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(Research Article)

Anthropogenic pressure and carbon sequestration potential of agro-systems in the Haut-Sassandra classified forest (Côte d'Ivoire)

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Abstract

To address climate change, it is essential to quantify forest carbon in order to design more appropriate forest management policies. This study assesses the carbon sequestration potential of agrosystems in the Haut-Sassandra Classified Forest (HSCF), a state-owned forest that is highly degraded in Côte d'Ivoire. In the context of increasing deforestation, mainly driven by cocoa cultivation, the research aims to quantify the carbon storage capacity of different land-use configurations. The methodology was based on monitoring vegetation cover from 2018 to 2020 in 12 permanent plots subjected to four treatments:

- Treatment (T1): cocoa plantations with maintenance and pod harvesting;
- Treatment (T2): cocoa plantations without maintenance, with pod harvesting;
- Treatment (T3): cocoa plantations without maintenance or pod harvesting;
- Treatment (T4): natural forest (control).

Floristic inventories and dendrometric measurements were used to analyze plant diversity, aboveground biomass (using allometric equations), and carbon stocks. The results show an increase in species richness and biomass across all treatments, particularly in unmanaged plots (T2 and T3). Carbon stocks increased by 69% (T2) and 77% (T3), compared with only 5% in the natural forest (T4). However, treatment T4 still exhibits the highest overall carbon stock. Although unmanaged plots show a substantial increase in carbon stocks, the forest remains the most important carbon sink.

Keywords: Carbon; Biomass; Permanent plot; Vegetation index; Ecosystems; Agrosystem

1. Introduction

In West Africa, data on forest biomass and carbon stocks remain limited [1]. A major priority for the region, and for Africa as a whole, is to curb deforestation and expand forest cover in order to mitigate the effects of climate change [2].

Côte d'Ivoire, which has diverse vegetation including dense tropical forests, has experienced a substantial decline in its forest heritage. Despite protection measures, the country recorded an annual deforestation rate of 1.86% during the 2000s [3]. Forest area, estimated at more than 15.6 million hectares in the 1980s, declined to less than 2.7 million hectares by 2019 [4]. This decline was exacerbated during the period of political and military instability, which affected even protected areas [5]. The Haut-Sassandra Classified Forest (HSCF), located in the central-western part of the country, exemplifies this trend: it lost 70% of its forest cover between 2002 and 2011, mainly due to agricultural

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expansion particularly cocoa farming and uncontrolled logging [5]. These transformations have led to significant carbon emissions [6], as well as a marked reduction in the vegetation's carbon sequestration capacity resulting from land-use changes.

In response to this situation, permanent plots were established in the HSCF to study the natural regeneration of forest cover. These experimental setups aim to reconcile forest conservation with agricultural activities. Although these studies have provided valuable insights, the biomass recovery potential under each tested scenario remains poorly understood. Moreover, the dynamics of carbon storage within these plots have not yet been analyzed.

This study therefore seeks to address the following questions: (i) What is the structural status of woody biomass in these plots? (ii) How much carbon is sequestered by the permanent plots?

The main objective of this study is to assess the contribution of trees in these plots to atmospheric carbon sequestration.

2. Methodology

2.1. Description of the Study Area

The present study was conducted within the Haut-Sassandra Classified Forest (HSCF), located between 6°52′ and 7°24′ N latitude and 6°59′ and 7°10′ W longitude. This forest has been part of the permanent forest estate of the Ivorian State since November 23, 1974, and covers an area of 102,400 ha. It is situated in the Haut-Sassandra region in the central-western part of Côte d'Ivoire and is bordered to the west by the Sassandra River (Figure 1).

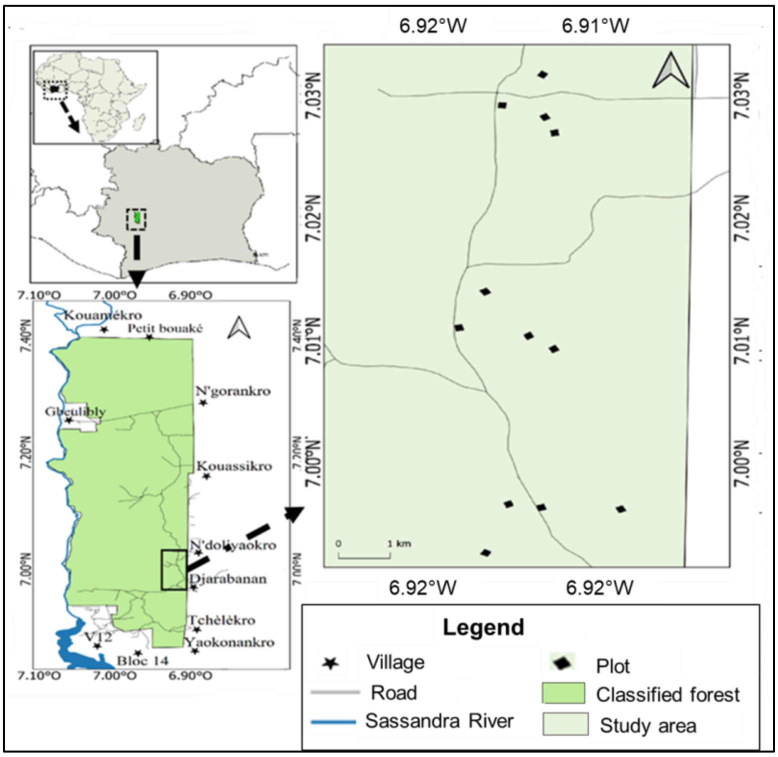


Figure 1 Geographical location of the Haut-Sassandra Classified Forest

The HSCF mainly belongs to the semi-deciduous dense humid forest zone. Its vegetation exhibits a certain degree of variability: (1) the southern and central parts are characterized by forests dominated by *Celtis* spp. and *Triplochiton scleroxylon* [7] and Adjanohoun, 1971); (2) the northern part represents a transition zone toward another type of semi-deciduous dense humid forest dominated by *Aubrevillea kerstingii* (Harms) Pellegr. and *Khaya grandifoliola* C. DC. [8]. The area also includes savanna patches as well as plant communities established on lateritic crusts.

The northern and northeastern periphery of the forest is inhabited by local communities (Gouro and Niédéboua), whose agricultural activities—particularly cocoa and coffee farming—have profoundly altered the environment [9]. Today, cocoa cultivation constitutes the dominant landscape matrix within the classified forest [9]. The specific study site is located in the southeastern part of the HSCF, near the villages of Djarabanan and N'Doly Yaokro (Figure 1).

2.2. Determination of Changes in Tree Diversity and Structure in the Permanent Plots of the HSCF between 2018 and 2020

2.2.1. Data Collection

For this study, an experimental design was established within the agrosystems of the Haut-Sassandra Classified Forest. The experimental setup consisted of 12 permanent plots measuring 50 m × 50 m (2,500 m^2), distributed across three different sites, with four plots per site. These permanent plots were subjected to four treatments related to agricultural activities.

The first treatment (T1) consisted of cocoa plantations in which maintenance activities and pod harvesting by the owner were allowed. The second treatment (T2) consisted of cocoa plantations where maintenance was prohibited but pod harvesting was permitted. The third treatment (T3) consisted of cocoa plantations in which maintenance, pod harvesting, and human access were prohibited. The fourth and final treatment (T4) consisted of forest considered as a control; in this treatment, human access was prohibited.

Within these permanent plots, annual floristic inventories were carried out from 2018 to 2020. The method used was the plot-based survey method. These surveys were conducted in subplots of 625 m^2 each, following the approach described by [10]. Specifically, each permanent plot was subdivided into four subplots measuring 25 m × 25 m (625 m^2), resulting in a total of 12 inventory subplots per treatment, or 48 subplots in total.

Within the 625 m^2 subplots, all woody species were identified, and the circumference of individuals with a diameter greater than or equal to 5 cm was measured.

2.2.2. Data Analysis

Species richness is defined as the number of species recorded within a given area. It is measured by counting all species identified in each permanent plot, without considering their abundance.

Structural diversity makes it possible to assess how plant species occupy space within a permanent plot. It can be evaluated at both horizontal and vertical levels. In this study, only the horizontal level of structural parameters was assessed. Horizontal structure expresses the arrangement and distribution of individuals across the horizontal plane. It is described through several parameters, among which density and basal area were determined in this study.

Density (D) is defined as the number of individuals per unit area [10]. It reflects the occupation of the soil by species. This index was calculated for each treatment using the following formula:

$$D = \frac{N}{S}$$

Where N = number of stems recorded and S = total area expressed in he Equation 1

Basal area represents the sum of the cross-sectional areas of the trunks of all trees within a plot, assuming that the measurement is taken at 1.30 m above ground level [10]. It provides a better representation of the horizontal occupation of space by plant species and allows an assessment of the stability of the vegetation cover. Its formula is as follows:

$$S = \sum_{i=1}^{n} D^2\pi/4 \ldots\ldots 2$$

Where D = diameter at breast height and π = 3.14.

2.3. Determination of Biomass and Carbon Stock over the 2018–2020 Period

Several calculation models exist, among which the allometric models developed by [12] is the most widely used. Regardless of the model adopted, the estimation of the amount of sequestered carbon was carried out in four steps: calculation of aboveground biomass, belowground biomass, total biomass, and deduction of carbon stock.

Aboveground biomass (AGB) was calculated for the species recorded during the inventories using the equation proposed by [12]. The basic mathematical model is as follows:

AGB= $\rho * \exp\left(-1.499 + (2.148 * \ln(D)) + (0.207 * \ln(D)\ 2) - (0.0281 * \ln(D)\ 3)\right)$

Equation 3

Where AGB = aboveground biomass of the tree (kg); D = trunk diameter at 1.30 m above ground; and ρ = species-specific wood density ($g \cdot cm^{-3}$).

Species-specific wood densities were obtained from the following database: the Global Wood Density Database (Zanne et al., 2009). For species whose wood density was unknown, a default value (ρ = 0.58 $g \cdot cm^{-3}$) corresponding to African tropical forests was applied.

However, the allometric equation developed by [12] is not valid for estimating the biomass of individuals with a diameter at breast height (DBH) outside the range of 5–156 cm. It is also not suitable for estimating the biomass of cocoa trees. Biomass estimation for cocoa trees is therefore based on two equations: the equation proposed by [13] for diameters between 1.3 cm and 26.8 cm, and that of [14] for larger diameters. In this study, the equation of [13] was used to estimate the biomass of cocoa trees in the permanent plots. The allometric equation used to calculate cocoa tree biomass is as follows:

AGB = $10^{(-1{,}625) + 2{,}626 + LogD}$

Where AGB = aboveground biomass (kg); D = diameter (m); and log = base-10 logarithm.

Belowground or root biomass (BGB: Belowground Biomass) was predicted from the estimation of aboveground biomass. Root biomass was estimated in accordance with the guidelines established by the [15]. According to these guidelines, the root biomass equivalent of standing vegetation is obtained by multiplying the value of aboveground biomass (AGB) by a coefficient R, whose value is estimated at 0.24:

Equation 4

BGB = AGB × R

Where BGB is the belowground biomass expressed in kg and R is the root fraction (0.24).

Total Biomass (TB) is obtained by summing aboveground biomass and belowground (root) biomass.

TB=AGB+BGB

Equation 5

Where TB = total biomass expressed in kg.

Equation 6

The total biomass estimated using the different equations was converted into the corresponding sequestered carbon stock by multiplying it by 0.5 [15].

TC = TB × 0,5 Equation 7

2.4. Statistical Analyses

Comparison tests are used to highlight relationships between explanatory variables and response variables [16] . Analysis of variance (ANOVA) was applied to compare the results of this study. The ANOVA test allows comparison of within-group variance and between-group variance. It is a parametric analysis, meaning that the measured variable is assumed to follow a normal distribution. The objective of the analysis is to determine whether the mean values measured across different groups are significantly different.

ANOVA is based on three assumptions: independence of observations, normality of the distribution, and homogeneity of variances (homoscedasticity). Normality was assessed using the Shapiro–Wilk test, while homogeneity of variances was verified using Levene's test. The significance level selected for this analysis was 0.05. Whenever the calculated probability was significant, the Kruskal–Wallis test was performed to conduct pairwise comparisons of means and to assess the significant differences among them.

3. Results

3.1. Plant diversity of the permanent plots

Floristic inventories conducted in each treatment allowed the identification of a total of 134 species, belonging to 100 genera and 40 families. The most dominant families were Fabaceae (15%), followed by Malvaceae (11%), Rubiaceae (7%), and Annonaceae, Cannabaceae, Sapotaceae, Meliaceae, and Moraceae (6%) (Figure 2). Conversely, the least represented families were grouped under the category *others*.

Furthermore, across all treatments, 162 species distributed among 128 genera and 28 families were recorded in year 0 (2018), 189 species distributed among 147 genera and 85 families in year 1 (2019), and 222 species distributed among 184 genera and 100 families in year 2 (2020).

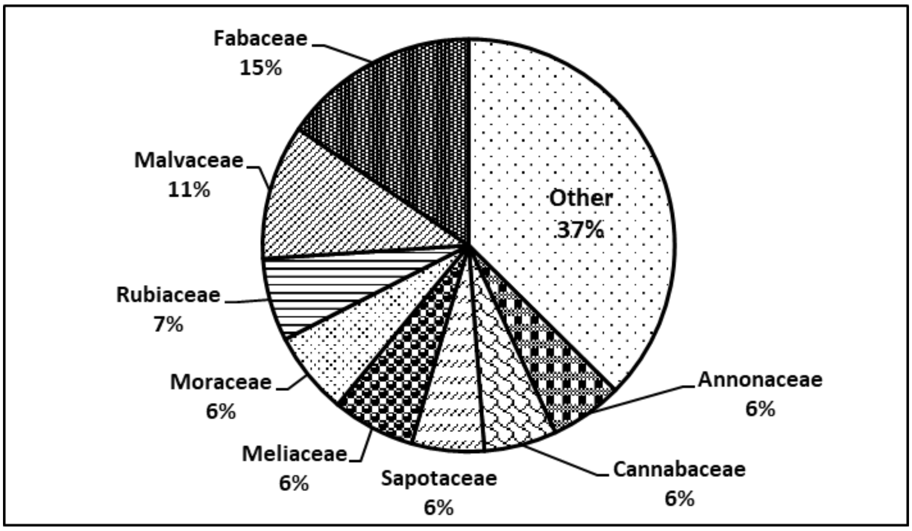
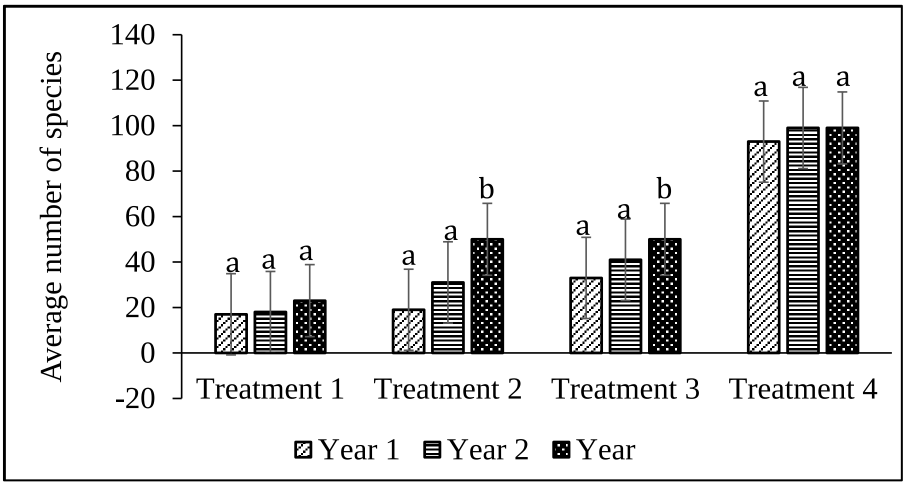


Figure 2 Proportions of plant species families in the permanent plots of the Haut-Sassandra Classified Forest



"Letters on the bars indicate differences in species richness at the 5% significance level according to the Kruskal–Wallis test. Species richness values sharing the same letters are not significantly different within the same treatment."

Figure 3 Changes in species richness across treatments established in the Haut-Sassandra Classified Forest

Figure 3 illustrates the changes in species richness over years 0, 1, and 2. The study shows an increase in the number of species in all treatments over the three monitoring years. Treatment T4 exhibited the highest species richness during each period; however, it showed the lowest growth rate in species richness (6%). In contrast, treatments T1, T2, and T3 displayed a progressive increase in species richness over time. The rates of change from year 0 to year 2 were 35% for T1, 163% for T2, and 52% for T3, respectively.

Statistical tests indicated that for treatments T1 and T4, there was no significant difference in species richness among the different periods, with F = 0.60 and p = 0.001, and F = 0.06 and p = 0.001, respectively. However, for treatments T2 and T3, a significant difference was observed between the species richness of the third period and that of the first two periods, which themselves did not differ significantly (F = 23.62 and p = 0.57; F = 23.65 and p = 0.61, respectively).

3.2. Structural diversity of the permanent plots

3.2.1. Stand density

Figure 4 illustrates the changes in the mean species density according to the forest type and the applied treatments. Overall, an increase in mean density was observed across all treatments. Treatment T1 exhibited the lowest density over the study period (3%). Treatment T3 recorded the highest rate of increase in density (28%), followed by T2 (13%) and the natural forest T4 (13%).

Statistical analyses indicated no significant difference in mean densities among the treatments (F = 0.007; p = 0.99).

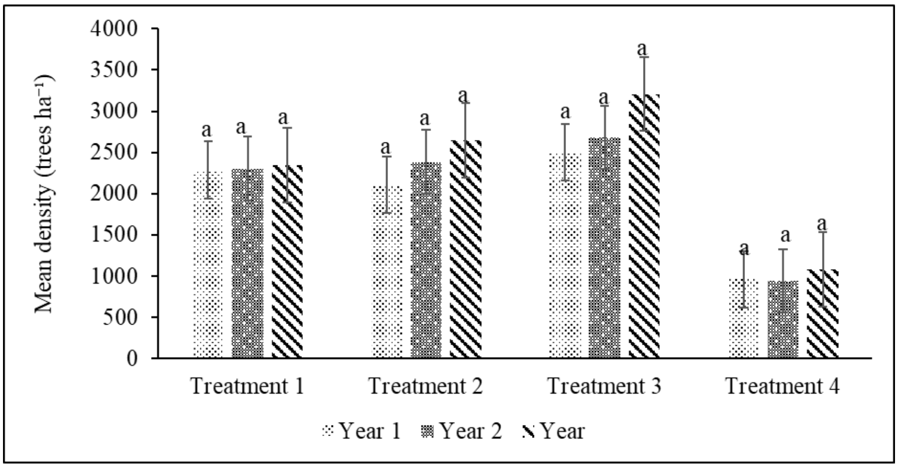


Figure 4 Rate of change in mean density in the permanent plots of the Haut-Sassandra Classified Forest

"Letters on the bars indicate differences in species richness at the 5% significance level according to the Kruskal–Wallis test. Species richness values sharing the same letters are not significantly different within the same treatment."

3.2.2. Basal area of the stands

Figure 5 shows changes in basal area across all treatments in the permanent plots of the Haut-Sassandra Classified Forest. For all treatments combined, the mean basal area was 11.32 m^2 ha^{-1} in year 0, 12.25 m^2 ha^{-1} in year 1, and 48.25 m^2 ha^{-1} in year 2.

Regardless of the year, basal area remained below 0.2 m^2 ha^{-1} in systems derived from treatments T1, T2, and T3. In contrast, basal area increased by 0.5 m^2 ha^{-1} in the conserved natural stand. As observed for treatments T1, T2, and T3, basal area in T4 remained almost constant over time.

Significant differences among treatments were observed from one year to another. Across all treatments, statistical analyses showed no significant difference between years 0 and 1, whereas both differed significantly from year 2, with F = 22.001 and p = 0.001 for T1, F = 31.94 and p = 0.001 for T2, F = 53.62 and p = 0.001 for T3, and F = 82.78 and p = 0.001 for T4.

3.2.3. Total biomass of the permanent plots

Table 1 presents the changes in mean biomass across all treatments over the three years of monitoring. Significant differences were observed. A strong increase in mean biomass was recorded over the three years in treatment T3 (77%), followed by T2 (69%) and T1 (40%), compared to the natural forest T4 (5%). The Kruskal–Wallis test showed no significant difference in biomass among years for treatments T1, T3, and T4, with F = 0.42 and p = 0.60 for T1, F = 2.16 and p = 0.23 for T3, and F = 2.16 and p = 0.98 for T4. However, a significant difference was observed for T2 (F = 9.07; p = 0.001).

Table 1 Biomass change rate in the permanent plots of the Haut-Sassandra Classified Forest

Year	Biomass (tMS/ha)			
	T1	T2	T3	T4
Year	21,29[a]	16,17[a]	20,68[a]	144,06[a]
Year	23,34[a]	19,52[ab]	23,97[a]	148,35[a]
Year	29,74[a]	27,25[b]	36,66[a]	151,10[a]

T1: maintained cocoa plantation + harvesting; T2: unmaintained cocoa plantation + harvesting; T3: unmaintained cocoa plantation + no harvesting; T4: initial forest.

3.2.4. Carbon stock of the permanent plots

Table 2 shows the changes in the carbon stock in the permanent plots of the Haut-Sassandra Classified Forest. In treatment T1, carbon increased from year 0 to year 1 with a growth rate of 10%, and from year 1 to year 2 with a rate of 27%. In treatment T2, carbon stock also increased, with a rate of 21% from year 0 to year 1 and 40% from year 1 to year 2.

In treatment T3, carbon increased from year 0 to year 1 by 16%, and from year 1 to year 2 by 53%. In treatment T4, carbon stock increased slightly, with a rate of 3% from year 0 to year 1 and 2% from year 1 to year 2.

Overall, the highest rates of increase in mean carbon stock were observed in T3 (77%), followed by T2 (69%) and T1 (40%). The lowest rate of carbon increase was recorded in T4, with a growth rate of 5%.

Table 2 Evolution of carbon stock in the permanent plots of the Haut-Sassandra Classified Forest

Year	Carbon (tC/ha)			
	T1	T2	T3	T4
Year 0	10,64[a]	8,09[a]	10,34[a]	72,03[a]
Year 1	11,67[a]	9,76[ab]	11,99[a]	74,17[a]
Year 2	14,87[a]	13,63[b]	18,33[a]	75,55[a]

4. Discussion

4.1. Changes in vegetation structure in the permanent plots of the Haut-Sassandra Classified Forest

The floristic inventories carried out in the permanent plots of the HSCF over the three years of monitoring made it possible to establish a floristic list of 134 plant species. These species are distributed among 100 genera and 40 families in the agrosystems. The study showed a decline in floristic richness in cocoa plots compared to natural forest. This decrease in the number of species in cocoa plots is due to repeated human intrusion for various farming activities (weeding, pod harvesting, thinning, selective clearing, and illegal logging), all of which are factors likely to reduce floristic composition and species richness. Similar results were reported by [17], who recorded 387 species belonging to 252 genera and 73 families in the same permanent plots of the HSCF.

The high number of forest species observed in unmaintained cocoa plots is due to the regeneration and growth of young plants in these plots. These activities also lead to the death of large trees to make way for cocoa trees, which explains the low number of species in maintained cocoa plantations. Our results are consistent with those of [18], who showed that anthropogenic activities reduce the number of species in an agrosystem, leading to the disappearance of large trees and their replacement by cocoa plantations.

The structural parameters analyzed in this study, particularly density and basal area, increased progressively from one year to the next. Indeed, the highest rates of change in density and basal area were observed in treatments T2 and T3, unlike plots T1 and the initial forest. This trend may be attributed to strong species regeneration in these plots and environmental stability. According to [19], environmental stability results in a higher degree of organization, such that a more stable environment contains more ecological niches and therefore more species. For this author, floristic dynamics closely follow structural dynamics. Thus, both compositional parameters (richness, density) and structural parameters (diversity) of stands generally increase along ecological succession gradients [4].

Furthermore, the number of species with special conservation status is higher in plots free from agricultural activities. This can be explained by the strong regeneration of these species. Indeed, in the absence of anthropogenic disturbance, nature regenerates itself by gradually implementing a recovery strategy. Moreover, species with special status, through their presence, abundance, and diversity, confirm the role of protected areas in biodiversity conservation in general [20, 21, 22] and of the HSCF in particular [23]. Despite the degradation of the HSCF, it still harbors important species with special status. Similar findings were reported by [24, 17]. Among these species are many endemic to the Upper Guinean forest block or listed on the IUCN Red List (2020). These species with special status are the most sensitive to human-induced disturbances [25]. Anthropogenic activities that result in forest destruction do not favor the survival of these species, which require specific microclimatic conditions [26].

Regarding chorological affinities, in all treatments, species of the Guineo-Congolian phytogeographical region (GC) account for the largest proportions. The dominance of these species in cocoa plantations would indicate a fairly good recovery of vegetation. These results are similar to those obtained by [17, 27].

4.2. Biomass dynamics in the permanent plots of the Haut-Sassandra Classified Forest

Overall, an increase in biomass was observed in all treatments over the three years of monitoring. Taking treatment T3 as an example, a continuous increase in biomass was recorded over the three periods. By calculating biomass change rates, it was found that treatment T3 exhibited the highest rate of biomass increase (77%). This can be attributed to the absence of agricultural practices and the restriction of human access to these plots, which promotes species regeneration. In addition, photosynthetic activity is high in these plots due to vegetation recovery.

Regardless of the treatment type, an increase in carbon content was observed over the three years. The study showed that carbon content was higher in cocoa plots than in the forest (treatment T4). Treatment T3 recorded the highest rate of carbon increase (77%), followed by treatment T2 (69%) and treatment T1 (40%). The high carbon rate observed in treatment T3 may be due to the rapid growth of species in these cocoa plots. These results are consistent with the theory that the larger a tree grows, the more carbon it sequesters, and it is therefore considered a carbon sink. Thus, although carbon stocks in cocoa plots remain low, they contribute to climate regulation through carbon dioxide sequestration [28].

Indeed, the lower amount of carbon sequestered in cocoa plantations compared to that stored in forest fragments can be explained by the fact that cocoa trees are shrubs. Consequently, their growth in circumference and height remains limited, which reduces their sequestration potential [6]. However, despite the lower rate of carbon increase in the forest, it sequesters more carbon than cocoa plots. This is explained by the presence of large-diameter trees and species with high wood density [29]. According to [30], trees are the main contributors to carbon sequestration, especially those with large diameters [31]. Protected areas, when well conserved, significantly contribute to climate regulation through carbon sequestration.

5. Conclusion

The general objective of this study was to assess the carbon sequestration potential of agrosystems in the HSCF in order to provide baseline data for efficient management and land-use planning. Specifically, the study aimed to analyze the structural dynamics of the permanent plots in the HSCF and to determine biomass changes in these plots.

Floristic inventories conducted in the permanent plots of the HSCF over the three years recorded a total of 162 plant species in year 0, compared with 189 species in year 1 and 222 species in year 2. Among the species recorded in the different treatments, forests were richer in species than environments modified by human activities through the establishment of cocoa plantations. Thus, cocoa plots that were not maintained by farmers showed the highest rate of increase in species richness between 2018 and 2020, reaching about 162%.

Biomass dynamics estimated from dendrometric data also indicated a substantial increase in biomass (77%) over the three years of monitoring. However, despite the highest rate of biomass increase being observed in cocoa plots, forests remain the ecosystems that sequester the largest amount of atmospheric carbon, with an average sequestration estimated at 151 tC ha^{-1}. Nevertheless, despite the low carbon stock observed in some forest plots, the abandonment of agricultural activities in treatment T1 also promoted significant carbon sequestration (18.33 tC ha^{-1}). Cocoa plots free from agricultural activities also play a considerable role in the sequestration of anthropogenic emissions. In light of these results, repeated human intrusion into these plots is detrimental to species dynamics and to the recovery of atmospheric CO_2.

At the end of this study, we propose several perspectives and recommendations. The study showed that permanent plots are diverse and that both species richness and carbon stocks increase over time in plots free from maintenance. Therefore, forest cover restoration appears necessary for a better assessment and enhancement of carbon sequestration potential.

We consequently recommend that decision-makers allow farmers to harvest cocoa plantations that are currently productive for a limited period of time without maintaining them. After several years of harvesting, the infiltrated populations should be relocated to allow natural regeneration of this classified forest and vegetation recovery. Awareness campaigns promoting the adoption of agroforestry practices should also be conducted in order to reconcile agricultural production with climate change mitigation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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