Original Research Article

Evaluating Carbon Sequestration and Biodiversity in Cocoa Agroforestry Systems: A Case Study from the Man Region, Côte d'Ivoire.

ABSTRACT

Aims: Cocoa-based agroforestry systems in the Man region of Côte d'Ivoire are essential for balancing agricultural productivity and environmental preservation. This study assessed these systems regarding plant biodiversity conservation and carbon sequestration.

Study Design and Methodology: The research was carried out in 21 cocoa plantations, aged between 14 and 32 years, across 60 botanical inventory plots, each measuring 10 by 20 meters. Tree heights and diameters were recorded to estimate Above Ground Biomass (AGB) using the equation AGB = 0.0673 × $(\rho D^2 H)0.976$, where D is diameter, H is height, and ρ is specific density. Below Ground Biomass (BGB) was calculated as BGB=AGB×0.24, while total biomass (BT) was obtained as BT=AGB+BGB. Carbon stock (C) was derived using C=BT×0.5. Statistical analysis was applied to compare mean carbon stocks across different plantation ages.

Results: The plantations, ranging from 8 to 32 years old, showed a diversity of companion species. The diversity of companion species in cocoa agrosystems varies from 4 in 8–10-year-old plantations to 12 in 14- and 15-year-old plantations. Carbon sequestration was age-dependent: younger plantations (5-10 years) sequestered 19.77 ± 2.32 tonnes per hectare, plantations aged 10-15 years stored 133.70 ± 253.50 tonnes, while middle-aged plots (15-20 years) reached 398.76 ± 861.51 tonnes. The oldest plantations (30-35 years) sequestered 137.94 ± 280.31 tonnes. Effective plantation management increased both carbon sequestration and biodiversity.

Conclusion: The study highlights the importance of species diversity and continuous management in cocoa-based agroforestry systems. Optimized agroecological practices enhance biodiversity conservation and carbon sequestration, providing practical insights for stakeholders involved in agricultural sustainability, biodiversity conservation, and climate change mitigation. Cocoa agroforestry aligns economic and environmental objectives, offering a sustainable agricultural model.

Keywords: *Theobroma cacao, climate change, carbon credit, agrotechnology*

1. INTRODUCTION

Sustainable management of natural resources has emerged as a critical global concern, particularly in light of the challenges presented by climate change and biodiversity loss [1]. Agriculture, as the predominant land use, plays a significant role in exacerbating these issues [1]. The extensive conversion of forested areas into agricultural land results in severe ecological consequences, including the loss of biodiversity, soil degradation, and climate change, which is further aggravated by agricultural runoff affecting adjacent waterways and causing eutrophication, leading to the formation of dead zones that are detrimental to marine life [1]. In order to address these challenges, it is imperative to adopt sustainable agricultural practices, such as agroecology and organic farming, which can enhance ecosystem services while maintaining agricultural productivity in the face of changing climatic conditions [1]. As highlighted by [2], agroforestry systems are particularly promising in this regard, as they integrate trees and crops to boost biodiversity and sequester carbon, while improving ecosystem services. These practices are essential for building resilient food systems and combating the environmental impacts of conventional agriculture [1,2].

In Côte d'Ivoire, where agriculture is a key driver of deforestation, the need for sustainable practices is even more pressing [3]. The cultivation of Theobroma cacao has markedly accelerated deforestation, primarily through an extensive agricultural model that has converted large expanses of tropical forests into cocoa plantations [3]. This rapid deforestation has been particularly pronounced in regions with high concentrations of cocoa cultivation, resulting in a dramatic reduction of forest cover from 12 million hectares in 1960 to approximately 3 million hectares by 2015—an estimated loss of nearly 75% [4]. This environmental degradation not only threatens biodiversity but also undermines the long-term sustainability of the cocoa sector itself [4]. [5] argue that agroforestry, especially when applied to cocoa systems, offers a valuable solution by mitigating deforestation while enhancing carbon sequestration. Such systems can restore degraded lands, support biodiversity, and increase resilience to climate change, making them an essential tool for sustainable resource management in cocoa-growing regions [5]. Building on this, [6] stress that cocoa agroforestry systems in West Africa are crucial for sustaining ecosystem services, which are vital for both environmental health and the livelihoods of local communities.

Given the importance of addressing both environmental and agricultural challenges, this study seeks to evaluate the potential of cocoa-based agrosystems for the sustainable management of plant biodiversity and carbon sequestration in the Man region of western Côte d'Ivoire. Specifically, the study will analyze how these systems affect biodiversity conservation and carbon storage, shedding light on their broader ecological benefits. [7,8] emphasize that smallholder agroforestry systems, such as those implemented in cocoa farms, have the potential to sequester significant amounts of carbon while maintaining agricultural productivity. This highlights the need for research that can guide land management strategies aimed at balancing productivity with environmental preservation [9]. Furthermore, understanding the carbon sequestration potential of cocoa agrosystems could inform policy decisions that promote sustainable farming practices, helping to combat climate change and conserve biodiversity [10]. Additionally, the study may open up economic opportunities, particularly through carbon credit programs, where local producers could benefit financially while contributing to global climate mitigation efforts [10]. This research highlights cocoa agroforestry's ecological and economic benefits, offering sustainable agricultural solutions for biodiversity conservation and climate change mitigation [10].

2. MATERIAL AND METHODS

2.1 STUDY AREA

This study took place in the Man region, western Côte d'Ivoire, an area known as the new cocoa loop due to its high cocoa production and diverse cropping systems [11,12]. Fieldwork was conducted in the villages of Gloyogouin, Dakouipleu, and Goziogouiné, where agriculture, particularly coffee and cocoa, dominates. Food crops like rice, maize, and cassava are also cultivated [11,12]. The region experiences a humid tropical climate with annual rainfall between 1,600 and 2,500 mm, characterized by an eight-month rainy season (March to October) and a four-month dry season (November to February) [11,12]. Average annual temperatures range from 24.8°C to 28.5°C [11,12]. The area's vegetation includes semi-deciduous dense forests, open forests, savannas (wooded, tree, and shrub), and mountain forests [11,12].

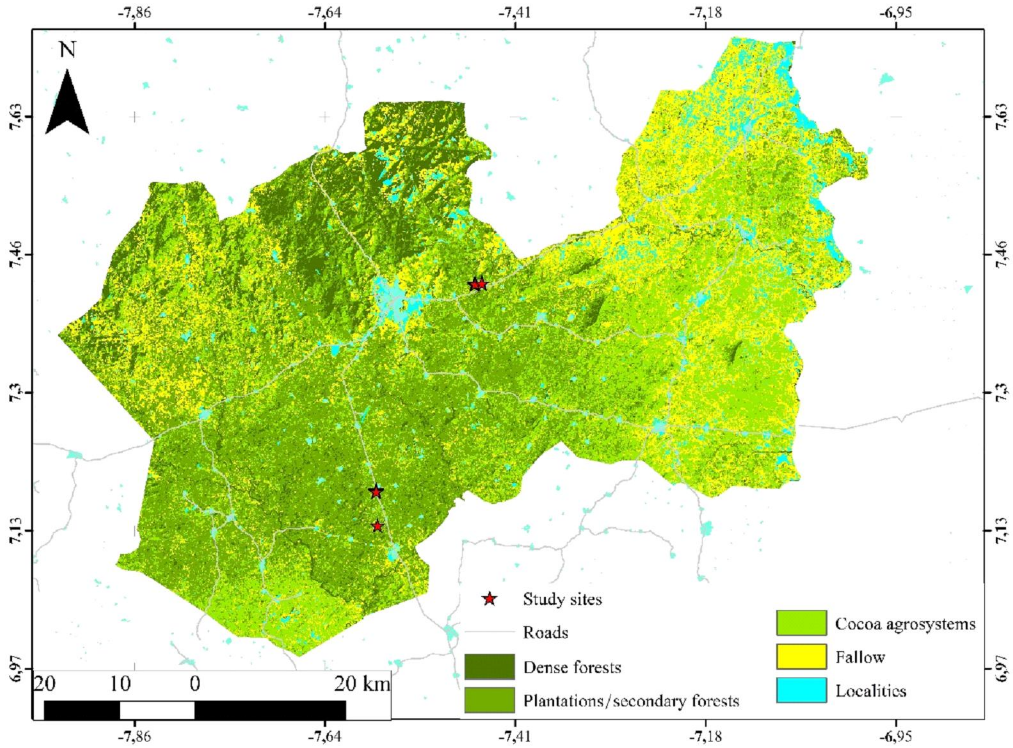

Fig.1. Presentation of the study site

2.2. SAMPLING PLAN

In each village, inventory plots were created according to the age and cropping system of cocoa plantations to analyze the relationship between agroforestry practices and both carbon sequestration and biodiversity. The selected sites reflect the region's prominence in cocoa production and showcase a range of agroforestry practices, providing an ideal setting for ecological and agricultural evaluations. Rectangular plots (20 m x 10 m) were used for botanical inventories in these plantations, and 2 to 5 plots were established per plantation depending on size. These plots were large enough to capture representative woody plants, including cocoa trees, while allowing for efficient species diversity assessments [11,12].

In total, 60 plots were set up across 21 cocoa plantations. This number ensures robust data collection by accounting for spatial variability in the agroforestry systems. The chosen method aims to assess plant biodiversity and carbon sequestration potential across the diverse agroforestry landscapes. Field measurements included tree diameter at breast height (DBH) and total height, which are essential inputs for allometric equations used to calculate the aboveground biomass (AGB) of each tree. These equations, which integrate specific wood density values, allow for accurate biomass estimates. This approach captures variability in plantation age, crop association, and management practices, offering insights into the ecological dynamics of these agroforestry systems [13].

2.3. DATA ANALYSIS

The aboveground biomass (AGB) for both associated trees and cocoa trees was calculated using an allometric equation developed by Chave and Réjou-Méchain, which is suited for dense, humid semi-deciduous forests [13]. The equation: $AGB = 0.0673 \times (\rho D^2 H)0.976$, where ρ is the specific wood density, D the tree diameter, and H the total height, provided precise biomass estimates. A standard wood density value of 0.58 g/cm^3 was applied for this analysis [14]. In this study, we used a standard density value of 0.58 g/cm^3, as recommended in the literature [14].

The belowground biomass (BGB) was estimated following IPCC guidelines, using the formula $BGB = AGB \times 0.24$, which reflects findings that root biomass accounts for roughly 24% of the total aboveground biomass [15]. The total biomass (BT) was then determined by summing the AGB and BGB, and carbon stock was estimated as $C = BT \times 0.5$, assuming that carbon constitutes 50% of the total biomass [15]. This approach is based on previous studies that indicate root biomass represents approximately 24% of aboveground biomass [15].

To analyze carbon sequestration and plant diversity, species were grouped into five strata based on diameter class:]0–5],]5–10],]10–15],]15–20], and]25– [. This classification allowed the study to explore the vertical structure of the vegetation and its relationship with biodiversity and carbon sequestration capacity. Each stratum reflects different ecological characteristics [16]. For example, the smallest stratum]0–5] represents young individuals essential for species regeneration, while]5–10] includes denser, medium-sized individuals, which play a critical role in carbon storage. The larger diameter classes represent older and mature trees that influence both biodiversity and carbon storage capacity, with the largest trees exerting the most significant effects [16].

Finally, statistical analysis was performed to assess differences in carbon stocks across agroforestry systems based on plot age. Analysis of variance (ANOVA) and Tukey HSD tests at a 95% confidence interval revealed whether variations in carbon stocks were statistically significant [17].

3. RESULTS

3.1. COMPANION PLANTS IN COCOA PLANTATIONS OF VARIOUS AGES

The age of cocoa plantations ranges from 8 to 32 years. There are plantations with companion species as well as strict monospecific plantations without companion species. The youngest plots, aged 8 and 10 years, are observed in the village of Glayogouin. This is an association of food crops with cocoa plantations. The associated food plants *are Manihot esculenta*, *Colocasia esculenta* and *Xanthosoma mafaffa*. *Spondias mombin* is the only woody species tolerated in this agrosystem. 14- and 15-year-old plantations were visited in the village of Dakouipleu. In 14- and 15-year-old cocoa plantations, a total of 12 companion species were identified in the cocoa-based agroforests, with *Persea americana* and *Coffea canephora* being the most prevalent (Fig. 2). Ten (10) companion species were recorded in cocoa plantations aged 16 and 20 years (Fig. 3). The most commonly encountered are *Cola nitida*, *Sterculia tragacantha* and *Albizia adianthifolia*. Agrosystems aged 30 years are observed in the villages of Glayogouin and Gôziogouiné. Cola nitida is essentially the companion species encountered in these cocoa plantations (Fig. 4). A 32-year-old plantation in Glayogouin has only *Citrus sinensis* and *Terminalia ivorensis* as companion species.

Fig.2. Companion species observed in 14- and 15-year-old cocoa plantations

Fig. 3. Companion species observed in 16- and 20-year-old cocoa plantations.

Fig.4. Companion species observed in 30-year-old cocoa plantations

3.2. DISTRIBUTION OF INDIVIDUALS ACCORDING TO STRATUM LEVELS

*Theobroma ca*cao individuals are observed to have maximum heights of less than 7 meters. In the cocoa agroforestry systems studied, the vertical structure of the plantations is primarily composed of companion species. The average values per inventory plot are presented in Table 1, which shows the distribution of individuals across five height strata (measured in meters):]0 – 5],]5 – 10],]10 – 15],]15 – 20], and]25 – [. The]0 – 5] stratum exhibits the lowest average density, with 26.09

individuals per hectare, although it shows considerable variation (±58.50). In contrast, the]5 – 10] stratum records the highest density, reaching 89.13 individuals per hectare. However, the density decreases to 21.74 individuals per hectare in the]10 – 15] stratum, and continues to decline in the]15 – 20] stratum, which contains only 10.87 individuals per hectare.

Table 1. Average distribution of individuals according to stratum levels

Strata (meters)	Average individuals (individuals/hectare)
]0 – 5]	26.09±58.50
]5 – 10]	89.13±163.44
]10 – 15]	21.74±26.48
]15 – 20]	10.87±22.53
]25 – [	34.78±124.70

3.3. CARBON SEQUESTRATION IN COCOA PLANTATIONS

In young plantations aged 5 to 10 years, the estimated average aboveground biomasses are of the order of 31.88±3.75 tonnes per hectare. The average belowground biomass obtained is 7.65±0.90 tonnes per hectare. The resulting average total biomass is 39.53±4.65 tonnes per hectare. The carbon sequestered in plantations aged 5 to 10 years is 19.77±2.32 tonnes per hectare.

In plantations aged 10 to 15 years, the average values collected for aboveground biomass allow an estimate of 215.64±408.87 tonnes per hectare. The resulting belowground biomass is 51.75±98.13 tonnes per hectare. The average value of total biomass is of the order of 267.40±507.00 tonnes per hectare. Plantations aged 10 to 15 years have an average carbon sequestration estimated at 133.70±253.50 tonnes per hectare.

As for medium-aged plantations, i.e. plots between 15 and 20 years old, the average value of above-ground biomass is 643.17±1389.52 tons per hectare. The estimated below-ground biomass has an average value of 154.36±333.49 tons per hectare. This allows for an estimate of the total biomass of 797.53±1723.01 tons per hectare. The carbon sequestered in plantations between 15 and 20 years old has an average value of 398.76±861.51 tons per hectare.

For the oldest plantations, those between 30 and 35 years old, the average values obtained for aboveground biomass are of the order of 222.49±452.12 tonnes per hectare. The belowground biomass resulting from this estimate is 53.40±108.51 tonnes per hectare. The total biomass of the oldest plots is estimated at 275.89±560.63 tonnes per hectare. Finally, the carbon stored by plantations aged 30 to 35 years is estimated at 137.94±280.31 tonnes per hectare.

Analysis of variance ($F = 0.73$; $\rho = 0.54$) performed on carbon stocks showed no significant difference. The age of plantations of *Theobroma cacao*-based agroforestry systems has no influence on the amount of carbon stored in inventory plots in the Man region.

4. DISCUSSION

4.1. DIVERSITY AND SPECIES ASSOCIATIONS IN COCOA-BASED AGROFORESTRY SYSTEMS

In cocoa-based agroforestry systems, there is a diversity of age and associated species, highlighting the dynamic nature of these ecosystems. Younger plantations are typically intertwined with food crops such as *Manihot esculenta*, *Colocasia esculenta*, and *Xanthosoma mafaffa*, which not only provide immediate nutritional benefits but also enhance the overall productivity of the system. As these agroforests mature, a distinct transition occurs, revealing a strong association with species like *Persea americana* and *Coffea canephora*. This shift underscores the importance of specific interactions between plants at different growth stages. In older plantations, the presence of species such as *Cola nitida* and *Citrus sinensis* indicates a further evolution in the agroforestry landscape, reflecting a more complex ecological framework. These findings align with previous studies demonstrating that integrating food crops with forest trees in cocoa plantations promotes resilience and enhances biodiversity within agroforestry systems [5]. Moreover, the association of companion species plays a vital role in maintaining soil fertility, providing protection against climatic hazards, and optimizing agricultural production within a sustainable framework [2]. This interconnectedness is further illustrated by the distribution of individuals according to their height, which highlights a multi-storey structure typical of diversified agroforests [18]. While older cocoa plantations may exhibit reduced diversity, they nonetheless continue to play a crucial role in carbon storage, as noted by [19]. The presence of companion trees in these systems significantly contributes to biomass accumulation and carbon sequestration, thereby reinforcing their ecological and economic value. In summary, the interactions between age, species diversity, and agroforestry practices are fundamental to the sustainability and productivity of cocoa-based systems.

4.2. CARBON SEQUESTRATION IN COCOA-BASED AGROFORESTRY SYSTEMS

The absence of significant differences in carbon stocks according to the age of the plantations can be largely explained by the variability in plot management systems. Specifically, the establishment and maintenance of companion species play a crucial role in modulating biomass accumulation and influencing carbon sequestration capacity [20]. This is particularly relevant because agroforestry systems are inherently heterogeneous, and their ability to store carbon is contingent upon various factors, including species diversity, the management of companion species, and agricultural practices [21]. It is essential to note, however, that the declared age of the plantations is generally based on the establishment date of the cocoa trees. This factor can be confounding, as plantations often experience frequent replacements of individuals due to tree mortality, diseases, or specific cultural practices. Consequently, even though certain plantations may be categorized as "old," they frequently contain a substantial proportion of relatively young individuals, which can significantly influence the overall plant cover [22]. These observations are corroborated by other studies demonstrating that cocoa mortality in agroforestry systems leads to a continuous turnover of individuals. [5] emphasize that trees are often replaced by young plants to sustain production, indicating that age heterogeneity among individuals is common within plantations. Moreover, the management of plantations over time, characterized by the integration or elimination of companion species and the introduction of new cocoa plants, contributes to maintaining ecological dynamism despite the overall age of the plot [23]. The variability in the age of individuals, even within plantations considered old, can also impact the systems' capacity to sequester carbon. Younger trees generally exhibit faster growth rates and can thus accumulate more biomass in a shorter period. In contrast, older trees contribute to the stability of the system regarding long-term carbon sequestration [24]. These intra-plot dynamics are crucial for understanding the variations observed in biomass and sequestered carbon across different plantation age classes, as illustrated by the results of this study. Consequently, while plantation age serves as a useful indicator, it does not necessarily reflect the actual population structure of cocoa trees within plots. This discrepancy may partly explain the considerable variations observed in carbon stocks and biomass values across different age classes. Such dynamics of individual replacement underscore the importance of considering not only the overall age of plantations but also their internal composition and the management practices that influence their structure [2]. By recognizing these complexities, we can gain a more nuanced understanding of the factors affecting carbon sequestration and biomass dynamics in cocoa agroforestry systems.

4.3. IMPLICATIONS OF THE STUDY FOR BIODIVERSITY CONSERVATION AND CARBON SEQUESTRATION IN COCOA PLANTATIONS

This study offers significant implications for various stakeholder groups, including agroforestry practitioners, policymakers, researchers focused on climate change mitigation, and conservationists. It highlights the importance of managing cocoa plantations as sustainable agroforestry systems. For agroforestry practitioners, integrating companion species and adopting sustainable agricultural practices can enhance yields and the systems' capacity to sequester carbon, encouraging strategies that promote biodiversity while maintaining agricultural productivity. For policymakers, the findings can inform land management policies by emphasizing the role of agroforestry systems in carbon sequestration and biodiversity conservation. This information could aid in developing policies that support the implementation of agroforestry practices, fostering integrated approaches to sustainable agriculture and climate change mitigation. Researchers will find a wealth of information that enriches the understanding of agroforestry systems' effects on climate, underscoring the need for further exploration of the complex interactions between species diversity, crop management, and carbon sequestration. This study also stimulates future research on optimizing the resilience of agricultural systems in the face of environmental challenges.Finally, for conservationists, the results emphasize the importance of biodiversity in cocoa agroforestry systems. It suggests that biodiversity conservation should extend beyond protected areas to be integrated into agricultural practices, potentially prompting advocacy for its incorporation into land management strategies.

5. CONCLUSION

This study highlights the diversity of agroforestry practices and the complexity of cocoa plantations in the Man region. The plantations studied, although ranging in age from 8 to 32 years, reveal a varied internal composition, with a significant presence of young individuals, reflecting a constant renewal process over time. This structural heterogeneity, due to cocoa tree replacement practices and the integration of companion species, plays a crucial role in maintaining the productivity and sustainability of the systems. The study also highlights that, despite the advanced age of some plantations, carbon sequestration does not vary significantly according to the reported age of the plantations. This observation can be attributed to the mixed composition of the plots, where young trees, even in older plantations, contribute significantly to biomass accumulation. The diversity of companion species observed in these agroforests shows the importance of agroecological management to maximize ecosystem services, particularly in terms of carbon storage and resilience of systems to environmental challenges. To maximize long-term benefits in cocoa plantations, it's essential to consider both the plots' age and their internal dynamics, like species diversity and management practices. This holistic approach enhances agroforestry sustainability, aids climate change mitigation, and improves farmers' livelihoods.

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DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares 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.

COMPETING INTERESTS

Authors have declared that no competing interests exist

CONSENT (WHERE EVER APPLICABLE)

Not applicable

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