International Journal of Plant & Soil Science

Volume 37, Issue 11, Page 412-427, 2025; Article no.IJPSS.146360
ISSN: 2320-7035

Floristic Diversity and Carbon Sequestration of Cocoa Agroforestry Systems in Nawa and Indénié-Djuablin Regions, Côte d'Ivoire

Kolman Krysley Tracey [a,b]*, Sanogo Souleymane [a,b] and Eponon Eboa Christophe Ghislain [a]

[a] UFR Biosciences, University of Félix HOUPHOUËT- BOIGNY, Abidjan, Ivory Coast.
[b] Biodiversity and Sustainable Agriculture (Wascal/CEA-CCBAD), Wascal/ African Centre of Excellence on Climate Change, Abidjan, Ivory Coast.

Authors' contributions

This work was carried out in collaboration among all authors. Author KKT designed the study, wrote the protocol, managed the study, performed the statistical analysis and wrote the first draft of the manuscript. Authors SS and EECG managed the analyses of the study. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i115855

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/146360

Original Research Article

Received: 21/09/2025
Accepted: 17/11/2025
Published: 26/11/2025

ABSTRACT

In the fight against the global challenges of climate change, carbon storage in agroforestry systems is seen as a biological mitigation strategy. The floristic diversity of agroforestry systems acts as a driver of carbon sequestration by increasing total biomass, stabilising soil carbon and ensuring the system's resilience to disturbances. The richer, more diverse and more structured the agrosystem, the more effective and sustainable its role as a carbon sink. In Côte d'Ivoire, farmers are

**Corresponding author: E-mail: traceykolman@gmail.com;*

***Cite as:** Kolman Krysley Tracey, Sanogo Souleymane, and Eponon Eboa Christophe Ghislain. 2025. "Floristic Diversity and Carbon Sequestration of Cocoa Agroforestry Systems in Nawa and Indénié-Djuablin Regions, Côte d'Ivoire". International Journal of Plant & Soil Science 37 (11):412–427. https://doi.org/10.9734/ijpss/2025/v37i115855.*

increasingly practising agroforestry, particularly in cocoa cultivation. However, the estimated carbon stock of cocoa-based agroforestry systems (AFS) has not been enough measured at the local level, particularly in main production areas such as Nawa and Indénié-Djuablin. This study aims to assess the estimate carbon stock in the Nawa and Indénié-Djuablin regions.

Then, this research was conducted on a sample size of 10 plantations and in each of them, a sampling scheme was etablished. In order to determine the floristic diversity of the AFs, we identified the species present using the forest survey method. We also determined the species richness of the inventoried species by calculating the Shannon, Simpson and Pielou biodiversity indices. The carbon stock of the AFS was estimated on the basis of above-ground, below-ground biomass and soil carbon stock. We first measured the DBH of trees at 1.3 meters and that of cocoa trees at 30 centimeters above the ground. The DBH measurements then enabled us to calculate the density, basal area, above-ground and below-ground biomass according to the allometric models. Finally, soil carbon stock was estimated based on the results of laboratory analysis of soil samples taken from the plantation and standard methodological guidelines.

Nawa contained the most diverse AFS (31 species) compared to 23 species in Indénié-Djuablin. The AFS in these two regions were mostly young (86%), and the carbon stock varied according to tree density, which in turn varies according to history, previous cultivation, and particularly associated species. The average density (cocoa trees and shade trees) was 805 trees.ha-1 (Nawa) and 686 trees.ha-1 (Indénié-Djuablin), and the average carbon stock was 66 tC.ha-1 (Nawa) and 36 tC.ha-1 (Indénié-Djuablin).

The AFS studied store more than monocultures but less than old-growth agroforests. The carbon storage data from this study could serve as a reference for generating carbon certification scenarios. This study was conducted on a limited sample size due to financial constraints. Furthermore, it would be interesting to continue the research by comparing the species of shade trees inventoried according to their ability to fix carbon, improve soil fertility or regulate the microclimate through shading.

Keywords: Theobroma cacao L.; agroforestry systems; biodiversity; carbon stock; climate change; Côte d'Ivoire.

1. INTRODUCTION

The continuous use of fossil fuels in the industrial sectors suggests the dire need for comprehensive reduction measures in utilising fossil fuel-based energy sources (Lau *et al*., 2021). This contributes to the catastrophic increase in global carbon emissions (Bose *et al*., 2024). In the context of combating the global challenges of climate change, carbon storage in terrestrial ecosystems is currently seen as an essential mitigation strategy. CO2 can remain in the atmosphere for 3–10 centuries. It is crucial to both drastically reduce emissions and apply carbon sequestration techniques. This requires immediate action to cut CO2 emissions and implement "negative emission" technologies to meet the goal of a decarbonised global economy by 2050 (Dasgupta & Mahanty, 2024). The floristic diversity of agroforestry systems acts as a driver of carbon sequestration by increasing total biomass, stabilising soil carbon and ensuring the system's resilience to disturbances. The richer, more diverse and more structured the agrosystem, the more effective and sustainable its role as a carbon sink.

In tropical areas, agroforestry systems, particularly those incorporating cocoa (*Theobroma cacao L.*), are essential for their ability to serve as carbon sinks while ensuring sustainable agricultural production (Dawoe *et al.,* 2016; Madountsap *et al.,* 2018; Ballesteros-Possú *et al.,* 2022).

Cocoa has a significant impact on the economies of producing countries. In Côte d'Ivoire, the world's leading producer, cocoa accounts for 10% of national GDP and 40% of exports, and the sector employs around 8 million people (Konan, 2024; FAO, 2025). In Ivorian cocoa plantations, the use of agroforestry systems is widespread and offers enormous potential for carbon storage in biomass and soils (Saj *et al.,* 2018; Kouadio *et al.,* 2025). However, this potential has not yet been sufficiently measured at the local level, particularly in key production areas such as the Nawa and Indénié-Djuablin regions (Vroh *et al.,* 2019; Koffi *et al*., 2025).

These two areas, characterised by divergent agroecological conditions and intensive cocoa production, provide a suitable environment for examining the effectiveness of agroforestry systems in carbon sequestration (Kouao *et al.,* 2022; Kouassi *et al.,* 2025). The objective of this study is to estimate the carbon sequestration potential of cocoa agroforestry systems in these regions. This will provide a more effective understanding of their role in mitigating climate change, while providing a scientific basis for sustainable agricultural and environmental policies in Côte d'Ivoire.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Nawa and Indénié-Djuablin (Fig. 1). The Nawa region is located in south-western Côte d'Ivoire between 5°57′57″-7°7′58″ west longitude and 5°17′40″-6°44′29″ north latitude. Nawa has a sub-equatorial climate. It has two wet seasons and two dry seasons. The long-wet season covers the period from April to July. The short-wet season lasts for three months (September-November). The long dry season begins in December and ends in March, and the short dry season lasts throughout August (Diomandé *et al.*, 2022). Average rainfall is between 1.600 and 1.800 mm per year. Average temperatures range between 26 and 28 °C, with April being the sunniest month (DonnéesMondiales, 2025). The region's terrain consists of vast plateaus and the vegetation is partly dense (Taï National Park, a biosphere reserve and UNESCO World Heritage Site). The soils of Nawa are mainly ferralitic, with textures ranging from clayey silt to silty sand (Guillaumet & Adjanohoun, 1971).

The Indénié-Djuablin region is located in the south-east of the country at 6° 43' 47" north latitude and 3° 29' 47" west longitude. Average rainfall ranges from 1.200 to 1.600 mm per year, with maximum sunshine in November (DonnéesMondiales, 2025). The terrain of this region consists of plains with an average altitude of 250 m (Vroh *et al.,* 2019). The vegetation is humid, wooded and herbaceous (Kouamé *et al.*, 2009). The soils of Nawa are mainly ferralitic (Guillaumet & Adjanohoun, 1971).

2.2 Material

2.2.1 Plant material

The plant material consists of cocoa trees and shade trees with a diameter of more than 10 cm.

2.2.2 Technical material

The study required the following equipment: a pair of boots, a notepad, an A4 notebook, a pen, a smartphone, a tape measure, oil paint, a paintbrush, a slate, a packet of chalk, 50 m of red and white tape, a roll of adhesive tape, 150 m of rope, a 1 kg measuring jug, a trowel, 10 packs of packaging bags, a pair of gloves and a pickaxe.

2.3 Methods

2.3.1 Selection of plantations

2.3.1.1 Pre-survey phase

Secondary data obtained from the ANADER and Coffee Cocoa Council databases were used to select cocoa farmers practicing agroforestry in the areas studied.

2.3.1.2 Survey phase

The plantations of the selected producers were visited. This enabled us to select those that met the following criteria: presence of associated shade trees larger than the cocoa trees; plots in production (from 4 years of age) and a minimum plot size of 1 hectare. Thus, out of 200 producers contacted, 10 plantations were selected in seven locations to host the sampling program. The selection of plantations was carried out from November to December 2024.

2.3.2 Sampling scheme

In each selected plantation, a 50m x 20m (1000 m²) plot was marked out using the surface floristic survey method, which consists of recording all taxa present on square, rectangular or circular areas (N'Dah *et al.*, 2022). In each plot, three circles with a radius of 30 m were marked out at equidistant intervals of 120° (Fig. 2). The companion tree species (trees and shrubs) were inventoried in the plantation. The 1000 m² plots were used to list the cocoa trees and characterize the associated trees. The circles with a radius of 30 meters were used to collect soil samples.

2.3.3 Data collection

2.3.3.1 Individual producer survey

We submitted an individual questionnaire to the owners of the 10 selected plantations to collect information on the age and area of the plantation, associated shade trees, density of associated trees, previous crop, technical itinerary and benefits derived from the presence of shade trees.

2.3.3.2 Tree identification

Identification consists of giving the scientific name of the trees. This was done using the local name and photos of the leaves and fruits taken in the field, which were then compared with existing databases in several publications, including La Flore Forestière de Côte d'Ivoire by Aubréville (1959), Woody Plants of Western African Forests by Hawthorne & Jongkind (2006), Photoguide for the Forest Trees of Ghana by Hawthorne & Gyakari (2006), Ligneux compagnons dans les exploitations cacaoyères by Kougbo *et al.* (2020), and Les arbres des cacaoyères Recueil by Sanial and Ettien (2022). The trees were identified throughout the plantation.

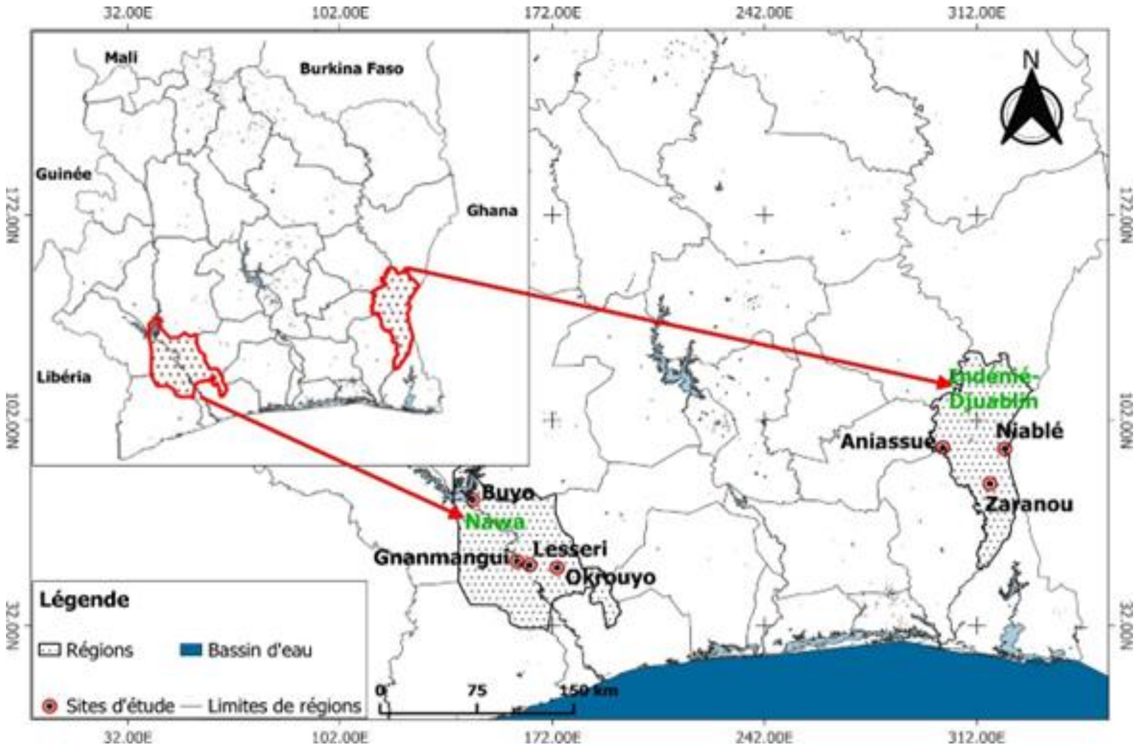

Fig. 1. Study area

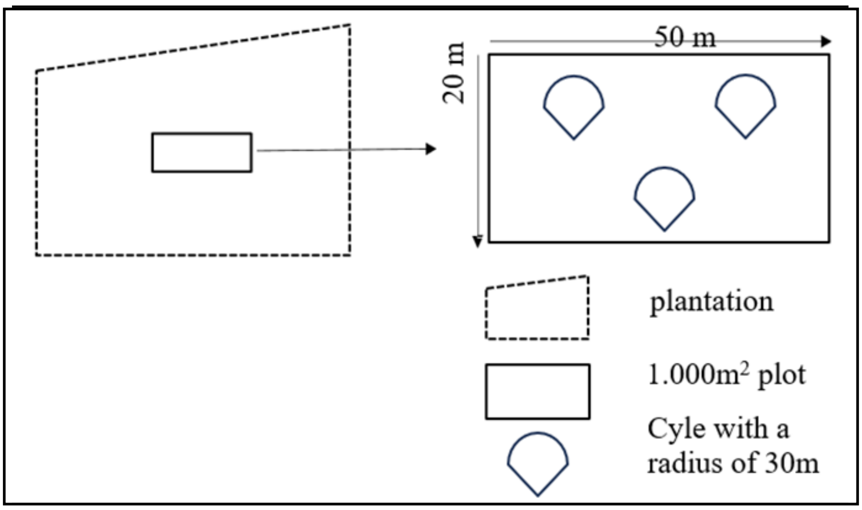

Fig. 2. Sampling device

2.3.3.3 Measurement of diameter at breast height (DBH) and tree count

The DBH of cocoa trees was measured 30 centimeters above the ground (Andrade *et al.*, 2008; Cerny, 2024). When the cocoa tree had a trunk composed of several small trunks starting from the collar, the DBH of each small trunk was measured and their sum constituted the DBH of the cocoa tree. The DBH of shade trees was measured 1.3 meters above the ground. Only trees with a DBH upper than 10 centimeters in the plot were included in the study. These measurements were taken with a tape measure and the DBH was recorded in a notebook along with the local name of the tree. The trees measured were marked with paint so that they would not be measured more than once. In each plot, all trees marked with paint were counted to establish tree density.

2.3.3.4 Soil sample collection

Soil samples were collected from holes measuring 50 cm square and 60 cm deep, dug for this purpose with a pickaxe. Three holes were dug in each circle (Fig. 2). In each hole, one sample was collected from 0 to 20 cm, another sample from 20 to 40 cm and another sample from 40 to 60 cm. The samples were packed in plastic bags and labelled with adhesive tape.

2.3.3.5 Analysis of soil samples

A total of 216 soil samples were collected at a rate of 9 samples per circle in 8 plots. In each region, one composite sample was taken at a depth of 20 cm, another composite sample at a depth of 40 cm and another composite sample at a depth of 60 cm. Organic carbon was analysed in the laboratory using the Walkley and Black method (1934). This method involves cold oxidation of the total organic carbon present in the soil using a potassium dichromate (K2Cr2O7) solution in presence of sulphuric acid (H2SO4).

2.3.3.6 Assessment of woody biodiversity

Density (N) is the number of trees per hectare. It is calculated using the following formula (Rondeux, 1993):

$$N = \frac{\text{number of trees in the plantation}}{\text{total area of the plantation}}$$

The basal area of a tree is the cross-sectional area of that tree at 1.30 m above the ground (Rondeux, 1993). It is the area occupied by tree per hectare. The basal area of a stand (G) represents the sum of the basal areas of the individual trees (g) that make up that stand (Pardré & Bouchon, 1988). They are calculated using the following equations:

$$\mathbf{G} = \sum_{i=1}^{n} \frac{\pi Di^2}{4} \times \frac{d}{n}$$

G = basal area of a stand;
Di = diameter of tree i;
d= stand density per hectare;
n= population size in the plot.

The species richness of each region was determined by calculating various biodiversity indices such as Shannon (H), Simpson (D) and Piélou (E) (Ramade, 1994; Shannon & Weaver, 1949). These three indices were calculated using the diversity function of the "vegan" package version 4.3.2 from RStudio.

2.3.3.7 Assessment of biomass, soil carbon and carbon stocks

Assessment of biomass: Tree biomass was assessed using allometric formulas to calculate the above-ground, below-ground and total biomass of each individual tree. The allometric formulas used for shade trees differ from those used for cocoa trees.

Shade trees: Above-ground biomass (AGB) is calculated according to Chave et al. (2014) using the following formula:

$$\text{AGB (kg/tree)} = 0.0673^* (pD^2)^{0.976}$$

where D = DBH

Belowground biomass (BGB) is calculated according to Mokany et al. (2006) using the following formula:

$$\text{BGB (t/ha)} = \text{BA*R}$$

Where R = 0.205 if BA < 125 t/ha or BA > 625 t/ha and R = 0.235 if 125 < BA < 625 t/ha.

Cocoa trees: Above-ground biomass is calculated according to Chave et al. (2005) using the following formula:

$$AGB\ (kg/tree) = \exp(-2.134+2.530 \cdot \ln(D)+0.850 \cdot \ln(\rho))$$

where D = DHP

The belowground biomass is calculated according to IPCC (2006) using the following formula:

$$BGB\ (t/ha) = 0.2 \times AGB$$

NB: The above-ground biomass after digital application gives us a result in kg/tree. We convert BA from kg/tree to t/ha using the following calculation:

$$BA\ (t/ha) = (BA\ (kg/tree) * Density) / 100$$

Shade trees and cocoa trees: The total biomass (TB) is obtained by adding AGB (t/ha) and BGB for the individual:

$$TB\ (tonnes/hectare) = AGB + BGB$$

The total biomass was first converted to carbon equivalent and then to CO2 according to IPCC (2006) using the following formulas:

$$C\ (t\ C.ha\text{-}1) = 0.5 * B \quad \text{and} \quad CO2\ (t\ CO2.ha\text{-}1) = 3.67 * C$$

The above-ground, below-ground and total biomass; as well as the conversions to carbon and CO2; were calculated using Excel.

Assessment of soil carbon: Once the organic carbon content per depth and per region had been obtained in the laboratory, we calculated the soil carbon equivalent according to IPCC (2006) using the following formulas:

$$C\ (t\ C.ha\text{-}1) = depth\ (cm) * \%C * 1.45*10$$

Then, we calculated the average soil carbon equivalent per region.

Assessment of carbon stock: Finally, the equivalent carbon stock of the plantation was calculated using the following formula:

$$\text{Total carbon T/ha} = \sum \text{carbon equivalent per tree} + \text{soil's carbon equivalent average per region}$$

2.3.4 Statistical analyses

Variables that conformed to normal distribution were analysed using one-way analysis of variance (ANOVA), while those that did not meet the assumptions of ANOVA, even after transformation, were analysed using Kruskal-Wallis parametric ANOVA on mean ranks using R software version R4.3.2. In cases where there was a difference between means, the P-value was calculated.

3. RESULTS AND DISCUSSION

3.1 Age of AFS

The survey results show that the majority (86%) of AFS surveyed are under 20 years of age (Fig. 3). This majority was observed in both regions visited. AFS over 20 years of age are in the minority (14%) and were all recorded in Nawa.

Following analysis of the survey data, AFS were grouped into two age categories: under 20 years (86%) and over 20 years (14%). The predominance of AFS under 20 years (86%) confirms that we are indeed dealing with young cocoa plots in the study area. In fact, in Nawa and Indénié-Djuablin, producers are rehabilitating their orchards or starting new plantations due to the ageing of orchards or the spread of Swollen Shoot. These practices have been reported by several authors in Côte d'Ivoire (Konan *et al.,* 2023; Doumbia *et al.,* 2024; Gnagbo *et al.,* 2024).

3.2 Previous Land Uses of AFS

In this section, the results reveal two trends. In the Indénié-Djuablin region, one-third of AFS are located on former fallow land, one-third on former forest land, and one-third on former orchards (Fig. 4). The second trend shows that in the Nawa region, half (50%) of AFS are established on former forest land. Similarly, the other half (50%) is established on former orchards. In this region, none AFS have been established on former fallow land. The Kruskal-Wallis test gives (P =.3); there is no statistically significant difference between the regions compared.

The survey results show that producers established the current AFS following fallow land, forests or ageing orchards. The results of the Kruskal-Wallis test show that the previous land uses are the same in Nawa and Indénié-Djuablin. These results could be explained by the vegetation and agricultural history of the regions. Indeed, Nawa and Indénié- Djuablin have dense forest vegetation and part of the forest has been destroyed to make way for cocoa cultivation, which was introduced in the 1870s (Koné *et al.,* 2014; Kouassi *et al.*, 2021). Furthermore, agriculture is a key sector of activity in both regions, where farmers practise fallow farming to regenerate the soil (Osseni *et al.,* 1989; Li & Nath 2024).

3.3 Floristic Diversity of AFS

Regarding species abundance, a total of 1.272 individuals were recorded, divided into 32 species, 28 genera and 14 families in the study area. In Nawa, we recorded 879 individuals divided into 31 species, 27 genera and 14 families. In Indénié-Djuablin, we recorded 393 individuals divided into 24 species, 21 genera and 10 families (Table 1). The results on species frequency show that the flora was dominated by *Termiliana superba* (23%), *Termiliana ivorensis* (13%) and *Ricinodendron heudelotii* (8%) in Nawa and Indénié- Djuablin. In Nawa, the least frequent species were *Adansonia digitata* (0.11%), *Cecropia pelelata* (0.11%), *Heritiera densiflora* (0.34%) and *Tieghemella heckelii* (0.34%). In Indénié- Djuablin, the least frequent species were *Adansonia digitata* (0.25%), *Albizia zygia* (0.51%) and *Khaya ivorensis* (0.51%) (Table 1). The results on the use or usefulness of associated species, according to farmers' perceptions, reveal that certain species have multiple uses. Indeed, according to repeated analyses, in Nawa, 21 species provide optimal shade for cocoa trees, 13 species are used in traditional medicine, 12 species are consumed locally, 12 species provide timber, 11 species provide firewood, 8 species produce fruit with commercial value, 5 species fertilize the soil and 3 species have cultural value. In Indénié-Djuablin, 15 species provide optimal shade for cocoa trees, 10 species provide traditional medicine, 10 species generate timber, 9 species are consumed locally, 8 species produce fruit with commercial value, 7 species provide firewood, 5 species fertilize the soil and 2 species have cultural value (Table 1). With regard to the results on the origin of species, in Nawa, 19 species are indigenous and 11 are exotic. However, in Indénié-Djuablin, 14 species are indigenous and 9 are exotic (Table 1). Regarding the vulnerability of the species encountered based on their IUCN status, six of them are vulnerable: *Entandrophragma angolense, Entandrophragma utile, Monodora myristica, Khaya ivorensis, Terminalia ivorensis* and *Tieghemella heckelii* (Table 1).

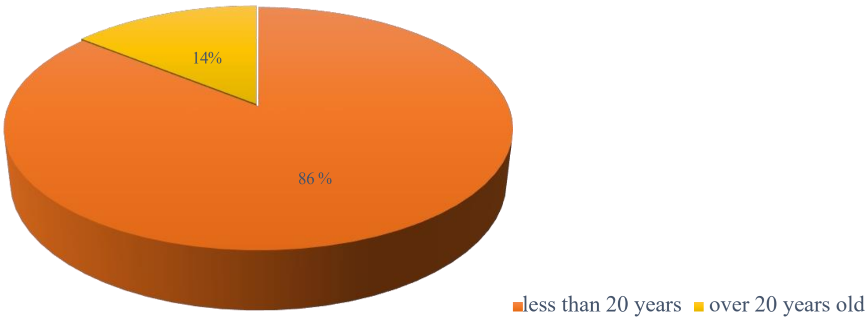

Fig. 3. Age of plantations

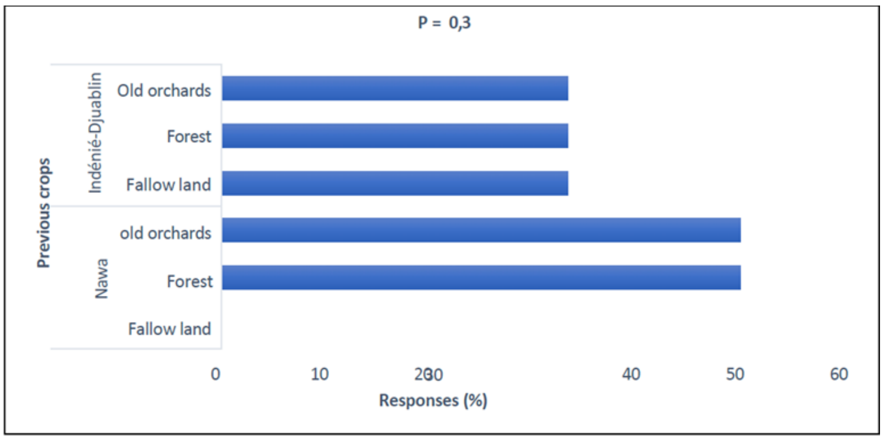

Fig. 4. Previous land uses by region

The inventories carried out identified 31 species divided into 27 genera and 14 families in Nawa, and 24 species divided into 21 genera and 10 families in Indénié-Djuablin. These species numbers are lower than the 179 species identified by Kouadio *et al*. (2025) in the cocoa plantations of central-western Côte d'Ivoire. This difference in the number of species could be explained by the methodology used. Indeed, the inventory methodology used by Kouadio *et al.* (2025) is that of forest inventories on a surface area (100 m x 50 m). This method differs from the surface survey method (50 m x 20 m) used in our work. Furthermore, the number of species obtained is also lower than the 84 species identified by Konan *et al.* (2023) in the cocoa plantations of western Côte d'Ivoire (Biankouma). The high number of species obtained by Konan *et al*. (2023) could be justified by the surface floristic survey, which consists of recording all woody (trees and shrubs) and non-woody (palms and banana trees) species. This choice in terms of floristic inventory would have favoured the discovery of a greater number of plant species. When, we consider the distribution of species by region, the AFS in Nawa recorded the highest number of species. This significant number of species in this region could be explained by the cultivation practices adopted by producers. The extensive knowledge of species among producers in Nawa could promote the preservation of a large number of species in cocoa plantations (Lipchitz & Pouch 2008; Olwig *et al.,* 2024).

When, we consider the distribution of species among themselves, the abundance of *Termiliana superba* (23%) and *Termiliana ivorensis* (13%) in AFS could be explained by their rapid growth, the quality of their shade and their promotion by the cocoa sector's support structures (ANADER and the Coffee Cocoa Council). These species grow rapidly, provide optimal shade for cocoa trees and are among the species distributed as seedlings during agroforestry promotion campaigns conducted by the relevant national and international institutions (Béhaghel, 1995; Tagbi *et al.,* 2015; Cuny *et al.,* 2023). As for *Ricinodendron heudelotii* (8%), its abundance in AFS could also be explained by its rapid growth, but also by its nutritional and economic importance in Ivorian cuisine (Nikiema *et al.,* 2024). In addition to these species, the species listed in the study area are generally used for shade for cocoa trees, traditional medicine, food for farmers, timber, fuelwood and soil fertilization (Smith *et al.,* 2014; Gyau *et al.,* 2015 and Koulibaly *et al.,* 2017). The significant proportion of native species in the Nawa and Indénié-Djuablin AFS shows the importance of local tree species in the lives of producers. Indeed, faced with the devastating effect of cocoa cultivation on forest cover, leading to the disappearance of several useful species, many producers tend to conserve native trees for their medicinal, food, fertilising and/or commercial value when creating plantations. The conservation of local tree species in plantations has also been reported by Cissé *et al.* (2016) in the cocoa agroforests of Lakota (central-western Côte d'Ivoire). Furthermore, research by Plas (2020) has shown that cocoa farmers in western Côte d'Ivoire preserve many native trees in their plantations, which are generally used for food, medical care or to protect young plants from the sun's rays. The vulnerability status of *Entandrophragma angolense, Entandrophragma utile, Monodora myristic, Khaya ivorensis, Terminalia ivorensis* and *Tieghemella heckelii* according to the IUCN (2015) could be justified by their indigenous origin coupled with their quality as timber. Indeed, these local species are overexploited by a poorly regulated domestic timber trade (Aubréville, 1959; Hawthorne & Jongkind, 2006; Hawthorne & Gyakari, 2006; Kougbo *et al.*, 2020; Sanial & Ettien, 2022).

3.4 AFS Biodiversity Indices

Biodiversity indices were higher in Nawa. Indeed, in Nawa, the averages for Shannon and Simpson were 2.05 and 0.82 respectively, compared to 1.88 and 0.80 in Indénié-Djuablin. The Pielou index showed a similar result for both regions with 0.87 (Table 2). However, statistical analyses showed that there was no significant difference between the specific richness of AFS in the two regions (Kruskal-Wallis, P=.6). The results highlight that there is average diversity in the community studied, with a relatively balanced distribution of individuals between species (no species is totally dominant).

The diversity indices calculated showed greater diversity in terms of AFS in Nawa. However, statistical analyses showed that there was no significant difference between the specific richness of AFS in the two regions. This similarity between the specific richness of the two regions could be explained by their vegetation. Indeed, Nawa and Indénié-Djuanblin share dense forest vegetation, which explains the high number of native species in AFS. The average diversity in the study area has been demonstrated in several studies in Côte d'Ivoire (Adou Yao & N'Guessan, 2006; Koulibaly *et al.,* 2017).

3.5 Stand Density (Cocoa Trees and Shade Trees) in AFS

In Nawa, the average stand density was 805 trees.ha^{-1} with a standard deviation of 161 trees.ha^{-1}. The minimum stand density was 640 trees.ha-1 and the maximum stand density was 1020 trees.ha-1. The minimum shade tree density was 70 trees.ha -1 and the maximum shade tree density was 180 trees.ha-1 (Fig. 5). In Indénié-Djuablin, the average stand density was 686 trees.ha-1 with a standard deviation of 227 trees.ha-1. The minimum stand density was 500 trees.ha-1 and the maximum stand density was 940 trees.ha-1. The minimum shade tree density was 30 trees.ha^{-1} and the maximum shade tree density was 170 trees.ha^{-1} (Fig. 5). The Kruskal-Wallis's test (P=.5) showed that there was no significant difference between stand densities in AFS in the two regions.

The calculated tree density ranged from 500 trees/ha to 1.020 trees/ha. These results are similar to those obtained in several studies conducted in Ivorian cocoa plantations (Konan *et al.,* 2023; Kouadio *et al.,* 2025). Furthermore, the high stand density in AFS could be justified by the fact that producers transplant cocoa trees at spacings of 2.5 m x 2.5 m or 2.5 m x 3 m to increase the survival rate of the cocoa. This cultivation choice allows producers to plant as many cocoa trees as possible on their plots. The high density of shade trees in AFS (30 to 180 trees/ha) could be explained on the one hand by the cultivation technique adopted by producers and on the other hand by the spacing used for planting shade trees. The establishment of these plots begins either with the introduction of cocoa trees after clearing the original forest or with the rehabilitation of old cocoa plantations, while retaining useful tree species. Then, in order to maintain shade and diversify their sources of income, farmers tend to keep the wild trees that emerge and introduce tree species at spacing that varies from one producer to another (Koko *et al.,* 2013; Cerny, 2024).

3.6 Basal Area of AFS

The results show that in the Nawa AFS, the average basal area was 27.4 m^2.ha^{-1} with a standard deviation of 23 m^2.ha^{-1}. The minimum basal area was 11.5 m2ha-1 and the maximum basal area was 61.4 m^2.ha^{-1} (Fig. 6). In Indénié-Djuablin, the average basal area was 24.5 m^2.ha^{-1} with a standard deviation of 13.3 m^2.ha^{-1}. The minimum basal area was 10 m² ha^{-1}and the maximum basal area was 36.5 m^2.ha^{-1} (Fig. 6).

Table 1. Proportions and IUCN status of shade trees inventoried in AFS per region

Species	IUCN status	Origin	Abundance		Frequency		Uses
			Nawa	Indénié	Nawa	Indénié	
Adansonia digitata	PM	IN	1	1	0.11%	0.25%	al.
Albizia adianthifolia	PM	IN	12	0	1.37%	0.00%	bo.bc.om.md.al.
Albizia zygia	PM	IN	8	2	0.91%	0.51%	md.bc.om
Anacardium occidentale L.	PM	EX	12	8	1.37%	2.04%	ve.
Aningeria superba	NC	IN	33	3	3.75%	0.76%	bo.bc.om
Bombax	PM	IN	0	9	0.00%	2.29%	bo.bc.om.md.al.
Cecropia pelatata	NC	EX	1	0	0.11%	0.00%	bc.om.al
Cedrela odorata	NC	EX	25	4	2.84%	1.02%	bo.om.fs
Ceiba pentandra L.	PM	EX	37	8	4.21%	2.04%	bo.om.al.cu
Citrus sinensis	NC	EX	15	9	1.71%	2.29%	al.ve.
Colaa acuminata	NC	IN	84	12	9.56%	3.05%	ve.al.md.cu
Entandrophragma angolense	VU	IN	36	31	4.10%	7.89%	bo.om.md
Entandrophragma utile	VU	IN	5	0	0.57%	0.00%	bo.om.
Gliricidia sepium	NC	EX	20	35	2.28%	8.91%	fs.
Heritiera densiflora	PM	IN	3	5	0.34%	1.27%	bo.om.
Hevea braziliensis	NC	EX	49	0	5.57%	0.00%	bc.om
Mangifera indica L.	NC	EX	12	21	1.37%	5.34%	al.ve.md.
Mansonia altissima	NC	IN	4	10	0.46%	2.54%	bo.om
Milicia excelsa	PM	IN	12	0	1.37%	0.00%	bo.om.md.cu
Monodora myristica	VU	IN	4	0	0.46%	0.00%	bc.om.al.md

Species	IUCN status	Origin	Abundance		Frequency		Uses
			Nawa	Indénié	Nawa	Indénié	
Musanga cecropioides	NC	IN	27	0	3.07%	0.00%	bc.om
Persea americana	NC	EX	7	8	0.80%	2.04%	al.ve.om
Prunus domestica L.	NC	EX	18	0	2.05%	0.00%	al.md
Psidium guajava	NC	EX	8	5	0.91%	1.27%	al.ve.
Ricinodendron heudelotii	NC	IN	71	13	8.08%	3.31%	ve.fs.om.md
Khaya ivorensis	VU	IN	26	2	2.96%	0.51%	bo.om.md
Terminalia ivorensis	VU	IN	120	90	13.65%	22.90%	bo.bc.om.fs.md
Terminalia superba	PM	IN	208	102	23.66%	25.95%	bo.bc.om.fs.md
Tieghemella heckelii	VU	IN	3	4	0.34%	1.02%	om.bo.bc.al
Triplochiton scleroxylon	PM	IN	5	6	0.57%	1.53%	om.bo.bc
Xylopia aethiopica	PM	IN	13	5	1.48%	1.27%	ve.md.al

Note: LC = Least Concern; VU = Vulnerable; NC = Not Classified; IN = Indigenous; EX = exotic; al = food; bo = timber; md = traditional medicine; bc = fuelwood; ve = sale/income diversification; fs = soil fertility; om = shade; cu = cultural; Indénié = Indénié-Djuablin

Table 2. Biodiversity indices by region

Region	Statistics	Shannon	Simpson	Pielou
Indénié-Djuablin	Average	1.88	0.80	0.87
	Maximum	2.37	0.86	0.91
	Minimum	1.57	0.75	0.87
	Standard Deviation	0.28	0.04	0.03
	Median	1.82	0.79	0.87
Nawa	Average	2.05	0.82	0.87
	Maximum	2.79	0.91	0.91
	Minimum	1.46	0.70	0.81
	Standard Deviation	0.39	0.06	0.03
	Median	1.92	0.82	0.87

The calculated basal area ranged from 10 m^2ha^{-1} to 61.4 m^2ha^{-1}. These results are similar to those obtained in several studies conducted in Ivorian agroforests (Konan *et al*., 2023; Cerny, 2024). Furthermore, the high basal area value could be justified by the rapid growth of the dominant species *Termiliana superba*, *Termiliana ivorensis* and *Ricinodendron heudelotii*.

3.7 Carbon Stock in Different Carbon Pools

In Nawa, the total carbon stock in AFS averaged 66.5 t C.ha-1 with a standard deviation of 83.2 t C.ha-1. The minimum total carbon stock was 16.6 t C.ha-1 and the maximum was 190.5 t C.ha-1 (Table 3). Considering the carbon stock in t $CO2.ha^{-1}$ the average was 244 t $CO2.ha^{-1}$ with a standard deviation of 305 t $CO2.ha^{-1}$. In Indénié-Djuablin, the total carbon stock in AFS averaged 36.3 t C.ha-1 with a standard deviation of 24.4 t C.ha-1. The minimum total carbon stock was 9.2 t C.ha-1 and the maximum was 56.7 t C.ha-1. Considering the carbon stock in t $CO2.ha^{-1}$ the average was 133 t $CO2.ha^{-1}$ with a standard deviation of 86 t $CO2.ha^{-1}$ (Table 3). There was a significant difference between the potential carbon stocks of the two regions (Kruskal-Wallis, P=.4).

The calculated carbon stock ranged from 9.2 t C.ha-1 to 190.5 t C.ha-1. These results are similar to those obtained in several studies conducted in agroforests in Colombia, Cameroon, Ghana and Côte d'Ivoire (Dawoe *et al.,* 2016; Madountsap *et al.,* 2018; Ballesteros-Possú *et al.,* 2022; Kouadio *et al.,* 2025). The estimated carbon stock is average, with carbon stocks ranging from 30–70 t C/ha on average. These AFS store more than monocultures but less than old agroforests. When we consider the averages of carbon stocks and their standard deviations by region, the AFS in Nawa show the greatest heterogeneity. This heterogeneity could be explained by the age of the AFS. Indeed, Nawa is the only region where AFS over 20 years old have been recorded. Due to their age, these AFS could harbor shade trees and/or cocoa trees with large DBH. This would justify an even upper estimated carbon stock (Jagoret *et al.,* 2020).

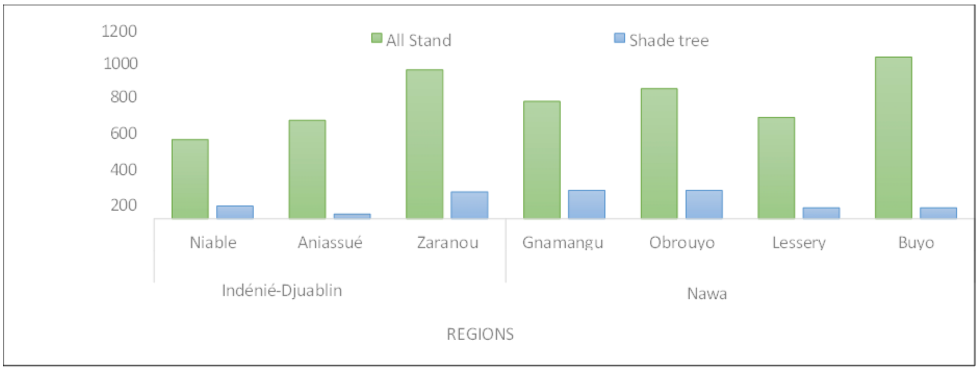

Fig. 5. All stand density and shade tree density in AFS by region

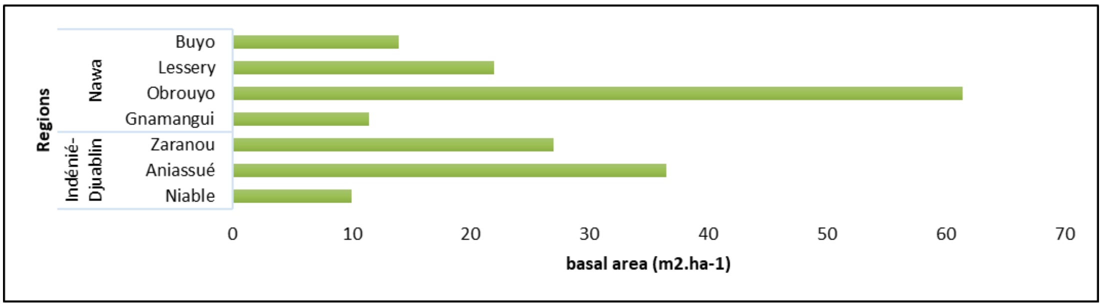

Fig. 6. Basal area of AFS by region

Table 3. Carbon stock according to carbon pools in AFS

Pools	Carbon Stock						
	Indénié-Djuablin			Nawa			
	Niablé	Aniassué	Zaranou	Gnamanguy	Obrouyo	Lessery	Buyo
Shade trees	1.3	5.4	8	2.5	10	4.4	1.9
Cocoa trees	7.8	37.5	48.4	14	180.2	15.4	36.8
Soil	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Total (t $C.ha^{-1}$)	9.2	43	56.7	16.6	190.5	19.9	38.8
Total (t $CO_2.ha^{-1}$)	34	158	208	61	699.4	73	142.5

By the way, estimating carbon stocks in cocoa-based agroforestry systems is a key lever for implementing the REDD+ mechanism (Reducing Emissions from Deforestation and Forest Degradation) in Côte d'Ivoire. By combining agricultural production and tree conservation, cocoa agroforests contribute simultaneously to reducing deforestation and increasing carbon stocks in agroecosystems. These systems thus constitute a sustainable solution for restoring degraded landscapes while improving producers' livelihoods (Alemagi *et al.,* 2014; Dawoe *et al.,* 2016). Accurate assessment of the carbon stored in the biomass and soil of AFS in Côte d'Ivoire makes it possible to quantify emission reductions and feed into the national Measurement, Reporting and Verification (MRV) system required by the United Nations Framework Convention on Climate Change or imposed by international certification standards such as the Verified Carbon Standard (VCS) or the Gold Standard (Grajales & Toukpo, 2024). These estimates, based on local data, reinforce the reliability of national greenhouse gas inventories and promote the economic valuation of sequestered carbon through payments for environmental services (PES) and carbon credits (Dugasseh & Zandersen, 2025). In addition, quantifying carbon in AFS makes it possible to better identify areas with high sequestration potential, guide national forest cover restoration policies, and continue the integration of agroforestry into territorial climate strategies. In Côte d'Ivoire, where cocoa-related deforestation remains one of the major challenges, recognizing the role of agroforests in carbon sequestration is a concrete opportunity to achieve the objectives of the National REDD+ Strategy and the National Forest and Climate Investment Plan (PNIFC) (Acheampong et al., 2014; Grajales & Toukpo, 2024; Kouadio *et al.,* 2024). Furthermore, the scientific estimation of carbon stocks is a fundamental step in the carbon certification process, as it indicates the amount of carbon actually sequestered or avoided by a given production system. In the context of cocoa-based agroforestry systems (AFS), this estimation provides the data needed to convert ecological performance into measurable economic units, known as carbon credits. These credits correspond to one ton of carbon dioxide equivalent (t CO_2e) captured or not emitted into the atmosphere. A rigorous estimation of carbon stocks, including above-ground, below-ground biomass and soil organic carbon, thus makes it possible to demonstrate the effective contribution of AFS to climate change mitigation and to guarantee the environmental credibility of projects submitted to certification bodies (Vervuurt *et al.,* 2022). In addition, these estimates are used to establish a baseline from which net sequestration gains are measured over the duration of the project (Kumah *et al.,* 2024). Our results on stock carbon enable us to assess the effectiveness of cocoa-based agroforestry systems in reducing greenhouse gas emissions and restoring degraded landscapes. In fact, well-structured AFS can store between 100 and 200 t C ha^{-1}, or up to 700 t CO_2e ha^{-1}, depending on species diversity and shade tree density (Kouadio *et al.,* 2024). Beyond a simple ecological measure, carbon estimation plays a key role in the economic valuation and international recognition of Ivorian cocoa. It serves as the basis for environmental certification (Rainforest Alliance, Fairtrade, ISO 14064) and the country's participation in voluntary carbon markets, thereby promoting remuneration for producers engaged in sustainable practices (Maathuis & Borrell, 2022). In addition, these estimates support national sustainability policies, including the 2023–2030 National Sustainable Cocoa Strategy, which incorporates carbon monitoring as an indicator of compliance with climate commitments and the environmental traceability requirements of European markets (Vervuurt *et al.,* 2022).Thus, measuring carbon stocks is not limited to a scientific indicator : it is an environmental and economic governance tool that is essential for aligning the cocoa sector with carbon neutrality and zero deforestation production targets. By enhancing the transparency and credibility of sustainability efforts, carbon stock estimation consolidates Côte d'Ivoire's position as a committed player in the transition to a responsible cocoa-climate economy (Kumah *et al.,* 2024).

4. CONCLUSION

The objective of this study was to determine the floristic diversity and estimate the carbon stock of living biomass (above and below ground) and soils in the AFS of Nawa and Indénié-Djuablin regions. The AFS in the two regions studied had average species richness with good species diversity and a balanced distribution of individuals between species. The species *Termiliana superba, Termiliana ivorensis, Ricinodendron heudelotii, Colaa acuminata and Entandrophragma angolense* were abundant as shade trees in the study area. The survey found that trees are used for food, timber, traditional medicine, fuelwood, supplementary income, soil fertilization, shade and cultural objects. Among the shade tree species inventoried, *Entandrophragma angolense, Entandrophragma utile, Monodora myristica, Khaya ivorensis, Terminalia ivorensi, and Tieghemella heckelii* are on the IUCN Red List. The density of shade trees ranged from 30 to 180 shade trees per hectare, and the average diversity indices, density, basal area and carbon stock were higher in the Nawa region. The average potential carbon stock was 66 t C.ha-1 with a standard deviation of 83 t C.ha-1 in Nawa and 36 t C.ha-1 with a standard deviation of 24 t C.ha-1 in Indénié-Djuablin. The results of this work have revealed strategies for optimising cocoa-based agroforestry systems in production areas. They also provide a basis for the development of sustainable development mechanisms and support for the implementation of greenhouse gas emission reduction processes in developing countries. The carbon storage data from this study could be used as a baseline for supporting REDD+ strategies.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

ACKNOWLEDGEMENTS

This study was funded by the African Centre of Excellence on Climate Change, Biodiversity and

Sustainable Agriculture, as part of the PhD programme in Climate Change and Biodiversity. We sincerely thank Felix Houphouët-Boigny University in Abidjan, Côte d'Ivoire, for providing us with the institutional support necessary to carry out this study. We would also like to thank the Coffee and Cocoa Council and the National Agency for Rural Development in the Nawa and Indénié-Djuablin regions of Côte d'Ivoire for giving us access to the databases needed to carry out this study.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Acheampong, E., Dawoe, E., Bosu, P., & Asante, W. (2014). Moving forward with REDD+ in Ghana: Shade systems, crown cover, carbon stocks, and socio-economic dynamics of smallholder cocoa agroforestry systems. Global Coordinator REAP Programme, 96 p.

Adou Yao, C. Y., & N'guessan, E. K. (2006). Spontaneous floristic diversity of coffee and cocoa plantations in the Monogaga classified forest, Côte d'Ivoire. *Schweiz. Z. Forstwes.*, 157(2), 31-36. https://doi.org/10.3188/szf.2006.0031

Alemagi, D., Duguma, L., Minang, P. A., Nkeumoe, F., Feudjio, M., & Tchoundjeu, Z. (2014). Intensification des systèmes agroforestiers cacaoyers dans le cadre d'une stratégie REDD+ au Cameroun : Obstacles, motivations et défis. *International Journal of Agricultural Sustainability*, 13(3), 187-203. https://doi.org/10.1080/14735903.2014.940705

Andrade, H. J., Segura, M. A., Somarriba, E., & Villalobos, M. (2008). Valoración biofísica y financiera de la fijación de carbono por uso del suelo en fincas cacaoteras indígenas de Talamanca, Costa Rica. *Agroforestería en las Américas*, 46, 45-50.

Aubréville, A. (1959). *The forest flora of Côte d'Ivoire*.

Ballesteros-Possú, W., Valencia, J. C., & Navia-Estrada, J. F. (2022). Assessment of a cocoa-based agroforestry system in the southwest of Colombia. *Sustainability*, 14, 9447. https://doi.org/10.3390/su14159447

Béhaghel, I. (1995). *Summary of trials of Terminalia superba (fraké-limba) provenances in Côte d'Ivoire and Congo*. Abidjan: CIRAD-Forêt, 37 p.

Bose, D., Bhattacharya, R., Kaur, T., Pandya, R., Sarkar, A., Ray, A., ... & Chemudupati, R. I. (2024). Innovative approaches for carbon capture and storage as crucial measures for emission reduction within industrial sectors. *Carbon Capture Science & Technology*, 12, 100238.

Cerny, C. (2024). *Quantification des stocks de carbone et évaluation de la biodiversité ligneuse des cacaoyères agroforestières de l'ouest de la Côte d'Ivoire (Man, district des montagnes)* [Master's thesis, Liège University, Belgium], 80 p.

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B. W., Ogawa, H., Puig, H., Riéra, A., ... & M. M. Réjou (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, 20, 3177-3190.

Chave, J., Réjou, M. M., & Burquez, A. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, 20, 3177-3190.

Cissé, A., Aka, K. J. C., Kouamé, D., Vroh, B. T. A., Adou, Y. Y., & N'guessan, E. (2016). Caracterisation des pratiques agroforestières à base de cacaoyers en zone de forêt dense semi-décidue : Cas de la localité de Lakota (Centre-Ouest, Côte d'Ivoire). *European Scientific Journal*, 12(21), 50-69. https://doi.org/10.19044/esj.2016.v12n21p50

Cuny, P., Plancheron, F., Bio, A., Kouacou, E., & Morneau, F. (2023). La forêt et la faune de Côte d'Ivoire dans une situation alarmante, Synthèse des résultats de l'Inventaire forestier et faunique national. *Bois et Forêts des Tropiques*, 355, 47-72.

Dasgupta, K., & Mahanty, A. (2024). Carbon sequestration in a changing climate: Management techniques and strategic solutions. *Asian Research Journal of Agriculture*, 17(4), 703–713.

Dawoe, E., Asante, W., Acheampong, E., & Bosu, P. (2016). Shade tree diversity and above-ground carbon stocks in *Theobroma cacao* agroforestry systems: Implications for REDD+ implementation in a West African cacao landscape. *Carbon Balance and Management*, 11, 17.

Diomandé, M., Kpan, O. J. G., Koffi, R. K., Koffi, A., & Biémi, J. (2022). Gestion intégrée des risques climatiques sur la production du cacao en Côte d'Ivoire. *ResearchGate*, 977-993.

Données Mondiales. (2025). Données climatiques et météorologiques. https://www.donneesmondiales.com/

Doumbia, M., Sib, O., Kouame, Y. A. G., Soro, S., Yeboué, N. L., & Traore, K. (2024). Importance, diversity, and economic value of trees associated with cocoa trees in different agroforestry systems. *World Journal of Advanced Research and Reviews*, 24(2), 2423–2439.

Dugasseh, F. A., & Zandersen, M. (2025). Farmer perceptions of REDD+ livelihood interventions as incentive mechanisms for reducing deforestation in the Juabuso-Bia cocoa forest landscape. *Forest Policy and Economics*, 175, 103494. https://doi.org/10.1016/j.forpol.2025.103494

Gnagbo, A., Pagny, F. P. J., Voui Bi, B. N. B., Guehi, L., Tiebré, M.-S., & Adou Yao, C. Y. (2024). Evaluating carbon sequestration and biodiversity in cocoa agroforestry systems: A case study from the Man region, Côte d'Ivoire. *International Journal of Environment and Climate Change*, 14(10), 691-700.

Grajales, J., & Toukpo, O. (2024). Production de cacao vert: La déforestation, l'héritage de guerre et capitalisme agraire en Côte d'Ivoire. *Journal of Agrarian Change*, 20 p. https://doi.org/10.1111/joac.1260

Guillaumet, J. L., & Adjanohoun, E. (1971). *La végétation de la Côte d'Ivoire*. Horizon Documentation IRD, 104 p.

Gyau, A., Smoot, K., & Diby, L. (2015). Drivers of tree presence and densities: The case of cocoa agroforestry systems in the Soubre region of the Republic of Côte d'Ivoire. *Agroforestry Systems*, 89, 149-161. https://doi.org/10.1007/s10457-014-9750-1

Hawthorne, W., & Gyakari, N. (2006). *Photoguide for the forest trees of Ghana: A tree-spotter's guide*. Hawthorne, W. D., & Jongkind, C. C. (2006). *Woody plants of western African forests*.

IPCC. (2006). *IPCC guidelines for national greenhouse gas inventories. Forestry*. The Institute for Global Environmental Strategies (IGES), Japan.

IUCN. (2015). *IUCN Red List of threatened species. Version 11*. IUCN Species Survival Commission. Gland, Switzerland and Cambridge, 37 p.

Jagoret, P., Saj, S., & Carimentrand, A. (2020). Agroforestry cocoa farming in Africa: The art of reconciling sustainable production and ecological services. CIRAD, 4 pages.

Koffi, A. B., Tondoh, E. J., Ehouman, E., Freycon, V., Piponiot, C., Amani, B. H. K., Aussenac, R., Kouadio, B. K., Kouamé, T. R., & Hérault, B. (2025). Drivers of soil organic carbon recovery during secondary succession along a West African climate gradient. *Ecological Indicators*, 178, 2-11.

Koko, L. K., Snoeck, D., Lekadou, T. T., & Assiri, A. A. (2013). Cocoa-fruit tree intercropping effects on cocoa yield, plant vigour, andlight interception in Côte d'Ivoire. *Agroforestry Systems*, 87, 1043-1052. https://doi.org/10.1007/s10457-013-9619-8

Konan, A. B. (2024). Economic impact of cocoa culture in Ivory Coast and in Ghana from 1980 to 2015. *Historical Archives & Anthropological Sciences*, 9(2), 62–67.

Konan, G. D., Kpangui, K. B., Kouakou, K. A., & Barima, Y. S. S. (2023). Typology of cocoa-based agroforestry systems according to the cocoa production gradient in Côte d'Ivoire. *International Journal of Biological and Chemical Sciences*, 17(2), 378-391.

Koné, M., Kouadio, K., Kouadio, Y. L., Neuba, D. F. R., & Malan, D. F. (2014). Dégradation de la forêt dense humide tropicale, cas de la région de l'indénié-Djuablin à l'est de la Côte d'Ivoire. *Journal of Animal and Plant Sciences, 21*(3), 3324–3338.

Kouadio, K. A. L., Kouakou, A. T. M., Zanh, G. G., Jagoret, P., Bastin, J-P., & Yao, B. S. S. (2025). Floristic structure, potential carbon stocks, and dynamics in cocoa-based agroforestry systems in Côte d'Ivoire (West Africa). *Agroforestry Systems, 99*, 12.

Kouamé, M. L. O., Egnankou, M. W., & Traoré, D. (2009). Ordination and classification of vegetation in the wetlands of south-eastern Côte d'Ivoire. *Agronomie Africaine, 21*(1), 1–13.

Kouao, J. M., Kouassi, A. M., & Kouamé, K. A. (2022). Prévision de la sécheresse météorologique et agrométéorologique dans un contexte de changements climatiques en Afrique de l'Ouest : Cas de la Côte d'Ivoire. *Revue Ivoirienne des Sciences et Technologie, 40*, 279–307.

Kouassi, G., Hounpkatin, K. O. L., Tondoh, E. J., Diby, L., & Kouamé, C. (2025). Mapping soil organic carbon as soil health indicator of cocoa landscapes in middle Côte d'Ivoire. *International Soil and Water Conservation Research*. In press.

Kouassi, J-L., Gyau, A., Diby, L., Bene, Y., & Kouamé, C. (2021). Assessing land use and land cover change and farmers' perceptions of deforestation and land degradation in South-West Côte d'Ivoire, West Africa. *Land, 10*, 429. https://doi.org/10.3390/land10040429

Kougbo, M., Malan, D., Dogba, M., & Konan, A. (2020). Pratiques culturales et diversité des ligneux compagnons dans les exploitations cacaoyères et hévéicoles à l'est de la Côte d'Ivoire. *African Crop Science Journal, 28*(2), 177–194. https://doi.org/10.4314/acsj.v28i2.4

Koulibaly, A., Amon, A. D., Konan, D., Goetze, D., & Traoré, K. (2017). Evaluation of the impact of the "clearing practice" on vegetation for sustainable cacao culture in Côte d'Ivoire. *International Journal of Science and Research (IJSR), 6*(1), 44–50.

Kumah, F. J., Kouabenan, A., Gebrekirstos, A., Koné, D., & Adjei-Nsiah, S. (2024). Les perceptions des agriculteurs et les facteurs socio-économiques influencent-ils les pratiques agroforestières du cacao et la gestion durable du carbone des sols en Afrique de l'Ouest? *Agroforestry Systems, 98*, 797–815. https://doi.org/10.1007/s10457-023-00950-z

Lau, H. C., Ramakrishna, S., Zhang, K., & Radhamani, A. V. (2021). The role of carbon capture and storage in the energy transition. *Energy & Fuels, 35*(9), 7364–7386.

Li, P., & Nath, A. J. (2024). The history and revival of swidden agriculture research in the tropics. *CABI Agriculture and Bioscience, 5*, 84.

Lipchitz, A., & Pouch, T. (2008). Les mutations des marchés mondiaux du café et du cacao. *Géoéconomie, 44*(1), 1–21. https://doi.org/10.3917/geoec.044.0101

Maathuis, I., & Borrell, V. (2022). The potential of agroforestry to enhance climate resilience in Côte d'Ivoire. *ResearchGate*. https://www.researchgate.net

Madountsap, T. N., Zapfack, I., Chimi, D. C., Kabelong, B. L.-P., Forbi, P. F., Tsopmejio, T. I., Tajeukem, V. C., Ntonmen, Y. A. F., Tabue, M. R. B., & Nasang, J. M. (2018). Carbon storage potential of cacao agroforestry systems of different age and management intensity. *Climate and Development*, 12 p.

Mokany, K., Raison, R. J., & Prokushkin, A. S. (2006). Critical analysis of root: shoot ratios in terrestrial biomes. *Global Change Biology, 12*(1), 84–96.

N'Dah, K. C., Koulibaly, A., Coulibaly, S., Boko, B., Dramane, K., Diomandé, V.-A., & Kouadio, Y. (2022). Potentiel de régénération naturelle des espèces ligneuses associées dans les agrosystèmes cacaoyers traditionnels de la zone rurale de Djèkro (Daloa, Côte d'Ivoire). *Agronomie Africaine, 33*(1), 97–108. https://www.ajol.info/index.php/aga/article/view/224383

Nikiema, D., Mouloungui, Z., Koua, O. K., Sandjon, B., Raynaud, C., Cerny, M., Fabre, J-F., Merah, O., Lacroux, E., Adjou, A., & Valentin, R. (2024). Overview of the establishment and uses of *Ricinodendron heudelotii* (Euphorbiaceae): Focus on the central and southern regions of Ivory Coast. *OCL, 31*, 12.

Olwig, M. F., Asare, R., Vaast, P., & Bosselmann, A. S. (2024). Can agroforestry provide a future for cocoa? Implications for policy and practice. In M. F. Olwig, A. S. Skovmand Bosselmann, & K. Owusu (Eds.), *Agroforestry as climate change adaptation* (pp. 1–19). Palgrave Macmillan. https://doi.org/10.1007/978-3-031-45635-0_6

Osseni, B., Diomandé, M., & CIRAD-IRFA. (1989). Importance of fallow land in traditional farming systems in Côte d'Ivoire. *Fruits, 44*(1), 13–19.

Pardré, J., & Bouchon, J. (1988). *Dendrometry* (2nd ed.). National School of Rural Engineering, Water and Forestry (ENGREF), Nancy, France.

Plas, B. (2020). Les cacaoyères agroforestières de la région de Man : Un système de culture à l'agonie ou l'émergence d'une stratégie post-forestière. Mémoire de Master en Agroécologie, Université de Liège, Belgique, 86 p.

Ramade, F. (1994). Qu'entend-on par biodiversité et quels sont les problématiques et les problèmes inhérents à sa conservation? *Bulletin de la Société Entomologique de France, 99*(1), 7–18.

Rondeux, J. (1993). *La mesure des arbres et des peuplements forestiers*. Presses Agronomiques de Gembloux, 738 p.

Saj, S., Jagoret, P., Mvondo Sakouma, K., Essobo, J.-D., Bouambi, E., & Todem-Ngogue, H. (2018). Chapitre 6- Compromis entre séquestration de carbone, conservation et productivité dans les systèmes agroforestiers à base de cacaoyers au Centre-Cameroun. *Éditions Quæ*, 99–112.

Sanial, E., & Ettien, R. (2022). Les arbres des cacaoyères : Recueil de connaissances paysannes sur les interactions entre arbres compagnons et cacaoyers en Côte d'Ivoire. *Nitidae*, 95 p.

Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication*. University of Illinois Press, 117 p.

Smith, D. E., Gnahoua, G. M., & Ohouo, L. (2014). Farmers in Côte d'Ivoire value integrating tree diversity in cocoa for the provision of ecosystem services. *Agroforestry Systems, 88*,1047–1066. https://doi.org/10.1007/s10457-014-9679-4

Tagbi, K. A., Radji, R., Adjonou, K., Kokutse, A. D., & Kokou, K. (2015). Evaluation des paramètres de croissance des essences forestières locales en plantation au Togo : Cas de *Terminalia superba* Engl. & Diels et *Terminalia ivorensis* A. Chev. *European Scientific Journal, 11*(33), 225–241.

Vervuurt, W., Slingerland, M. A., Pronk, A. A., & Van Bussel, L. G. J. (2022). Modélisation des émissions de gaz à effet de serre de la production de cacao en République de Côte d'Ivoire. *Système Agroforestier, 96*, 417–434. https://doi.org/10.1007/s10457-022-00729-8

Vroh, B. T. A., Abrou, N. E. J., Gone Bi, Z. B., & Adou Yao, C. Y. (2019). Système agroforestier à cacaoyers en Côte d'Ivoire : Connaissances existantes et besoins de recherche pour une production durable. *Revue Marocaine des Sciences Agronomiques et Vétérinaires, 7*(1). https://agrimaroc.org/index.php/Actes_IAVH2/article/view/675

Walkley, A., & Black, I. A. (1934). An examination of the *Degtjareff* method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science, 37*(1), 29–38.

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/146360