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ASSESSMENT OF SOIL CARBON STOCKS ACROSS DIFFERENT AGE CLASSES IN *Azadirachta indica* (A. JUSS.) AGROSYSTEMS IN THE FAR NORTH REGION OF CAMEROON

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ABSTRACT

The Far North Region is one of Cameroon's ecologically fragile areas. Reforestation using *Azadirachta indica* is among the successful initiatives that have been adopted by local communities; however, it has not been subject to an ecological assessment despite the ongoing phenomenon of climate change. The aim of this study is to assess soil carbon stocks in order to contribute to mitigating the effects of climate change in Cameroon's arid zone. The study was conducted across four departments and focused on carbon sequestration. A split-plot design with five replicates was used. Soil samples were collected and analysed. The results show that the total soil carbon stock is approximately 85.16 tCO_2/ha, depending on the different sites. This study clearly demonstrates the important role these agrosystems play in mitigating the effects of climate change. If managed sustainably, they will act as genuine carbon sinks in the semi-arid zone of Cameroon.

Keywords: Agrosystems, *Azadirachta Indica*, Carbon, Climate Change, Mitigation

1 INTRODUCTION

Natural carbon sequestration is a key issue for climate protection and the stability of ecosystems. Indeed, agroforestry systems offer significant potential for carbon storage and thus contribute directly to climate change mitigation [1]. This role is particularly crucial in the Sudano-Sahelian region, where agroforestry systems play a part in climate change adaptation and mitigation [2]. More broadly, the ecosystem services provided by forests, including carbon sequestration, are essential for climate stability [3]. In practical terms, this process takes place within a carbon sink, where atmospheric CO_2 is fixed by photosynthetic plant organisms through the process of photosynthesis [4]. A carbon sink is defined as any reservoir, process or mechanism that removes a greenhouse gas, aerosol or greenhouse gas precursor from the atmosphere [5]. As part of the fight against climate change through the mitigation of greenhouse gas (GHG) emissions, many African countries, and Cameroon in particular, signed the United Nations Framework Convention on Climate Change on 14 June 1992 and ratified it on 19 October.

At COP 22 in Marrakesh (Morocco) in 1016 [6] and COP 23 in Bonn in 2017 [7], agroforestry systems were proposed as the most effective solutions for reducing emissions and socio-economic vulnerability of populations, notably through the 'Koronivia Joint Work on Agriculture' decision adopted in Bonn. This international approach has been taken up at national level [8]. Several previous studies have been carried out on carbon stocks in the Sudano-Sahelian zone of Cameroon, such as that by [9] on the plant diversity and carbon sequestration of *Borassus aethiopum* agroforestry stands in the Far North Region of Cameroon; and [10] on the carbon sequestration potential of *Anacardium occidentale* agrosystems in Ngong; and [11] on the carbon sequestration potential of *Azadirachta indica* agrosystems in Yagoua. These authors have contributed to the assessment of epigeic and hypogeic carbon. As part of our study, we will contribute to the assessment of soil carbon stocks in northern Cameroon, specifically in the Far North Region.

2 MATERIAL AND METHODS

2.1 Description of the study area

The Far North Region of Cameroon, with Maroua as its capital [12], covers an area of approximately 34,246 km² with an estimated population of 3,480,414 inhabitants, characterised by a high population density [13]. More specifically, the study is being carried out in the departments of Diamaré, Mayo-Danay, Mayo-Kani and Mayo-Tsanaga (Fig. 1).

Figure 1: Map showing the location of the study sites

2.1.1 Climatic factors

The Far North region of Cameroon is characterised by a Sudano-Sahelian climate, with a dry season running from November to April and a rainy season from May to October. Annual rainfall ranges from 400 to 900 mm and decreases from south to north. Temperatures are very high all year round, with an annual average of 28 °C and maximum temperatures reaching up to 45 °C in April–May. The dry season is characterised by the harmattan, a dry, dusty wind blowing in from the Sahara [14].

2.1.2 Vegetation and flora

The dominant vegetation is the shrubby savannah characteristic of the Sudano-Sahelian zone. It is heavily influenced by human populations [15]. The flora is fairly diverse and the vegetation is dominated by several forest species, including: *Guiera senegalensis, Combretum micranthum, Combretum nigricans, Anogeissus leiocarpus, Piliostigma thonningii,* *Balanites aegyptiaca, Ziziphus mauritiana, Acacia seyal, Annona senegalensis, Faidherbia albida, Acacia nilotica and Diospyros mespiliformis.* During the dry season, the annual herbaceous plants wither whilst still standing and cover the ground with a layer of straw. The herbaceous cover, ranging from sparse to continuous, reveals the tracks left by livestock and the paths trodden by farmers to reach their fields and water sources. This physical degradation of the vegetation cover is exacerbated by overgrazing and the repeated passage of herds [16]. It is reported that *Azadirachta indica* is gaining ground throughout the area and is becoming the most abundant plant species. This abundance is encouraged by reforestation. In the urban area, the roads are lined with this species [17].

2.1.3 Soils

The region's soils are highly diverse, ranging from bare, clay-textured soils found in the karals and hardés, sandy-clay soils, and sandy-silty alluvial soils, which are found in the plains and particularly on the outskirts of the mayo, thus providing the basis for intensive agricultural activity [18].

2.2 Methodology

2.2.1 Soil phytomass

Within each 2,000 m^2 survey area, soil samples were collected from 0.25 m × 0.25 m sub-plots. These samples were taken at depths of 0–10 cm, 10–20 cm and 20–30 cm across the 12 basic plots, in accordance with the recommendations set out by [19] (Fig. 2).

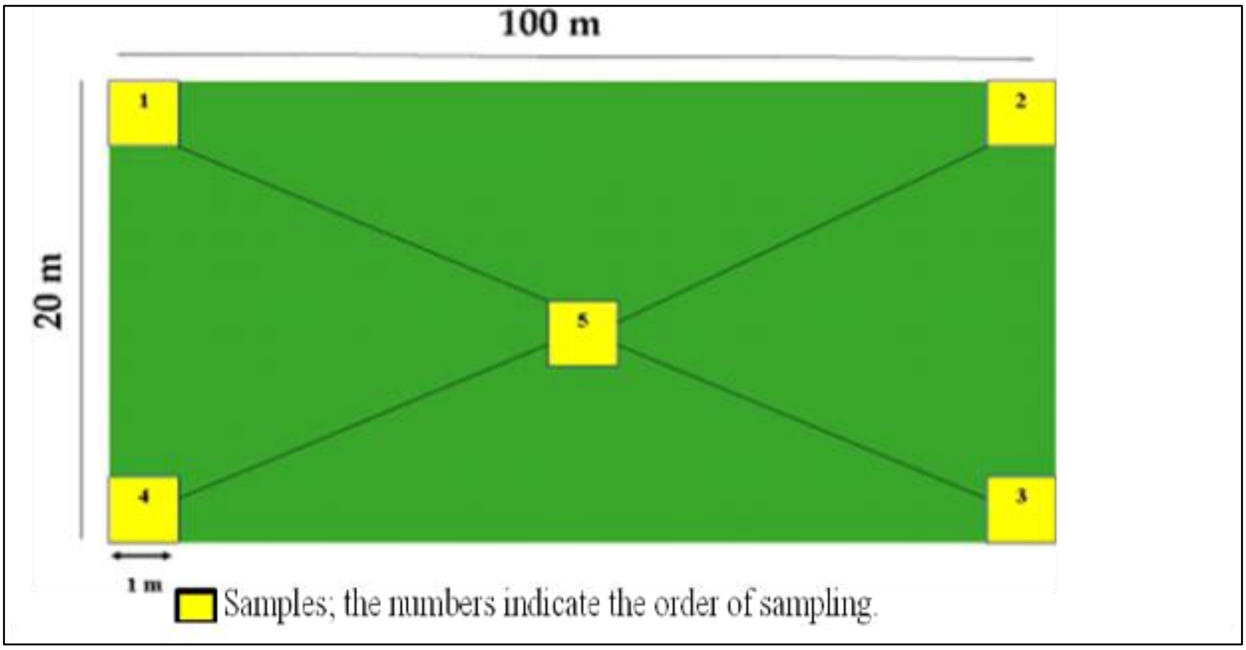

Figure 2: Diagram illustrating the sampling method for surface horizons

Soil samples from each depth level were collected using a machete and a trowel, then immediately placed in a sealed bag inside a cool box, kept in the shade to prevent evaporation. In total, three samples were collected per sampling unit, corresponding to a total of 15 samples per stand, which were then homogenised to produce a single sample. A total of 180 soil samples (12 sites × 3 depths × 5 replicates) were collected from all 12 stands studied, to a depth of 30 cm. A further set of soil samples was collected using a 100 cm^3soil cylinder to determine the bulk density.

2.2.2 Assessment of the physico-chemical characteristics of the soils

Physical and chemical parameters were taken into account during the analyses; these include, amongst others: particle size distribution, pH, total nitrogen content, organic matter (OM) content, organic carbon content and moisture content.

2.2.2.1 Physical analyses

2.2.2.1.1 Particle size analysis

The particle size analysis was carried out in accordance with [20] standard NF X31-107.

- **Definition and purpose**: This is a procedure used to determine the distribution of particles in soil according to their size and weight. It allows the dry mass of the particles to be broken down according to their diameter (mm).
- **Principle**: The analysis was carried out using the Robinson pipette method on air-dried soil samples sieved to 2 mm. The organic matter was first destroyed by treatment with hydrogen peroxide. The soil was then dispersed by rotary agitation in vials after the addition of sodium hexametaphosphate $(NaPO_3)_6$. The various particle size fractions were determined by pipetting for the clay and silt fractions and by sieving for the sand.
- **Method** Place 20 g of soil into a 1000 ml Erlenmeyer flask, then proceed to destroy the organic matter using diluted hydrogen peroxide (50 ml) at room temperature overnight, followed by gentle heating on a hotplate.

2.2.2.1.2 Bulk density (Da)

The apparent density (Da) was calculated in accordance with [21] Standard NF ISO 11464.

- **Definition and purpose**: It corresponds to the mass per unit volume of dry soil in situ. It is one of the most important parameters in studies of soil structure. It is, in fact, linked to the nature and organisation of the soil's constituents [22]. It also enables the calculation of porosity and thus provides an indirect assessment of permeability, resistance to root penetration [23], the cohesion of soil horizons [24, 25] and soil water-holding capacity [26].
- **Principle / Method**: The apparent density was determined by taking a defined volume of soil using a cylinder driven into the ground. After drying the sample in an oven at 105°C for 48 hours, it was weighed again. The dry weight of the sample P divided by the volume of the sample V gave the bulk density (Da) in g/cm^3. It is calculated using the following formula: Da= P/V.

2.2.2.2 Chemical analyses

These are the parameters that most influence soil behaviour and fertility. They are: hydrogen ion concentration (pH), total nitrogen (N) and organic carbon (CO).

2.2.2.2.1 Determination of hydrogen ion concentration (pH of water and pH of KCl)

The determination of hydrogen ion concentration (water pH and KCl pH), which enabled us to assess the soil's acidity or alkalinity, was carried out in accordance with Standard NF ISO 10390; [27].

- **Definition and purpose**: The hydrogen ion concentration, denoted by pH, is a measure of the chemical activity of hydrogen ions H^+ in solution. Measuring the pH of a soil enables its acidity or alkalinity (acid-base status) to be determined. pH is a way of expressing the concentration of hydrogen ions in a soil-to-water mixture at a ratio of 1:2.5; it is expressed on a scale of 0-
- 14. Low pH values (0-6.5) indicate acidity; values of 7.5-14 indicate alkalinity; and values between 6.5 and 7 indicate a neutral pH.
- **Principle**: The pH measurement was carried out on a soil-water solution for the water pH and a soil-KCl solution for the soil pH, in a ratio of 1:2.5, using a pH meter fitted with a glass electrode. The pH meter was calibrated beforehand using standard solutions.

Procedure

The pH measurement involves the following steps:

- Place 10 g of soil into a 100 ml beaker that has been previously tared.
- Add 25 ml of distilled water and KCl solution to measure the water pH and KCl pH respectively. Stir to ensure thorough mixing.
- The KCl pH is measured 30 minutes after stirring, whilst the water pH is measured after at least 16 hours.
- The pH meter used for the measurement is switched on 30 minutes beforehand and then calibrated to pH 9, pH 7 and pH 4. It is then immersed in the resulting suspension and the pH (acidic, basic or neutral) is read on the instrument.

2.2.2.2.2 Determination of total nitrogen (N)

Total nitrogen (N) was measured in accordance with standard NF EN ISO 23470; [28].

- **Definition and purpose**: Total nitrogen represents the sum of ammoniacal nitrogen and organic nitrogen in the soil. It is used to measure the concentrations of nitrogen (ammoniacal and organic) in the soil.

- **Principle**: Total nitrogen was determined using the [29] method following heat treatment of the sample with a mixture of sulphuric acid (H_2SO_4) and salicylic acid ($C_6H_4(COOH)OH$). The nitrates present in the sample were first fixed by salicylic acid, then reduced to ammonia using a catalyst consisting of copper sulphate ($CuSO_4$). The distillate was collected in boric acid (H_3BO_3) and then titrated with sulphuric acid (H_2SO_4).

Procedure

- Add 2 g of the sample and 7 ml of a sulphuric acid/salicylic acid mixture to mineralise the sample.
- Add approximately 1.5 g of sodium thiosulphate and allow to react for approximately 15 minutes.
- Add 3 ml of concentrated sulphuric acid, 0.2 g of catalyst and 50 ml of water, then allow to cool.
- Distil until 150 ml of distillate is obtained.
- Titrate, whilst stirring continuously using a magnetic stirrer, with sulphuric or hydrochloric acid (0.01 N). The total nitrogen is given by the following formula:
- N (%) = $((V - V_0) \times 14 \times t) / p = (V - V_0) \times 0.07$ where V: volume of H_2SO_4; V0: volume of
- H_2SO_4 used for the blank titration; t: normality of H_2SO_4 (0.01 N); p: soil sample (2 g).

2.2.2.3 Organic carbon (CO) content

The organic carbon (CO) content was determined in accordance with Standard NF ISO 14235, [30].

- **Definition and purpose**: the organic carbon content is used to determine the organic matter content present in the soil.
  - **Principle**: Organic carbon was determined using the [31], which involves oxidation with potassium dichromate ($K_2Cr_2O_7$) in an acidic medium (H_2SO_4). The analysis was carried out by calorimetry. The organic matter content was obtained by multiplying the organic carbon content by Sprengel's factor, which is 1.724 for cultivated soils and 2 for uncultivated soils. Soil carbon stock was estimated using the formula employed by [32]: **SCOS = % TCO × Da × P,**where TCO: organic carbon content; Da: bulk density; P: depth.

2.3 Methodology

The steps for determining MO and CO are as follows:

- Place 0.5 g of soil into a 500 ml Erlenmeyer flask and carefully add 10 ml of 1 $NK_2Cr_2O_7$ and 20 ml of concentrated H_2SO_4, stirring gently; allow to react for approximately 30 minutes under a fume cupboard.
- Add, in succession, 150 ml of water, 10 ml of H_3PO_4 and 1 ml of indicator.
- Stir the solution using a magnetic stirrer and titrate with $FeSO_4{\cdot}7H_2O$ until a bright green color is obtained. This is because the amount of $K_2Cr_2O_7$ used exceeds the amount required for the oxidation of C. The excess K2Cr2O7is titrated using FeSO4·7H2O. This back-titration therefore allows us to calculate the amount of K2Cr2O7that has been neutralised by the C. The equivalence point is indicated by the color change of the redox indicator (diphenylamine, $(C_6H_5)2NH$) from purple to colorless, or from purple to green.

2.3.1 Determination of moisture content at 105°C

The moisture content at 105°C enabled us to estimate the water content in accordance with Standard NF X15-110; [33].

Procedure

Moisture content at 105°C is used to estimate the water content. The procedure involves:

- Placing 5 g of the fresh sample into a pre-tared flask, then drying the soil sample in an oven at 105°C for 24 hours.
- Allow to cool in a desiccator and weigh. The equivalent moisture content is then determined using the following formula:
- **H = (Gross weight, air-dried) – (Gross weight, dried at 105 °C) / (Net weight, air-dried) × 100**
- Bring to the boil to remove excess hydrogen peroxide; add 250 ml of hydrochloric acid to break down aggregates and limestone; then wash with distilled water to remove excess HCl.
- Transfer the filtrate (suspension of silt and clay) to a 1-litre cylinder and make up to 950 ml with distilled water.
- Add 20 ml of dispersant, sodium hexametaphosphate. The residue (sand) is dried in an oven and weighed after cooling.

- Shake the cylinder by inverting it (using a rotary shaker) to resuspend the soil completely.
- (6) Place the extension flask on the laboratory bench, remove the stopper, taking care to collect the soil suspension wetting the stopper, and make up the extension flask to 1 litter. After stirring manually with a rod, proceed to the sampling (using a Robinson pipette) of the clays and silts, and wait for the time required to collect the fine clays and silts and the clays.
- The textural classes were determined using the FAO Textural Triangle, once the proportions of the different textural fractions had been calculated.

2.4 Statistical analysis of the data

The data collected are both qualitative and quantitative. The quantitative data are subjected to an analysis of variance. Significant means are distinguished using Duncan's test. The statistical software used is STATGRAPHICS Plus 5.0 and the R software package.

3 RESULTS

3.1 Carbon stock

3.1.1 Physico-chemical characteristics of agrosystems with *Azadirachta indica*

3.1.1.1 Bulk density of the soil

For the age/site interaction of the agrosystems, the bulk density of the soils ranges from 0.73 ± 0.02 g/cm^3 in the Mayo-Danay agrosystems aged]0–10[years to 1.05 ± 0.15 g/cm^3 in those at Diamaré aged ≥ 20 years (Table 1). Despite the observed variation, there is no significant difference (0.47 > 0.05).

Table 1: Apparent density according to the age–site interaction.

Age (years) / Site	**]0–10[**	**[10–20[**	**≥ 20**	**Average**
Diamaré	0.79±0.04	0.79±0.04	1.05±0.15	0.88±0.15
Mayo-Danay	0.73±0.02	0.78±0.38	0.88±0.18	0.79±0.22
Mayo-Kani	0.82±0.05	0.98±0.04	0.95±0.07	0.92±0.09
Mayo-Tsanaga	0.85±0.17	0.95±0.16	0.81±0.15	0.87±0.15
Average	0.79±0.09	0.88±0.20	0.92±0.15	0.87±0.16

Depending on the interaction between soil age and depth, the bulk density varies from 0.72 ± 0.25 g/cm^3 for soils at a depth of 10–20 cm and aged [10–20] years to 0.95 ± 0.12 g/cm^3 in soils 0–10 cm deep and aged ≥ 20 years (Table 2). Analysis of variance shows no significant difference (0.41 ≥ 0.05) between the depth and age of the agrosystems.

Table 2: Bulk density according to the age/depth interaction.

Age (years)/Depth (cm)	**]0–10[**	**[10–20[**	**≥ 20**	**Average**
0–10	0.84±0.15	1.03±0.14	0.95±0.12	0.93±0.17
10–20	0.78±0.05	0.87±0.07	0.92±0.18	0.87±0.10
20–30	0.77±0.06	0.72±0.25	0.91±0.19	0.80±0.18
Average	0.79±0.09	0.88±0.20	0.92±0.15	0.87±0.16

With regard to the site/depth interaction on bulk density, the highest value is observed at a depth of 0–10 cm in the Mayo-Tsanaga (1.03 ± 0.11 g/cm^3). The depth of 20–30 cm shows the lowest value in the Mayo-Danay (0.8 ± 0.07 g/cm^3) (Table 3).

Table 3: Bulk density according to the site /depth interaction.

Sites/Depth (cm)	Diamaré	Mayo-Danay	Mayo-Kani	Mayo-Tsanaga	Average
0–10	0.94±0.18	0.85±0.25	0.95±0.08	1.03±0.11	0.93±0.16
10–20	0.9±0.19	0.82±0.08	0.91±0.06	0.84±0.06	0.87±0.10
20–30	0.8±0.07	0.73±0.36	0.89±0.14	0.73±0.09	0.80±0.18
Average	0.88±0.15	0.79±0.22	0.96±0.09	0.87±0.15	0.87±0.16

The analysis of variance shows no significant difference (0.65 > 0.05). The Mayo-Tsanaga is the densest at our experimental site, with a density ranging from 1.03 ± 0.11 g/cm3.

3.1.1.2 Soil texture

The topography of the study sites varies considerably, ranging from flat areas to areas with hills in places. This variability could be conducive to the development of diverse ecosystems. Biological activity at the study sites would also reflect the richness of these soils.

3.1.1.2.1 Sand content

With regard to the interaction between age and site in relation to sand content, the percentage of sand ranges from 14.15 ± 0.01 % in agrosystems where the age is between [10–20[years in the Diamaré department to 67.04 ± 0.01 % in the Mayo-Tsanaga department (Table 4). The analysis of variance shows a significant difference (0.0000 < 0.001). For this interaction between age and site in terms of sand content, the soils of the four departments exhibit different textures.

Table 4: Sand content according to the age/site interaction

Age (years)/Site	] 0–10[	[10–20[	≥ 20	Average
Diamaré	25.11±0.01	14.15±0.01	67.06±0.01	35.44±24.19[a]
Mayo-Danay	64.81±0.01	50.09±0.01	15.66±0.01	43.52±21.85[c]
Mayo-Kani	27.59±0.01	39.11±0.01	55.98±0.01	40.89±12.36[b]
Mayo-Tsanaga	67.04±0.01	30.18±0.01	40.94±0.01	46.05±16.42[d]
Average	46.14±20.70[c]	33.38±13.74[a]	44.91±20.12b	41.47±18.85

Means in the same column and the same row marked with different letters are statistically different at the 0.05 significance level.

3.1.1.3 Silt content

With regard to the interaction between age and site, the silt content ranges from 4.65±0.01% in agrosystems aged between [10–20[years in Diamaré to 28.3±0.1% in those aged 20 years or more in Diamaré (Table 5). The analysis of variance shows a significant difference (0.0000 < 0.001).

Table 5: Silt content according to the age/site interaction.

Ages (years)/Site	]0–10[	[10–20[	≥20	Average
Diamaré	14.69±0.01	4.65±0.01	28.3±0.1	15.88±10.28[b]
Mayo-Danay	8.81±0.01	15.97±0.01	7.27±0.01	10.68±4.02[a]
Mayo-Kani	19.26±0.01	8.66±0.01	23.35±0.01	17.09±6.56[c]
Mayo-Tsanaga	26.44±0.01	14.89±0.01	16.11±0.01	19.15±5.49[d]
Average	17.3±6.73[b]	11.04±4.83[a]	18.76±8.27[c]	15.7±7.39

Means in the same column and the same row marked with different letters are statistically different at the 0.05 level.

3.1.1.3.1 Clay content

With regard to the interaction between age and site on clay content, this varies from 7.85 ± 0.01 % in agrosystems where the age is between [10–20[years in Diamaré to 49.82 ± 0.01 % in Mayo-Tsanaga, where the age is 20 years or more (Table 6). The analysis of variance shows a significant difference (0.0000 < 0.001).

Table 6: Clay content according to the age/site interaction

Age (years)/Site	]0–10[	[10–20[	≥ 20	Average
Diamaré	26.44±0.01	49.81±0.01	26.79±0.01	34.35±11.60[c]
Mayo-Danay	13.35±0.01	7.85±0.01	49.48±0.01	23.56±19.58[a]
Mayo-Kani	40.3±0.1	35.7±0.1	49.82±0.01	41.94±6.24[d]
Mayo-Tsanaga	30.79±0.01	32.39±0.01	28.5±0.1	30.56±1.69[b]
Average	27.72±10.12[a]	31.44±15.78[b]	38.65±11.51[c]	32.60±13.16

Means in the same column and the same row marked with different letters are statistically different at the 0.05 level.

3.1.1.4 Total nitrogen

With regard to the interaction between age and site on the percentage of nitrogen, the variation ranges from 0.19±0.01 percent in systems where the age is ≥ 20 years in Mayo-Tsanaga to 0.72±0.01 percent in the 0–10-year-old agrosystems of Diamaré (Table 7). The analysis of variance shows a significant difference (0.0000 < 0.001).

Table 7: Nitrogen content according to the age/site interaction

Age (years)/Site	]0–10[	[10–20[	≥ 20	Average
Diamaré	0.72±0.01	0.52±0.01	0.3±0.1	0.51±0.19[d]
Mayo-Danay	0.63±0.01	0.31±0.01	0.28±0.01	0.41±0.17[c]
Mayo-Kani	0.58±0.01	0.34±0.01	0.32±0.01	0.41±0.13[b]
Mayo-Tsanaga	0.42±0.01	0.26±0.01	0.19±0.01	0.29±0.10[a]
Average	0.58±0.11[c]	0.36±0.10[b]	0.27±0.07[a]	0.41±0.16

Means in the same column and the same row marked with different letters are statistically different at the 0.05 significance level.

3.1.1.5 Carbon-to-nitrogen ratio

The interaction between age and site on the C/N ratio at the study sites ranges from 3.17±0.01 at Mayo-Tsanaga (where the age is between]0–10[years) to 8.5±0.1 at Mayo-Danay (where the age is ≥ 20 years) (Table 8). The analysis of variance shows a significant difference (0.0000< 0.001).

Table 8: Carbon-to-nitrogen ratio according to the age/site interaction

Age (years)/Site	]0–10[	[10–20[	≥20	Average
Diamaré	3.52±0.01	4.86±0.01	6.36±0.01	4.91±1.23[a]
Mayo-Danay	6.3±0.1	6.34±0.01	8.5±0.1	7.05±1.09[c]
Mayo-Kani	4.13±0.01	6.65±0.01	7.66±0.01	6.15±1.57[b]
Mayo-Tsanaga	3.17±0.01	4.3±0.1	7.3±0.1	4.92±1.85[a]
Average	4.28±1.27[a]	5.54±1.03[b]	7.45±0.80[c]	5.76±1.67

Means in the same column and the same row marked with different letters are statistically different at the 0.05 level.

3.1.1.6 pH

Depending on the interaction between age and site, the pH ranges from 5.11±0.01 in soils from Mayo-Tsanaga that are ≥ 20 years old to 6.80 ± 0.01 in those from Diamaré that are between]0–10[years old (Table 9). The analysis of variance shows a significant difference (0.0000 < 0.001).

Table 9: pH content according to the age/site interaction

Age (years)/Site	]0–10[	[10–20[	≥ 20	Average
Diamaré	6.80±0.01	6.20±0.1	5.20±0.1	6.06±0.70[d]
Mayo-Danay	6.27±0.01	6.23±0.01	5.13±0.01	5.87±0.56[a]
Mayo-Kani	6.69±0.01	6.30±0.1	5.20±0.1	6.06±0.67c
Mayo-Tsanaga	6.71±0.01	6.14±0.01	5.11±0.01	5.98±0.70[b]
Average	6.62±0.21c	6.22±0.08b	5.16±0.07a	5.99±0.64

Means in the same column and the same row marked with different letters are statistically different at the 0.05 level.

3.1.1.7 Moisture

The interaction between age and site shows that moisture content ranges from 13.23 ± 0.01 % in the Mayo-Kani department for trees aged]0–10[years to 66.6 ± 0.1 % in the same department for trees aged ≥ 20 years (Table 10). The analysis of variance shows a significant difference (0.0000 < 0.001).

Table 10: Moisture content according to the age/site interaction

Age (years)/Site	]0–10[	[10–20[	≥20	Average
Diamaré	25.25±0.01	32.02±0.01	47.7±0.1	34.99±9.97[a]
Mayo-Danay	17.73±0.01	32.58±0.01	62.18±0.01	37.49±19.59[b]
Mayo-Kani	13.23±0.01	35.4±0.1	66.6±0.1	38.41±23.22[c]
Mayo-Tsanaga	27.54±0.01	46.27±0.01	48.6±0.1	40.80±9.99[d]
Average	20.94±5.99[a]	36.57±6.00[b]	56.27±8.64[c]	37.93±16.16

Means in the same column and the same row marked with different letters are statistically different at the 0.05 level.

3.1.2 Soil carbon stock

3.1.2.1 Soil organic carbon content

Depending on depth, the soil organic carbon content at the sites ranges from 1.91 ± 0.27 tC/ha at a depth of 20–30 cm to 2.87 ± 0.48 tC/ha at a depth of 0–10 cm (Table 11). Analysis of variance shows that there is a significant difference (0.0000 < 0.001).

With regard to the age/site interaction on organic carbon content across the sites, it ranges from 1.69 ± 0.39 tC/ha in the Mayo-Kani agrosystems, which are between]0–10[years old, to 2.60 ± 1.02 tC/ha in those of Diamaré, which are ≥ 20 years old. The analysis of variance shows no significant difference (0.21 > 0.05) (Table 11).

Table 11: Soil organic carbon content according to the age/site interaction.

Age (years)/Site	]0–10[	[10–20[	≥20	Average
Diamaré	2.34±0.67	2.41±0.61	2.60±1.02	2.45±0.69
Mayo-Danay	2.19±0.29	2.35±0.26	2.53±0.69	2.36±0.42
Mayo-Kani	1.69±0.39	2.56±0.74	2.24±0.15	2.17±0.57
Mayo-Tsanaga	2.53±0.88	2.55±0.10	2.19±0.29	2.42±0.49
Average	2.19±0.61	2.47±0.44	2.39±0.57	2.35±0.54

As regards the age/depth interaction on organic carbon content across all sites, it ranges from 1.68 ± 0.24 tC/ha for the 20–30 cm depth in agrosystems aged]0–10[years to 2.97 ± 0.67 tC/ha for the 0–10 cm depth in agrosystems aged ≥ 20 years (Table 12). Analysis of variance shows a significant difference (0.0000 < 0.001). In fact, the agrosystems stores an average of 2.87 ± 0.54 tC/ha.

Table 12: Soil organic carbon content according to the age/depth interaction.

Age (years)/Depth (cm)	]0–10[	[10–20[	≥20	Average
0–10	2.73±0.52	2.91±0.32	2.97±0.67	2.87±0.54[c]
10–20	2.16±0.54	2.39±0.26	2.26±0.15	2.27±0.34[b]
20–30	1.68±0.24	2.1±0.27	1.95±0.10	1.91±0.27[a]
Average	2.19±0.61[a]	2.47±0.44[a]	2.39±0.57[a]	2.35±0.54

Means in the same column marked with different letters are statistically different at the 0.05 level.

3.1.2.2 Soil carbon

For the age/site interaction, soil carbon ranges from 15.46 ± 7.51 tC/ha in agrosystems aged ≥ 20 years in Mayo-Kani to 28.12 ± 16.28 tC/ha in those aged ≥ 20 years in Diamaré. The analysis of variance shows no significant difference (0.07 > 0.05) (Table 13).

Table 13*:* Soil carbon stock according to the age–site interaction

Age (years)/Site	]0–10[	[10–20[	≥ 20	Average
Diamaré	19.65±6.40	19.91±3.84	28.12±16.28	22.56±9.88
Mayo-Danay	15.46±1.92	19.74±2.26	25.66±6.90	20.43±5.69
Mayo-Kani	17.36±1.82	25.42±7.73	15.87±7.51	19.42±7.14
Mayo-Tsanaga	24.76±7.85	24.58±3.96	18.90±3.19	22.75±5.49
Average	19.41±5.68	22.04±4.97	22.42±9.86	21.29±7.09

For the interaction between age and depth in the various agrosystems, soil carbon stock ranges from 16.34±2.56 tC/ha in those aged between]0–10[years with a depth of 20–30 cm and 27.85±11.69 tC/ha in those aged ≥ 20 years with a depth of 0–10 cm (Table 14). The analysis of variance shows no significant difference (0.49 > 0.05).

Table 14: Soil carbon stock according to the age/depth interaction

Age (years)/Depth (cm)	]0–10[	[10–20[	≥ 20	Average
0–10	22.32±7.63	24.12±6.14	27.85±11.69	21.09±8.47
10–20	17.57±2.12	22.69±2.94	17.49±7.89	19.25±5.20
20–30	16.34±2.56	18.44±2.24	17.77±1.27	17.52±2.10
Average	19.41±5.68	22.42±4.97	22.04±9.86	21.29±7.09

With regard to the interaction between site and soil depth in the agrosystems, soil carbon stock ranges from 16.47±2.74 tC/ha in agrosystems with a soil depth of 20–30 cm in the Mayo-Danay department to 31.27±14.03 tC/ha in those with a soil depth of 0–10 cm in the Diamaré department (Table 15). Analysis of variance revealed no significant differences (0.84 > 0.05).

Table 15: Soil carbon stock as a function of site and depth.

Site/Depth (cm)	Diamaré	Mayo-Danay	Mayo-Kani	Mayo-Tsanaga	Average
0–10	31.27±14.03	23.86±7.64	24.84±7.39	28.43±5.71	21.09±8.47
10–20	19.29±4.09	20.60±5.14	16.82±9.04	20.63±2.61	19.25±5.20
20–30	17.12±1.76	16.47±2.74	16.95±1.04	19.18±2.66	17.52±2.11
Average	22.56±9.88	20.43±5.69	19.42±7.14	22.75±5.49	21.29±7.09

3.1.2.3 Total soil carbon in *Azadirachta indica* agrosystems

The total carbon content in *Azadirachta indica* agrosystems shows that carbon levels range from 19.42±0.57 tC/ha in the Mayo-kani to 22.75±0.49 tC/ha in the Mayo-Tsanaga (Table 16). The total carbon content recorded amounts to 85.16±2.17 tC/ha. Generally speaking, this study suggests that the total carbon sequestered by the soil varies between the different sites.

Table 16: Total soil carbon in *A. indica* agrosystems

Total carbon / Sites	S.COS
Diamaré	22.56±0.69a
Mayo-Danay	20.43±0.42a
Mayo-Kani	19.42±0.57a
Mayo-Tsanaga	22.75±0.49a
Total	**85.16±2.17**

4 DISCUSSION

The bulk density of the soils ranges from 0.73 ± 0.02 to 1.05 ± 0.15 g/cm^3 in agrosystems of varying ages across the four departments. This variation may be due to difficulties with water and air movement, resulting in poor soil aeration. According, this results in slower infiltration and drainage, as well as difficulties with root growth and seedling emergence. The apparent soil density broadly reflects the degree of soil compaction and, indirectly, the total porosity. When it is high, the soil lacks the pores necessary for root growth, water-holding capacity is

reduced and fluid circulation is slowed, according to [34] in their work on changes in soil bulk density and the C/N ratio under exotic and local cassava varieties under natural conditions in Kisangani (DR Congo).

Agrosystems with high carbon stocks in silt and sand are found in the Diamaré region. This result is to be expected, as soil texture is one of the main characteristics influencing its organic matter content and, consequently, its organic carbon content [35]. These soils exhibit a high rate of organic matter decomposition, with values (C/N ratio ranging from 3 to 10). Other factors, such as particle size distribution and pH, may explain these variations in the C/N ratio. This ratio is higher in finer-textured soils and in acidic soils [36]. Soil texture can influence plant composition as well as root development, depending on the site and the age of the plants. This soil texture is favourable for the growth of *Azadirachta indica*. The biological activity observed, particularly in the Mayo-Kani area, also reflects the fertility of these soils. According to [37] and [38], in clay soils where the density of the material is very high, roots penetrate only into cracks or the traces of old roots that are decomposing.

he soil pH ranges from 5.11 ± 0.01 to 6.80 ± 0.01. The use of organic fertiliser over time helps to reduce soil acidity in agrosystems. This is indigenous knowledge practised by farmers to combat desertification effectively, as few plants are adapted to acidic soils. The alkaline nature of the soils at these sites is thought to be conducive to healthy plant growth. This would explain the diversity of species in this department. Similarly, [39] states that most plants thrive in soil with a pH close to neutral: pH (6.5). This finding also shows that farmers make less use of chemical inputs in favour of organic inputs. Organic fertilisers act as a buffer against chemical fertilisers to prevent an increase in soil acidity, as confirmed by [40].

Nitrogen levels are high in agrosystems aged]0–10[years. This situation can be explained by the fact that, whilst plant biomass is quite substantial at the site, its decomposition is not rapid. This may be due, on the one hand, to drought, which does not favour biological activity, and, on the other hand, to the occurrence of bushfires, which can considerably reduce soil microfauna and macrofauna. The results obtained corroborate those of [41], who found a very low quantity of organic matter in the vertisols of the Logone Valley. These soils consequently exhibit poor mineralisation and consequently have a low nitrogen content in the humus.

Soil moisture in agrosystems with *A. indica* appears to be higher. Local communities observe better tree growth; soil moisture increases with age, leading to enhanced plant growth. These results are consistent with those of [40] Dangai (2022), who demonstrated that age enables species to develop more effectively. Soil moisture appears to be higher around *A. indica*. Local communities observe better growth and significant crop development around *A. indica* as a result of improved soil quality. These findings contradict those of [42], who showed that the shade cast by certain species had a negative effect on the yield of certain crops. The surface layer is rich in organic carbon. Biological activity at this depth appears to be greater than at greater depths. [43] demonstrated that soil carbon stocks in the savannahs of the Lésio-Louna and Léfini reserves on the Tékés Plateau in the Republic of the Congo vary according to soil horizons. Thus, the carbon stocks obtained in this study ranged from 1.91 ± 0.27 tC/ha to 2.87 ± 0.48 tC/ha. These results are similar to those obtained by [43] (2.35 ± 0.24 tC/ha) in *Anacardium occidentale* agrosystems in Ngong, northern Cameroon.

Overall, this soil therefore exhibits poor mineralisation and consequently has a low carbon content in the humus. Biological activity at this site appears to be absent. The results obtained corroborate those of [41]. This study showed that the sites are predominantly sandy. This situation can be explained by the fact that, whilst biomass is fairly abundant at the site, its decomposition is not rapid. This may be due, on the one hand, to drought, which does not favour biological activity, and, on the other hand, to the occurrence of bushfires, which can considerably reduce soil microfauna and macrofauna. According to [44], the practice of bushfires considerably reduces the organic carbon content.

The organic carbon content at the sites ranges from 1.91 ± 0.27 tC/ha at a depth of 20–30 cm to 2.87 ± 0.48 tC/ha at that depth. These results are lower than those estimated by the [45], which are 31 tC/ha for dry tropical areas, and those obtained by [46] (42 tC/ha) in cocoa agrosystems in the humid tropical zone of Nairobi, Kenya.

Low temperatures slow down the rate of mineralisation of the organic matter that constitutes the soil's significant carbon pool [47]. Generally speaking, the stimulation of plant productivity at higher temperatures will increase carbon input into the soil, leading to an environmental impact through greater CO_2 release into the atmosphere. The increase in greenhouse gas (GHG) concentrations in the atmosphere is now recognised as the main cause of climate change, resulting in a rise in global temperatures and the frequency of extreme weather events, as well as a rise in sea levels [48].

For the site/depth interaction, soil carbon ranges from 15.46 ± 7.51 tC/ha to 28.12 ± 16.28 tC/ha. For the interaction between age and depth across different agrosystems, soil carbon stocks range from 16.34 ± 2.56 tC/ha to 27.85 ± 11.69 tC/ha. These values vary according to soil type and climatic conditions in each area. However, these results fall within the range obtained by [10] (22.03 ± 4.14; 30.33 ± 6.52 tC/ha) in agrosystems with *Anacardium occidentale* in the Bénoué region of northern Cameroon.

The total carbon content in *Azadirachta indica* agrosystems shows that carbon levels range from 19.42 ± 0.57 tC/ha in the Mayo-Kani to 22.75 ± 0.49 tC/ha in the Mayo-Tsanaga. This finding highlights the importance of soil carbon stock management for agrosystems operators. According to various authors, the carbon sequestration capacity of agrosystems varies considerably [49].

5 CONCLUSION

The populations in the study area have a good understanding of climate change. They possess significant carbon sequestration potential, there by contributing to climate change mitigation in the Far North Region of Cameroon. However, the total soil carbon stock amounts to 85.16 tCO_2/ha. These agrosystems offer several benefits. They help to improve living conditions for the population, enhance soil fertility, conserve biodiversity and improve climatic conditions. This study represents an essential step in the decision-making process on environmental issues in Cameroon.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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