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Soil Organic Carbon and Nitrogen Dynamics in Arabica Coffee Agroforestry Systems in the Noun Division, West Cameroon

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Abstract

Agroforestry systems (AFSs) offer viable solutions to climate change because of the below-ground biomass (BGB) that is maintained by the soil. Therefore, spatially explicit estimation of their BGB is crucial to account for emission reduction efforts. A study to assess soil organic carbon (SOC) and nitrogen dynamics in Arabica coffee agroforests was conducted in two subdivisions (Foumbot and Kouoptamo) of the Noun Division in western Cameroon. The methodological approach involved the collection of 150 soil samples taken at different depths: 0 - 10, 10 - 20 and 20 - 30 cm. Depending on the depth, the SOC stock is 27.93 ± 1.13 tC/ha at 10 cm depth, 22.37 ± 1.47 tC/ha at 20 cm and 20.79 ± 0.31 tC/ha at 30 cm. According to the age classes of the Arabica coffee systems (ACA), the C/N ratio in our study area averaged 26.94 ± 13.60 for the (5 - 20) year old systems in Foumbot and 60.64 ± 48.80 for the (20 - 35) year old systems in Kouoptamo. Depending on the depth, at 10 cm this ratio is higher in Kouoptamo than in Foumbot with a maximum value of 57 and 38 respectively for the two subdivisions. In view of the results obtained, it would be important to analyse the types of microorganisms responsible for the decomposition of organic matter which is linked to soil organic carbon.

Keywords

Agroforestry Systems, Coffee Trees, Soil Organic Carbon, Noun Division, West Cameroon

1. Introduction

Soils are a key component of the global carbon (C) cycle and are the main reservoir of organic carbon storage from biomass on Earth (Batjes et al., 2020). The most recent estimates of the global pool of soil organic carbon (SOC) account for 1325-1408 Pg C (1 Pg (Petagram) = 1 billion billion metric tons) in the first meter and 2060 Pg C in the first two meters of soils (Batjes, 2016). The amount of carbon stored in soils is estimated at 1500 billion tonnes, about two (02) times more than the atmosphere, and three (03) times more than terrestrial vegetation (FAO, 2017). In addition, tropical grasslands/savannas store between 99 and 104 Mg/ha over 0 - 100 cm; (Duarte-Guardia et al., 2019) and 151 Mg/ha over 0 - 300 cm; (Carvalhais et al., 2014). Soil organic carbon (SOC) is essential for agroecosystem productivity and climate change mitigation (Balesdent et al., 2005; Chabbi et al., 2017; Minasny et al., 2017; Chenu et al., 2019; Malou et al., 2021). However, the depth used for soil surveys worldwide is only 27 cm on average (Yost & Hartemink, 2020). The demand for coffee is growing. In 30 years, it has increased from 6 million tonnes to 9 million tonnes produced today. Mostly grown in South America, coffee is a cause of deforestation (Soto-Pinto et al., 2010). But coffee is also at risk. In addition to the 60% of wild coffee species threatened with extinction due to deforestation, if the temperature rises by more than three degrees, it will be very serious because the areas available for Arabica coffee cultivation could be reduced by 50% by 2050 compared to 2000, while global demand will double (Berthereau, 2021). The only solution is to develop methods that integrate the tree into the system. Agroforestry allows coffee producers to diversify their income (Vaast et al., 2005). Combined with perennial crops, it could be an important carbon sink (Albrecht & Kandji, 2003; Montagnini & Nair, 2004) or improve infiltration (Plata-Rocha et al., 2011).

From independence until the end of the 1980s, coffee growing was a valuable source of income for the Cameroonian state (Epanda et al., 2022). Its contribution to the Gross Domestic Product (GDP) was 10% between 1960-1985. Following the crisis, agricultural diversification in the ACA has led to a decline in coffee yields in the Division of Noun. Coffee is one of the main perennial crops in the division, having sustained the Cameroonian economy for several decades until the crisis of the 1980s, which forced the Cameroonian state to liberalize the sector (Fongang, 2008). The reaction of producers to the liberalization of the coffee sector led to the revival of this sector in the highlands of western Cameroon (Kammeugne, 2015). Coffee is the third most consumed beverage in the world after water and tea, and its consumption is increasing with more than 10 million tons of coffee produced worldwide in 2019. It is therefore important to review the production strategy for this crop in Noun. To date, few empirical studies on the dynamics of SOC in coffee landscapes have been conducted in the Noun ACA. Only the examination of the biodiversity of FASs has been done. The results show that the presence of shade trees improves connectivity and biodiversity comparable to natural forests (Ávila et al., 2001; Harmand et al., 2006; Jha & Dick, 2008; Dossa et al., 2008; Soto-Pinto et al., 2010; Jha & Vandermeer, 2010). At the local level, studies on carbon in FAS have focused more on the above-ground pool, indicating a lack of studies on soil organic carbon in FAS. ACA are based on family farming (Bulter, 2013). A better characterisation of organic carbon stocks and fluxes in these systems still requires much effort. However, the comparability of carbon storage between different depths and ages of Arabica coffee-based FASs remains poorly studied. With this in mind, the present study seeks to answer the following main question: What are the dynamics of soil organic carbon stocks in Arabica coffee-based SAFs in Noun Division?

2. Materials and Methods

2.1. Study Site

The study took place in the West Cameroon region, Noun Division. Its surface area is about 7687 km^2 for a population of 434,542 inhabitants or 57 inhabitants per km^2 (Mbarga et al., 2013). The division of Noun is located between longitude 10˚32' - 11˚13'E and latitude 5˚36' - 5˚55'N. The division has nine subdivisions (Bangourain, Foumban, Foumbot, Kouoptamo, Koutaba, Magba, Malentouen, Massangam and Njimom). The presence of SAFs with Arabica coffee trees guided this work in Foumbot and Kouoptamo. The soils of the Bamoun plateau are black due to the influence of volcanic activity. However, these soils, which are not very developed and very fertile, are now becoming poorer due to overexploitation (Noun Divisional Delegation for Agriculture, 2013). There are also ferralitic and hydromorphic soils that are less fertile than the previous ones (Mouncherou et al., 2011). In the south, north and west, there are important forest galleries in which perennial crops such as coffee and cocoa trees are grown (Noun Divisional Delegation for Agriculture, 2013). The climate of the area is savannah with two seasons: a rainy season from March to October and a dry season from November to February (Wandji, 1995). The annual temperature is 22˚C and the average annual rainfall is about 916.6 mm/year (Ngapgue, 2007). The dominant vegetation is savannah with forest galleries that meander in places along the major rivers (Moupou, 1991). The main activity is agriculture (Mouncherou et al., 2011). The study was carried out in Foumbot and Kouoptamo sub-divisions (**Figure 1**).

2.2. Methods

2.2.1. Sampling Device

The international methods used at the Laboratory of the Research Unit for Soil Analysis and Environmental Chemistry (URASCE) of the University of Dschang, recommended by Pauwels et al. (1992) were used in this study. They consisted of taking two soil samples at each depth level (one disturbed for the calculation of carbon percentage and the other undisturbed for the calculation of bulk density). This method was chosen because of the availability of this glassware in the laboratory. Arabica coffee agroforestry systems (ACA) belonging to the age classes (5 - 20), (20 - 35), (35 - 50) and (>50) were chosen because of the floristic composition and the presence of Arabica coffee trees. In addition to the plots belonging to the different age classes, another control plot without coffee trees was identified in order to compare the results. The choice of the Noun division is justified by the strong presence of ACA but also because it is a high altitude zone

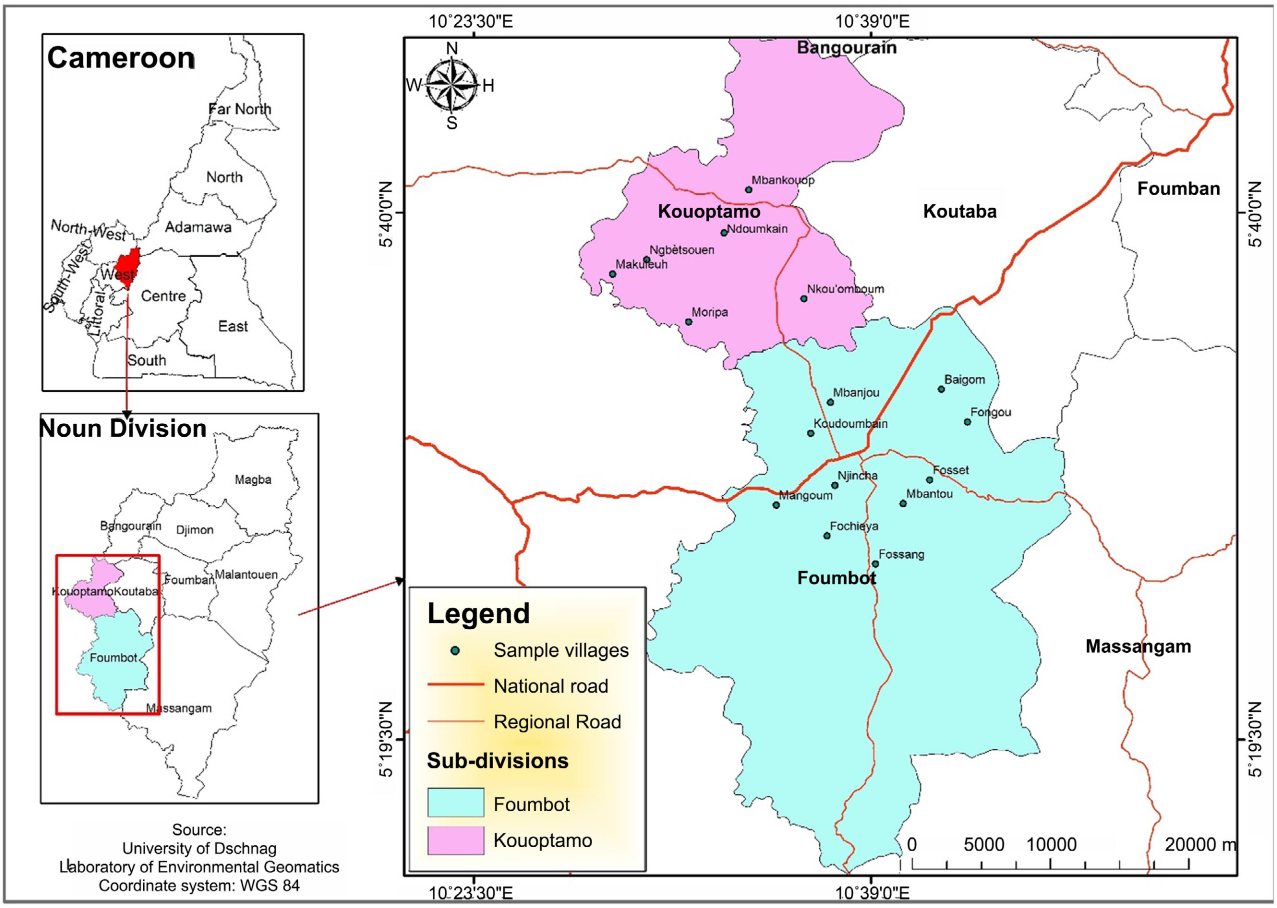

Figure 1. Location map of the study site.

(1200 m) where Arabica coffee cultivation is adapted. In each subdivision, five (05) plots of 2400 m^2 (40 × 60 m) were selected. The method used to delimit the sample plots was adapted from that developed by (Hairiah et al., 2010). In each main plot of 2400 m^2, an area of one square meter was delimited (sampling area). Thus, 5 profiles were dug by hand, each 30 cm deep (**Figure 2**).

The five pits were arranged so that there was one main characterisation pit in the centre and four pits towards the four edges of the plot (Riotte et al., 2014; Sekhar et al., 2016; Riotte et al., 2021) in order to incorporate spatial variability, in particular of soil organic carbon. In these five profiles, two soil samples were taken per depth, one disturbed with a cylinder of known volume (100 cm) for the calculation of carbon and the other undisturbed with another cylinder of known volume (100 cm) for the determination of bulk density taken according to depths 0 - 10 cm, 10 - 20 cm and 20 - 30 cm. A total of 150 soil samples were taken. The samples were then dried and crushed with a porcelain mortar and sieved with a 2 mm mesh sieve.

2.2.2. Analysis of Soil Samples

1) Estimation of soil carbon stock

- **Soil carbon content (C_h)**

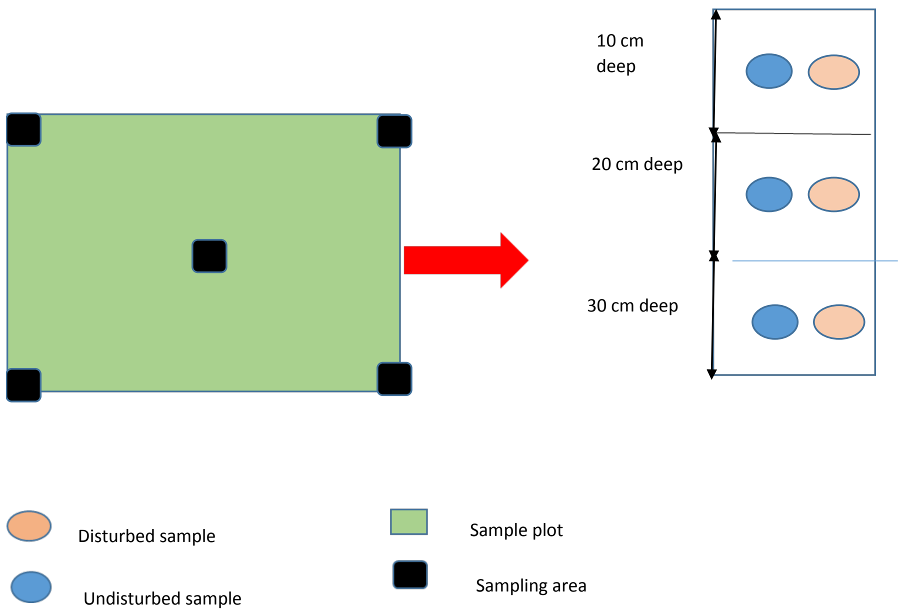

Figure 2. Diagram of field sampling profiles.

Once in the laboratory the CO (%) was determined by the Walkley and Black (1934) method. Then 10 ml of excess potassium dichromate ($K_2\ Cr\ O_{27}$) was added followed by 20 ml of concentrated $H_2\ SO_4$. The CO content was determined by back-assaying the excess dichromate with ferrous iron sulphate ($FeSO_4 \cdot H_2O$) under magnetic stirring.

The soil carbon stock was obtained by the relation:

$$\text{soil} = C_h \times D_a \times h$$

where h is the depth considered; C_h carbon content at depth h and D_a soil bulk density.

- **Determination of bulk density (D_a)**

For the analyses, once in the laboratory, the soil and root samples were weighed separately to get their fresh weights (Pf) and then oven dried to get their dry weights (Ps). Then a test sample for each root element was calcined and reweighed.

- The method used to calculate soil carbon stocks is to measure the total organic C content at different soil depths and to transform these data, taking into account the bulk density and the stoniness or coarse element load of the soil. Carbon stocks are calculated according to the formula:

$$C\left(\text{kg/m}^2\right) = C\left(\text{mg}\cdot\text{g}^{-1}\ \text{soil}\right) * D_a * e$$

with: D_a, the bulk density ($g \cdot cm^{-3}$) and e, the thickness of the soil horizon expressed in dm. For soils with coarse elements (>2 mm in diameter) the organic stocks are calculated according to the following formula:

$$C\left(\text{kg/m}^2\right) = C\left(\text{mg/g soil}\right) * \left(100\%\ \text{coarse matter}\right) * D_a * e.$$

(adapted from Penman et al., 2003)

Stocks were calculated for the reference depths of 0 - 10 cm; 0 - 20 cm and 0 - 30 cm. The Walkley and Black (WB) method for soil organic carbon determination thus has limitations with respect to recovery factors and is generally considered as an approximate or semi-quantitative method for estimating SOC. Equally, the higher analytical costs when the WB method is used and the pollution of the environment due to the chemicals used (Enang et al., 2018).

2) Nitrigen determination

The determination of total nitrogen was done by the Kjeldahl method. It consists of the complete mineralisation of organic nitrogen by heat treatment with a mixture of concentrated sulphuric acid and salicylic acid. The mineralisation was accelerated by using a catalyst (copper sulphate + selenium) and by increasing the boiling temperature by adding potassium sulphate. The mineralisation was followed by steam distillation of the nitrogen as NH_3; after alkalinisation of the mineralised extract with sodium hydroxide (NaOH). The distillate was captured in boric acid ($H_3 BO_3$) and then titrated with sulphuric acid or dilute hydrochloric acid (0.01N). 2 g of fine soil was used as a test sample. The Kjeldahl method remains the best because it gives a reliable precision and does not present any limit either on the process or the type of results obtained.

The value of the C/N ratio was obtained from the carbon and nitrogen contents.

3) Statistical Analysis

Analyses of variance at the 5% threshold were carried out with R software after checking the normality of the distributions and the homogeneity of the mean variances. The Kruskal-Wallis test was used to analyse the differences in carbon and nitrogen content and in soil organic carbon stocks according to age and depth. The Steel-Dwass test was used to compare two means.

3. Results

3.1. Organic Carbon

At Kouoptamo the COS is higher in the (35 - 50) year old systems with values ranging from 26.93 ± 1.56 to 21.69 ± 0.99 at 10 and 30 cm depth respectively (**Table 1**). The ANOVA test reveals that there is a significant difference between the young (5 - 20) year old plots and all other age classes including the neutral control (F = 3.992 and P-Value = 0.015) (**Table 2**). As a function of depth, the SOC stock decreased from 26.93 ± 1.56 to 14.56 ± 0.66 and there was no significant difference between the organic carbon stock of the ACA at 10 cm soil depth (**Figure 3**). At Foumbot, the SOC is higher in the (35-50) year old ACAs with values ranging from 31.15 ± 0.41 to 20.96 ± 0.80 at 10 and 30 cm depth respectively as shown in **Figure 4**. Depending on the depth, this stock varies from 21.30 tC/ha to 31.15 tC/ha at 10 cm soil depth, then from 18.37 tC/ha to 31.38 tC/ha at 20 cm soil depth and finally from 16.40 tC/ha to 23.16 tC/ha at 30 cm soil depth (**Figure 3**). However, there is a significant difference between the carbon stock of the control plot and that of the other four age classes at the 10 cm depth (F = 28.47, $P = 0.0001$).

Table 1. Carbon stocks as a function of depth and age of FAS at Kouoptamo.

Depth	Age range				
	Test control	5 - 20 years	20 - 35 years	35 - 50 years	50 years and over
10 cm	25.04 ± 1.47	24.49 ± 2.40	22.94 ± 0.89	26.93 ± 1.56	24.99 ± 1.75
20 cm	21.67 ± 1.27	18.42 ± 1.28^{a}	18.71 ± 0.97$^{\alpha}$	20.82 ± 1.41	24.03 ± 0.65
30 cm	15.82 ± 0.25	16 .67 ± 0.66	14.56 ± 0.66	21.69 ± 0.99***	16.60 ± 0.33

Table 2. Carbon stocks as a function of depth and age of FAS at Foumbot.

Depth	Age range				
	Test control	5 - 20 years	20 - 35 years	35 - 50 years	50 years and over
10 cm	13.73 ± 1.48	31.38 ± 1.13***	28.02 ± 0.96***	31.15 ± 0.41***	21.30 ± 1.62**$^{a\alpha}$
20 cm	12.82 ± 1.59	26.32 ± 1.47***	25.08 ± 0.85***^{b}	27.91 ± 0.77***^{c}	18.37 ± 0.84*$^{\alpha}$
30 cm	14.36 ± 1.00	17.79 ± 1.51*	23.16 ± 0.31***^{a}	20.96 ± 0.80**$^{\beta}$	16.40 ± 1.11$^{\gamma}$

*Significant difference between control and other plots with $P \le 0.1$; **$P \le 0.05$; ***$P \le 0.001$; ^{a}Significant difference between the 5 - 20 year plot and the other plots with $P \le 0.1$; $^{b}P \le 0.05$; $^{c}P \le 0.001$; $^{\alpha}$Significant difference between the 20 - 35 year old plot and the other plots with $P \le 0.1$; $^{\beta}P \le 0.05$; $^{\gamma}P \le 0.001$.

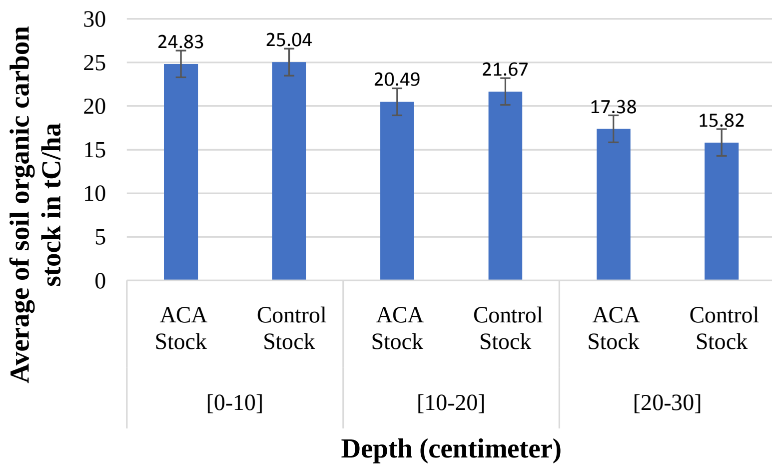

Figure 3. SOC stock as a function of depth at Kouoptamo.

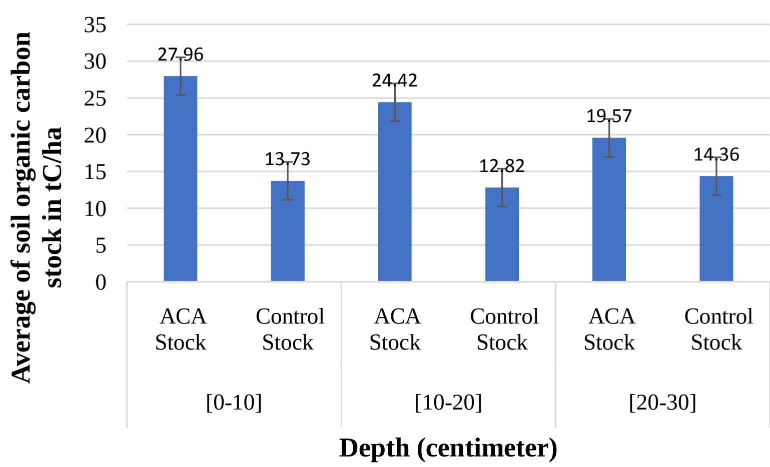

Figure 4. SOC stock as a function of depth at Foumbot.

3.2. Nitrogen Content

3.2.1. Depth Effect on Total Nitrogen Content

The results obtained show that nitrogen contents vary from 0.09 ± 0.04 to 0.15 ± 0.10 at Kouoptamo against 0.16 ± 0.05 mg N g^{-1} to 0.19 ± 0.08 mg N g^{-1} at Foumbot. The kruskal wallis test revealed a horizon effect on nitrogen levels (*P*-value = 0.0001). The Steel Dwass test showed that there was a significant difference between depths 10 and 30 (0.09) and (0.19). The distribution of nitrogen contents is shown in Table 3.

3.2.2. Age Effect on Total Nitrogen Content

Table 4 reports the nitrogen contents from 0 - 30 cm. The highest average was obtained with the oldest plot at both sites and the lowest in the 20 - 35 year old plot at Kouoptamo and 5 - 20 year old plot at Foumbot. The Steel Dwass test revealed a significant difference between the oldest ACA and the rest of the ACA for the total nitrogen content parameter and a non-significant difference between this old plot and the control plot (Table 4).

3.2.3. C/N Ratio

The raw data of total carbon and nitrogen contents obtained in the Arabica coffee FASs according to age classes were used to calculate the C/N ratio (Figure 5). According to age, these results reveal that the ratio is high in the (35 - 50 years) plot in Foumbot (34.62) and low in the (5 - 20 years) plot in Kouoptamo (15.02). The Kruskal-Wallis test showed that there is a significant difference between the C/N ratio of horizons according to the age of the systems (*P*-value = 0.002). Depending on the depth, at 30 cm this ratio is higher in Kouoptamo than in Foumbot with a maximum value of 118 and 42 respectively for the two subdivisions. The Kruskal-Wallis test (*P*-value = 0.006) showed an effect on the depth of the ACA (Figure 6).

Table 3. Nitrogen content according to depth.

Depth	Test control	Percentage nitrogen in mg N g^{-1} at Kouoptamo	Percentage nitrogen in mg N g^{-1} at Foumbot
10 cm	0.12 ± 0.02	0.09 ± 0.04	0.16 ± 0.05
20 cm	0.15 ± 0.05	0.12 ± 0.08	0.18 ± 0.07
30 cm	0.13 ± 0.03	0.15 ± 0.10	0.19 ± 0.08

Table 4. Nitrogen content according to the age of the systems.

Depth	Percentage nitrogen in mg N g^{-1} at Kouoptamo	Percentage nitrogen in mg N g^{-1} at Foumbot
5 - 20 years	0.17 ± 0.11	0.16 ± 0.03
20 - 35 years	0.06 ± 0.02	0.20 ± 0.08
35 - 50 years	0.09 ± 0.05	0.17 ± 0.09
50 years and over	0.17 ± 0.08	0.17 ± 0.07

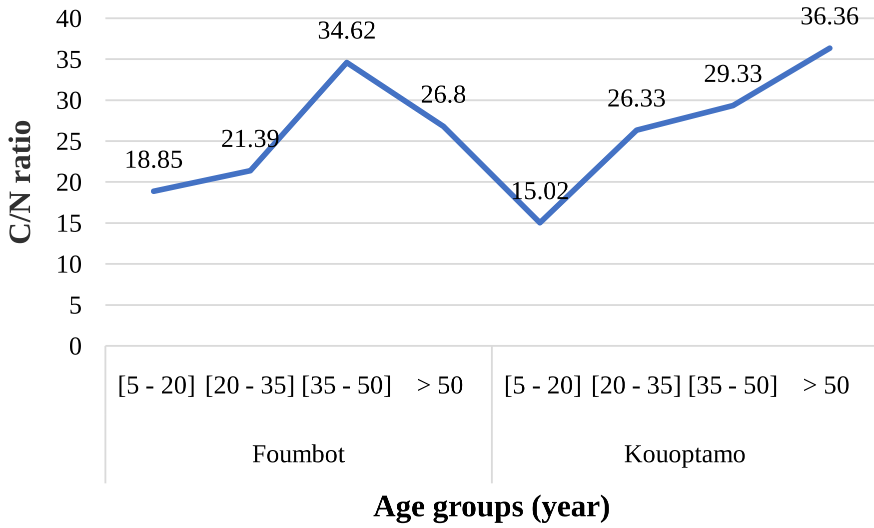

Figure 5. C/N ratio as a function of age of ACA.

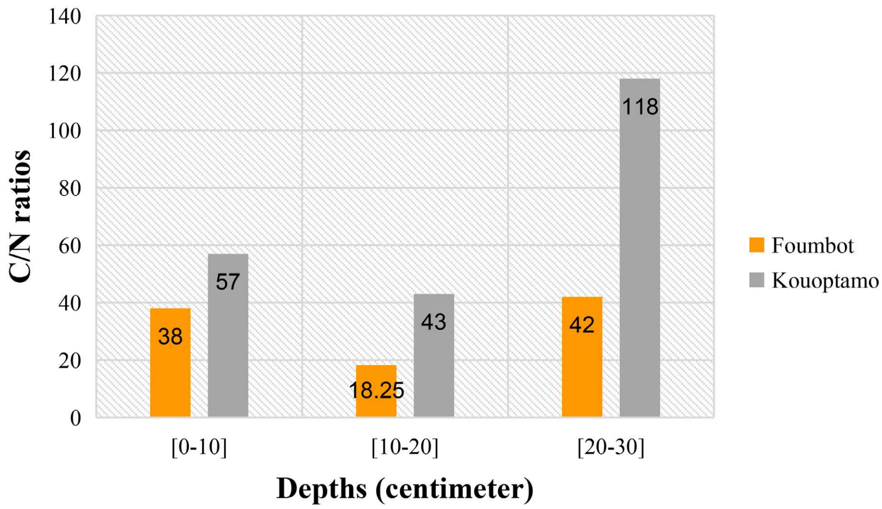

Figure 6. C/N ratio as a function of soil depth in ACA.

4. Discussion

The carbon and nitrogen contents obtained in this study in the ACA show that there are significant differences between horizons. Depending on soil depth, for a secondary forest in Ayos commune in central Cameroon, Silatsa et al. (2015) found a mean total stock of 58.90 ± 8.07 tC/ha at 30 cm, a value 23.16 ± 0.31 tC/ha higher than that found in the present study. This difference could be explained by the fact that AFSs are not designed in the same way or the density of trees in AFSs varies according to the agro-ecological zone; just as the species associated with ACA do not have the same capacity to store carbon. Land management practices are also a determining factor in the variation of carbon content. At 20 cm our study revealed an average stock of 26.32 ± 1.47 tC/ha. This result is close to 26.24 tC/ha found by Subba et al. (2018) in West Bengal, India. Similarly, considering the depths 0 - 10 cm, 10 - 20 cm and 20 - 40 cm, soils under AFSs in Bonito, Brazil store 26.71 tC/ha; 21.36 tC/ha and 43.68 tC/ha respectively (Martinelli, 2018). Furthermore, the same author shows that in Brazil about 60 t·ha^{-1} of carbon is stored between 0 - 30 cm which means that carbon storage is a function of the type of land use and the prevailing climatic conditions. These results differ from those of Banchard et al. (2005) who found that under highly intensified vegetable crops in the soils of the Lesser Antilles Martinique-Guadeloupe organic carbon stocks are lower, both in the 0 - 10 cm horizon and in the 0 - 30 cm horizon, regardless of the age of the FAS. However, the work of Malou et al. (2021) in Senegal shows that at 30 cm depth, SOC stocks in farmers' fields varied between 2.3 and 59.8 Mg C ha^{-1} (mean ± standard deviation, 14.6 ± 0.14 Mg C ha^{-1}). SOC stocks were slightly influenced by soil type, but were only weakly correlated with clay and silt content of the soils. SOC stocks differed significantly between the three village territories studied due to contrasting farming systems. This remains different when soil texture changes as for Yost and Hartemink (2019) organic carbon stocks are relatively low in the upper 20 - 40 cm of sandy soils with a value of 11 - 12 Mg C ha^{-1} in the upper 30 cm for Arenosols under fallow after millet or groundnut cultivation near Tivaouane or Louga, especially in West Africa and Senegal in particular. In West Africa, between 22 and 30 Pg C ha^{-1} are stored in soils, which represents about 24% and 25% - 35% of total carbon stocks respectively. For the 0 - 30 cm depth, estimates vary between 14.6 and 24.4 PgC ha^{-1} (Henry et al., 2020). Carbon stocks in soils result from the balance between three processes: organic inputs (aerial and root litter, soil amendments), the decomposition of these inputs by soil biological activities and the stabilisation of OM by the soil mineral matrix (clay particles, oxides) (Derrien et al., 2016). Depending on the age classes of coffee FASs, the organic carbon stock in our study area varies from 14.56 ± 0.66 tC/ha to 24.49 ± 2.40 tC/ha in Kouoptamo and from 16.40 ± 1.11 tC/ha to 31.38 ± 1.13 tC/ha in Foumbot. These results corroborate those found by Norgrove and Hauser (2013) who reported 90.9 tC/ha in a cocoa farm in the locality of Zoatoupsie, 10 km from Mbalmayo in southern Cameroon. The present study provides an organic carbon stock of between 51.7 and 106.4 tC/ha depending on the depth of the soil. According to Derrien et al. (2016), the carbon storage capacity of an agroforestry system varies between 12 and 228 tC/ha with an average value of 95 tC/ha. The values obtained in this research are within this range.

However, carbon and nitrogen contents show a decreasing gradient from surface to depth regardless of the age of the system. These results confirm those obtained by Kachaka (2014), Kalima (2018), Loumoni (2018) and Kooke et al. (2019). The rationale is the accumulation of organic matter and the consequent high biological activity as well as the low exploration of the root system at depth. The highest total nitrogen contents were obtained in Foumbot in the (20 - 35) classes of AFSs with an average of 0.20 ± 0.08 mg N g^{-1} and the lowest are observed in the same age AFSs in Kouoptamo with an average nitrogen content of 0.06 ± 0.02 mg N g^{-1}. These N contents are close to those obtained by Kalima

(2018) in an *Acacia auriculiformis-based* agroforestry system with 2 and 4 year old plantations (2.02%; 2.21% and 2.23%), results of low litterfall and low litter decomposition rate (Kalima, 2018). On the other hand, other authors such as Isaac et al. (2010) found carbon and nitrogen enrichment of soils under *Acacia auriculiformis* after 4 years of planting. Similarly, Kasongo et al. (2009) obtained six times higher levels in a 17-year-old stand, compared to savannah conditions. Similarly, the distribution of carbon stocks can be reflected in the mineralisation processes according to Ifo et al. (2017) this mineralisation normally takes place when the C/N ratio is between 9 and 12, it becomes slow when the C/N ratio is higher or equal to 12. Bationo et al. (2007) added that when the C/N ratio is lower than 9 the soils reflect a rapid decomposition of organic matter. This study revealed a C/N ratio higher than 12 depending on age or depth with values ranging from 15.02 to 36.36 depending on age and from 18.25 to 118 depending on depth, reflecting a very slow decomposition of organic matter, which leads to an accumulation of organic matter and consequently of SOC. This could explain the fact that the SOC is high in the 35 to 50 year old ACA and low in the young ACA.

5. Conclusion

This research estimated the organic carbon stocks of coffee-based AFSs in the Noun Division of West Cameroon. The main results show that COS and nitrogen contents are higher in the (35 - 50) classes of AFSs in Kouptamo and those of (5 - 20) classes in Foumbot. In addition, this study revealed a significant difference between organic carbon stocks according to the age and depth of the AFSs. Furthermore, these results were confirmed by the C/N ratio, which indicates a very slow decomposition of ACA according to age and depth. In view of the results obtained, it would be important to 1) extend the chronosequence to a higher age range of around 20 years; 2) take into account the properties of the soil (structure, texture, infiltration, etc.) because of their importance in understanding the phenomena governing the restitution of mineral elements in the soil; 3) analyse the types of microorganisms responsible for decomposing the organic matter that is linked to the organic carbon in the soil.

Conflicts of Interest

The authors declare that they have no competing interests.

Authors' Contributions

ATOUPKA Abdel Malik: Implementation of the study.

Pr TEMGOUA Emile: Study design, technical follow-up in the field and input by orientation.

Pr TEMGOUA Lucie Félicité: Design of the study, technical follow-up in the field and amendments to the manuscript.

ATCHOMBOU Baurel: Data collection and amendments to the manuscript.

TASSIAMBA Steve: Analysis of field data and amendments to the manuscript.

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