INNSPUB

International Journal of Biosciences | IJB |
ISSN: 2220-6655 (Print); 2222-5234 (Online)
Website: https://www.innspub.net
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Vol. 28, Issue: 1, p. 44-55, 2026

RESEARCH PAPER OPEN ACCESS

Evaluation of the impact of floristic diversity on the productivity of cocoa-based agroforestry systems in the new cocoa production area: The case of the Biankouma department (Western Côte d'Ivoire)

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Key words: Agroforestry systems, Floristic diversity, Cocoa yield, Côte d'Ivoire

Received Date: December 22, 2025 **Published Date:** January 06, 2026

DOI: https://dx.doi.org/10.12692/ijb/28.1.44-55

ABSTRACT

This study aims to assess the impact of associated species on the productivity of cocoa-based agroforestry systems in the department of Biankouma. To achieve this, the plot method combined with the itinerant survey method was used in different plantations grouped into four age classes (0 to 5 years, 6 to 20 years, 21 to 35 years, and 36 years and older). The analyses carried out identified 161 species divided into 124 genera and 48 families. Plantations aged 0 to 5 years show high floristic diversity with high Shannon and Evenness Indices. Plantations aged 6 to 20 years and 21 to 35 years recorded the lowest floristic diversity values with high yields. The results also showed that species density is high in plantations aged 0 to 5 years and those aged 36 years and over with low yields. Furthermore, analysis of the impacts of floristic diversity showed that yield increases significantly with the density of cocoa trees, the heights and circumferences of cocoa trees and associated plant species. However, it decreases with the age of the cocoa trees (0 to 5 years and over 30 years), the diversity and high density of associated species. Targeted management of associated species, optimal density, and selection of useful species therefore appear essential to improve productivity in cocoa-based agroforestry systems.

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INTRODUCTION

Cocoa (*Theobroma cacao* L.) is one of the main export crops in tropical countries. It occupies a strategic place in the agricultural economies of West Africa, particularly in Côte d'Ivoire, the world's leading producer of cocoa beans (FAOSTAT, 2023). This crop is an essential source of income for millions of smallholders, while raising sustainability concerns such as deforestation, soil depletion, and biodiversity loss (Ruf and Schroth, 2004).

Faced with these challenges, agroforestry is gradually establishing itself as a credible and sustainable alternative to intensive monoculture systems. This production method is based on integrating trees into agricultural systems, offering both ecological benefits-soil conservation, climate regulation, habitat for wildlife—and economic advantages through product diversification (Nair, 1993; Tscharntke *et al.*, 2011). Applied to cocoa farming, agroforestry helps maintain tree cover, contributing to mitigating the effects of climate change, improving the resilience of plantations, and partially restoring the ecological functions of forests (Gockowski and Sonwa, 2011).

A central element of these agroforestry systems is floristic diversity, i.e., the variety of plant species present in cocoa plots. This diversity can significantly influence cocoa productivity through various mechanisms: improving soil fertility, regulating humidity, reducing disease pressure, and creating a microclimate favorable to cocoa tree development (Clough *et al.*, 2011; Asare *et al.*, 2014). However, the effects of this diversity are not always positive and can vary depending on the type and density of associated species, canopy management, and local agroecological characteristics (Jagoret *et al.,* 2014).

In this context, the Biankouma region in western Côte d'Ivoire stands out for its relatively diverse agroforestry landscapes. However, recent agricultural dynamics, driven by intensification of production, tend to homogenize cropping systems, sometimes to the detriment of biodiversity. It is therefore crucial to better understand how the diversity of species associated with cocoa trees in these agroforestry contexts influences the productivity of cocoa tree. Thus, the overall objective of this study is to assess the impact of associated species on the productivity of cocoa-based agroforestry systems in the department of Biankouma. Specifically, this will involve (1) determining the floristic diversity of cocoa plantations in the department of Biankouma; (2) evaluating the production of cocoa-based agroforestry systems in the department of Biankouma; (3) establishing the relationship between floristic diversity and the productivity of cocoa-based agroforestry systems in the department of Biankouma.

MATERIALS AND METHODS

Presentation of the study area

This study was conducted in the Biankouma Department, located between 7°21′00″ and 8°06′00″ north latitude and 7°03′00″ and 8°15′00″ west longitude. This department in western Côte d'Ivoire is 233 km from Daloa and 46 km from the city of Man, which is also the regional capital. It is located in a transition zone between the rainforest and mesophilic sectors. It features savanna and forest formations with mixed formations intermingling (Guillaumet and Adjanohoun, 1971). The population living in this department is mainly engaged in agriculture. In fact, these populations are mainly involved in the cultivation of coffee, rice, cassava, and oil palms (N'Guessan, 2020). More recently, they have become interested in cocoa cultivation (Koua *et al.*, 2020).

The present study was conducted in six (06) villages in the Biankouma Department, namely Bounta, Touoba, Moroulé, Somba, Chocopleu, and Klapleu (Fig. 1).

Selection of sampling sites

The choice of this area was guided by the fact that the Biankouma Department is the new frontier of cocoa production in terms of production dynamics and cocoa farmer migration (Koua *et al.*, 2020). The villages and producers were chosen based on agroforestry practices, the availability of farmers, and the age of the plantations. Five (05) age classes were selected.

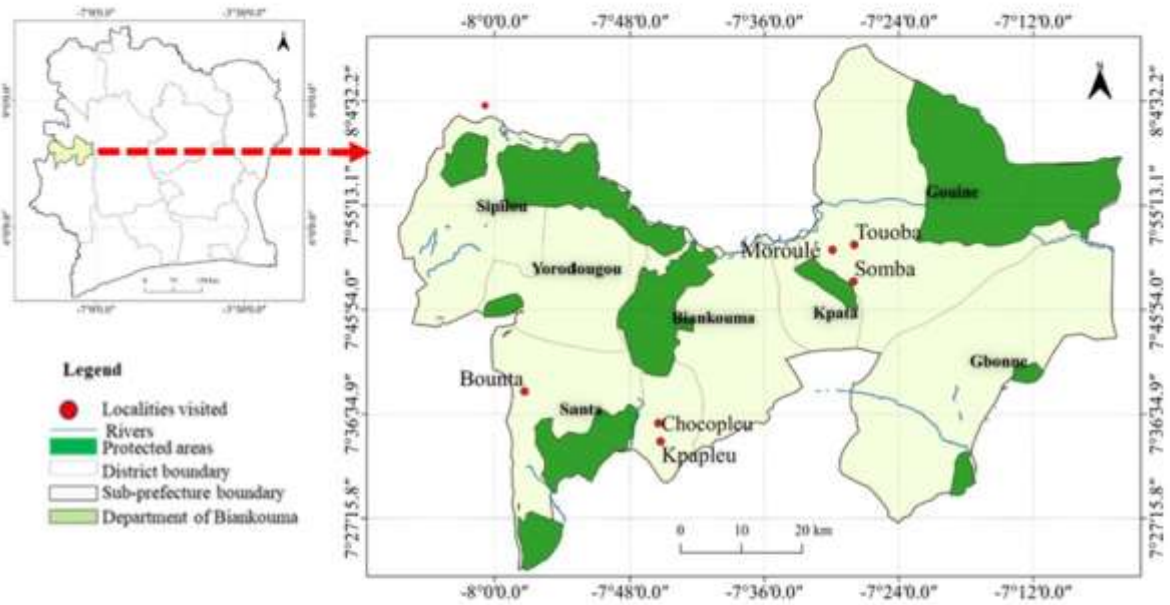


Fig. 1. Geographic location of the Biankouma department (Lokpolé, 2024)

These are plantations aged between 0 and 5 years; plantations aged between 6 and 20 years; those aged between 21 and 35 years; and those aged 36 years and over. The different age classes were determined using data from surveys conducted by Konan (2025) as part of the Cocoa 4 future project.

Data collection

For data collection, inventory methods associated with socio-economic surveys were carried out in the selected cocoa plantations.

Flora inventories

For the floristic inventories, plots covering an area of 0.5 ha (100 m × 50 m) were set up to record all non-woody species (banana trees and palm trees) and woody species other than crops (trees and shrubs) with a diameter greater than or equal to 8 cm (Felfili *et al.*, 2004).

For each individual identified, the circumference was measured at a height of 1.30 m above the ground for woody species and palms. Within each plot, sub-plots measuring 20 m × 20 m, or 400 m² (Fig. 2), were established using a GPS and a decameter (Zoghaib, 2021) in order to count and record cocoa trees and all associated crops and monitor the productivity of cocoa plantations. In addition, dendrometric measurements were taken in the 400 m² sub-plots. The diameter of the cocoa trees was measured 30 cm above the ground using a caliper. The height of the cocoa trees was also measured using a graduated rod. For coffee trees, the diameter was measured 15 cm above the ground, while that of cashew trees was measured 1.30 m above the ground (Noiha *et al.*, 2023). A total of 40 plots and 40 sub-plots were set up across all plantations in the Biankouma department. Subsequently, itinerant surveys were carried out in the plantation over an area of one hectare in order to identify all woody and non-woody species that had not been recorded in the plots.

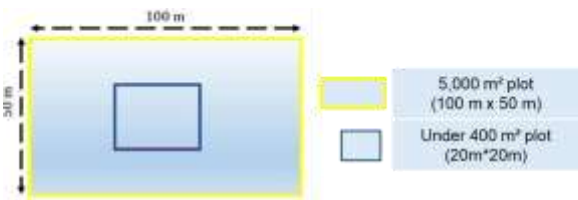


Fig. 2. Experimental data collection system

Monitoring production in cocoa plantations

Ten representative cocoa trees were randomly selected and numbered from 1 to 10 for production monitoring. Production monitoring in the cocoa plantations of the Biankouma Department consisted of biweekly visits to the 400 m² subplots to harvest ripe pods from each selected cocoa tree. The number of visits per plot, the number of the cocoa tree, the weight of the pods harvested, and the fresh weight of the beans per tree after shelling were then recorded on a monitoring sheet. The average number of pods per tree (Nbcab) is a variable that can be quantified by counting the pods. Production was monitored throughout the small harvest period, which, according to, runs from April to September. Production data for the last five (05) years was provided by one of the most significant cooperatives in the Department of Biankouma, namely CAMOBIAN COOP CA. This data specifies the production of producers for each year, as well as the production of large and small cocoa harvests in Côte d'Ivoire.

Determination of the floristic diversity of agroforestry systems

Floristic composition

Floristic richness, which corresponds to the number of species in a community or stand (Ramade, 1994), was taken into account. The number of families and species present in each plot was determined, as well as the number of individuals of each species.

The conservation status of plant species in cocoa-based agroforestry systems in the Department of Biankouma was determined according to the classification of the International Union for Conservation of Nature (IUCN, 2024).

Floristic diversity indices

The diversity indices considered in this study are species richness, the Shannon-Weaver diversity index (H'), Pielou's equitability (E), and the Simpson diversity index (D'). The Shannon-Weaver index (Shannon and Weaver, 1948) measures the potential for interaction between the species that make up a community. This index takes into account the number of species present and the distribution of individuals within these species. It is obtained from the following mathematical relationship:

$$H' = -\sum\left(\frac{ni}{N}\right) Log2\left(\frac{ni}{N}\right) \quad (1)$$

Where ni is the number of individuals of species *i* and N corresponds to the total number of individuals of all species.

The Pielou equitability index (Piélou, 1966) expresses the regularity and equitable distribution of species within a community. It is obtained using the following formula:

$$E = \frac{H'}{Log2\ S} \quad (2)$$

Where E is the Piélou equitability index, S is the total number of species recorded, and H' represents the Shannon index. This index, which varies from 0 to 1, is at its maximum when species have identical abundances in the population and at its minimum when a single species dominates the entire population.

The Simpson diversity index (D') is the probability that two (02) individuals selected at random will be of different species. It is represented by the reciprocal of the Simpson index (D'). The Simpson diversity index (D') is calculated using the following formula:

$$D' = 1 - \sum\left(\frac{ni}{N}\right)^2 \quad (3)$$

Where ni is the number of individuals of species *i* and N is the total number of individuals of all species. When the value of the Simpson index tends towards 1, diversity is at its maximum; when it tends towards 0, diversity is at its minimum.

Structural diversity analysis

Structural density took into account the height, circumference, and density of the trees. In terms of the height of the cacao trees and associated trees, an analysis of variance was performed to determine the average.

The density of a species (*D*) is the number of individuals of that species per hectare. Species density was estimated using the formula developed by Kent and Coker (1992). It is represented by the formula below:

$$D = \frac{n}{S} \quad (4)$$

D is the density (individuals/ha); n is the number of stems present on the surface area considered, and S is the surface area considered in hectares.

Overall cocoa yield

The equation for the marketable cocoa yield of a cocoa plantation (kg ha^{-1}) can be formulated as follows:

$$Rdtcm = (\text{Nbcab x Ptf x Ct}) \text{ x Denscac} \quad (5)$$

Nbcab: average number of pods per cocoa tree, Ptf: average weight of fresh beans per pod (kg), Ct: conversion coefficient between fresh bean weight and marketable cocoa weight, Denscac: number of cocoa trees ha^{-1} .

The overall cocoa yield is the sum of the yield from the first harvest and the yield from the second harvest:

$$\text{Rendement global du cacao} = \text{Rdt petite traite} + \text{Rdt grande traite} \quad (6)$$

Following the work by Asare *et al.* (2017), an annual ratio was established between the main milking and the minor milking. The yields from large-scale milking were divided by those from small-scale milking to obtain a coefficient with a five-year average of 2.4. Thus, to estimate the yield from large-scale milking, the yield from small-scale milking is multiplied by this coefficient of 2.4 (Asare *et al.*, 2017).

Statistical analyses

Descriptive statistics were used to summarize the main characteristics of the data, such as frequencies, means, medians, and standard deviations. This provides an overview of the farmers' responses and the results obtained.

Principal component analysis (PCA) and a correlation test were performed to determine the floristic diversity variables that influence yield. The Tukey test was used to compare the means between these variables and the age classes. The significance level was set at 5%.

RESULTS AND DISCUSSION

Floristic composition of cocoa plantations

The floristic inventory carried out in the various plantations identified 161 species divided into 48 families and 124 genera. The family with the highest number of species is Fabaceae, with 23 species, or 14%. This family is followed by Moraceae (10%), Euphorbiaceae (6%), Meliaceae (6%), Rubiaceae (5%) and Sterculiaceae (5%), which comprise 15, 10, 10, 5 and 5 species respectively (Fig. 3). Taking into account the age of the plantations, those between 6 and 20 years old are the richest in terms of species (89 species). They are followed by plantations between 0 and 5 years old with a total of 77 species. However, plantations aged 36 years and over are the least species-rich (Fig. 4).

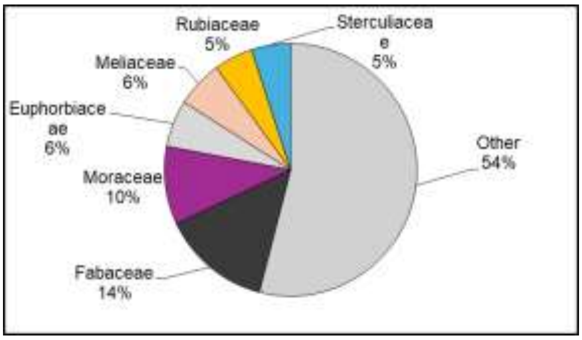


Fig. 3. Botanical families most represented in all plantations

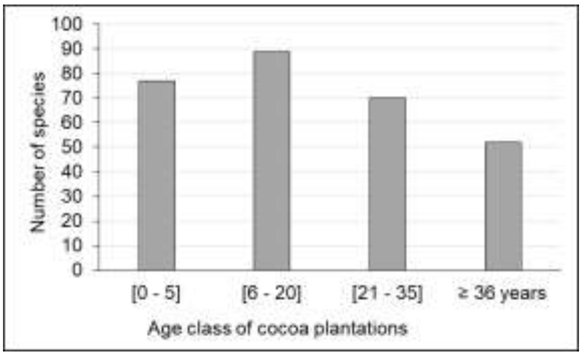


Fig. 4. Distribution of the number of species according to the age of the cocoa plantations

Furthermore, the results showed that the largest number of associated species is of minor concern in the different plantation classes, with rates above 60% (Fig. 5). These plantations are also home to many threatened species, including vulnerable and endangered species.

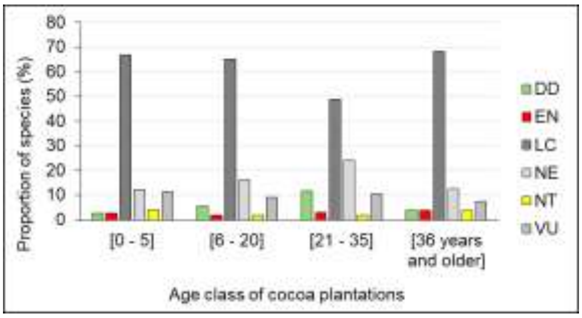


Fig. 5. Distribution of associated species according to their conservation status

Vulnerable species are mainly represented in plantations aged 0 to 5 years and those aged 21 to 35 years, with respective rates of 11.49% and 10.59%. They are found in plantations aged 6 to 20 years (9.3%) and those aged 36 years and over (7.59%). Among the vulnerable species found in these environments are *Cordia platythyrsa Bak*, *Terminalia ivorensis* A. Chev, *Entandrophragma angolense* C. DC.*, and Nesogordonia papaverifera* (K. Schum. Capuron ex R. Germ). In addition, two species were considered endangered, namely *Coffea arabica* L. and *Pterocarpus erinaceus* Poir. The large number of threatened species within the various plantations demonstrates the contribution of cocoa-based agroforestry systems to the preservation of species of interest. Our results corroborate those of Kouakou *et al.* (2017). In their work, these authors showed that farmers domesticate most of the species that are endangered, rare, or threatened in their plantations.

Specific diversity of species associated with cocoa trees

The analysis of variance showed that, in terms of species richness, there is a significant difference between the age classes of the plantations ($p<0.05$) (Table 1). Indeed, species richness within the different plantations showed that species richness is greater in plantations between 6 and 20 years old, with a value of 91 species. These are followed by plantations aged 0 to 5 years, 21 to 35 years, and those aged 36 years and over.

Table 1. Floristic diversity indices of associated plant species

Diversity indices	Age classes			
	[0 - 5	[6 - 20	[21 - 35	[36 years and older[
Specific wealth	78^{a}	91^{b}	70^{a}	52^{ab}
Shannon index (H')	2.79^{a}	2.57^{a}	1.30^{a}	1.66^{a}
Equity index (E)	0.64^{a}	0.57^{a}	0.31^{a}	0.42^{a}
Simpson index (D')	0.81^{a}	0.73^{a}	0.39^{a}	0.55^{a}

In the same row, values with the same letters are statistically identical at the 5% level.

With regard to diversity indices, no significant differences were observed ($p>0.05$) (Table 1). In fact, all diversity index values are statistically identical. However, these diversity indices (Shannon, Pielou's Equitability, and Simpson) decrease with the age of the plantation. In terms of the Shannon index, the 0-5 age class has a high diversity value of 2.79, followed by plantations aged 6-20 (2.57), plantations aged 21 to 35 and those aged 36 and over have low diversity values of 1.30 and 1.66, respectively. With regard to the evenness and Simpson indices, plantations aged 0 to 5 years recorded the highest values for the evenness and Simpson indices, which were 0.64 and 0.81, respectively. This is followed by plantations aged 6 to 20 years, with values of 0.57 and 0.73 for the evenness and Simpson indices, respectively. The lowest values for these indices were obtained in plantations aged 21 to 35 years and 36 years and older (Table 1). This variation in the Shannon, Piélou's Evenness, and Simpson indices with the age of the plantations could be explained by the fact that when cocoa plantations are established, farmers associate more species with young cocoa trees to provide shade for the young cocoa plants. Shade is essential for the proper development of young cocoa trees, and this diversity decreases with the age of the plantations. Our results corroborate those of Kpangui *et al.* (2015) and Zanh *et al.* (2019), Anthelme *et al.* (2024).

These authors have shown that in the main cocoa-producing areas of Côte d'Ivoire, farmers associate a wide variety of species with cocoa trees for their multiple benefits, namely shade and many other uses. According to these authors, when establishing plantations, farmers opt for a higher density of associated species, which they gradually eliminate as the plantations come into production.

Structural diversity s of plant species associated with cocoa trees

The analysis of variance showed that there is a significant difference between the average circumference values of cocoa trees and associated trees according to the age of the plantations ($p<0.05$) (Table 2). The circumference and density values of cocoa trees and associated species are statistically different. In terms of cocoa trees, the average circumferences vary according to their age. The average circumference of cocoa trees is 23.81 cm for plantations aged 0 to 5 years, increasing to 27.48 cm for those aged 6 to 20 years and 40.92 cm for plantations aged 21 to 35 years. However, there is a decrease in the average circumference of older plantations aged 36 years and over (30.84 cm). In addition, the average density of cocoa trees is higher in plantations aged 6 to 20 years (203.42 individuals/ha) and lower in those aged 36 years and over. This significant variation in the density of cocoa trees according to their age could be explained, on the one hand, by the fact that farmers, when establishing a cocoa plot, densify the cocoa trees until the plantation enters production, and on the other hand, by the mortality of cocoa trees due to their aging, soil depletion, and competition with species other than cocoa trees. Our results corroborate those of Kouadio *et al.* (2025). According to these authors, the density of cocoa trees decreases in the older age classes. In contrast to cocoa trees, a high density of associated species is observed in plantations aged 36 years and older (342 individuals/ha) and those aged 0 to 5 years (271.66 individuals/ha). Low density values were observed in plantations aged 6 to 20 years (194.42 individuals/ha). The high density of associated species in plantations aged 0 to 5 years and those aged 36 years and older could be explained, on the one hand, by the fact that when new cocoa plots are established, farmers deliberately leave plant species there to provide shade for the young cocoa plants. Over time, they gradually eliminate associated species when the plantation reaches its optimal production phase, hence the low density observed in plantations aged 6 to 20 years and those aged 36 years and over. On the other hand, by replanting old cocoa trees. In older plantations, the gaps left by the mortality of cocoa trees are replaced by woody species or banana trees that will serve as shade plants for young cocoa trees. Our results corroborate those of Zanh *et al.* (2019), Konan *et al.* (2023). In terms of the height of cocoa trees and associated species, no significant differences were observed according to age class ($p>0.05$). All height values are statistically identical across plantation age classes (Table 2).

Table 2. Densities of cocoa trees and associated plant species

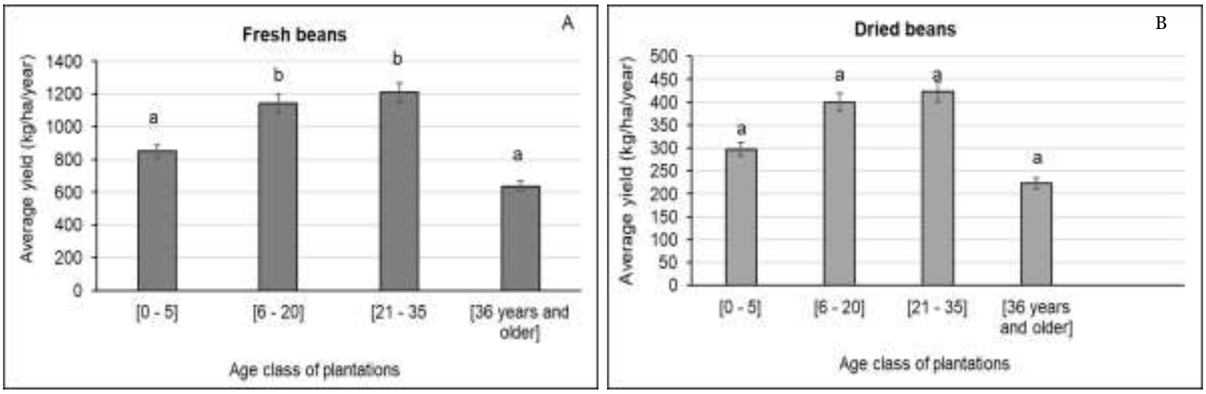
Structural parameters	Species types	Age class of cocoa plantations			
		[0-5	[6-20	[21-35	[36 years and older[
Circumference (cm)	Cocoa trees	23.81^a	27.48^a	40.92^b	30.84^a
	Related species	41.37^a	39.86^a	49.05^b	34.75^a
Density (individuals/ha)	Cocoa trees	157.33^a	203.42^a	139.62^a	86^b
	Related species	271.66^a	194.42^a	224.75^a	342^b
Heights (m)	Cocoa trees	1.92^a	3.22^a	4.16^a	3.06^a
	Related species	4.90^a	4.58^a	6.51^a	3.12^a

Values with the same letters in the same row are statistically identical at the 5% level.

However, plantations aged 21 to 35 years recorded 4.16 m and 6.51 m as the highest average height values for cocoa trees and associated species, respectively. They are followed by plantations aged 6 to 20 years (3.22 m), then 36 years and older (3.06 m) for cocoa trees, and 0 to 5 years (4.90 m) and 6 to 20 years (4.58 m) for associated species. The lowest average values for the height of cocoa trees were observed in plantations aged 0 to 5 years (1.92 m) and those aged 36 years and over (3.12 m) for cocoa trees and associated species, respectively. The variation in the height of associated species and that of cocoa trees with the age of the cocoa trees could be due, on the one hand, to shade management by farmers. Indeed, as cocoa trees enter the production phase, farmers gradually eliminate plant species in order to optimize yield. This observation was made by Kpangui (2015) in south-central Côte d'Ivoire; on the other hand, by reintroducing associated species into older plantations. This practice was demonstrated by Sanial (2018) during their work in southwestern Côte d'Ivoire.

Productivity of agroforestry systems based on cocoa trees

Analysis of variance showed that there is a significant difference in fresh cocoa bean yield according to cocoa age class ($p<0.05$). Fresh bean yield values are statistically different between plantation age classes ($p<0.05$). Plantations aged 21 to 35 years recorded the highest fresh bean yields (1208.12 kg/ha/year). The lowest fresh bean yields were observed in plantations aged 36 years or older (637.08 kg/ha/year) (Fig. 6A).



Values with the same letters are statistically identical at the 5% threshold.

Fig. 6. Average yield of fresh (A) and dry (B) beans

Furthermore, no significant difference in dry bean yields was observed between plantations ($p > 0.05$). However, plantations aged 21 to 25 years recorded the highest yield value of 422.84 kg/ha/year. Low dry bean yields were recorded in plantations aged 36 years and older, with a value of 222.98 kg/ha/year (Fig. 6B). The low cocoa bean yield observed in plantations aged 36 years and older could be due, on the one hand, to the aging of the cocoa trees (Assiri *et al.*, 2009) and, on the other hand, to the high density of species associated with cocoa trees (Essola, 2014). This low yield could also be due to the replanting of old plantations (Zanh *et al.*, 2019). On the other hand, the high yield in plantations aged 6 to 20 years and those aged 21 to 35 years could be explained by the fact that these age classes correspond to periods of high cocoa production. This observation was made by Assiri *et al.* (2009). It confirms the low productivity of cocoa orchards

Relationship between floristic diversity and productivity of agroforestry systems

Principal component analysis (PCA) highlights a clear structuring of plantations into two distinct groups according to their age. The first two axes explain 94.09% of the total variability (Fig. 7A), reflecting excellent representation quality.

The first group includes the 6-20 and 21-35 age classes, located on the negative side of axis F1 and characterized by high cocoa tree density, large cocoa tree dimensions (height and circumference), and the highest yields. The second group includes plantations aged 0-5 years and ≥36 years, positioned on the positive side of F1, and associated with higher levels of diversity indices (Shannon, Simpson, and evenness) but lower dendrometric and productive performance.

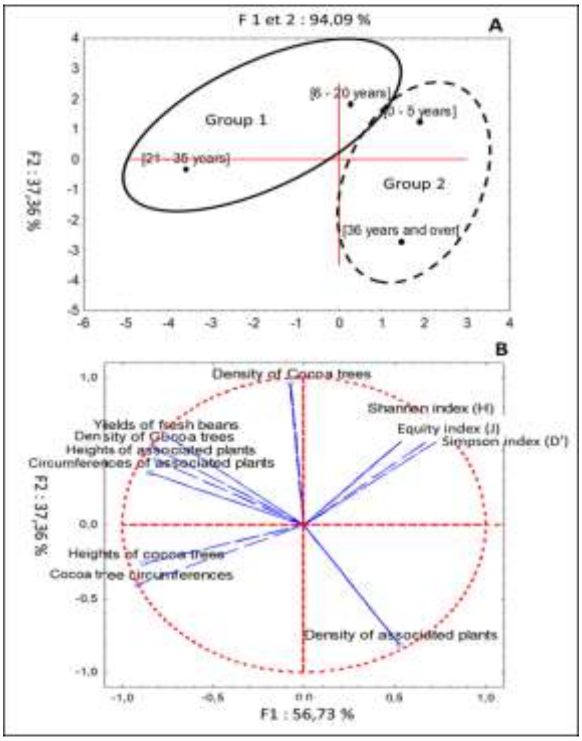


Fig. 7. Factorial map showing the distribution of plantation age classes (A), correlation circle of diversity parameters and yield on the factorial axes (B)

The correlation circle (Fig. 7B) confirms this organization. Indeed, there is a positive correlation between cocoa tree yield and cocoa tree dendrometric variables (cocoa tree density, cocoa tree height, cocoa tree circumference), as well as the height and circumference of associated species. This means that yield increases significantly with the density of cocoa trees, the heights and circumferences of cocoa trees and associated plant species. On the other hand, there is a negative correlation between yield and diversity indices and the density of associated species. This means that yield decreases with the age of plantations, diversity and high density of associated species . These results highlight that the intermediate age of plantations (6 to 20 years and 21 to 35 years) represents the most favorable period for cocoa productivity, while the initial (0 to 5 years) and late phases of the cycle (over 36 years) are marked by structural or ecological constraints affecting agronomic performance. Indeed, excessive floristic diversity in young orchards (0 to 5 years) and a high density of associated species in plantations aged 36 years and over could lead to intense interspecific competition, reducing cocoa trees' access to light, water, and nutrients. This observation was also made by Jagoret (2011) and Essola (2014). According to these authors, cocoa tree productivity decreases when grown under high shade. Also, according to the work of Clough *et al.* (2011), high-yield plantations are associated with low density of associated species.

CONCLUSION

The overall objective of this study, which was to assess the impact of associated species on the productivity of cocoa-based agroforestry systems in the department of Biankouma, showed that the level of floristic diversity significantly influences the productivity of cocoa-based agroforestry systems depending on their age in the department of Biankouma. Indeed, analyses showed that plantations aged 0 to 5 years have high floristic diversity but low cocoa yields, while those aged 21 to 35 years have low density of associated species and high yields (1208.12 kg/ha/year). Plantations aged 36 years and older, with a high density of associated species, recorded low yields (637.08 kg/ha/year).

These results indicate that excessive plant diversity can limit the development of cocoa trees by generating competition for light and nutrients. To improve productivity, it is recommended that associated species be selected according to their ecological functions (shading, nitrogen fixation, pest protection) in order to maintain a balance between biodiversity and yield. For future studies, it would therefore be interesting to conduct more in-depth research on the choice of species to associate with cocoa trees in order to optimize the productivity of agroforestry systems.

ACKNOWLEDGMENTS

The authors of this work would like to express their sincere thanks to the organizations that support cocoa producers in the Soubré region, in particular ANADER, for facilitating their integration into the region. Our thanks also go to the Academy of Sciences, Arts, Cultures of Africa and African

Diasporas (ASCAD) and the European initiative DeSIRA under grant number FOOD/2019/412-132 and the French Development Agency for co-financing the activities of this study.

We would also like to thank the village authorities and producers for their collaboration in the production of this work.

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