Agroforestry Systems

The estimated mean biomass of cocoa trees across the three cocoa-based agroforestry system (AFS) groups was 14.003 t DM ha^{-1} (Table IX). Cocoa tree biomass ranged from 8.32 t DM ha^{-1} to 19.39 t DM ha^{-1}. The highest biomass was observed in Group 2. followed by Group 1. with respective values of 19.39 t DM ha^{-1} and 14.32 t DM ha^{-1}. In contrast. Group 3 recorded the lowest biomass (8.32 t DM ha^{-1}). Regarding mean carbon stock in the AFS. cocoa trees sequestered an average of 7.003 t C ha^{-1}. The highest carbon stocks were found in Group 2 (9.39 t C ha^{-1}) and Group 1 (7.16 t C ha^{-1}). while the lowest carbon stock was observed in Group 3 (4.16 t C ha^{-1}). The differences among mean values were statistically significant (F = 136.4; P = 0.000).

Table 6 Biomass and Carbon Stock of Cocoa Trees According to Agroforestry Systems

Groups	Individual	Biomass (t DM ha^{-1}	Carbon (t C ha^{-1})
G1	4223	14.3^{b}	7.16^{b}
G2	1857	19.39^{c}	9.69^{c}
G3	991	8.32^{a}	4.16^{a}
Total	7071	42.01	21.01

Within the same row. values followed by the same letter are not significantly different ($p < 0.05$. Tukey's HSD test). G1 = Group 1; G2 = Group 2; G3 = Group 3

3.3.3. Biomass and Carbon Sequestration by Trees Associated with Cocoa According to Agroforestry Systems

In the plantations. the mean biomass of trees associated with cocoa was estimated at 16.73 t DM ha^{-1} (Table VII). including 13.64 t DM ha^{-1} from forest trees and 3.09 t DM ha^{-1} from perennial crops. Considering different types of associated trees. biomass was higher in forest species. which recorded 40.28 t DM ha^{-1}. while the lowest biomass was observed in introduced trees. with 9.28 t DM ha^{-1}. Regarding aboveground carbon. trees associated with cocoa sequestered an average of 8.361 t C ha^{-1}. including 6.82 t C ha^{-1} from forest trees and 1.54 t C ha^{-1} from perennial crops associated with cocoa. Group 1 had the highest carbon stock (11.07 t C ha^{-1}). followed by Group 2 (9 t C ha^{-1}). Group 3. which had the lowest biomass. naturally sequestered the smallest amount of carbon. with a value of 5.03 t C ha^{-1}. Tukey's test indicated that for perennial crops. there were significant differences in carbon sequestration between Group 3 and Group 1. and between Group 3 and Group 2. However. no significant difference was observed between Group 2 and Group 1 ($F = 10.26$; $p = 0.0000428$). For other trees associated with cocoa. no significant differences were found in carbon stocks among the different groups ($F = 4.10$; $p = 0.01868$).

Table 7 Biomass and Carbon Stock of Trees Associated with Cocoa According to Agroforestry Systems

	Perennial crops		Forest trees	
Parameters	Biomass (t DM ha^{-1})	Carbon (t C ha^{-1}))	Biomass (t DM ha^{-1})	Carbon (t C ha^{-1})
G1	2.85^{b}	1.43^{b}	19.28^{a}	9.64^{a}
G2	3.35^{a}	1.67^{a}	14.67^{a}	7.33^{a}
G3	3.08^{a}	1.54^{a}	6.97^{a}	3.49^{a}

Within the same row. values followed by the same letter are not significantly different ($P < 0.05$. Tukey's HSD test). G1 = Group 1; G2 = Group 2; G3 = Group 3

3.4. Relationship between Structural Diversity of Cocoa-Based Agroforestry Systems and Carbon Stock

3.4.1. Biomass and Carbon Stock According to Age Classes

Table VIII presents the biomass and mean carbon stock of cocoa trees and associated trees according to age classes. The total aboveground biomass was 26.62 t DM ha^{-1}. including 13.77 t DM ha^{-1} for cocoa trees and 12.85 t DM ha^{-1} for trees associated with cocoa. Plantations older than 25 years and those aged 15–25 years. with respective values of 31.66 t DM ha^{-1} and 28.55 t DM ha^{-1}. exhibited the highest biomass. The lowest biomass was observed in plantations aged 3–5 years (23.96 t DM ha^{-1}) and 5–15 years (22.29 t DM ha^{-1}). Regarding carbon stock. the mean value was 13.31 t C ha^{-1}. including 6.88 t C ha^{-1} for cocoa trees and 6.43 t C ha^{-1} for associated trees. Carbon sequestration was highest in plantations aged 15–25 years (14.27 t C ha^{-1}) and over 25 years (15.84 t C ha^{-1}). However. the lowest carbon stocks were observed in juvenile plantations aged 3–5 years and 5–15 years. with respective values of 11.98 t C ha^{-1} and 11.15 t C ha^{-1}. No significant differences were found in carbon stock among the age classes. except between Group 1 and Group 2 ($F = 78.52$. $p = 0.000$).

Table 8 Biomass and Carbon Stock of Cocoa Trees and Associated Trees According to Age Classes

Parameters	B cac	B arb as	Total	Carb cac	Carb arb as	Total
] 3-5 ans]	8.52	15.44	23.96[a]	4.26	7.72	11.98[a]
] 5-15ans]	12.33	9.96	22.29[a]	6.17	4.98	11.15[a]
15-25ans]	16.65	11.9	28.55[b]	8.32	5.95	14.27[b]
>25 ans	17.57	14.09	31.66[c]	8.79	7.05	15.84[c]
Total	55.07	51.3	106.46	27.54	25.7	53.24

Within the same row. values followed by the same letter are not significantly different ($p < 0.05$. Tukey's HSD test). B_cac = Biomass of cocoa trees; B_assoc = Biomass of trees associated with cocoa
C_cac = Carbon stock of cocoa trees; C_assoc = Carbon stock of trees associated with cocoa

3.4.2. Biomass and Carbon Stock by Diameter Classes

For cocoa tree diameter classes. the mean biomass and carbon stock were 4.11 t DM ha^{-1} and 2.05 t C ha^{-1}. respectively. The highest values were recorded in the [10–20] cm diameter class. with 8.5 t DM ha^{-1} corresponding to 4.25 t C ha^{-1}. The lowest biomass was observed in the [30–40] cm diameter class. with a value of 1.2 t DM ha^{-1}. equivalent to 0.6 t C ha^{-1}. Intermediate values were observed in the other diameter classes (Table IX). Differences in mean biomass among diameter classes were statistically significant ($F = 130.45$; $p = 0.00000$). Regarding the diameter classes of trees associated with cocoa. the mean biomass and carbon stock were 6.13 t DM ha^{-1} and 3.07 t C ha^{-1}. respectively (Table X). However. diameter classes greater than 50 cm exhibited the highest biomass. with a value of 15 t DM ha^{-1}. corresponding to 7.5 t C ha^{-1}. The [30–40] cm diameter class contained the lowest biomass (3.2 t DM ha^{-1}). equivalent to 1.6 t C ha^{-1}. Differences in mean biomass among diameter classes were also statistically significant ($F = 579.78$; $p = 0.0000$).

Table 9 Biomass and Carbon Stock by Diameter Classes of Cocoa Trees

cocoa tree diameter classes	Individual	Biomass t DM ha^{-1}	Carbon (t C ha^{-1})
[2.5-10 cm]	3146	4[a]	2.2[a]
] 10 -20 cm]	3462	8.5[b]	4.3[b]
] 20-30 cm]	433	3.1[c]	1.5[c]
] 30-40 cm]	25	1.2[d]	0.6[d]
] 40-50 cm]	3	3.2[e]	1.6[e]
>50 cm	2	4.7[f]	2.4[f]
Total	7071	24.7	12.35

Within the same row. values followed by the same letter are not significantly different ($p < 0.05$. Tukey's HSD test).

Table 10 Biomass and Carbon Stock by Diameter Classes of Associated Trees

Diameter Classes of Associated Trees	Individus	Biomass (t DM ha^{-1})	Carbon (t C ha^{-1})
[2.5-10 cm]	584	6.1[a]	3.1[a]
] 10 -20 cm]	265	3.6[b]	1.8[b]
] 20-30 cm]	85	3.4[c]	1.7[c]
] 30-40 cm]	32	3.2[d]	1.6[d]
] 40-50 cm]	17	5.5[e]	2.7[e]
>50 cm	19	15[f]	7.5[f]
Total	1002	36.7	18.4

Within the same row. values followed by the same letter are not significantly different ($p < 0.05$. Tukey's HSD test)

4. Discussion

The multiple correspondence factor analysis identified three groups of cocoa-based agroforestry systems in the Bonon Department. The results showed that Group 1 comprises plantations with a high density of productive cocoa trees. an average height of 5.3 m. and a higher total number of species than the other two groups. owing to the larger number of plantations included. However. this group exhibited a relatively low mean species richness per plot. Group 2 is characterized by a moderately high density of productive cocoa trees. with an average height of 6.6 m. In this group. trees other than perennial crops are more dominant compared to Group 3. where coffee and cashew trees occur at higher densities among the species associated with cocoa. In Group 3. the average height of cocoa trees is 6.7 m. Overall. these parameters indicate that Group 2 currently represents the main target area for cocoa-based agrosystem development projects in the study area. Agricultural support institutions (CNRA. ICRAF. and ANADER) advise cocoa farmers to associate fast-growing trees (approximately 20 trees ha^{-1}) with cocoa either at the early growth stage of cocoa plants or prior to their establishment in the fields (ASSIRI. 2010). This practice results in a high tree density. giving plantations a structure that is generally continuous over time and can be confused with secondary forest formations (SONWA et al.. 2007). In addition. the advanced age of these plantations means that they are not regularly maintained. allowing trees to grow freely. The low number of large trees observed in Groups 3 and 1 may be explained by farmers' practices of removing large trees from cocoa plots to reduce shading. while retaining only a few fruit trees to benefit from their production. Indeed. mature cocoa plantations do not require shade to achieve good yields. as productivity is often higher when cocoa farms are exposed to sunlight (ASSIRI et al.. 2009). Consequently. farmers introduce numerous fruit trees and perennial crops into cocoa plantations to fill empty spaces. diversify income sources. and compensate for the low productivity of aging plantations. This type of system is specific to Group 3. Furthermore. the floristic inventory conducted across the 52 plantations identified a total of 41 plants species associated with cocoa trees. Some of these species are retained during land clearing or introduced when plantations are young (0–5 years old). Our results are comparable to those reported by Mbade (2012). who recorded 45 species in cocoa-based agroforestry systems (CAFS) in Pendiki. Cameroon. However. they are lower than those obtained by Laird et al. (2007). who documented 59 species in similar systems in Cameroon. Conversely. our results are higher than those reported by Jagoret et al. (2011). who found only 30 species in CAFS older than 40 years in central Cameroon. Indeed. within the floristic list obtained. the most abundant species across the three SAF groups were mainly *Mangifera indica*. *Persea americana*. *Elaeis guineensis*. *Cola nitida*. *Anacardium occidentale*. and *Coffea arabica*. The absence or rarity of certain species. as well as the low diversity index values. can be explained by the establishment process of these systems. which initially involves the felling of almost all native species. leaving only useful species to accompany cocoa trees during their growth. This practice results in a low density of large trees within plantations. Farmers subsequently introduce edible local or exotic species to provide shade and diversify income sources (Vroh et al.. 2014; Tano. 2012). Moreover. the variation in floristic diversity among the different agroforestry systems (AFS) in the locality of Bonon depends largely on farmers' decisions. as they determine both the quantity and the quality of trees to be retained in their plantations according to their perceived benefits. According to cocoa farmers. the species left standing are useful either for traditional medicine. nutrition. soil fertility improvement. difficulties related to tree felling. or for shade provision. particularly in the case of most forest species. The three AFS show similarities in terms of family composition and abundance. The families Musaceae. Rubiaceae. and Anacardiaceae are the most abundant in terms of individual numbers in the surveyed plantations. These results are consistent with those of Adou Yao et al. (2016). who demonstrated that farmers' choices of associated species in cocoa-based agroecosystems are strongly influenced by the uses and benefits of these species to the farmers. Furthermore. the biomass and carbon results obtained indicate low variability among the different agroforestry systems (AFS). On average. AFS recorded a biomass of 30.69 t DM ha^{-1}. corresponding to a carbon stock of 11.54 t C ha^{-1}. These values are comparable to those reported by Albrecht and Kandji (2003). who stated that carbon sequestration in agroforestry systems worldwide ranges from 12 to 228 t C ha^{-1}. However. our results are higher than those reported by Somarriba et al. (2013) for cocoa plantations in six Central American countries. where carbon stocks ranged from 7 to 10.5 t C ha^{-1}. In the present study. cocoa trees alone sequestered an average of 7.07 t C ha^{-1} in their biomass. with a planting density of 585 stems ha^{-1}. This value remains lower than that reported by Kpangui (2015). who obtained an average carbon stock of 11.23 t C ha^{-1} at a density of 1.764 stems ha^{-1} in central Côte d'Ivoire. This difference may be explained by the lower cocoa tree density in our study areas. due to mortality associated with the cultivated varieties and prevailing ecological conditions. In addition. senescent cocoa trees are being replaced by young plants and other crops within the same plots. Moreover. trees associated with cocoa sequester more carbon than cocoa trees within the different agroforestry systems (8.67 t C ha^{-1}). This can be explained by the fact that the majority of carbon is stored in large forest trees (Saj et al.. 2013). Furthermore. from one height class to another. and from one diameter class to another. the mean carbon stock values increase. Thus. tree diameter and height significantly influence the amount of carbon sequestered. Indeed. the larger the diameter and the taller the tree. the higher the carbon stock it contains. Our results are consistent with those of MacPherson (1998) and Nowak and Crane (2001). who indicated that tree density. height. and diameter are key parameters determining carbon sequestration. Similarly. across different age classes. the mean biomass and carbon stock values vary. The substantial amount of carbon stored in large-diameter trees highlights their significant role in greenhouse gas mitigation.

5. Conclusion

This study. conducted in the locality of Bonon. revealed that assessing the carbon stock of cocoa-based agroforestry systems (AFS) is a crucial element to consider when proposing alternatives. improvements. and conservation strategies for these systems. Based on the floristic characteristics obtained from cocoa plantation surveys. three cocoa-based agroforestry systems were identified. According to this typology. Group 1. characterized by a high density of productive cocoa trees. accounted for 61.53% of the surveyed plantations and exhibited the highest diversity. It was followed by Group 2. representing 26.53% of the plantations. in which forest trees dominated among the associated woody species. Finally. Group 3. with 11.54% representation. was characterized by a high density of perennial crops. The floristic inventory across the plantations recorded a total of 41 plant species. excluding cocoa. distributed among 34 genera and 24 botanical families. Group 1 contained 30 species. belonging to 25 genera and 19 botanical families. Group 1 recorded 30 species. distributed across 25 genera and 19 botanical families. Group 2. less diverse than Group 1. contained 24 species distributed among 19 genera and 16 families. Finally. Group 3. which was less diverse than Group 1 but more diverse than Group 2. comprised 26 species across 19 genera and 17 families. Overall. carbon sequestration in the studied plantations. as well as their carbon storage capacity. depends not only on farmers' choices and management practices but also on parameters such as tree density. biodiversity. height. and diameter. Considering the ecological impact in our study area. the average amount of carbon sequestered across all three AFS combined was 11.45 t C ha^{-1}. with cocoa trees sequestering 7.003 t C ha^{-1} and associated trees sequestering 8.66 t C ha^{-1}.

Compliance with ethical standards

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Disclosure of conflict of interest

All authors declare that there are no conflicts of interest related to this article.

Statement of informed consent

All authors confirm their participation in the design. execution. and analysis of the study and have approved the final version of the manuscript.

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Appendix

List of species associated with cocoa trees in the Bonon area

N°	Species	Family	Wood density	Biological type	Chorological affinity
1	*Albizia zygia* (DC.) J.F.Macbr	Mimosaceae	0.49	me	GC-SZ
2	*Alcornea cordifolia (*schum and Thonn.) Mull. Arg.	Euphorbiaceae		mi	GC-SZ
3	*Alstonia boonei* De wild.	Apocynaceae	0.32	mg	GC
4	*Anacardium occidentale* Linn.	Anacardiaceae	0.45	me	i
5	*Antiaris toxicaria* Var.africana (Engl.) C.C. Berg	Moraceae	0.38	me	GC
6	*Artocarpus altilis*	Moraceae	0.43	me	i
7	*Azadirachta indica* A. Jus	Meliaceae	0.64	mi	i
8	*Blighia unijugata* Baker	Sapindaceae	0.51	me	GC
9	*Blighia sapida* K. D. Koenig	Sapindaceae	0.76	me	GC-SZ
10	*Carica papaya* Linn. Var. bady Aké Assi	Caricaceae		mp	GC
11	*Ceiba pentandra (*Linn.) Gaerth.	Bombacaceae	0.31	mg	GC-SZ
12	*Citrus limon* Burn. f.	Rutaceae	0.74	mi	i
13	*Citrus reticulata* Blanco.	Rutaceae	0.74	mi	i
14	*Citrus sinensis* (L.) Osbeck	Rutaceae	0.78	mi	i
15	*Coco nucifera* Linn.	Arecaceae		mg	i
16	*Coffea Arabica* L.	Rubiaceae	0.62	mi	i
17	*Cola nitida (*Vent.) Schott and Endl..	Sterculiaceae	0.61	me	GC

18	*Cordia senegalensis* Juss. Juss.	Boraginaceae	0.54	me	GC
19	*Elaeis guineensis* Jacq.	Arecaceae		me	i
20	*Ficus exasperata* Vahl.	Moraceae	0.34	mi	GC-SZ
21	*Ficus sur* Forsk.	Moraceae	0.41	mi	GC-SZ
22	*Hevea brasiliensis* (Kunth) Mull Arg	Euphorbiaceae	0.47	me	i
23	*Holarrhena floribunda (*G.Don) Dur.and Schinz var.	Apocynaceae	0.47	me	GC-SZ
24	*Mangifera indica* Linn.	Anacardiaceae	0.55	me	i
25	*Millettia zechiana* Harms	Fabaceae	0.7	mi	GC
26	*Morinda lucida* Bentch.	Rubiaceae	0.54	me	GC-SZ
27	*Musa paradisiaca* Linn.	Musaceae		G	i
28	*Napoleonaea vogelii* (Hook.f.) Planch.	Napoleonaeaceae	0.58	mi	GC
29	*Nesogordonia papaverifera* (A. Chev.) R.Capuron.	Sterculiaceae	0.65	mg	GC
30	*Newbouldia laevis* (P. Beauv.) Seemann ex Bureau	Bignoniaceae	0.34	mi	GC
31	*Parkia biglobosa* (Jacq.) Benth.	Mimosaceae	0.53	mi	SZ
32	*Persea americana* Will.	Lauraceae	0.55	mg	i
33	*Psydium guajavia* L.	Myrtaceae	0.65	mi	i
34	*Ricinodendron heudelotii* (Bill.) Pierre ex pax	Euphorbiaceae	0.21	me	GC
35	*Tamarindus indica* Linn.	Caesalpiniaceae	0.98	mi	GC-SZ
36	*Terminalia superba* Engl. and Diels	Combretaceae	0.46	mg	GC
37	*Terminatia ivorensis* A. Chev.	Combretaceae	0.44	mg	GC
38	*Tetrapleura tetraptera* (Schum. and Thonn.) Taub.A	Mimosaceae	0.57	me	GC
39	*Trema guineensis* (Schum. and Thonn.) Ficalho	Ulmaceae	0.34	mi	GC-SZ
40	*Vitellaria paradoxa* C.F. Gaertn.	Sapotaceae	0.55	mi	SZ
41	*Xylopia aethiopica* (Dunal) A. Rich.	Annonaceae	0.44	me	GC-SZ

GC : Guineo-Congolian species. GC-SZ : Guineo-Congolian–Sudano-Zambezian species. SZ : Sudano-Zambezian species. i : Introduced species. me : mesophanérophytres. mi : Microphanérophytes. Mg : Megaphanéropytes. G: Geophytes