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Floristic structure, potential carbon stocks, and dynamics in cocoa-based agroforestry systems in Côte d'Ivoire (West Africa)

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Abstract With about 46% of global production, Côte d'Ivoire is the world's leading producer of cocoa beans. However, this production contributes to deforestation, exacerbating the effects of climate change. In response to this observation, this study aims to deepen knowledge on the contribution of agroforestry systems in cocoa production areas in Côte d'Ivoire to atmospheric carbon storage. These main areas are the Centre-West, South-West, and West. In these areas, floristic richness was determined in 115 plots. Carbon stocks in living biomass, dead matter, and soil were evaluated. The dynamics of carbon stocks with age were also determined. The results revealed that the West area contains the most diversified cocoa agroforests, with 161 species compared to 71 and 119 in the Centre-West and South-West, respectively. *Entandrophragma angolense*, *Nesogordonia papaverifera*, and *Sterculia oblonga*, common to these areas, are on the IUCN Red List. Carbon stock varies by area, its history, the practices present, and especially the associated species. Thus, in the former cocoa production zone (Centre-West) and the current main production zone (South-West), *Elaeis guineensis* is the main carbon reservoir, with 25.576 tC.ha^{-1} in the Centre-West and 36.862 tC.ha^{-1} in the South-West. In the West, local trees form the main carbon reservoir with 11.701 tC.ha^{-1}. The dynamics of total carbon stocks show heterogeneous changes in production areas according to the different stages of development of agroforestry systems. This is evidence of the complexity of carbon flow and the dynamics of cocoa systems, which are strongly influenced by the sociology of the producers.

Keywords Cocoa · Carbon stock · Climate change · Agroforestry systems · Côte d'Ivoire

Introduction

At the end of the nineteenth century, the tropical forests of Côte d'Ivoire covered a vast area, estimated at 16 million hectares (Aké Assi and Boni 1990). However, this forest area has gradually decreased, from 7.8 million hectares in 1990 to less than 3 million hectares in 2020, with a loss of more than 50% of the forest surface between these two periods (Plancheron et al. 2023). In the existing literature, the introduction

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of cash crops such as cocoa (*Theobroma cacao*), coffee (*Coffea arabusta* and *Coffea canephora*), and rubber (*Hevea brasiliensis*) in the nineteenth century is identified as the main cause of this deforestation rate (Diallo 2023). The conversion of Ivorian forest lands into cash crops, such as cocoa plantations, has direct implications on climate change and biodiversity (Legagneux et al. 2018).

Indeed, according to the Intergovernmental Panel on Climate Change (IPCC), land-use change represents the second largest source of CO2 emissions. In international discussions, including within the framework of the REDD + mechanism aimed at reducing greenhouse gas emissions linked to deforestation and forest degradation, the management of tropical forests and ecosystems affected by human disturbances remains at the forefront of debates. In light of this issue, conserving biodiversity and carbon stocks emerges as a significant challenge (Scheldeman and Zonneveld 2012).

Furthermore, to adopt sustainable agriculture in place of conventional farming, numerous scientific studies have proposed the adoption of agroforestry, specifically the introduction of trees into crops. A meta-analysis of the most effective agroforestry options in terms of carbon storage in different regions reveals that agroforestry systems located in tropical areas exhibit high carbon storage values, estimated at 4.85 $tCha^{-1}$ and 2.23 $tCha^{-1}$ for aboveground carbon and underground carbon, respectively (Feliciano et al. 2018). Moreover, according to Vroh and Akoi (2024), agroforestry in cocoa cultivation offers many benefits, as it provides a wide variety of goods and services, such as non-timber forest products, firewood, construction wood for housing, fruits, other food items, and medicinal materials. Fundamentally, these products help make cocoa producers more resilient to fluctuations in cocoa prices and damage to crops (Andres et al. 2016). Moreover, agroforestry provides other services such as pollination, natural pest control, biodiversity conservation, carbon sequestration, and more (Blaser et al. 2018). It combines agricultural production with environmental conservation measures (Schroth et al. 2011). Indeed, according to Michon et al. (1995), cocoa agroforests maintain a certain level of biodiversity, which can approach that of secondary forests. According to these authors, agroforestry presents an opportunity to combat poverty and conserve biodiversity (Deheuvels 2011). Saj et al. (2017) view agroforestry as an opportunity for the conservation of many species present in forested areas. Therefore, these systems can serve as effective buffer zones and be part of conservation action priorities. It has even been suggested that agroforests could have a conservation potential for certain species greater than that of exploited forests (Abada Mbolo et al. 2016).

As part of its commitment to the REDD + process to contribute to the fight against climate change and ensure sustainable management of its forest cover, Côte d'Ivoire has focused on developing its own databases. This includes establishing its Forest Reference Emission Level (FREL) to be submitted to the United Nations Framework Convention on Climate Change (UNFCCC), as well as implementing Measurement, Reporting, and Verification (MRV) mechanisms (FAO 2017). To this end, forest inventories have been conducted and data collected to assess forest biomass in the country. However, this approach to quantifying carbon sequestration excludes cocoa-based agroforestry systems, even though these are part of activities eligible for greenhouse gas emission reduction mechanisms, such as the Clean Development Mechanism (CDM) and REDD +, as well as the conservation and enhancement of carbon sinks (Boukeng et al. 2023). These mechanisms provide incentives to reward efforts to reduce GHG emissions. A better understanding of the contribution of cocoa-based agroforestry systems to carbon storage could thus allow producers in these regions to benefit from opportunities related to carbon credits.

In this context, it is relevant to ask what the effects of management practices and age are on the diversity and carbon stock of cocoa-based agroforestry systems. One answer to this question suggests that the characteristics of cocoa production sites in Côte d'Ivoire, their history, and cultivation systems influence the dynamics of carbon storage in these systems. The overall objective of this study is therefore to deepen the understanding of the contribution of agroforestry systems in cocoa-producing areas of Côte d'Ivoire to atmospheric carbon storage. To achieve this, the activities carried out are: (i) assessing the floristic diversity of cocoa agroforestry systems in Côte d'Ivoire; (ii) estimating carbon stocks in the different components (living biomass, dead matter, and soil) of cocoa agroforestry systems; and (iii) determining the dynamics of carbon stocks in cocoa production areas in Côte d'Ivoire.

Methods

Study area

As presented by the Fig. 1, the study area includes the three main Cocoa bean-production of Côte d'Ivoire Côte d'Ivoire: Bonon (Centre-West, 6° 45′ 0″ –7° 10′ 0″ N latitude and 5° 52′ 0″ –6° 14′ 0″ W longitude), Soubré (W 5° 19′ 00″ –6° 34′ 00″ N latitude and 6° 12′ 00″ –7° 08′ 00″ Wlongitude) and Biankouma (W 7° 21′ 00″–8° 06′ 00″ N latitude and 7° 03′ 00″–8° 15′ 00″ W longitude). The Centre-West region is the second largest cocoa-bean producing region accounting for 12% of national production (Amon et al. 2021). The Central-West region of Côte d'Ivoire is characterized by a humid climate with a rainy season from March to October and a dry season from November to February. This region receives an average monthly rainfall ranging from 73.84 to 106.80 mm and temperatures between 26 and 27 °C (Konan et al. 2023). Located in a mesophilic zone, Bonon has semi-deciduous dense forest vegetation on plateaus at an altitude of approximately 260 m (Avenard 1971) and ferralitic soils (Perraud 1971). The Central-West is predominantly populated by the Gouro ethnic group, along with Baoulés, Sénoufos, Malinkés, and migrants from Burkina Faso, Mali, and Guinea. Traditional agriculture dominates here, including cocoa, coffee, cashew, and food crops such as yam and maize (Krouba et al. 2018).

The South-West region, with 34% of national production (Blé et al. 2022), is the main current cocoa bean production area in Côte d'Ivoire. This region is dominated by perennial crop plantations, both traditional and industrial (CRN 2016). It has a subequatorial climate with four seasons: two rainy seasons (April-June and September–November) and two dry seasons (July–August and December-March). Average monthly temperatures range between 24 and 27 °C (Konan et al. 2023). Annual rainfall varies between 1600 and 1800 mm (Blé et al. 2022). The terrain consists of plateaus with elevations between 200 and 300 m (Avenard 1971). The soils are mainly ferralitic (Perraud 1971). The population includes indigenous groups, the Bakoué and Bété, as well

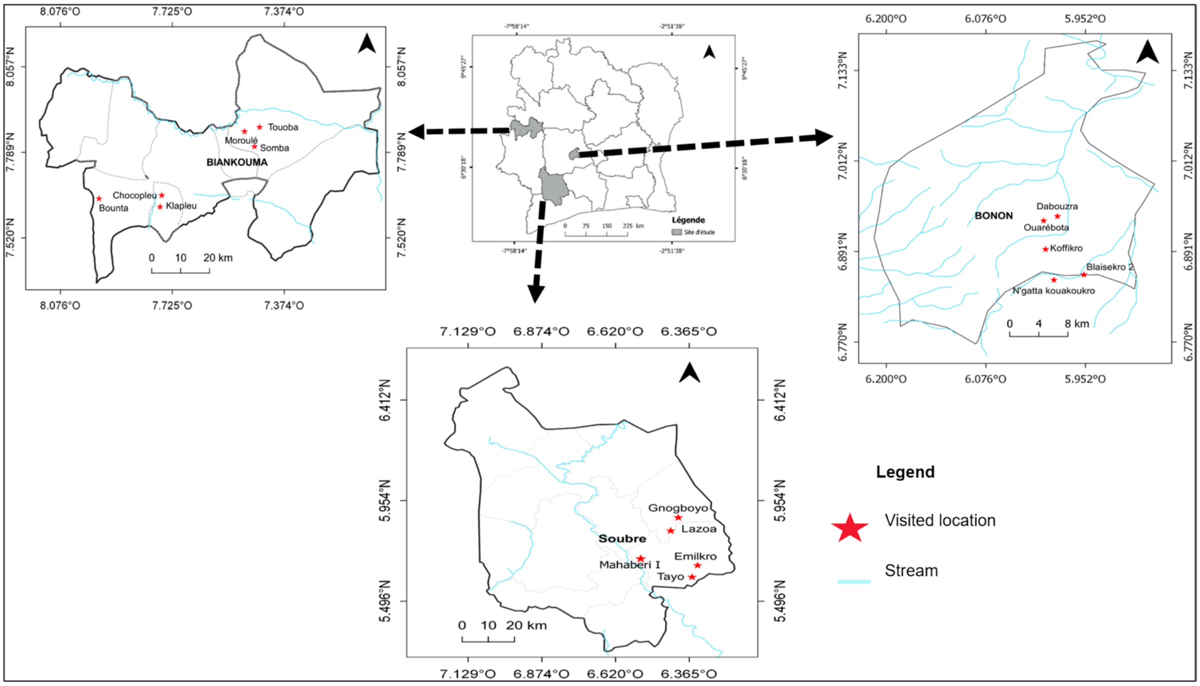


Fig. 1 Geographical location of study areas and sites in Côte d'Ivoire

as non-native groups such as the Agni, Baoulé, and Gouro, along with migrants from Mali and Burkina Faso, mostly engaged in agriculture. The main crops in the region are cocoa, rubber, oil palm, banana, cassava, yam, and rice.

The last region, Biankouma, appears to be the new cocoa production front in terms of production dynamics and migration for cocoa farming (Koua et al. 2020). Although 30-year-old plantations have been observed in this region, their number and production were marginal. It is characterized by diverse vegetation, including dense humid semi-deciduous forests, savannas, and forest-savanna mosaics. Subject to a mountainous climate, it experiences two seasons: a rainy season (March to October) and a dry season (November to February), with average monthly temperatures ranging between 24 and 28 °C. The terrain is dominated by mountains reaching up to 1000 m in altitude, with primarily ferralitic soils. Annual rainfall varies from 5 to 150 mm (Konan et al. 2023). The indigenous population consists of the Yacouba, Toura, and Mahouka ethnic groups, alongside non-native Baoulé, Lobi, Sénoufo, Malinké, and Agni, as well as Burkinabé immigrants. Agriculture (rice, yam, coffee, cocoa) and trade, facilitated by proximity to Guinea, are the main economic activities. The relative presence of forests in this region has led to significant pressure from cocoa farmers, making this area a new frontier for cocoa production in Côte d'Ivoire. The agroforestry systems targeted in this study are part of the cocoa plantation network set up as part of the Cocoa4future project (https://www.cocoa4future.org).

Data collection

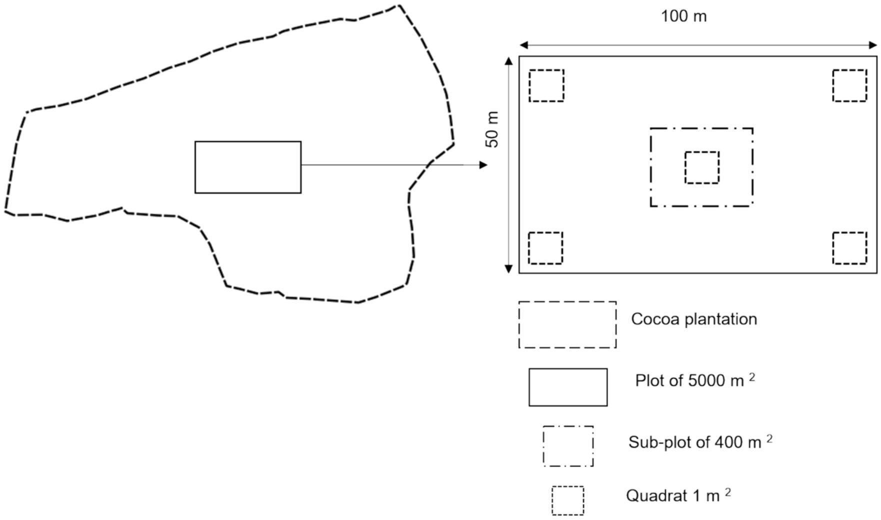
The data collection was consisted into forest inventory. Plots of a 0.5 ha area (100 m × 50 m), sub-plots of 400 m^2 (20 × 20 m) and five sub-quadrats of 1 m^2 (1 × 1 m) as presented in Fig. 2 were established using a GPS and penta-decameter (Kooke et al. 2019; Zoghaib 2021).

The 0.5 ha plots were used to inventory woody species (trees and shrubs) and non-woody species (palms and banana plants). The 400 m^2 subplots were used to record cocoa trees and associated crops. The 1 m^2 quadrats allowed for the collection of litter or dead organic matter and soil samples.

In total, data were collected from 115 plots of 5000 m^2 each and 115 subplots of 400 m^2 each, distributed across the three production areas: 39 in Bonon, 40 in Biankouma, and 36 in Soubré. Regarding the 1 m^2 quadrats, a total of 575 were installed, with five quadrats per plot. These plots were divided into 7 age classes: [0–4 years], [5–10 years], [11–15 years], [16–20 years], [21–25 years], [26–30 years], and > 30 years, within each zone.

The estimation of the carbon stock in cocoa AFS was done considering three components namely: (1) living biomass -ground biomass (AGB) and root biomass (BGB), non-woody cocoa trees and associated crops; (2) dead biomass, represented

Fig. 2 Sampling device



solely by the litter in this study; and (3) soil carbon. The biomass of the tree species herbaceous as well as associated crops, was estimated using the non-destructive method with allometric equations adopted from Picard et al. (2012).

Data collection was consisted into dendrometric data collection using measuring tapes. In each plot, a global inventory of woody species (trees and shrubs) and non-woody species (banana and palm) with a diameter ≥ 8 cm was carried out (Vroh et al. 2015; Felfili et al. 2004). For each individual identified, the diameter was measured at a height of 1.30 m above the ground.

About cocoa trees and associated crops, dendrometric measurements were carried out in the sub-plot (400 m^2). Diameter of the cocoa trees was measured at 30 cm above the ground using a calliper. The height of the cocoa trees was also measured using a graduated stake. For coffee trees, the diameter was measured at 15 cm above the ground, while that of cashew trees was measured at 1.30 m above the ground (Kpangui 2015; Noiha et al. 2015).

According to the IPCC guidelines (2006), dead organic matter includes both litter and dead wood. Due to the scarcity of dead wood in the fields during data collection, only the litter was considered. Indeed, dead wood is often removed from the fields for use as firewood by local populations. For the collection of litter and soil samples, samples were taken from the five 1 m^2 quadrats (Fig. 2). These samples were weighed using a precision balance (0.05 g), before being dried in an oven at 80 °C until a constant weight was achieved.

To assess soil carbon stocks, five soil samples were collected from each quadrat using an auger at a depth of 30 cm. A 127.56 cm^3 cylinder ($L = 6.5$ cm and $d = 5$ cm) was inserted into the soil to collect soil samples for bulk density calculation. A total of 575 samples were collected from all 115 plots. A composite sample was collected from each plot for laboratory analysis to determine the total carbon content using the sulfochromic oxidation method of organic carbon (Walkley and Black 1934). This method involves the oxidation of soil organic matter with potassium dichromate (K2Cr2O71N) in an acidic medium, at a soil/K_2(Cr2O7) ratio of 0.25/10.

Data analysis

Floristic and structural characterization of agroforestry systems

Species richness, family abundance, and tree stand density, as well as the Shannon–Wiener diversity index (H), Pielou's evenness index (E), and the Sorensen similarity index, were used for the floristic characterization of agroforestry systems. According to Ramade (1994), species richness refers to the number of species in a community or stand. The relative abundance (Ar) of a species or family in a given plant community is the numerical importance of individuals of that species or family in the community relative to the total number of individuals. The density of a species (D in stems/ha) is the number of individuals of that species per hectare.

The Shannon–Weaver diversity index is used to evaluate the heterogeneity and diversity of a biotope. This index has a minimum value when all individuals belong to the same species and a maximum value when each individual belongs to a distinct species (Shannon and Weaver, 1948). The Shannon–Weaver diversity index (H) is obtained from the following formula: $\mathrm{H} = -\sum\left(\frac{\mathrm{ni}}{\mathrm{N}}\right)\ln\left(\frac{\mathrm{ni}}{\mathrm{N}}\right)$

With H as the Shannon index; ni as the number of individuals of species i; N as the total number of individuals of all species.

The Piélou evenness index measures the distribution of each species within the occupied space. It tends toward 0 when all individuals belong to a single species and reaches 1 when all species have equal coverage (Piélou 1966). It is obtained from the following formula: $\mathrm{E} = \mathrm{H}/\ln\mathrm{S}$

With E being the Piélou evenness index, H the Shannon index, and S the total number of species in a biotope.

The Sorensen similarity index measures the resemblance between two floristic communities. If $K > 50\%$ then the two surveys belong to the same plant community. f $K < 50\%$, then the two surveys belong to different plant communities.

The Sorensen similarity index is calculated using the following formula: $K = (2c/a + \mathrm{b}) \times 100$

With a representing the number of species in plant community 1, b representing the number of species in plant community 2, and c representing the number of species common to both plant communities 1 and 2.

Carbon stock estimation

The above-ground biomass was calculated using non-destructive methods coupled with the allometric equations. The list of the different equations considered in this study is presented in the following Table 1.

The wood densities used for each specie were extracted from the R Studio software and checked against the Global Wood Density Database (Zanne et al. 2009). Belowground biomass (BGB) was determined using the methodology adopted by the IPCC (2003). This involves multiplying the above-ground biomass (ABP) value by the root-shoot (R) ratio, which is estimated to be 0.24 (IPCC 2006). Total biomass was obtained by adding above-ground biomass (AGB) and below-ground biomass (BGB).

Estimating carbon stocks

The conversion of the total biomass, estimated from different equations, into a carbon stock is done by multiplying by a fraction of carbon. A value of 0.5 is used in line with the recommendations of Mille and Louppe (2015).

The total biomass of cocoa trees, woody plants, non-woody plants and intercropping are converted into carbon by multiplying each obtained value by 0.5. Regarding the potential carbon stock of the litter estimation, the total biomass obtained per site is multiplied by 0.37 according to the work of Zoghaib (2021). This coefficient also corresponds to the carbon fraction (CF) contained in the dry biomass.

The assessment of soil carbon stock (t C ha^{-1}) was performed by multiplying the carbon content (%) by the bulk density (g cm^{-3}) and by the depth or thickness of the sampling layer (m) following method adopted by Poeplau et al. (2017). The bulk density is obtained by dividing the dry mass of the soil (g) by the volume of the cylinder (cm^3) (Audry et al. 1973).

Statistical analysis of the data

Statistical analysis was consisted to the one-way analysis of variance (ANOVA) when the Shapiro normality test indicated a *p*-value greater than 0.05 ($P > 0.05$), to compare the means, with a significance level of 5%. In case of a significant difference ($p < 0.05$) between the means, the Tukey test was applied to determine the different classes of homogeneity. However, when the Shapiro normality test was less than 0.05 ($P < 0.05$), a nonparametric Kruskal–Wallis test was performed. All statistical analyses were performed with R software**.**

Results

Floristic characteristics of cocoa-based agroforestry systems

In Bonon, Centre-West of Côte d'Ivoire, the floristic procession includes 71 species belonging to 56 genus and 28 families. The highest species richness was observed in [5–10 years] agroforestry systems, with a value of 17 species. On the other hand, the lowest average richness was observed in the youngest farms (0–4 years), i.e. 7.80 species (Table 2). The [5–10 years] agroforestry systems have the highest

Table 1 Allometric equations for estimating aboveground biomass of inventoried species

Species or type	Allometric equations	References
Theobroma cacao	$\text{Log AGB} = (-1.684 + 2.158 \times \text{Log (D)} + 0.892 \times \text{Log (H)}$	Somarriba et al. (2013)
Elaeis guineensis	$\text{AGB} = \exp\ (-2.\ 134 + 2.\ 530 \times \ln(\text{D}))$	Brown (1997)
Musa sp.	$\text{AGB} = 0.030 \times \text{D}^{2.13}$	Hairiah et al. (2010)
Coffea sp.	$\text{AGB} = 0.281 \times \text{D}^{2.06}$	Hairiah et al. (2010)
Anacardium occidentale	$\ln \text{AGB} = 4.66 + 0.28 \times \ln\ (\text{D})$	Noiha et al. (2023)
Other woody species	$\text{AGB} = 0.0673 \times (\rho \times \text{DBH}^2 \times \text{H})^{0.976}$	Chave et al. (2014)

AGB Above-ground biomass (kg), *D* Trunk diameter at 15 cm from the ground (coffee tree), 30 cm (cocoa), 130 cm (all other species), *H* Height of the tree in metres, *Ln* natural logarithm, *Log* logarithm to base 10, *ρ* species specific density ($g.cm^3$)

Table 2 Diversity indexes of agroforestry systems according to different age classes

Variables (individual/ha)	Age class of agroforestry systems (years)							*P*
	[0–4]	[5–10]	[11–15]	[16–20]	[21–25]	[26–30]	> 30	
Site 1: Bonon								
Species richness	7.80^{a}	17^{b}	9.80^{c}	12.80^{c}	9.50^{c}	12.70^{c}	11.66^{c}	0.02
Average number of families	6.60^{a}	12.83^{b}	9^{ab}	10.40^{ab}	8.83^{ab}	11.16^{ab}	9.83^{ab}	0.002*
Average number of genus	7.80^{a}	15.66^{b}	9.20^{a}	$11{,}60^{ab}$	$9{,}33^{a}$	$12{,}33^{ab}$	$11{,}33^{ab}$	0,008 **
Site 2: Soubré								
Species richness	17.60^{a}	13^{a}	12^{a}	14.80^{a}	11.40^{a}	11.20^{a}	10.20^{a}	0.87
Average number of families	11.80^{a}	10.80^{a}	9.40^{a}	11.20^{a}	8.80^{a}	9.16^{a}	8^{a}	0.85
Average number of genus	16.40^{a}	12.60^{a}	11.20^{a}	14^{a}	11^{a}	10.50^{a}	9.60^{a}	0.76
Site 3: Biankouma								
Species richness	22.80^{c}	23.00^{a}	12.80^{c}	14.80^{c}	10.83^{c}	8.11^{b}	21.20^{c}	0.009**
Average number of families	14.20^{a}	15.40^{a}	9.40^{b}	11.40^{ab}	8.83^{b}	7.55^{b}	12.60^{ab}	0.04 *
Average number of genus	19.80^{c}	20.60^{a}	11.80^{c}	18.60^{c}	10.16^{c}	7.88^{b}	18.20^{C}	0.008**

For each line, the values followed by the same letter are not significantly different at the 5-p.c. threshold. Test significance: "* < 0.05", "** < 0.01", "*** < 0.001"

number of families, i.e. 12.83 families, as well as the highest number of genus (15.66 genus). In contrast, the age group [0–4 years] has the smallest number of families (6.60 families) and genus (7.80 genus). The differences between floristic richness, the number of genus and the number of families per age group are statistically different.

Regarding the Soubré area, the floristic inventory records 119 species distributed across 91 genera and 36 families, the agroforestry systems located in young cocoa plantations ([0–4 years]) have the greatest richness in terms of species, families and genus, with 17.60 species, 11.80 families and 16.40 genus respectively. In contrast, agroforestry systems older than 30 years have the lowest diversity, with only 10.20 species, 8 families and 9.60 genus. However, statistical tests did not reveal significant differences between the different variables ($P > 0.05$).

In the new cocoa production front of Biankouma, the floristic assemblage includes 161 species distributed across 110 genera and 47 families. The highest species richness is also observed in the agroforestry systems aged [0–4 years] and [5–10 years], with 22.80 species and 23.00 species respectively. These two ages groups also have the largest number of families (14.20 and 15.40 respectively) and genus (19.80 and 20.60 respectively). On the other hand, the lowest value in terms of species, families and genus is observed in agroforestry systems aged [26–30 years], with 8.11, 7.55 and 7.88 respectively. The values obtained between the age groups are significantly different ($P < 0.05$).

In the three sites studied, *Musa paradisiaca* (banana) is the species with high density in the AFS cocoa outside the main crop (cocoa). The species occupies respectively more than 91.82%, 68.25% and 64.37 in Bonon, Soubré and Biankouma. The banana tree is associated with the palms of Bonon (2.21%), Soubré (7.63%) and Biankouma (2.79%). Banana trees and palms are the most abundant species in cocoa AFS.

However, specific differences were observed in the different sites considered in this study. In Bonon area cocoa trees are genuslly associated with other fruit species such as avocado (2.1%) while they are not observed in other sites. As presented in the Table 3, in the Biankouma region, the presence of indigenous species in AFS cocoa such as *Ficus sur* (3.96%), *Albizia adianthifolia* (2.01%), *Millettia zechiana* (1.43%) and *Ficus exasperata* (1.08%) is observed.

According to the criteria defined by IUCN Red List, vulnerable species are observed in the cocoa plantations with varying relative frequencies (Table 4). Among these species, *Entandrophragma angolense* (Tiama), *Nesogordonia papaverifera* (Kotibé) and *Sterculia oblonga* (Eyong) are the most common in the study area. However, *Albizia ferruginea* and *Entandrophragma utile* are only observed in

Table 3 Relative abundance of associated species in cocoa-based agroforestry systems with a relative abundance greater than or equal to 1%

Associate species	Relative abundance (%)		
	Bonon	Soubré	Biankouma
Albizia adianthifolia	–	–	2.01
Elaeis guineensis	2.21	7.63	2.79
Ficus exasperata	–	1.17	1.08
Ficus sur	–	–	3.96
Millettia zechiana	–	1.41	1.43
Musa paradisiaca	91.82	68.25	64.37
Persea americana	2.1	1.09	–
Rauvolfia vomitoria	–	2.01	–

Table 4 Relative abundance of vulnerable species in study areas

Species with special	Relative abundance (%)		
	Bonon	Soubré	Biankouma
Afzelia africana	–	–	0.03
Albizia ferruginea	–	0.08	–
Cordia platythyrsa	–	0.10	0.05
Cussonia bancoensis	–	–	0.10
Entandrophragma angolense	0.28	0.08	0.40
Entandrophragma cylindricum	–		0.03
Entandrophragma utile	–	0.02	–
Garcinia kola	0.55	–	0.38
Khaya grandifoliola	–	0.06	0.50
Khaya senegalensis	–	–	0.08
Milicia regia	–	0.13	0.03
Nesogordonia papaverifera	1.38	0.17	0.35
Pterygota macrocarpa	–	–	0.23
Ricinodendron heudelotii	1.93	–	–
Sterculia oblonga	0.55	0.19	0.60
Terminalia ivorensis	–	0.38	0.35

the Soubré area. Vulnerable species are more abundant in the western area of the study represented by Biankouma.

Table 5 presents the analysis of Shannon–Weaver diversity and Pielou's evenness in the three production zones studied. Diversity is lower in the Center-West (Bonon, $0.13 < H < 0.95$) compared to the Southwest (Soubré, $0.93 < H < 2.26$) and the West (Biankouma, $0.81 < H < 1.99$) across the different age classes. With average H values of 1.51 and 1.53 in Soubré and Biankouma, respectively, these two zones appear to be more diverse than the Bonon region (average $H = 0.53$). The most diverse zone is located in the West of Côte d'Ivoire.

Regarding the species distribution in the plantations, the results from the Piélou evenness index show a much better distribution of species in the plantations of Soubré and Biankouma compared to those of Bonon, regardless of the age classes considered.

The analyses of floristic similarities between adjacent age classes show overall values above 50% across all study areas. The highest floristic similarities were observed in the Soubré plantations, with an average Sørensen coefficient of 58.55%. The lowest are observable in the Bonon plantations, with an average value of 55.96% (Table 6).

In all three production areas studied, 5% (10 species), 11.90% (24 species), and 33.20% (67 species) are specific to the Center-West, Southwest, and West zones of Côte d'Ivoire, respectively (Fig. 3). Furthermore, 22.30% of the species, or 45 species, are specific to the three production regions studied. The analysis also shows that 4% (8 species) are found in both Bonon and Soubré, 20.30% (41 species) in Soubré and Biankouma, and 3.5% (7 species) in Biankouma and Bonon (Fig. 3).

Average density of cocoa trees, species and associated crops

Analysis of results from tree density revealed different trends according to the type of system. The density of cocoa is higher in the new system areas compared to the oldest ones. In fact, cocoa trees density in the Biankouma zone is higher than the other zones regardless of the age of the plantation (Table 7). Observed densities are 840, 1040 and 1770 individuals per hectare respectively for Bonon, Soubré Biankouma area. Considering wood trees, they reach about 150.78 individuals per hectare in Biankouma versus 17.20 individuals per hectare in Bonon after cocoa plantations establishment.

Overall, the density of woody plants in Biankouma decreased over last three decades (30 years) while the density increased to 73.33 trees per hectare in Bonon (Table 7). The opposite trend is observed for banana trees when cocoa plantations are established. In contrary, considering banana trees, the high density is observed in the oldest systems (Bonon with 1238.40

Table 5 Shannon–Weaver diversity index (H) and Pielou's Evenness (E)

Age class of agroforestry systems (years)	Shannon–Weaver diversity (H)			Pielou's evenness (E)		
	Bonon	Soubré	Biankouma	Bonon	Soubré	Biankouma
[0–4]	0.13	1.50	1.93	0.09	0.51	0.61
[5–10]	0.49	1.16	1.99	0.19	0.44	0.64
[11–15]	0.46	0.93	1.68	0.24	0.35	0.66
[16–20]	0.95	2.26	1.46	0.41	0.88	0.53
[21–25]	0.43	1.64	1.12	0.21	0.64	0.48
[26–30]	0.64	1.58	0.81	0.28	0.68	0.40
> 30	0.59	1.47	1.73	0.27	0.62	0.58
Average H and E	0.53	1.51	1.53	0.24	0.59	0.56

Table 6 Sørensen similarity indices of agroforestry systems according to different age classes

Age class of agroforestry systems (years)	Similarity indice (Sørensen %)		
	Bonon	Soubré	Biankouma
[0–4]–[5–10]	52.63	70.59	57.86
[5–10]–[11–15]	64.71	59.46	65.81
[11–15]–[16–20]	50.85	54.21	63.83
[16–20]–[21–25]	59.65	48.60	58.33
[21–25]–[26–30]	57.14	53.57	49.48
[26–30]–> 30	50.75	64.86	50.43
Average similarity index	55.96	58.55	57.62

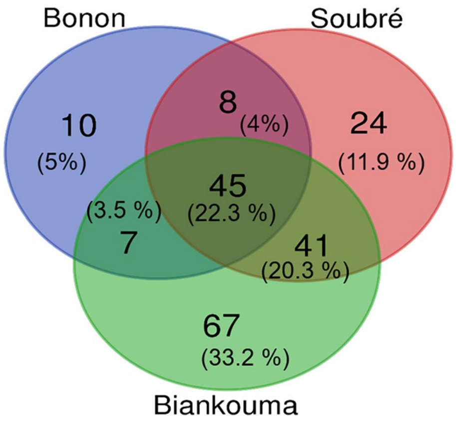


Fig. 3 Floristic similarity between the production areas of Bonon, Soubré, and Biankouma

individual per hectare) compared to the new systems such as Biankouma (with 128.25 individuals per hectare) and Soubré (with 223.60 individuals per hectare). Considering both Bonon and Soubré systems the density of bananas trees decreases considerably over a period of 16 and 20 years. Banana tree density estimated was 375.20 and 4.40 individuals per hectare respectively in Bonon and Soubré. From this period onward, banana density increased and was estimated at 131.60 individuals per hectare in Biankouma.

Regarding palm trees, the highest density is observed in agroforestry systems with ages ranged from 0 to 4 years in the West and South-West regions, with 57.20 and 30.80 individuals per hectare respectively. Considering the Centre-West region, the observed palm density was 6.40 individuals per hectare. In the West area, palm trees density increases gradually to reach highest level over 30 years, with a low density observed between 5 and 10 years. On the other hand, as presented into Table 5, in the Centre-West of Côte d'Ivoire, the density of palm trees reaches a peak of 50.67 individuals per hectare between 26 and 30 years. After adoption of the agroforestry systems, in the Centre-West (Bonon) and West (Biankouma) of Côte d'Ivoire, high density of associated crops was observed and estimated at185 and 220 individuals per hectare respectively in Bonon and Biankouma. However, this density decreases considerably at Bonon area, reaching 20 individuals per hectare when the systems are between 16 and 20 years old. In Biankouma, the density drops to 13.89 individuals per hectare between 26 and 30 years. In the south-west zone, the density of associated crops was 20 individuals per hectare between 5 and 10 years.

Carbon stock of cocoa system components

In line with carbon stock estimation in the agroforestry systems of the Centre-West, four flora species groups are distinguished according to their significant capacity to stock carbon. These species include

Table 7 Average density of cocoa trees, species and associated crops by age class of agroforestry systems in the regions of Bonon, Biankouma and Soubré

Production area	Age class of agroforestry systems (year)							P
	[0–4]	[5–10]	[11–15]	[16–20]	[21–25]	[26–30]	> 30	
Cocoa density								
Bonon	840 ± 354.26	1004.17 ± 410.92	1405 ± 382.18	1365 ± 479.78	1204.17 ± 636.48	1029.17 ± 688.37	766.67 ± 325.06	0.13
Soubré	1040 ± 1313.11	975 ± 235.19	1240 ± 395.13	1270 ± 168.39	1145 ± 310,95	970.83 ± 168.39	890 ± 156.72	0.09
Biankouma	1770 ± 655.36	2365 ± 336.62	2445 ± 382.18	2475.83 ± 479.78	1245.83 ± 636.48	1477.78 ± 668.37	1000 ± 642.99	0.01
Wood density								
Bonon	17.20 ± 13.16	56.33 ± 20.22	32 ± 33.20	73.20 ± 31.16	47 ± 48.61	56.67 ± 37.39	73.33 ± 80.89	0.04
Soubré	115.60 ± 164.45	37.20 ± 17.30	43.60 ± 36.94	40.80 ± 24.15	27.60 ± 18.46	45 ± 43.60	25.20 ± 15.47	0.95
Biankouma	150 ± 150.78	104 ± 50.30	50.40 ± 45.75	56.80 ± 42.09	31 ± 36.06	17.11 ± 10.25	86 ± 59.77	0.02
Banana tree density								
Bonon	1238.40 ± 923.55	827.33 ± 445.95	495.20 ± 496.93	375.20 ± 300.75	753.33 ± 554.95	783.33 ± 504.80	1075.33 ± 1306.35	0.31
Soubré	223.60 ± 264.61	324 ± 337.64	256.80 ± 112,86	4.40 ± 6.69	25.60 ± 32.32	40.67 ± 53.82	106.40 ± 135.97	0.02
Biankouma	128.25 ± 60.26	108.40 ± 35.14	54.80 ± 62.40	131.60 ± 105.89	124.67 ± 118.07	160.67 ± 109.68	191.60 ± 213.81	0.52
Palm tree density								
Bonon	6.40 ± 6.07	13.33 ± 19.70	2.40 ± 5.37	1.60 ± 3.58	14 ± 8.29	50.67 ± 42.16	39.33 ± 18.83	0.00
Soubré	30.80 ± 24.68	14.80 ± 18.20	17.60 ± 18.89	18 ± 13.71	8.80 ± 7.29	16.33 ± 11.34	13.20 ± 13.75	0.67
Biankouma	57.20 ± 105.05	35.20 ± 29.52	57.20 ± 72.30	44 ± 51.59	106.33 ± 144.88	56.22 ± 33.20	180.40 ± 164.19	0.19
Crop density								
Bonon	185 ± 106.95	208.33 ± 272.79	115 ± 109.83	20 ± 44.72	70.83 ± 84.29	45.83 ± 43.06	45.83 ± 36.80	0.19
Soubré	0 ± 00	20 ± 44.72	0 ± 00	0 ± 00	0 ± 00	0 ± 00	10 ± 22.36	0.61
Biankouma	220 ± 260.65	105 ± 207.97	220 ± 354.17	25 ± 55.90	54.71 ± 88.62	13.89 ± 22.05	250 ± 404.66	0.29

Significance threshold of the Kruskal–Wallis test: significant if “$p < 0.05$”

palms, bananas, woody plants, and cocoa trees. Estimation of carbon in the different areas showed that stock values observed for palms are ranged from 8.134 ± 10.119 tC.ha^{-1} in systems aged 0–4 years to 66.763 ± 61.839 tC.ha^{-1} in the systems over 30 years of age. Related to banana plants, the carbon stock varies between 3.017 ± 1.779 tC.ha^{-1} for systems aged 0–4 years and 2.990 ± 3.164 tC.ha^{-1} for those over 30 years old. Similarly, for woody plants, carbon stock of banana plants is ranged between 0.715 ± 0.811 tC.ha^{-1} for systems of 0–4 years old to 17.605 ± 25.166 tC.ha^{-1} for those with 5–10 years. Regarding the cocoa trees, their carbon stock potential varies from 0.359 ± 0.210 tC.ha^{-1} for systems with 0–4 years old to 3.052 ± 1.094 tC.ha^{-1} for those with 16–20 old.

In Soubré area, palm and cocoa trees are distinguished by their high capacity to store carbon in living biomass (Table 8). Palm trees stock about 79.905 ± 109.867 tC.ha^{-1} for young systems (0–4 years) versust 20.613 ± 25.984 tC.ha^{-1} for systems between 21 and 25 years old. Concerning cocoa trees, the carbon stocks are ranged from 0.794 ± 0.861 tC.ha^{-1} in systems with 0–4 years old, and reach a minimum of 3.407 ± 0.665 tC.ha^{-1} for system between 16 and 20 years old.

Concerning the new cocoa production front (Biankouma), three species of the living biomass compartment have been identified: cocoa trees, woody plants and palm trees. The carbon stock of cocoa trees increases from 1.319 ± 1.418 tC.ha^{-1} between 0 and 4 years to 4.466 ± 2.110 tC.ha^{-1} between 16 and 20 years. For woody plants, the carbon stock was 12.533 ± 14.424 tC.ha^{-1} between 0 and 4 years, then increases to 19.400 ± 14.663 tC.ha^{-1} for systems over 30 years old. Palms have a carbon stock of 4.387 ± 8.843 tC.ha^{-1} for young systems (0–4 years), reaching 11.664 ± 11.070 tC.ha^{-1} for systems over 30 years old.

Table 8 Summary of average carbon stocks (tC.ha^{-1}) of the different carbon compartments by age class of agroforestry systems in the Bonon, Biankouma and Soubré zones

Compartments	Age class of agroforestry systems (year)							p
	[0–4]	[5–10]	[11–15]	[16–20]	[21–25]	[26–30]	> 30	
Site 1: Bonon								
Cocoa trees	0.359 ± 0.210	1.842 ± 0.482	2.533 ± 0.755	3.052 ± 1.094	2.595 ± 0.859	2.104 ± 1.034	1.835 ± 0.975	0.000
Woody	0.715 ± 0.811	17.605 ± 25.166	2.254 ± 0.590	3.922 ± 3.206	6.670 ± 5.092	8.662 ± 11.901	14.217 ± 15.183	0.02
Banana trees	3.017 ± 1.779	2.747 ± 1.508	1.618 ± 1.159	1.509 ± 1.794	2.469 ± 1.953	2.541 ± 1.812	2.990 ± 3.164	0.44
Palm trees	8.134 ± 10.119	31.921 ± 53.328	1.561 ± 3.490	0.065 ± 0.144	24.682 ± 25.318	45.906 ± 47.668	66.763 ± 61.839	0.00
Crops	0.757 ± 0.440	0.488 ± 0.569	0.249 ± 0.440	0.077 ± 0.173	0.265 ± 0.375	0.129 ± 0.155	0.144 ± 0.145	0.17
Litter	0.002 ± 0.001	0.003 ± 0.001	0.003 ± 0.001	0.003 ± 0.001	0.003 ± 0.001	0.003 ± 0.001	0.003 ± 0.001	0.78
Soil	0.464 ± 0.058	0.333 ± 0.029	0.582 ± 0.176	0.400 ± 0.167	0.475 ± 0.201	0.442 ± 0.132	0.395 ± 0.110	0.07
Site 2: Soubré								
Cocoa trees	0.794 ± 0.861	1.541 ± 0.583	1.860 ± 0.288	3.407 ± 0.665	3.292 ± 0.959	2.360 ± 0.453	2.540 ± 0.740	0.000
Woody	0.970 ± 0.909	0.926 ± 0.590	0.758 ± 0.778	0.858 ± 0.487	0.601 ± 0.738	0.858 ± 1.140	0.974 ± 0.729	0.89
Banana trees	0.243 ± 0.299	0.378 ± 0.398	0.347 ± 0.204	0.006 ± 0.010	0.094 ± 0.127	0.136 ± 0.127	0.190 ± 0.250	0.07
Palm trees	79.905 ± 109.867	25.815 ± 41.314	26.675 ± 28.592	41.439 ± 51.458	20.613 ± 25.984	42.855 ± 42.440	20.732 ± 16.615	0.77
Crops	0.000 ± 0.000	2.835 ± 6.340	0.478 ± 1.070	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	1.001 ± 2.239	0.61
Litter	0.001 ± 0.001	0.002 ± 0.001	0.003 ± 0.001	0.002 ± 0.001	0.002 ± 0.001	0.002 ± 0.001	0.003 ± 0.001	0.07
soil	0.344 ± 0.120	0.470 ± 0.057	0.452 ± 0.280	0.374 ± 0.143	0.374 ± 0.115	0.282 ± 0.104	0.328 ± 0.045	0.33
Site 3: Biankouma								
Cocoa trees	1.319 ± 1.418	2.514 ± 0.952	3.575 ± 0.586	4.466 ± 2.110	2.717 ± 1.209	3.669 ± 2.046	1.754 ± 1.942	0.04
Woody	12.533 ± 14.424	3.471 ± 2.024	2.765 ± 2.610	14.399 ± 10.780	18.110 ± 21.377	11.227 ± 8.374	19.400 ± 14.663	0.09
Banana trees	0.389 ± 0.196	0.325 ± 0.155	0.154 ± 0.173	0.564 ± 0.492	0.474 ± 0.477	0.727 ± 0.418	0.751 ± 0.588	0.10
Palm trees	4.387 ± 8.843	3.377 ± 3.987	4.395 ± 4.403	4.467 ± 7.038	6.486 ± 5.438	3.180 ± 3.406	11.664 ± 11.070	0.40
Crops	1.339 ± 1.437	0.686 ± 1.182	2.322 ± 3.165	0.296 ± 0.662	0.233 ± 0.344	0.114 ± 0.283	2.526 ± 3.429	0.40
Litter	0.002 ± 0.001	0.002 ± 0.001	0.004 ± 0.002	0.002 ± 0.001	0.002 ± 0.001	0.002 ± 0.001	0.002 ± 0.001	0.32
soil	0.674 ± 0.275	0.686 ± 0.185	0.628 ± 0.847	0.702 ± 0.321	0.573 ± 0.061	0.646 ± 0.104	0.570 ± 0.167	0.80

Significance threshold of the Anova and Kruskal–Wallis tests: significant if "$p < 0.05$"

Considering all the three production areas, the species in the living biomass compartment that store the least carbon are intercrops, and the compartments that store the least carbon are litter and soil (Table 8).

Dynamics of carbon storage in agroforestry systems according to their stage of evolution

The dynamics of the total carbon stock as a function of the stage of evolution of agroforestry systems genusly show a heterogeneous evolution in the three cocoa production areas considered in this study (Fig. 4). In Bonon, the carbon stock of AFS cocoa was estimated at 13.449 tC.ha^{-1} for young stand (0–4 years). The carbon stocks increase over time to reach 54.940 tC.ha^{-1} between 5 and 10 years. After this period, the carbon in AFS cocoa drops to 8.800 tC.ha^{-1} between 11 and 20 years. However, considering the earliest stage, the carbon stock had knower an increasing over time.

The situation is less contrasted in the regions of Soubré and Biankouma. In fact, in these areas, a genusl downward trend has been observed in Soubré, from 82.257 tC.ha^{-1} when the farm was set up to 25.768 tC.ha^{-1} after 30 years. The opposite trend was observed in Biankouma, where stocks appear to be increasing overall over time. Thus, between 0 and 4 years, when AFS cocoa was established, the carbon volume was 20.642 tC.ha^{-1}. This volume gradually reached 36.667 tC.ha^{-1} around 30 years.

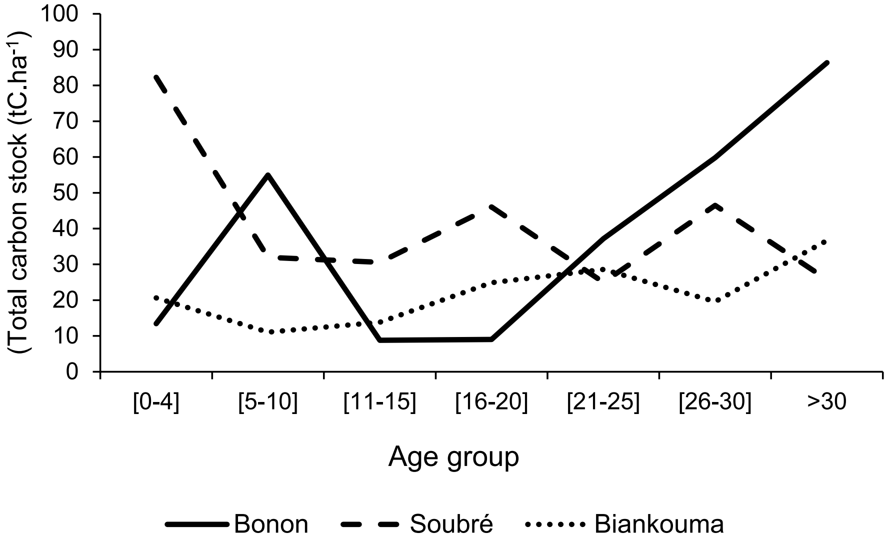


Fig. 4 Dynamics of carbon storage in agroforestry systems in the Bonon, Biankouma and Soubré zones

Discussion

Loss of floristic diversity in cocoasystems

The results of this study showed that floristic richness in the production areas decreased based on the production history of the cocoa area. Thus, between 0 and 4 years, floristic richness was 7.80 species per hectare oldest production area (Bonon), 17.60 species per hectare in the current main production area (Soubré in the Southwest), and 22.80 species per hectare in new cocoa production front of western Côte d'Ivoire (Biankouma). In older plantations (> 30 years), this trend can also be observed overall, with around 10 species per hectare in the initial areas and approximately twenty in the latest. This trajectory of species diversity is confirmed by the Shannon–Weaver diversity indices. The decline in floristic diversity observed over time could be explained by regular weeding activities in the cocoa understory, which would gradually eliminate species present in the plantation. Moreover, the canopy created by mature cocoa trees would limit sunlight penetration through the plantation, reducing the dormancy of certain seeds buried in the soil and the development of young plants. These activities and the environment induced by cocoa plantations lead to greater extinction of species with particular status in the older cocoa production areas compared to the newer ones, as shown in Table 4. Furthermore, the future of a species in a plantation depends on its function for the cocoa trees or for the farmer. Indeed, for farmers, the choice of a companion species in cocoa cultivation, whether native or exotic, addresses a dual concern: finding an adequate balance of shade and identifying trees that are compatible with cocoa trees in order to optimize bean yield (Sonwa et al. 2007). In addition to these main reasons, other socio-anthropological needs of the producer can be added: totems, wood for rituals, medicinal species, etc. (Cissé et al. 2018; Kougbo et al. 2019; Assalé et al. 2020) or economic needs through the sale of fruit from these species (Jagoret et al. 2014; Zanh et al. 2016; Kougbo et al. 2023). These practices are also observed in Ghana (Asase and Tetteh 2010; Anglaaere et al. 2011), Nigeria (Oke and Odebiyi 2007), and Cameroon (Saj et al. 2017; Temgoua et al. 2018), the three main cocoa bean producers after Côte d'Ivoire. These results also demonstrate a good knowledge of the species associated with cocoa trees and their distribution in the field by the farmers, as evidenced by the relative consistency of Pielou's evenness index over time. These observations are confirmed by the Sørensen similarity coefficient, which is generally above 50% from one age class to another. Thus, the species belong to the same floristic assemblage in each of the areas (Diatta et al. 2021). This observation seems obvious since most of the species inventoried in the cocoa plantations are woody plants that persist in the area because they are chosen by the farmer.

Moreover, the presence of a significant number of plant species in the Biankouma plantations could be explained by the relatively recent practice of cocoa cultivation in this area. Indeed, in older areas such as Bonon and Soubré, there are fewer trees due to the competition they may have with cocoa plantations. Several research studies have recommended that farmers eliminate certain types of trees from their plantations to optimize production (Asare 2005; Gala Bi et al. 2017). Trees have long been considered vectors of parasitic attacks (Gala Bi et al. 2017) and diseases such as the cocoa swollen shoot virus (CSSV) (Oro 2011; Kouakou 2014), as well as a source of increased humidity, thus intensifying brown rot in the plots (Cilas and Despréaux 2004; Guessan-Bi et al. 2024). Furthermore, the traditional practice of felling and slash-and-burn clearing to establish cocoa plantations in the older production areas of the Center-West and Southwest has significantly reduced the number of trees in cocoa plantations.

Crop association as a cocoa replanting strategy

In terms of associated non-woody species, banana (plantain and desert) and palm are the most common species in cocoa cultivation in the areas studied. The density of banana trees is abundant in the oldest production area, in Bonon in the Centre-West, compared to the other two areas. The work showed that the main non-timber crops associated with cocoa trees in the AFS are banana and palm trees in the two main cocoa-producing areas (Centre-West and South-West). Considering the Centre-West region the density of banana trees is the highest with 1238.40 individuals per hectare at the young age of the AFS. This strong presence of banana trees in this former of cocoa production represents a cultural innovation implemented in this region with a view to replanting cocoa. Indeed, in this area, facing to the drastic reduction of forests, climatic instability marked mainly by a water deficit and an increase in temperature (Barima et al. 2016; Kouakou et al. 2018), the banana tree is used by the populations as a shade plant for young cocoa trees (Konan et al. 2023). Indeed, the cocoa tree represents an adequats adapted to the shade (Tondoh et al. 2015; Adden 2017) and is not very tolerant of open environments exposed to direct sunlight (Myers et al. 2000; Ruf and Schroth 2004; Snoeck 2010). Cocoa farmers therefore introduce several banana trees so that the large leaves provide shade for the young cocoa trees. In addition, a more humid environment created at the base of the banana plant is beneficial for cocoa trees during the harsh dry season. In addition to its role in the replanting of fallow cocoa trees, the banana tree is an important source of additional income for farmers and an undeniable contribution to the food security of the population (Mopi et al. 2024).

In the South-West, the role of the banana tree in the Centre-West region is partly replaced by the palm tree. The palm tree is indeed planted with the cocoa tree in the corridors of the farm. Here, too, the long palm trees serve as shade for the cocoa tree. Palm is also an important source of additional foreign exchange for planters (Jagoret et al. 2009; Vroh et al. 2019). Additionally, endogenous cocoa replanting strategies in the study sites of central-western and western Côte d'Ivoire seem to be working well and allow some bean production to be maintained in these areas despite the reduction in forest resources.

Persistence of ancestral practices in the forest

In Biankouma, in western Côte d'Ivoire where forest areas are still found, the density of trees in cocoa plantations is decreasing over time. This finding proves the persistence of traditional or ancestral practices in cocoa cultivation, characterized by the gradual elimination of shade trees (Adou et al. 2016). These trees are conserved during land clearing for their economic value and to provide shade for young cocoa trees (Duguma et al. 2001). At regular intervals, often after the main harvest, farmers selectively cut down or prune shade trees to allow the light needed for cocoa trees to grow and develop (Adou et al. 2016). In addition, this observation could suggest a continuity of the actors involved in cocoa cultivation. Indeed, people who cultivate cocoa are moving in search of new forest areas suitable for this cultivation (Dabalen and Paul 2014; Bamba et al. 2018). Thus, populations migrated from eastern Côte d'Ivoire to the west, through the Centre-West and South-West, depending on the availability of the forest (Kouadio and Desdoigts 2012). The old cocoa production areas have in common a species that stores the most carbon in contrast to the new production.

The carbon stock in Soubré farms is significantly higher between 0 and 4 years of age than in the other study areas. This carbon reservoir can be explained by the large storage capacity of palm trees, which are widely present in cocoa plantations in this region.

This observation can be explained by the replanting techniques adopted at Soubré, which differ from those of the other sites. Indeed, in Soubré, we have noticed that cocoa trees are planted 3 or 4 years after the palm tree is grown, so that the palm trees provide shade for the young cocoa trees. The high carbon storage capacity of palm trees can be explained by the presence of individuals with developed leaves, robust rachis, abundant leaflets and a developed heart. These characteristics lead to a significant increase in palm biomass (Jaffré et al. 1983), which results in a high carbon content. Thus, the carbon stock in the cocoa plantation less than 4 years old is naturally high compared to other cocoa production sites. Despite this mixed farming, often with a dominance of palm or rubber trees, the producer still considers that his plantation remains a cocoa plantation. Later, he did not hesitate to remove the plants planted with the cocoa tree in order to obtain a farm where the cocoa tree was dominant.

In Bonon, in the oldest cocoa production area of the sites studied, the cocoa tree is mainly associated with banana, cashew and old palm trees that exist in fallows. The banana tree being a monocarpic species, i.e. it flowers only once during its life and dies after producing the seeds, it is regularly renewed on farms. Its carbon volume therefore genuslly remains fairly constant on the farm. Also, in Bonon, there is a decrease in carbon between 10 and 20 years due to the gradual elimination of palm trees in the plantation. This elimination occurs because at this age, palms reach the same stratum as cocoa trees, resulting in competition for light and nutrients in the soil. The farmer therefore gradually eliminates them for the production of palm wine from the sap of the palm tree, and leaves the young palm plants to develop at the foot of those that have been eliminated. Later, the carbon stocks of cocoa trees and other species present increase with the increase in measurements of intercropping (in this case cashew trees), cocoa trees and palm trees left in the field.

The situation observed in the new western production area seems to be similar to ancestral agroforestry practices in West Africa (Jagoret et al. 2019; Assiri et al. 2009; Ngono et al. 2015). Thus, in this new cocoa production area in western Côte d'Ivoire, woody plants are the main sources of carbon storage. Indeed, in this area, woody plants are deliberately left on the farm to provide shade for the young cocoa trees. These woody plants, often of large diameters, are important carbon reservoirs on the farm (Bouken et al. 2023). Subsequently, the producers eliminate some of the woody plants to allow the cocoa trees to benefit from sufficient solar radiation for optimal production. This agroforestry system, thanks to the in-situ conservation of local woody species, seems to us to be more sustainable since it allows the production of cocoa beans while ensuring the conservation of plant species useful to local populations.

Heterogeneous dynamics of carbon stocks in different compartments and in different sites

The analysis of the total carbon storage dynamics in cocoa agroforestry systems, according to their development stage in three production zones, reveals a heterogeneous evolution. These results contrast with those of Seghieri and Harmand (2019), who observed an increase in carbon storage capacity with the age of the systems. Saj et al. (2017) also highlighted that a significant release of carbon occurs during the establishment of a cocoa plantation, followed by an increase in storage as the cocoa trees and associated trees grow, sometimes reaching levels similar to those of forest systems.

This heterogeneity could result from the complexity of agroforestry systems in Côte d'Ivoire, characterized by the diversity of actors, practices, and adaptation measures in response to constraints. Additionally, the data used for this analysis, which compares plantations of different ages without following the same plots over time, could explain these variations. The producers' origins and household conditions also influence cocoa cultivation practices. For example, Cissé et al. (2016) show that indigenous populations, more familiar with tree species, tend to preserve them, unlike non-indigenous people who prefer to eliminate them in favor of cocoa trees. Thus, cocoa plots of indigenous people are generally more wooded.

Finally, unlike Seghieri and Harmand (2019), this study integrates several compartments (cocoa, woody plants, banana trees, oil palms, crops, litter, and soil), all contributing to carbon storage.

In detail, several local parameters help explain the variation in carbon stock observed in each of the sites. Thus, in the Centre-West of Côte d'Ivoire, the increase in carbon stock during the first ten years of production could be due to the species introduced into the fields through numerous agroforestry extension campaigns in the region and the significant presence of oil palm. Indeed, in response to the advanced deforestation in this area due to cocoa cultivation, NGOs, agricultural cooperations, and support structures distributed numerous seedlings of fast-growing forest species to the populations. These trees, combined with a high density of banana trees and oil palms, create the shade favorable for the development of young cocoa plants. However, after 10 years, when the shading becomes a source of disease for cocoa trees, such as brown rot and the resurgence of mirids. Indeed, excessive shading creates a more humid microclimate, favoring the proliferation of diseases such as cocoa brown rot. (Asitoakor et al. 2024; Kouassi et al. 2024), and mirids, which particularly affect production. (Asitoakor et al. 2024). Knowing this, the populations therefore proceed to eliminate certain trees initially introduced into the farms, but especially the banana tree, which is a heliophilous species that no longer finds optimal development conditions. These practices lead to a drop in carbon stocks, which decrease from 54.940 to 9.028 tC.ha^{-1}. After 20 years, the increase in carbon stock could be attributed to the increase in volume of the residual trees and palms present in the farm, but also to the replanting of bananas in gaps. Indeed, at this stage, certain tree species, both local and exotic, having been introduced and preserved in the cocoa farm, reach notable sizes (Vroh et al. 2015). These mature trees would represent, in some tropical regions, up to 94% of the total carbon stock (Zekeng and Mbolo 2012). Furthermore, with age, diseases becoming more recurrent, especially the Cocoa Swollen Shoot Virus in this area (Kouakou et al. 2012; Zro et al. 2024), many cocoa trees die, creating gaps in the farms. The cocoa farmers fill these gaps with banana trees before replanting cocoa. These banana trees then sequester carbon, increasing the overall stock in the plantations.

In the South-West of Côte d'Ivoire, the decrease in carbon stocks between 0 and 15 years could be attributed to the gradual elimination of certain associated species during the establishment of cocoa plantations. According to Duguma et al. (2001), farmers often establish cocoa plantations after partial forest clearing, while retaining certain economically valuable or moderately shading forest trees for the young cocoa trees. Subsequently, some fruit trees are introduced into the plots. This management explains the presence of many species inventoried in this area during ecological surveys, leading to peaks in carbon stocks. The observed dynamic, with a sawtooth pattern between 15 and more than 30 years, seems to be intrinsically linked to the agroforestry practices of conversion and restructuring specific to the South-West of Côte d'Ivoire.

As for the West of Côte d'Ivoire, particularly in Biankouma, the decrease in carbon stocks between 0 and 15 years is a result of the traditional practice of cocoa farming in forested areas. This practice, documented by Adou Yao et al. (2016) and Barima et al. (2016), involves directly planting the cocoa seeds in the understory and gradually eliminating trees as the young cocoa plants develop. During the period from 15 to 25 years, carbon stocks show a recovery, increasing from 13.844 to 28.596 tC.ha^{-1}, likely due to the normal growth of local and exotic trees retained over time, which reach notable sizes (Vroh et al. 2015). Later (26–30 years and then > 30 years), a reduction in carbon stocks followed by an increase can be explained by natural mortality observed, leading to replanting operations in gaps, as described in the previous production zones of the Centre-West and South-West.

Conclusion

The study conducted in the main cocoa-producing areas in Côte d'Ivoire, specifically the Centre-West (Bonon), South-West (Soubré), and West (Biankouma), allowed for the determination of floristic diversity, quantification of carbon stocks in living biomass, dead matter, and soils, as well as cocoa-based agroforestry systems. The results show that the western region of Côte d'Ivoire has a greater species diversity with 16.22 species per hectare compared to the former production areas of the Centre-West (11.61 species per hectare) and the South-West (12.89 species per hectare). Regarding carbon stocks, four living biomass reservoirs, namely palm (*Elaeis guineensis*), banana (*Musa sp*), trees, and cocoa (*Theobroma cacao*), store the majority (98.07%) of carbon in the Centre-West. In Soubré, the palm tree, with 36.862 tC.ha^{-1}, is the main carbon reservoir associated with cocoa. In the new production area of western Côte d'Ivoire, local trees are the main carbon reservoirs with 11.701 tC.ha^{-1}. Compared to living biomass, dead matter (litter) and soils store less carbon in the three cocoa production areas, with cumulative values of 0.44 tC.ha^{-1} in Bonon, 0.38 tC.ha^{-1} in Soubré, and 0.64 tC.ha^{-1} in Biankouma. The dynamics of total carbon stocks show heterogeneous changes in production areas according to the different states of evolution of agroforestry systems in each area. These changes could be due to the local bio-physical, agronomic, and socio-demographic conditions of each site studied. These results are essential for designing strategies to optimize agroforestry systems in production areas. They also provide a basis for the development of clean development mechanisms and support the implementation of the process to reduce emissions related to deforestation and forest degradation in developing countries (REDD+) at the national and regional levels. Furthermore, the data on carbon storage dynamics from this study could become a key reference for creating carbon certification scenarios, thus facilitating the emergence of a voluntary carbon market.

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Author contributions All authors whose names appear on the submission made substantial contributions to the conception of the work, revised it critically for important intellectual content, approved the version to be published; and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Data availability I would like to inform you that, for the time being, the data used in this article are not yet available online. However, if their provision becomes necessary for the evaluation or publication of the article, I am at your disposal to prepare and provide them to you as soon as possible.

Declarations

Competing interest The authors declare no competing interests.

Appendix

List of plant species inventoried in the different cocoa production areas.

No	Species	Families	Chorology	Cocoa production areas		
				Central-West	South-West	West
1	*Acacia mangium* Wild	Mimosaceae	i	×	×	
2	*Adansonia digitata* L	Bombacaceae	SZ	×		
3	*Aegle marmelos* L	Rutaceae	i			×
4	*Afzelia africana* Sm	Fabaceae	GC-SZ			×
5	*Afzelia bella* Harms var. gracilior Keay	Caesalpiniaceae	GCW		×	×
6	*Albizia adianthifolia* (Schumach.) W. Wight	Fabaceae	GC	×	×	×
7	*Albizia ferruginea* (Guill. & Perr.) Benth	Fabaceae	GC-SZ		×	×
8	*Albizia lebbeck* (Linn.) Benth	Fabaceae	GC-SZ	×		×
9	*Albizia zygia* (DC.) J.F. Macbr	Fabaceae	GC-SZ	×	×	×
10	*Alchornea cordifolia* (Schum. & Thonn.) Müll.Arg	Euphorbiaceae	GC-SZ		×	×
11	*Allophylus* africanus P. Beauv	Sapindaceae	GC			×
12	*Alstonia boonei* De Wild	Apocynaceae	GC		×	×
13	*Amphimas pterocarpoides* Harms	Fabaceae	GC		×	×
14	*Anacardium occidentale* Linn	Anacardiaceae	i	×	×	×
15	*Annona muricata* Linn	Annonaceae	GC	×	×	
16	*Annona senegalensis* Pers	Annonaceae	SZ			×
17	*Anthocleista djalonensis* A. Chev	Gentianaceae	GC-SZ			×
18	*Anthocleista vogelii* Planch	Loganiaceae	GC			×
19	*Anthonotha crassifolia* (Baill.) J. Léonard	Fabaceae	GC			×
20	*Anthonotha fragrans* (Baker f.) Exell & Hillc	Fabaceae	GC			×
21	*Anthonotha macrophylla* P. Beauv	Caesalpiniaceae	GC		×	×
22	*Antiaris toxicaria* Lesch	Moraceae	GC-SZ	×	×	×
23	*Artocarpus altilis* Leaves	Moraceae	i		×	×
24	*Artocarpus heterophylla* Lam	Moraceae	i			×
25	*Azadirachta indica* A. Juss	Melinaceae	i	×	×	
26	*Baphia bancoensis* Aubrév	Fabaceae	GCi		×	
27	*Baphia nitida* Lodd	Fabaceae	GC	×	×	×
28	*Baphia pubescens* Hook.f	Fabaceae	GC			×
29	*Bixa orellana* Linn	Bixaceae	i	×		
30	*Blighia sapida* K. D. Koenig	Sapindaceae	GC-SZ	×	×	×
31	*Blighia unijugata* Baker	Sapindaceae	GC	×	×	×
32	*Blighia welwitschii* (Hiern) Radlk	Sapindaceae	GC			×
33	*Bombax buenopozense* P. Beauv	Bombacaceae	GC	×	×	×
34	*Bridelia micrantha* (Hochst.) Baill	Phyllanthaceae	GC		×	×
35	*Bridelia speciosa* Müll. Arg	Euphorbiaceae	SZ			×
36	*Canarium schweinfurthii* Engl	Burseraceae	GC-SZ		×	
37	*Carapa procera* DC. De Wilde	Meliaceae	GC-SZ		×	×
38	*Carica papaya* L	Caricaceae	GC	×	×	×
39	*Cassia siamea* Lam	Caesalpiniaceae	i		×	
40	*Cedrela odorata* L	Meliaceae	i	×	×	×
41	*Ceiba pentandra* (L.) Gaertn	Bombacaceae	GC-SZ	×	×	×
42	*Celtis adolfi-fridericii* Engl	Ulmaceae	GC			×
43	*Celtis milbraedii* Engl	Ulmaceae	GC	×	×	×

No	Species	Families	Chorology	Cocoa production areas		
				Central-West	South-West	West
44	*Celtis zenkeri* EngI	Ulmaceae	GC			×
45	*Chrysophyllum cainito* L	Sapotaceae	i		×	
46	*Chrysophyllum taïense* Aubrév. & Pellegr	Sapotaceae	GCWS2		×	
47	*Citrus limon* L. Burm. F	Rutaceae	i	×		×
48	*Citrus maxima* (Burm.) Merr	Rutaceae	i	×	×	×
49	*Citrus reticulata* Blanco	Rutaceae	i	×	×	×
50	*Citrus sinensis* (L.) Osbeck	Rutaceae	i	×	×	×
51	*Cleistopholis patens* (Benth.) Engl. & Diels	Annonaceae	GC		×	×
52	*Cocos nucifera* L	Arecaceae	i	×	×	
53	*Coffea arabica* L	Rubiaceae	i	×	×	×
54	*Cola acuminata* (P. Beauv.) Schott & Endl	Malvaceae	GC	×	×	
55	*Cola cordifolia* (Cav.) R. Br	Malvaceae	GC-SZ	×		×
56	*Cola gigantea* A. Chev	Sterculiaceae	GC-SZ			×
57	*Cola heterophylla* (P. Beauv.) Schott & Endl	Sterculiaceae	GC			×
58	*Cola nitida* (Vent.) Schott & Endl	Malvaceae	GC	×	×	×
59	*Cordia platythyrsa* Bak	Boraginaceae	GC		×	×
60	*Cordia senegalensis* Juss	Boraginaceae	GC			×
61	*Crescentia cujete* L	Bignoniaceae	i	×		
62	*Cussonia bancoensis* Aubrév. & Pellegr	Araliaceae	GC			×
63	*Dacryodes klaineana* (Pierre) H.J. Lam,	Burseraceae	GC			×
64	*Deinbollia pinnata* (Poir.) Schumach. & Thonn	Sapindaceae	GC			×
65	*Dialium aubrevillei* Pellegr	Fabaceae	GCW			×
66	*Dialium dinklagei* Harms	Caesalpiniaceae	GC		×	×
67	*Dichrostachys cinerea* (Linn.) Wight & Arn. subsp. Cinerea	Mimosaceae	GC-SZ			×
68	*Diospyros canaliculata* De Wild	Ebenaceae	GC		×	×
69	*Diospyros heudelotii* Hiern	Ebenaceae	GCW			×
70	*Diospyros mespiIiformis* Hochst. ex A. DC	Ebenaceae	GC-SZ			×
71	*Diospyros viridicans* Hiern	Ebenaceae	GC			×
72	*Discoglypremna caloneura* (Pax) Prain	Euphorbiaceae	GC		×	×
73	*Distemonanthus benthamianus* Benth	Fabaceae	GC		×	×
74	*Doryopteris kirkii (Hook.)* Alston	Pteridaceae	GC			×
75	*Dracaena arborea (Willd.)* Link	Agavaceae	GC			×
76	*Drypetes ivorensis* Hutch. & Dalz	Euphorbiaceae	GC			×
77	*Elaeis guineensis* Jacq	Arecaceae	GC	×	×	×
78	*Entandrophragma angolense* (Welw.) C. DC	Meliaceae	GC	×	×	×
79	*Entandrophragma cylindricum* (Sprague) Sprague	Meliaceae	GC			×
80	*Entandrophragma utile* (Dawe & Sprague) Sprague	Meliaceae	GC		×	
81	*Erythrina senegalensis* DC	Fabaceae	GC-SZ		×	×
82	*Erythrina vogelii* Hook.f	Fabaceae	GC			×
83	*Erythrophleum ivorense* A. Chev	Caesalpiniaceae	GC			×
84	*Erythrophleum suaveolens* (Guill. & Perr)	Caesalpiniaceae	GC-SZ		×	×

No	Species	Families	Chorology	Cocoa production areas		
				Central-West	South-West	West
85	*Ficus elastica* Roxb	Moraceae	i	×		
86	*Ficus exasperata* Vahl	Moraceae	GC-SZ	×	×	×
87	*Ficus kamerunensis* Warb. ex Mildbr. & Burret	Moraceae	GC	×		
88	*Ficus lutea* Vahl	Moraceae	GC		×	×
89	*Ficus mucuso* Ficalho	Moraceae	GC		×	×
90	*Ficus ottoniifolia* (Miq.) Miq	Moraceae	GC			×
91	*Ficus sur* Forsk	Moraceae	GC-SZ	×	×	×
92	*Ficus thonningii* Blume	Moraceae	GC-SZ	×		×
93	*Ficus trichopoda* Baker	Moraceae	GC-SZ		×	×
94	*Ficus umbellata* Vahl	Moraceae	GC		×	×
95	*Flueggea virosa* (Willd.) Voigt	Commelinaceae	GC-SZ			×
96	*Funtumia africana* (Benth.) Stapf	Apocynaceae	GC		×	×
97	*Funtumia elastica* (Preuss) Stapf	Apocynaceae	GC		×	
98	*Garcinia kola* Heckel	Clusiaceae	GC	×		×
99	*Gliricidia sepium* (Jacq.) Walp	Fabaceae	i		×	×
100	*Glyphaea brevis* (Spreng.) Monach	Tiliaceae	GC			×
101	*Gmelina arborea* Roxb	Verbenaceae	i	×	×	
102	*Griffonia simplicifolia* (Vahl ex DC.) Baill	Caesalpiniaceae	GC		×	×
103	*Guarea cedrata* (A. Chev.) Peliegr	Meliaceae	GC			×
104	*Harungana madagascariensis* Lam. ex Poir	Hypericaceae	GC		×	×
105	*Hevea brasiliensis* (A. Juss.) Müll. Arg	Euphorbiaceae	i	×	×	×
106	*Holarrhena floribunda* (G. Don) Dur. & Schinz	Apocynaceae	GC-SZ	×	×	×
107	*Irvingia gabonensis* (Aubry-Lecomte ex O'Rorke) Baill	Irvingiaceae	GC		×	×
108	*Jatropha curcas* L	Euphorbiaceae	GC-SZ	×		
109	*Khaya anthotheca* (Welw.) C.DC	Meliaceae	GC		×	
110	*Khaya grandifoliola* C. DC	Meliaceae	GC		×	×
111	*Khaya senegalensis* (Desv.) A. Juss	Meliaceae	SZ			×
112	*Kigelia africana* (Lam.) Benth	Bignoniaceae	GC-SZ	×		×
113	*Laccosperma secundiflorum*(P.Beauv.)	Arecaceae	GC			×
114	*Lannea nigritana* (Sc. Elliot) Keay var. nigritana	Anacardiaceae	GC-SZ			×
115	*Lannea welwitschii* (Hiern) Engl	Anacardiaceae	GC		×	
116	*Lecaniodiscus cupanioides* Planch	Sapindaceae	GC		×	×
117	*Lonchocarpus sericeus* (Poir.) DC	Fabaceae	GC-SZ		×	
118	*Lophira lanceolata* Keay	Ochnaceae	SZ			×
119	*Macaranga hurifolia* Beille	Euphorbiaceae	GC			×
120	*Mangifera indica* L	Anacardiaceae	i	×	×	×
121	*Mansonia altissima* (A. Chev.) A. Chev var. altissima	Malvaceae	GC			×
122	*Mareya micrantha* (Benth.) Müll. Arg	Euphorbiaceae	GC		×	×
123	*Margaritaria discoidea* (Baill.) G.L. Webster	Euphorbiaceae	GC-SZ			×
124	*Milicia excelsa* (Welw.) C. C. Berg	Moraceae	GC	×	×	×

No	Species	Families	Chorology	Cocoa production areas		
				Central-West	South-West	West
125	*Milicia regia* (A.Chev.) C.C.Berg	Moraceae	GCW		×	×
126	*Millettia lane-poolei* Dunn	Fabaceae	GCW			×
127	*Millettia rhodontha* Baill	Fabaceae	GCW	×	×	×
128	*Millettia takou* Lorougnon	Fabaceae	GCi			×
129	*Millettia zechiana* Harms	Fabaceae	GC	×	×	×
130	*Mitragyna ciliata* Aubrév. & Pellegr	Rubiaceae	GC			×
131	*Monodora brevipes* Benth	Annonaceae	GC			×
132	*Monodora myristica* (Gaertn.) Dunal	Annonaceae	GC		×	
133	*Monodora tenuifolia* Benth	Annonaceae	GC			×
134	*Morinda longiflora* G. Don	Rubiaceae	GC-SZ		×	
135	*Morinda lucida* Benth	Rubiaceae	GC-SZ	×	×	×
136	*Moringa oleifera* Lam	Rubiaceae	GC-SZ		×	×
137	*Morus mesozygia* Stapf ex A. Chev	Moraceae	GC	×	×	×
138	*Musa paradisiaca* L	Musaceae	i	×	×	×
139	*Musanga cecropioides* R. Br	Cecropiaceae	GC		×	×
140	*Myrianthus arboreus* P. Beauv	Cecropiaceae	GC		×	×
141	*Myrianthus lïbericus* Rendle	Cecropiaceae	GC			×
142	*Nauclea diderrichii* (De Wild. & T. Durand) Merr	Rubiaceae	GC		×	×
143	*Nesogordonia papaverifera* (A. Chev.) R. Capuron	Sterculiaceae	GC	×	×	×
144	*Neuropeltis acuminata* (P. Beauv.) Benth	Convolvulaceae	GC			×
145	*Newbouldia laevis* (P. Beauv.) Seem. ex-Bureau	Bignoniaceae	GC	×	×	×
146	*Olax subscorpioidea* Oliv	Olacaceae	GC-SZ			×
147	*Parinari curatellifolia* Benth	Chrysobalanaceae	SZ			×
148	*Parkia bicolor* (Jacq.) R.Br. Ex G.Don	Mimosaceae	SZ	×	×	×
149	*Parkia biglobosa* (Jacq.) Benth	Mimosaceae	SZ		×	
150	*Pericopsis laxiflora (Benth) Meeuv*	Fabaceae	GC-SZ			×
151	*Persea americana* Mill	Lauraceae	i	×	×	×
152	*Piptadeniastrum africanum* (Hook.f.) Brenan B	Mimosaceae	GC		×	
153	*Pouteria alnifolia* (Bak.) Roberty	Sapotaceae	GC-SZ			×
154	*Pouteria altissima* (A. Chev.) Baehni	Sapotaceae	GC	×		
155	*Pouteria aningeri* Baehni	Sapotaceae	GC		×	×
156	*Pseudospondias microcarpa* (A. Rich.) Engl	Anacardiaceae	GC-SZ			×
157	*Psidium guajava* L	Myrtaceae	i	×	×	×
158	*Psychotria psychotrioides* (DC.) Roberty	Rubiaceae	GC-SZ			×
159	*Pterocarpus erinaceus* Poilr	Fabaceae	SZ			×
160	*Pterocarpus santalinoides* DC	Fabaceae	GC-SZ		×	
161	*Pterygota macrocarpa* K. Schum	Malvaceae	GC			×
162	*Pycnanthus angolensis* (Welw.) Warb	Myristicaceae	GC		×	×
163	*Raphia hookeri* G. Mann & H. Wendl	Arecaceae	GC		×	×
164	*Rauvolfia vomitoria* Afzel	Apocynaceae	GC-SZ	×	×	×
165	*Ricinodendron heudelotii* (Baill.) Pierre ex Pax	Euphorbiaceae	GC	×	×	×

No	Species	Families	Chorology	Cocoa production areas		
				Central-West	South-West	West
166	*Rothmannia longiflora* Salisb	Rubiaceae	GC		×	×
167	*Rothmannia whitfieldii* (Lindl.) Dandy	Rubiaceae	GC		×	×
168	*Samanea dinklagei* (Harms) Keay	Fabaceae	GCW		×	
169	*Senna siamea* (Lam.) H.S.Irwin & Barneby	Fabaceae	i	×		
170	*Solanum erythracanthum* Bojer ex Dunal	Solanaceae	NEO	×		
171	*Solanum rugosum* Dun	Solanaceae	GC	×	×	×
172	*Spathodea campanulata* P. Beauv	Bignoniaceae	GC	×	×	×
173	*Spondias mombin* Linn	Anacardiaceae	GC-SZ		×	×
174	*Sterculia oblonga* Mast	Sterculiaceae	GC	×	×	×
175	*Sterculia rhinopetala* K. Schum	Sterculiaceae	GC		×	
176	*Sterculia setigera* Del	Malvaceae	SZ			×
177	*Sterculia tragacantha* Lindl	Sterculiaceae	GC-SZ		×	×
178	*Strombosia pustulata* Oliv. var. lucida (J. Léonard) Vill	Olacaceae	GC			×
179	*Tectona grandis* L.f	Verbenaceae	i	×	×	
180	*Terminalia ivorensis* A. Chev	Combretaceae	GC		×	×
181	*Terminalia laxiflora* EngI	Combretaceae	SZ			×
182	*Terminalia macroptera* Guill. & Perr	Combretaceae	SZ			×
183	*Terminalia mentaly* H. Perrier	Combretaceae	i		×	
184	*Terminalia scimperiana* Hochst	Combretaceae	SZ			×
185	*Terminalia superba* EngI. & Diels	Combretaceae	GC	×	×	×
186	*Tetrorchidium didymostemon* (Baill.) Pax & K. Hoffm	Euphorbiaceae	GC			×
187	*Theobroma cacao* L	Sterculiaceae	i	×	×	×
188	*Trema guineensis* (Schum. & Thonn.) Ficalho	Ulmaceae	GC-SZ	×	×	×
189	*Trema orientalis* (L.) Blume	Ulmaceae	GC-SZ	×		
190	*Trichilia monadelpha* (Thonn.) J.De Wild	Meliaceae	GC		×	×
191	*Trichilia prieuriana* A.Juss	Meliaceae	GC			×
192	*Trichilia tessmannii* Harms	Meliaceae	GC			×
193	*Triplochiton scleroxylon* K. Schum	Sterculiaceae	GC	×	×	×
194	*Vernonia amygdalina* Delile	Asteraceae	GC-SZ	×		×
195	*Vernonia colorata* (Willd.) Drake	Asteraceae	GC-SZ	×	×	
196	*Vitex doniana* Sweet	Verbenaceae	GC-SZ			×
197	*Vitex fosteri* Wright	Verbenaceae	GC		×	
198	*Vitex rivularis* Gürke	Verbenaceae	GC		×	
199	*Xylopia aethiopica* (Dunal) A. Rich	Annonaceae	GC-SZ	×	×	×
200	*Zanthoxylum gilletii* (De Wild.) P. G. Waterman	Rutaceae	GC		×	
201	*Zanthoxylum leprieurii* Guill. & Perr	Rutaceae	GC-SZ		×	
202	*Zanthoxylum Zanthoxyloides* (Lam.) Zepern. & Timler	Rutaceae	GC-SZ	×	×	×

GCi species endemic to Côte d'Ivoire, *GCW* species endemic to West Africa, *GC* species of the dense humid forest of the Guineo-Congolian domain, *SZ* species belonging to the Sudanian-Zambezian region savannas and open forests, *GC-SZ* species common to the Guineo-Congolian and Sudanian-Zambezian regions, *i* introduced or cultivated species.

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