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RESEARCH ARTICLE

STRUCTURAL EVOLUTION AND CARBON SEQUESTRATION IN THE NIEGRÉ CLASSIFIED FOREST (SOUTH-WEST) IN COTE D'IVOIRE

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Abstract

This study was conducted to support the sustainable management of the Niégré classified forest by analyzing its vegetation structure and the carbon stock sequestered within it. The methodology randomly sampled 100 m x 20 m (2,000 m²) plots in various biotopes, including old-growth forests, and fallow of 1–10 years, 11–19 years, 20–30 years, and 30 years or more. In each plot, chest height diameters (CHD) and height measurements were taken for all woody species with a diameter of 2.5 cm or greater. 419 species across 286 genera and 92 families were recorded, with the most dominant families being Fabaceae, Rubiaceae, and Euphorbiaceae. The distribution of individuals across diameter classes followed an "inverted J" curve in all biotopes, indicating robust natural regeneration. The study also demonstrated the forest's significant capacity for carbon storage, highlighting the crucial role of forest plant species in sequestering carbon dioxide emissions from human activities.

Introduction:

Tropical forests are invaluable for species conservation, human survival, and the overall health of the planet. Unfortunately, plant biodiversity is rapidly declining worldwide (Thomas et al., 2004; Ehikpa, 2018), with 0.1% of species disappearing every decade (Pimm and Ravin, 2017). Côte d'Ivoire's forest ecosystems are no exception. According to Aké-Assi (1984) and Adingra (2017), they are among the most threatened, primarily due to the country's economy, which remains heavily reliant on agriculture, population growth, and timber exploitation. The state of the forests—measured in terms of both area and health—is deeply concerning (Koné et al., 2014; Gbozé et al., 2020). Côte d'Ivoire currently has one of the lowest rates of forest cover, and plant biodiversity is increasingly at risk from activities that place mounting pressure on these ecosystems. The country experienced annual deforestation rates of 1.86% during the 2000s (Koné et al., 2014). Despite these challenges, tropical forests are critical in combating climate change (Lubalega, 2016), as they account for 40-50% of terrestrial carbon and play a vital role in the global carbon cycle (Pan et al., 2011).According to Gbozé et al. (2020), the loss of forest cover in tropical regions accounts for approximately 10-15% of global annual greenhouse gas emissions. As Hufty (2001) emphasizes, conservation must be the primary focus in biodiversity efforts. In Côte d'Ivoire, protected areas are central to the national biodiversity conservation strategy, with classified forests benefiting from legal measures

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designed to ensure their protection (Eblin, 2018). However, since the 1970, these forests have faced significant population encroachment, hindering their sustainable conservation (Amani, 2008). This is particularly true for the Niégré classified forest, one of the major forest reserves in southwestern Côte d'Ivoire (Leonard and Ibo, 2005). Studies by SODEFOR reveal that the population settlement rate within this massif increased from 25% to 40% between 1992 and 2006 (SODEFOR, 2007), which is likely higher today. This study aims to address the following research questions: What is the floristic richness and structural diversity of the Niégré classified forest in its current state? What is the capacity of its carbon sequestration? The general objective of the study is to establish a baseline for the carbon stock in this forest ecosystem. Specifically, the study aimed to: (a) determine the floristic richness and structural diversity of the forest, and (b) assess the carbon stock as an ecosystem service provided by the classified forest.

Materials and Methods:

Study Site

The Niégré classified forest, covering an area of 92,500 hectares, is located in southwestern Côte d'Ivoire, between latitudes 5° and 5°40'N and longitudes 6° and 6°30'W (Figure 1). It spans across the Nawa and Gbôklè regions, situated between the departments of Sassandra and Guéyo. The forest derives its name from the Niégré River, which flows through the area from northeast to southwest (Eblin et al., 2018). The landscape is predominantly characterized by plateaus interspersed with numerous valleys. The soils are ferralitic, originating from granite, with minimal degradation. The region experiences a transitional equatorial climate, marked by four distinct seasons and high annual rainfall averaging 1,470 mm.Temperatures in the study area range from 25°C to 29°C. The forest is a rainforest, with the dominant climax vegetation being dense evergreen rainforest (Guillaumet and Adjanouhoun, 1971).

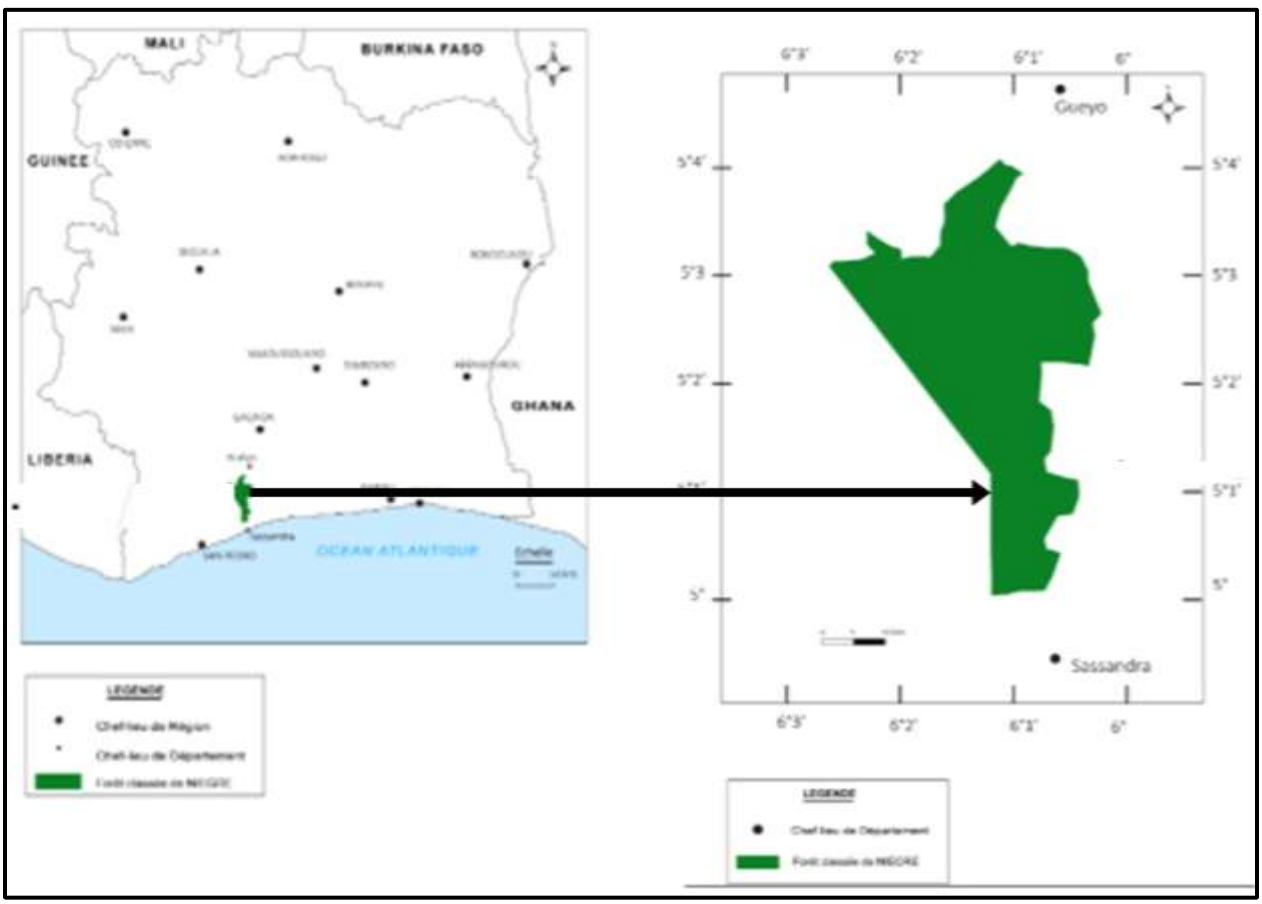

Fig 1:-Location of the Niégré classified forest in Côte d'Ivoire.
(SODEFOR, 2007**)**

Data Collection

The sampling design aimed to establish plots across the different vegetation types present on the site: old-growth forests and post-cultivation follows, categorized into four age classes: (1) fallow 1–10 years old, (2) fallow 11–19 years old, (3) fallow 20–29 years old, and (4) fallow30 years and older. Two botanical survey methods were employed in this study. The area survey method involved the random installation of 20 plots, each measuring 100 m x 20 m (2,000 m²), across the different biotopes. This method was used to record all vascular plant species present in the sampled area and to measure the diameter at breast height (DBH) of woody plants with a diameter of at least 2.5 cm, measured 1.30 m above the ground within the delimited plots (N'Guessan, 2018; N'Guessan et al., 2019). The distribution of plots was as follows: old-growth forest (n = 4 plots), fallow land 1–10 years old (n = 4 plots), fallow land 11–19 years old (n = 4 plots), fallow land 20–30 years old (n = 4 plots), and fallow land 30 years or older (n = 4 plots). The height of all woody plants was also measured to stratify the vegetation. Additionally, a roving inventory was conducted to further explore the floristic composition of the forest. During this inventory, the biotopes were traversed in all directions, and all encountered plant species were recorded (Aké-Assi, 1984). Botanical species were identified in the field using Hawthorne's identification key (1996), with additional reference works such as Arbres, Arbustes et Lianes des Zones Sèches de l'Afrique de l'Ouest (Arbonier, 2002). The species names were updated according to Lebrun and Stork (1991–1997), and the nomenclature follows that of APG IV (2016).

Data Analysis

Floristic Richness and Structural Diversity

Floristic richness was assessed by counting all the species present in a biotope, regardless of their abundance. A floristic database was created to organize the taxonomic information, including family, genus, species, subspecies or variety, and the author's name for each species.

Vegetation structure was analyzed using several parameters, including density, basal area of all stems with a diameter at breast height (DBH) of at least 2.5 cm, and the distribution of individuals across various diameter classes:]2.5; 10[,]10; 20[,]20; 30[,]30; 40[,]40; 50[,]50; 60[,]60; 70[,]70; 80[,]80; 90[,]90; 100[, [100, +[. Stem distribution curves based on diameter classes were also constructed to assess the stability of the different biotopes on the site.

In terms of vegetation stratification, four strata were identified based on Kouamé (1998): the lower shrub stratum (height < 4 m), the upper shrub stratum (height 4–8 m), the lower tree stratum (height 8–16 m), and the upper tree stratum (height 16–32 m and higher).

Density was defined as the number of individuals per unit area (i.e., stems per hectare) and was calculated using the following formula:

Basal area represents the cross-sectional area of the trunks of all trees in the survey, assuming the measurement is taken 1.30 m above the ground. It was calculated using the following formula:

$$d = n/s \qquad S = D^2 \times \pi/4$$

Woody biomass

Above-ground biomass

Above-ground biomass (AGB) refers to the mass of dry plant matter per unit area, which is divided into trunk biomass and crown biomass (branches). The AGB of individual trees was estimated using the allometric equation of Chave et al. (2014) from the 'BIOMASS' package in the R® + RStudio software. The formula for calculating AGB is as follows:

AGB=f(D,H,WD)\text{AGB} = \text{f}(D, H, WD)AGB=f(D,H,WD)

Where:

- **AGB** is the above-ground biomass (in Mg),
- **D** is the diameter (cm) of the trunk at breast height,
- **H** is the height (m) of the tree,
- **WD** is the specific density of the wood (g/cm³)

This formula was applied by executing the following command in R:

```
AGB<- computeAGB(D = data$D, WD = data$WD, H = data$H)
```

Before executing this command, the ‘BIOMASS’ package was activated in R.

Below-ground Biomass

Below-ground biomass (BGB) was estimated based on the above-ground biomass (AGB) following the guidelines set by the IPCC (2006). According to these guidelines, the root biomass of standing woody plants can be determined by multiplying the AGB value by a root-to-shoot ratio coefficient (R), which is estimated at 0.37.
The formula for estimating BGB is as follows:

$$BGB = AGB \times R$$

Where:
- **BGB** is the below-ground biomass (in tonnes),
- **AGB** is the above-ground biomass (in tonnes),
- **R** is the root-to-shoot ratio coefficient, set at 0.37.

Total Biomass of Standing Woody Plants

The total biomass (BT) of standing woody plants was estimated by summing the above-ground biomass (AGB) and below-ground biomass (BGB) using the following formula:

BT = AGB + BGB

Where:
- **BT** is the total biomass (in tonnes),
- **AGB** is the above-ground biomass (in tonnes),
- **BGB** is the below-ground biomass (in tonnes).

Estimation of Sequestered Carbon and Atmospheric CO_2 Stocks

The total biomass estimated using the various equations was converted into the corresponding sequestered carbon stock by multiplying it by a factor of 0.47, as per the IPCC (2006) guidelines. To estimate the sequestered atmospheric CO2 stock, it is important to recognize that the atomic mass of carbon (MaC) is 12 and that of oxygen (MaO) is 16. The molecular mass of CO2 ($MmCO_2$) is calculated as follows:

$MmCO_2$ = MaC + 2MO soit $MmCO_2$ = 12 + 2 x(16) = 44.
Thus, the ratio of CO2 to carbon is given by the formula MmCO2/MaC, which equals 3.66. Therefore, the stock of atmospheric CO2 sequestered by the total biomass within the forest was estimated by multiplying the carbon stock from the biomass by this factor of 3.66.

Results:-

Floristic Richness and Structural Diversity

The flora of the Niégré forest consists of 419 species across 20 inventoried plots. These species are distributed among 286 genera and 92 families. The most dominant families identified were Fabaceae (44 species, or 10.50%), Malvaceae (24 species, or 5.73%), Euphorbiaceae (20 species, or 4.77%), Rubiaceae (20 species, or 4.77%), Apocynaceae (20 species, or 4.77%), and Moraceae (19 species, or 4.53%).

A total of 6,234 individuals with a diameter at breast height (dbh) of ≥ 2.5 cm were counted across all biotopes, corresponding to a density of 1,558.5 individuals per hectare (ha) over a sampled area of 4 ha. Density varied across the different biotopes. The highest density was found in old-growth forests (371.75 plants/ha), followed by fallow land aged over 30 years (349 plants/ha). Fallow land aged 20–29 and 10–19 years had densities of 332.25 and 305.75 plants/ha, respectively. The youngest fallows had the lowest density, with 224.75 plants/ha.

The total basal area for all biotopes combined was 16,792.24 m² over the 4 ha, yielding an average of 4,198.06 m²/ha. The basal area in old-growth forests was 429.81 m².The distribution of individuals by height class (Figure 2) reveals a clear increase in the number of woody plants from recent fallows to older fallows. This shift is characterised by a reduction in the number of young trees, with a corresponding increase in the number of larger trees. The distribution of individuals by diameter class (Figure 3) varies across the different biotopes. It follows an ‘inverted J’ curve in all biotopes, indicating good natural regeneration of the flora. This pattern also demonstrates a decline in the number of individuals as their diameter increases.

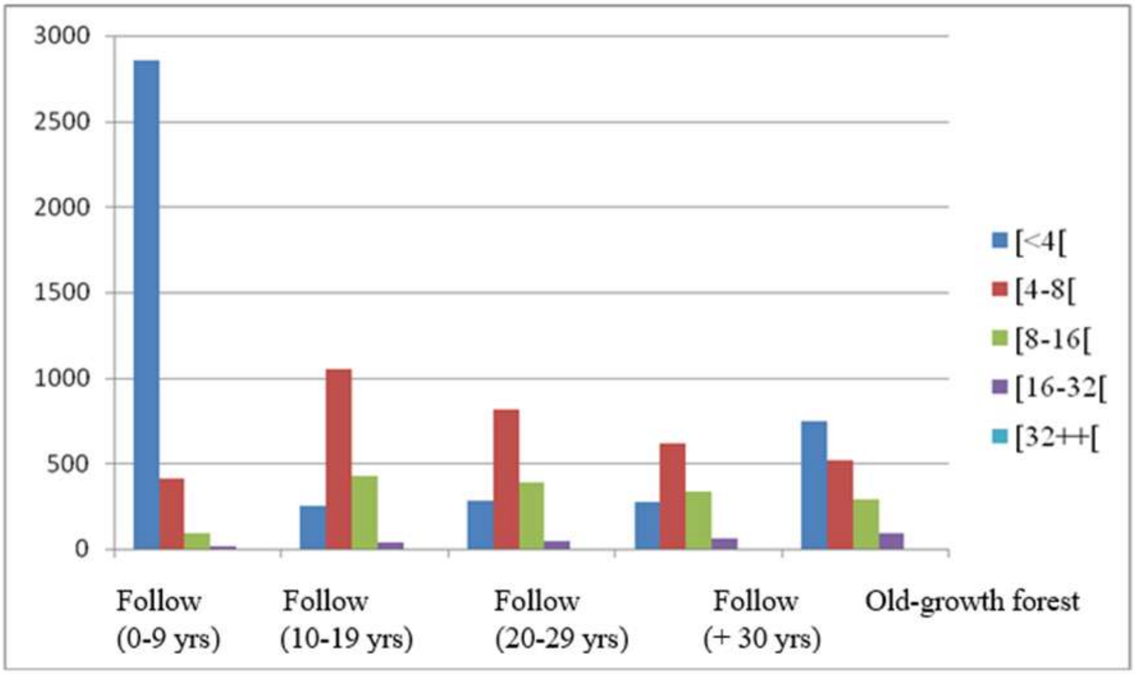

Fig2:-Distribution of stems by height class in the different biotopes.

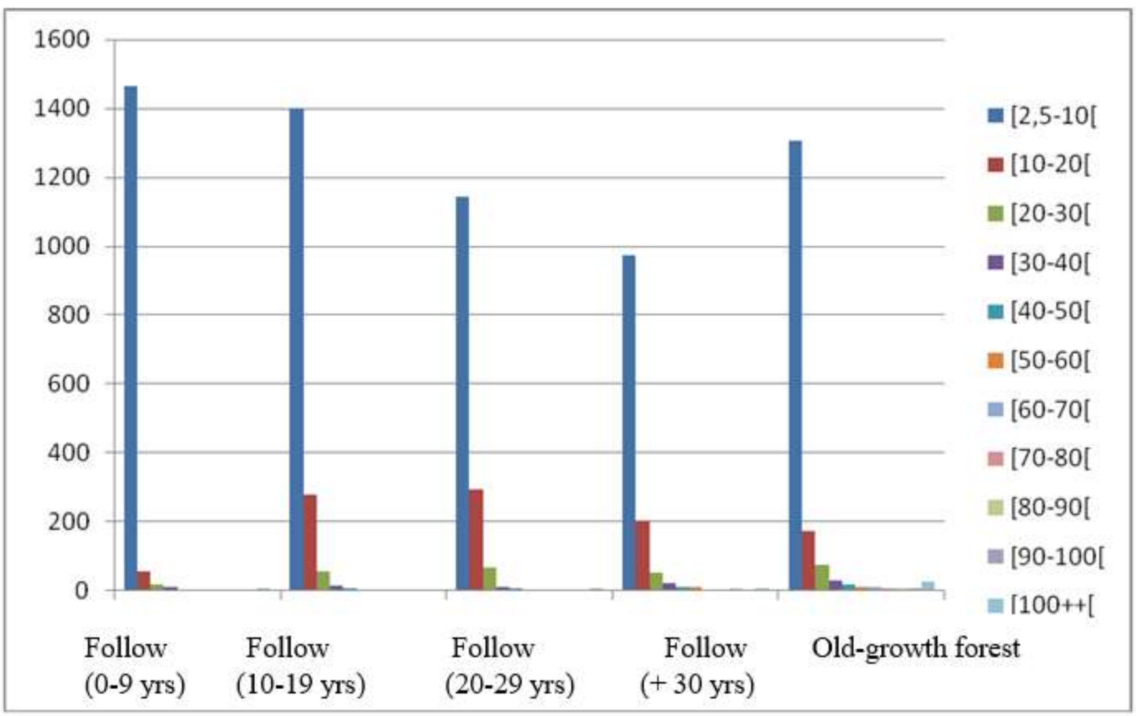

Fig 3:- Distribution of stems by diameter class in the different biotopes.

Estimation of Biomass, Carbon, and CO2 Levels in the Different Types of Biotopes
The biomass of the Niégré classified forest is estimated at 716.2 t/ha, with carbon and CO2 stocks sequestered at 284.48 t/ha and 1,237.75 t/ha, respectively. It is important to note that these carbon and CO2 stock values vary across different biotopes. Old-growth forests exhibit the highest values, with 164.71 t/ha of carbon and 513.26 t/ha of CO2 equivalent. This is followed by fallow land aged 30 years or more (80.18 t/ha of carbon and 314.60 t/ha of CO2 equivalent), fallow land aged 20–29 years (52.06 t/ha of carbon and 210.05 t/ha of CO2 equivalent), and fallow

land aged 10–19 years (34.44 t/ha of carbon and 125.12 t/ha of CO2 equivalent). The lowest stocks are found in fallow land aged 0–9 years, with 12.49 t/ha of carbon and 24.25 t/ha of CO2 equivalent.

Influence of the Height and the Diameter on the biomass, carbon sequestration

Trees with heights ranging from 16 to 32 meters store the most carbon and sequester the highest levels of CO2. The biomass for these trees is estimated at 687.34 t/ha, with a carbon stock of 266.01 t/ha and a CO2 equivalent sequestration of 1,030.67 t/ha. The next tallest height class, 8-16 meters, has a biomass of 160.78 t/ha, which corresponds to a carbon stock of 79.33 t/ha and a CO2 equivalent sequestration of 228.77 t/ha. Trees in the 4 – 8 meter height class follow, with an estimated biomass of 25.55 t/ha, a carbon stock of 25.55 t/ha, and a CO2 equivalent sequestration of 50.22 t/ha. Trees under 4 meters store the least carbon, with only 3.74 t/ha of biomass, 1.14 t/ha of carbon, and 6.32 t/ha of CO2.

Trees with a diameter greater than 90 cm are the most significant in terms of biomass, with an estimated 429.78 t/ha. The carbon stock sequestered is 218.03 t/ha, and the equivalent CO2 sequestration is 497.22 t/ha. The next most important diameter class is [20-30 cm], with a biomass quantity of 164.21 t/ha. Following that, the [10-20 cm] diameter class contains 73.44 t/ha of biomass, storing 29.60 t/ha of carbon and sequestering 132.11 t/ha of CO2. The [30-40 cm] class has a biomass of 80.21 t/ha, an estimated carbon stock of 29.31 t/ha, and a CO2 equivalent sequestration of 152.59 t/ha. Trees in the [70-80 cm] diameter class have a biomass of 55.23 t/ha, sequestering 55.23 t/ha of carbon and 88.16 t/ha of CO2. The [50-60 cm] diameter class follows with a biomass of 55.10 t/ha, storing 24.52 t/ha of carbon and 92.50 t/ha of CO2. The remaining diameter classes, [40-50 cm] and those with a diameter less than 10 cm, are the least significant in terms of carbon sequestration, with biomass values of 54.15 t/ha and 35.24 t/ha, respectively. These classes sequester 22.14 t/ha of carbon and 15.66 t/ha of CO2, and 56.16 t/ha of carbon and 68.29 t/ha of CO2, respectively.

Discussion:-

Diversity and Structure

The floristic inventories conducted in the Niégré classified forest identified 419 species across 286 genera and 92 families. This represents a significant portion of Côte d'Ivoire's total flora, accounting for 10.79% of the 3,882 species documented by Aké Assi (2001; 2002). Given that the study area was limited to just 4 hectares, this number is likely to increase with further exploration. The most dominant families on the site are Fabaceae, Rubiaceae, Euphorbiaceae, Malvaceae, and Apocynaceae, which are commonly found in many Ivorian forests. Indeed, several other Ivorian forests also exhibit dominance by this set of families (Kouamé, 1998; Bakayoko, 1999; Nusbaumer et al., 2005; N'Guessan, 2016; Adingra, 2017).

The observed ‘inverted J’ distribution of diameter classes is characteristic of environments undergoing regeneration (Wala et al., 2005). This distribution is typically linked to natural regeneration, where a high concentration of individuals is present in smaller diameter classes. According to N'Guessan (2018), the higher values of basal area and tree density found in fallows older than 30 years and in old-growth forests, compared to younger fallows (less than ten years old), can be attributed to the differing levels of human pressure. Older fallows and old-growth forests experience less human disturbance, facilitating natural growth and regeneration.

The structural parameters examined, particularly tree density and basal area, provide crucial baseline data that can inform management objectives for sustainable forest conservation and restoration (N'Guessan, 2019).

Biomass and Carbon Stock

The results of this study indicate that the carbon stock in the Niégré classified forest increases with the age of the fallow land. Carbon stock ranged from 12.49 t/ha and 24.25 t/ha of CO2 equivalent in fallow lands aged 0-9 years, to 80.18 t/ha of carbon and 314.60 t/ha of CO2 equivalent in fallows of 30 years or more. However, these values remain lower than those observed in old-growth forests, where the carbon stock reaches 164.71 t/ha and CO2 equivalent stock is 513.26 t/ha. These findings highlight the important role the Niégré classified forest plays in mitigating atmospheric CO_2, which is one of the primary greenhouse gases driving global warming (IPCC, 2006).

Our study also demonstrates that larger trees, particularly those in the 16-32 m height class, contribute more significantly to carbon stock, with 266.01 t/ha of carbon and 1,030.67 t/ha of CO_2 sequestration, compared to smaller trees below 4 meters in height. This is attributed to the greater access to sunlight and larger leaf surface area of taller trees, which enhances their capacity for carbon sequestration.

Protected areas, such as the Niégré classified forest, offer multiple benefits. They serve as models for balancing conservation with economic development, providing vital ecosystem services like maintaining stable microclimates for agriculture and contributing to carbon sequestration. These areas also highlight the impacts of human intervention on ecosystems and demonstrate the reciprocal relationship between humans and nature. Furthermore, they preserve both cultural and biological diversity, support indigenous production and consumption practices, and serve as ecological links between various protected landscapes. Protected areas also function as valuable laboratories for studying ecosystems and their dynamics in a controlled, undisturbed environment.

Conclusion:-

The inventories conducted in this study identified 419 species, with the most prominent botanical families being Fabaceae, Rubiaceae, Euphorbiaceae, Malvaceae, and Apocynaceae. The distribution of individuals by diameter class exhibited an inverted J curve across the various biotopes, indicating strong natural regeneration of the forest flora. The findings also demonstrated that forest trees have a significant capacity for carbon storage, underscoring the crucial role that forest ecosystems play in sequestering carbon dioxide emissions resulting from human activities. These results emphasize the importance of preserving such forests for climate change mitigation and biodiversity conservation.

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