GSAR Journal of Agriculture and Veterinary Sciences
ISSN: 3048-9075 (Online)
Abbreviated key title: Glob.J. Agri.Vet.Sci.
Frequency: Monthly
Published By GSAR Publishers
Journal Homepage Link- https://gsarpublishers.com/journal-gjavs-home/

Effects of cultivation time on soil physical, chemical properties, soil organic carbon, total nitrogen stocks and dioxide carbon emission in Southeast of Chad

By

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Article History

Received: 31/01/2025
Accepted: 06/02/2025
Published: 08/02/2025

Vol – 2 Issue – 2

PP: -23-35

Abstract

This study aimed to examine the effects of agricultural activities on soil physico-chemical, SOC, TN stocks and CO_2 emissions as a function of cultivation duration. The study was carried out in southeastern Chad, focusing on three localities near the city of Am-Timan: Darasna (North-East), Madina (South) and Goz-Mabile (West). These sites have been intensively cultivated for flood recession sorghum production under glyphosate use for 25 35 and 50 years, respectively. Six soil profiles were collected and a total of 144 samples were obrained-36 per site. Soil samples were collected randomly from each plot at 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm and 50-60 cm in triplicate per experimental unit. The results indicated that soil pH in the study area was slightly alkaline and influenced by cultivation duration, with the highest pH observed after 25 years of cultivation. Additionally, soil bulk density and texture were affected by the duration of agricultural practices. The highest bulk density was recorded after 25 years of cultivation, while lower bulk densities were observed after 35 and 50 years of farming practices, highlighting the impact of cultivation time on soil compaction. A decline in SOC and TN stocks was evident with more than 25 years of cultivation, along with an increase in CO_2 emissions, particularly in the topsoil (0-20 cm) and subsurface (20-40 cm). Reducing cultivation duration may enhance soil fertility by improving soil physicochemical, as well as soil organic matter, ultimately contributing to increase crop yields and climate change mitigation.

Keywords: *Soil organic carbon, Total nitrogen, Carbon dioxide emission, Agricultural land, Chad, Vertisol*

1. Introduction

Soil organic carbon (SOC) and total nitrogen (TN) are crucial components of the agricultural ecosystems due to their significant contributions to soil quality, fertility and crop productivity (Olorunfemi et *al.,* 2020). Additionally, SOC plays a pivotal role in global climate mitigation because it's potential to function as a carbon dioxide (CO_2) sink (Chen et *al.,* 2009; Martin et *al.,* 2016). Globally, SOC stocks are approximately two and three times greater than carbon stored in the vegetation and the atmosphere respectively (Lal, 2004; Friedlingstein et *al.,* 2020). However, due to its susceptibility to land use and or land cover changes, SOC can act as either a source or a sink of CO_2, depending on the management practices employed (Chen et al., 2009; Zanatta and Salton, 2010; Olorunfemi et *al.,* 2020). According to several studies, land cover changes and unsustainable agricultural practices contribute significantly to the loss of SOC and TN (Chen et al., 2009; Don et *al.,* 2011; Veldkamp et *al.,* 2020; Winkler et *al.,* 2021). Winkler et *al.* (2021) reported that, on global scale, the conversion of natural ecosystems to agricultural land has resulted in a decline of 116 Gt of SOC in the top 2 meters of soil, with significant losses observed in the tropical regions. Similarly, the conversion of primary forest to cropland is

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responsible for 25-30% reduction in of SOC (Don et *al*., 2011).

Studies conducted in various regions of Africa revealed low levels of SOC and TN in agricultural soils (Girmay et *al*., 2008; Girmay and Singh, 2013, Gelaw and Singh, 2014; Bal et *al*., 2023; Okolo et *al*., 2023). Furthermore, land use changes are the second largest source of CO_2 emissions (Lozano-García and Parras-Alcántara, 2013), while agricultural practices account for approximately 20% of global greenhouse gas emissions (IPCC, 2007; Van der Werf et *al*., 2009). Canadell et *al*. (2009) estimated that land use changes in Sub-Sahara Africa alone contribute to emissions approximately 0.24 Pg C per year carbon.

The growing interest in understanding the effects on agricultural activities on SOC, TN and CO_2 emissions is driven by evidence that even small changes in SOC and TN stocks can result in significant CO_2 emissions, exacerbating climate change (Li et *al*., 2013; Albaladejo et *al*., 2013). However, agricultural soils also possess substantial potential for carbon sequestration on a global scale (Mcguire et *al*. 2009).

Assessing the effects of agricultural activities on soil physical and chemical properties, SOC, TN and CO_2 emissions is therefore essential for improving soil fertility and mitigating greenhouse gases (GHG) emissions (Lal, 2004). Despite the abundance of global research on this topic, relatively few studies have evaluated the impacts of agriculture on organic carbon stocks, total nitrogen stocks and CO_2 emissions in Africa, particularly in the Sudano-Sahelian region.

Land pressure, including soil overexploitation of soil, unsuitable cultivation practices and the disappearance of long-term fallow are profoundly altering the environment of Chad (Naitormbaide et al., 2011; Clément, 2019; Mouaromba et *al*., 2021; Bahouro et *al*., 2023). In Chad, the increasing population, driven in part by the massive influx of refugees combined with the reconversion of fishermen to agriculture due to declining water level in Lake Chad, has intensified pressure on the region's soils (Mouaromba et *al*., 2021). Currently, Chad is undergoing significant agricultural expansion, with intensive agricultural zones observed throughout country. As a result, soils in Chad are subjected to intensive exploitation, often with up to three harvests per year, which contributes to their degradation and the loss of fertility. Mouaromba et *al*. (2021) and Mikela et *al*. (2022) conducted field studies to assess the impact of intensive agriculture on soil organic matter (SOM). However, there is limited information on SOC stocks (Jones et *al*., 2013; Adoum et *al*., 2020). Adoum et *al*. (2020) reported SOC stocks ranging from 4.65 and 72.52 Mg C ha^{-1} in the topsoil (0-30 cm), while, Jones et *al*. (2013) estimated SOC stocks between 10-90 Mg C ha^{-1} at a depth of 1m. Despite the intensification of agricultural activities, there remains a lack of comprehensive data on the effects of agricultural practices on soil physicochemical properties, SOC and TN stocks and CO_2 emissions.

The objectives of this study are: (*i*) to assess the impact of intensive agricultural practices on soil physicochemical properties across four sites, considering the duration of cultivation, (*ii*) to quantify the distribution of SOC and TN stocks and CO_2 emissions across these sites over time and (*iii*) evaluate the rate of change in SOC soil, TN and CO_2 emission as a function of cultivation duration. We hypothesized that (*i*) that the duration of agricultural activities significantly influences soil physicochemical properties, as well as and carbon-nitrogen dynamics, in Sudano-Sahelian context; (*ii*) prolonged cultivation leads to a measurable reduction in SOC and TN stocks due to increased soil compaction and degradation of organic matter; and (*iii*): sites with shorter cultivation histories retain higher soil fertility and carbon sequestration potential, owing to less intensive land use practices.

Our study is the first field study investigation conducted at different time intervals across country to assess the changes in SOC, TN stocks and CO_2 emissions over an extended period (0-50 years) following the conversion of natural land cover to agricultural land-use systems.

2. Material and methods

2.1 Study area and sampling

The study was carried out in southeast of Chad, located between latitudes and 10°44'56.9" N and 11°21'3454" N, and longitudes 19°46'5908" E and 20°14'19.5"E, from November 2022 to December 2023. Three localities of the city of Am-Timan were selected: Darasna (Northeast), Goz-Mabile (West) and Madina (South) (Figure 1). These sites have been intensively cultivated for flood-recession sorghum production under glyphosate application for 25; 35 and 50 years, respectively. Additionally, control site was identified in the Wachoun region (Center), where natural vegetation comprising weeds nearly 2 m tall and scattered.

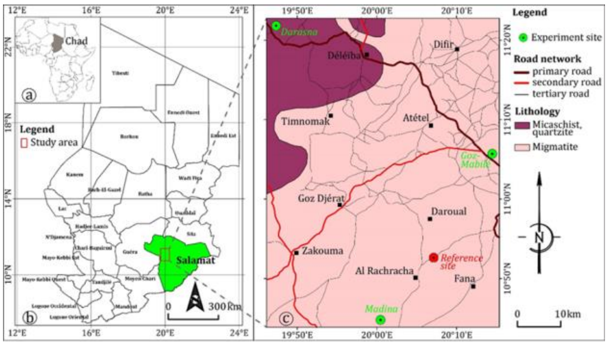

Figure 1 : Location of sampling area

The study area falls under Sahelo-Sudanese (So) climate zone, as defined by Auberville (1982). Thus climate is characterized by a short rainy season lasting 3 to 4 months, peaking in August, followed by a prolonged dry season of 5 to 8 months. The mean annual rainfall is approximately 938.8 mm (Zagalo et *al*., 2017). The P/ETP aridity index ranges between 0.09 and 0.2, refelecting an arid to semi-arid environment highly sensitive to climatic variability (Olivry, 1996).

The study sites fall within two distinct vegetation zones: the Sudanian and Sahelian zones. The Sudanian zone is characterized by open forests dominated by *Combretaceae* and legumes species, while the Sahelian vegetation is compriseted sparse shrublands and wooded savannas. Dominant trees species in the Sudanian zone include *Acacia sieberiana, Acacia polyacantha, Anogeissus leiocarpus, Combretum nigricans, Combretum Glutinosum* and *Terminalia species.* In constrast, the Sahelian zone features species such as Acacia. *nilotica, Balanites aegyptiaca, Anogeissus leiocarpus, Ziziphus mauritiania* and*Combretum glutinosum* (Binot, 2005).

Soil samples were randomly collected from each experimental plot at 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm and 50-60 cm within triplicates per depth per experimental unit. A total of six soil profiles described (Figure 2), resulting in collection of 36 samples per site and a total of 144 samples across all sites.

Figure 2:Different soil profiles sampled in the study sites at Madina (left) and Goz-Mabilé (right)

2.2 Soil physical and chemical analysis

The analyses were carried out at UMR 242 iEES Paris Centre IRD, located in Bondy, (Île-de-France, France). Bulk density (Bd) was dmeasured by the cylinder method. Disturbed samples were utilized to determine particle-size distribution through dispersion and sedimentation, employing the pipette method. Dispersion was achieved with 1 M NaOH solution and the samples were and shaken for 16 hours. Soil pH was determined in a 1:2.5 soiltowater suspension using pH meter with a glass electrode (Sparks et *al.,* 2020). Soil organic carbon and total nitrogen were quantified using an elemental CHNS analyser (Euro EA Elemental Analyser vector, USA) and Isotope Mass Spectrometer (EA-IRMS), respectively, following the methods outlined by Nelson and Sommers (1996; Sparks et *al.,* 2020). Isotopes δ^{13}C were determined using an isotope-ratio mass spectrometer (EA-IRMS).

2.3 X-ray diffraction (XRD)

The DRX was conducted at the Laboratory Pole of Experimentation and Analysis of Tropical Soils and Sediments at the iEES in Paris. Powder samples were side-loaded to minimize preferred orientation and scanned continuously in the air-dried state. The mineralogical composition of the clay fraction (< 2 µm) was analyzed using oriented powder samples, which were scanned continuously from 2 to40° 2θ at a scanning rate of 1.2°/min. Thermal treatments included heating to 550°C in the air-dried state, followed by exposure to ethylene glycol vapor for 24 h at 60 °C. Raw diffraction data were collected and analyzed using a Brucker D8-Advance diffractometer equipped with copper Kα radiation (λ = 1.5418 Å). Rapid screening of the primary minerals in the bulk fraction was performed following the classification system of Cook et *al.* (1975) and reference data from the PDF files provided by Brown and Brindley (1980).

2.4 Soil organic carbon and total nitrogen stock, equivalent carbon dioxide

SOC stocks and TN stocks were calculated for the 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm and 50-60 cm soil layers using the following equations:

$$\text{SOC Stock}_{\text{layer x}} = \sum_{\text{i}=1}^{\text{n}} \text{SOC} \times \text{Bd} \times \text{h} \times 0.1 \quad (\text{Eq. 1})$$

$$\text{TN Stock}_{\text{layer x}} = \sum_{\text{i}=1}^{\text{n}} \text{TN} \times \text{Bd} \times \text{h} \times 0.1 \quad (\text{Eq. 2})$$

Where SOC stock and TN are expressed in Mg ha^{-1}, Bd represents the soil bulk density in Mg m^{-3}; SOC and TN are expressed in percentage and *h* denotes soil depth in cm. The calculation account for for gravel content, assuming that these particles have a negligible SOC concentration.

To assess the impact of land use on the organic carbon stock under flood-recession sorghum cultivation, the variation in stocks (Mg C $\text{ha}^{-1}\text{year}^{-1}$) was calculated as the difference between the carbon stocks of the alternative practice and control, using the following equations:

$$\Delta SOC\ Stock_{layer\ x}(MgC\ ha^{-1}\ an^{-1}) = \left[\!\!\left[\frac{Stock_{t_n} - Stock_{t_0}}{t_n}\right]\!\!\right] \quad (\text{Eq. 3})$$

$$\Delta TNStock_{layer\ x}(MgN\ ha^{-1}\ an^{-1}) = \left[\!\!\left[\frac{Stock_{t_n} - Stock_{t_0}}{t_n}\right]\!\!\right] \quad (\text{Eq. 4})\ )$$

Where Stock_{tn} represents SOC or TN stocks under the alternative practice, $\text{Stock}_{\text{to:}}$ is SOC or TN stocks under control and t_n denotes the duration of cultivation.

To convert carbon to CO_2-equivalent (CO_2eq), the organic carbon stock is multiplied by a factor of 3.67, as proposed by Kauffman and Donato (2012) and Hamilton and Casey (2016), using the following equation:

$$\text{CO}_2\text{eq}\ (\text{MgCO}_2) = 3.67 \times \text{SOC stocks}\ (\text{Eq. 5})$$

2.5 Statistical analyses

All statistical analyses, including descriptive statistics, analysis of variance (ANOVA and Pearson's correlation coefficients were performed using R Project software (version 4.2.0). Correlation analysis was conducted to evaluate relationships between soil indicators, and statistical tests were considered significant at the 0.05 level.

3. Results

3.1 Soil physical properties variability across different sites

Error! Reference source not found. presents the soil physicochemical characteristics of the soil measured across the six profiles. According to FAO (1999) classification, the studied soils are classified as Vertisols. Soils with strongly aggregated angular blocks were observed in all soil profiles.

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The mean Bd did not differ significantly ($p > 0.05$) across the soil layers (0-20 cm, 20-40 and 30-60 cm). However, Bd was significantly higher ($p < 0.05$) in 25-years cropping (Darasna) compared to the control, 35 years (Madina) and 50 years (Goz-Mabile) at all depths (0–20 cm, 20-40 cm and 40-60 cm). Across all sites, an increase of Bd with depth was observed, except in Madina (Error! Reference source not found.).

Clay content was higher in 0-20 and 20-40 cm soil layers in 25 years cultivated soil compared to the Control. At 40-60 cm, the highest clay content was observed in 35 years of farming practices (72.3 %) than in 25 years (69.3 %) 50 years (63.2) of cultivation and the Control (54.5 %). Across all sites, of clay content generally increased with depth, except in 50 years agricultural soil (Error! Reference source not found.).

In all soil depths, silt content was significantly higher ($p < 0.05$) in the Control compared to 25 years, 35 years and 50 years farming practices. Sand content followed the same trend as silt, being higher in the Control than 25 years, 35 years and 50 years of cultivation (Error! Reference source not found.). An increase in sand content with depth was observed in the Control and 50 years of cultivation r, whereas a decrease with depth was noted 25 years and 35 years of cultivation (Error! Reference source not found.).

Table 1 : Soil physico-chemical parameters, soil organic carbon, total nitrogen stocks and carbon dioxide equivalent corresponding to different sites

		Physical properties					Chemical properties				Stocks		
Sites	Depth (cm)	Bd (g.cm^{-3})	Clay (%)	Silt (%)	Sand (%)	Texture	pH	SOC (%)	TN (‰)	C/N	SOCS (Mg C.ha^{-1})	TNS (Mg N.ha^{-1})	CO$_2$eq (Mg CO2.ha^{-1})
Control	0-20	1.19 ± 0.06ab	49.67 ± 14.38a	32.45 ± 8.81a	17.88 ± 10.56a	Clayed	6.85 ± 0.28ab	1.69 ± 0.7ab	1.44 ± 0.41a	14.4 ± 2.1ab	20.12 ± 8.5a	17.47 ± 4.91a	64.39 ± 27.2a
	20-40	1.26 ± 0.1ab	51.2 ± 13.02a	30.52 ± 4.55ab	18.28 ± 11.02a	Clayed	6.8 ± 0.35bc	1.73 ± 0.6ab	1.12 ± 0.31a	14.63 ± 2.15ac	21.85 ± 7.2a	14.33 ± 4.63a	69.93 ± 23.03a
	40-60	1.41 ± 0.04ac	54.49 ± 6.56a	25.97 ± 6.86ac	19.54 ± 9.11a	Clayed	6.65 ± 0.14bc	2.53 ± 0.62a	1.28 ± 0.22a	16.66 ± 3.74a	35.65 ± 8.31b	18 ± 3.16a	114.07 ± 26.61b
25 years (Darasna)	0-20	1.55 ± 0.06c	66.78 ± 8.77a	19.41 ± 6.43bc	13.81 ± 5.36a	Clayed	7.23 ± 0.25b	1.45 ± 0.41b	1.07 ± 0.25a	13.30 ± 0.99bcd	22.61 ± 6.84a	16.71 ± 4.05a	72.36 ± 21.9a
	20-40	1.58 ± 0.03c	68.9 ± 7.99a	18.09 ± 7.85c	13.01 ± 4.49a	Clayed	7.21 ± 0.2b	1.60 ± 0.25ab	1.12 ± 0.25a	13.96 ± 1.27ad	25.34 ± 4.25ab	17.64 ± 3.9a	81.10 ± 13.61ab
	40-60	1.58 ± 0.07c	69.33 ± 8.47a	18.89 ± 6.26bc	11.77 ± 5.38a	Clayed	7.22 ± 0.14b	1.44 ± 0.27b	1.09 ± 0.34a	14.09 ± 1.24ad	22.73 ± 4.53a	17.23 ± 5.06a	72.75 ± 14.5a
35 years (Madina)	0-20	1.07 ± 0.09b	62.72 ± 28.21a	17.24 ± 6.49c	20.04 ± 33.85a	Clayed	6.19 ± 0.53c	1.59 ± 0.91ab	1.56 ± 0.92a	10.74 ± 0.38d	17.58 ± 10.55a	20.71 ± 7.19a	56.25 ± 33.75a
	20-40	1.08 ± 0.01b	69.6 ± 7.32a	22.57 ± 5.07a	7.83 ± 3.06a	Clayed	6.22 ± 0.49ac	1.78 ± 0.34ab	1.63 ± 0.52	11.10 ± 0.79d	19.24 ± 3.75a	17.63 ± 5.6a	61.58 ± 12a

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				c					a			
	40-60	1.05 ± 0.02b	72.31 ± 2.78a	16.97 ± 4.48c	10.72 ± 4.46a	Clayed	6.25 ± 0.4ac	1.75 ± 0.34ab	1.52 ± 0.32a	11.12 ± 0.98bd	18.48 ± 3.7a	15.97 ± 3.53a	59.13 ± 11.85a
50 years (Goz-Mabile)	0-20	1.03 ± 0.17b	64.49 ± 7.12a	22.55 ± 5.09ac	12.97 ± 4.71a	Clayed	6.76 ± 0.31bc	1.45 ± 0.41b	1.10 ± 0.27a	13.3 ± 0.99bcd	15.42 ± 6.29a	11.69 ± 4.15a	49.34 ± 20.11a
	20-40	1.13 ± 0.16b	66.22 ± 4.69a	20.67 ± 6.67ac	13.11 ± 4.26a	Clayed	6.76 ± 0.23bc	1.60 ± 0.25ab	1.12 ± 0.25a	13.96 ± 1.27ad	17.89 ± 2.75a	12.6 ± 3.41a	57.26 ± 8.81a
	40-60	1.19 ± 0.37ab	63.17 ± 9.51a	21.71 ± 4.25ac	15.12 ± 7.95a	Clayed	6.83 ± 0.21ab	1.44 ± 0.27b	1.09 ± 0.34a	14.09 ± 1.24ad	16.97 ± 6.4a	12.42 ± 4.17a	54.30 ± 20.49a

3.3 Mineralogy and composition of the clay fraction (< 2 µm)

XRD analyses were conducted on the clay fractions of soils from Control and cultivated sites at depths of 0-10 cm, 20-30 and50-60 cm, respectively. The mineralogical analysis revealed the presence of smectite, illite, kaolinite and chlorite in across soils profiles. Specifically, the clay fractions contained smectite, illite (in Control and 35 years of cultivation) as well as kaolinite, chlorite (in 25 and 50 years of farming practices) at 0-10 cm, 20-30 cm and 50-60 cm, respectively (Error! Reference source not found.).

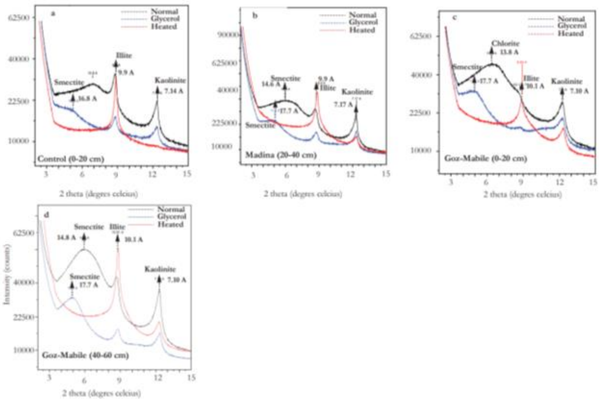

Table *1*). Regarding the C/N ratio, the values ranged from 11.1 to 14.1. Across all soil layers; the C/N ratio was significantly lower ($p < 0.05$) in 35 years of cultivation and similar in the others sites.

Table *1*). In topsoil layer (0-20 cm) and subsurface r (20-40 cm), SOC stocks followed the order 25 years > Control > 35 years > 50 years of cultivation. In the subsoil (40-60cm), the

Figure 3: XRD clay fraction of different soil in Control (a), Madina (b-c) and Goz-Mabile (d)

3.3 Soil chemical properties variability across different sites

Overall, the soil pH in the study area was within the slightly alkaline range. Across all the soil layers, the pH was significantly higher ($p < 0.05$) in 25 years of cultivation, followed the order of Control > 50 years > 35 years of cultivation.

In all the soil layers, the SOC content ranged from 1.44 % to 2.53%. The SOC content was significantly higher ($p < 0.05$) in the Control and 35 years of cultivation compared to 50 years and 25 years, respectively (**Error! Reference source not found.**). The TN content ranged from 1.07% to 1.63%. Among all soil layers, the highest TN content was observed in 35 years of cultivation, followed by the Control site, with lower values recorded in 25 and 50 years of agricultural soils. In the Control site, a decrease in TN content was observed between 0-20 cm and 20-40 depths, followed by an increase at 40-60 cm. Conversely, in the cultivated sites, the opposite trend was observed, with an increase in TN content from 0-20 cm to 20-40 cm, followed by a decrease at 40-60 cm (

3.4 Soil organic carbon, total nitrogen stocks and carbon dioxide equivalent variability across different sites

On average, SOC stocks ranged from15.42 Mg C ha^{-1} to 22.61 Mg C ha^{-1} at 0-20 cm soil depth 17.89 Mg C ha^{-1} to25.34 Mg C ha^{-1} at 20-40 cm soil depth, and 16.97 Mg C ha^{-1} to 35.65 Mg C ha^{-1} at 40-60 cm soil depth (

highest SOC stocks were recorded in the Control, followed by 25 years, 35 years and 50 years of framing practices, although there were no significant difference ($p > 0.05$) in SOC stocks among the sites (

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Table ***1***, Figure 4a). SOC stocks increased in 25 years of cultivation by 2.49 Mg C ha^{-1} (11.01%) and 3.49 Mg C ha^{-1} (13.77%). Among sites where SOC stocks decreased, the greatest reduction were recorded in 50 years and 35 years of cultivation, with declines of 23.35% and 18.12% in the topsoil, 52.23% and 12.62%) in subsurface 11.94% and 48.26% in subsoil respectively.

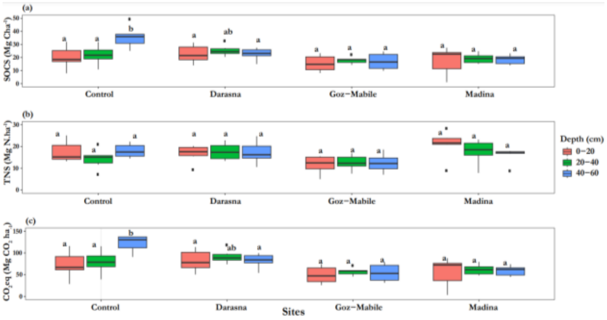

Table ***1***). In topsoil and subsurface, the highest TN stocks were recorded in 35 years of cultivation followed by the Control, 25 years and 50 years of cultivation. In subsoil, the

Table ***1***, Figure 4b). Regarding TN stocks, the greatest decreases were observed in 50 years of cropping, with reductions of 33.08% (11.69 Mg N ha^{-1}) in the topsoil, 12.07% (12.6 Mg N ha^{-1}) in the subsurface and 31.00% (12.42 Mg N ha^{-1}) in the subsoil.

Agricultural activities contributed to emissions ranging from 49.34$MgCO_2$ to 81.1 $MgCO_2$ at 0-20 cm soil depth, 57.26 to

Table ***1***, Figure 4c).

Figure 5highlights the spatial variation in SOC stocks (Figure 5a and Figure 5d), TN stocks (Figure 5b and Figure 5e) and CO_2eq (Figure 5c and Figure 5f). Significant differences in these parameters were observed across the study areas at 0-20 cm and 40-60 cm soil depths.

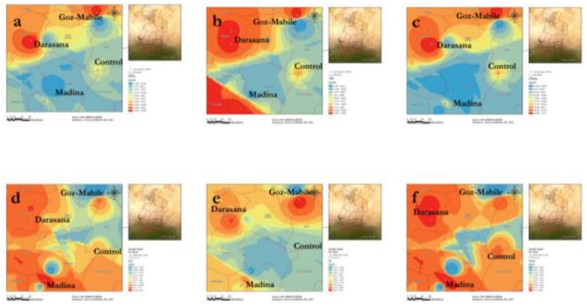

Figure 5 : Map of soil organic carbon, total nitrogen stocks and carbon dioxide equivalent in the 0-20 (a-c) and 40-60 cm (d-e) soil depth.

3.5 Changes in SOC and TN stocks losses

The mean estimated SOC loss (ΔSOC) was2.49 Mg C ha^{-1} yr^{-1}, 3.49 Mg C ha^{-1} yr^{-1} and -12.91 Mg C ha^{-1} yr^{-1} at 0-20 cm soil depth, -2.54Mg C ha^{-1} yr^{-1}, -2.61Mg C ha^{-1} yr^{-1} and -17.17Mg C ha^{-1} at 20-40 cm soil depth yr^{-1}, -4.7Mg C ha^{-1} yr^{-1}, -3.96 Mg C ha^{-1} yr^{-1} and -18.68Mg C ha^{-1} yr^{-1} at 40-60 cm depth. The average SOC loss was significantly higher (p <

Figure 4: Dynamic of soil organic carbon stocks (a: SOCS), Total Nitrogen stocks (b: TNS) and dioxide carbon equivalent (c: CO_2eq)) along the soil profile for difference time period from all sites: Darasna (25 years of cultivation), Madina (35 years of cultivation) and Goz-Mabilé (50 years of cultivation) On average, TN stocks ranged 11.69 Mg N ha^{-1} to 20.71 Mg N ha^{-1} at 0-20 cm soil depth, 12.6 Mg N ha^{-1} to17.64 Mg N ha^{-1} at 20-40 cm soil depth, and 12.42Mg N ha^{-1} to 18.00 Mg 40-60 cm soil depth (

highest TN stock was observed in the Control (18.00 Mg N ha^{-1}), followed by 25 years (17.23 Mg N ha^{-1}), 35 years (15.97 Mg N ha^{-1}) and 50 years (12.42 Mg N ha^{-1}) of cultivation (

81.10 $MgCO_2$ at 20-40 cm soil depth, and 54.30 $MgCO_2$ to 114.07 $MgCO_2$ at 40-60 cm soil depth. 25 years of cropping exhibited CO₂-equivalent (CO_2eq) emissions compared to the Control, 35years and 50 years of cultivation in both topsoil (0-20 cm) and subsurface (20-40 cm) (

0.05) in 0-40 cm soil layer compared to for the 0–20 cm (Figure 6a).

Regarding ΔTNS loss, intensive agricultural accounted for an average loss of -0.77 Mg N ha^{-1} yr^{-1}, 3.31 Mg N ha^{-1} yr^{-1}, -0.77 Mg N ha^{-1} yr^{-1} in 25 years of cropping (0–20 cm, 20–40 cm and 40–60 cm, respectively) -0.21 Mg N ha^{-1} yr^{-1}, 3.30Mg C ha^{-1} yr^{-1} and -2.04 Mg N ha^{-1} yr^{-1} in 35 years of cultivation, -5.78 Mg C ha^{-1} yr^{-1}, -1.73 Mg N ha^{-1} yr^{-1} and -5.58 Mg N ha^{-1} yr^{-1} in 50 years of cultivation (Figure 6b).

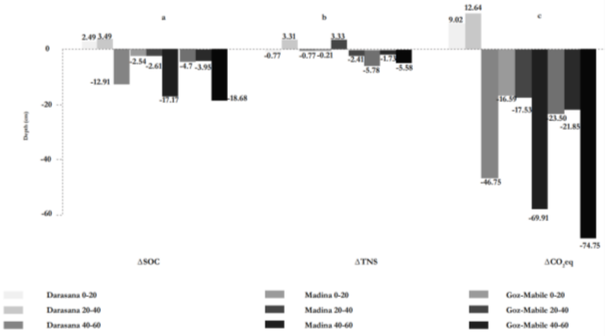

Figure 6: Variation of SOC; TN stocks and CO2eq gain and/or loss for the period 50 years for different sites

Agricultural activities resulted in emission of 9.02 CO_2eq yr^{-1}, 12.64 Mg CO_2eq yr^{-1} and -46.75 CO_2eq yr^{-1} in 25 years of cultivation (0–20 cm, 20–40 cm, and 40–60 cm, respectively), -16.59 CO_2eq yr^{-1}, -17.53 CO_2eq yr^{-1} and -69.91 Mg CO_2eq

yr^{-1} in 35 years of cultivation, and -23.5 Mg CO_2eq yr^{-1}, -21.85 Mg CO_2eq yr^{-1} and -74.75 Mg CO_2eq yr^{-1} in 50 years of cropping (Figure 6c). The highest ΔCO_2eq emissions were recorded in 50 years and 35 years of farming practice, respectively with values of 49.34 Mg CO_2eq (23.37%), 57.26 Mg CO_2eq (18.11%) and 54.30 Mg CO_2eq (52.39%) in the topsoil, 56.25 Mg CO_2eq (12.64%) and 61.58 Mg CO_2eq (11.94%) in subsurface, 59.13 Mg CO_2eq (48.16%) in the subsoil.

4. Discussion

4.1 Effect of land use on soil physical and chemical properties

Land cover changes, such as conversion of grazing lands to intensively cultivated cropland significantly degrade physical and chemical soil properties (Admasu et *al.*, 2014, Tellen and Yerima, 2018, Aredehey et *al.*, 2019, Bufebo et *al.*, 2020, Molla et *al.*, 2021). Cultivation duration has been shown to decrease Bd, indicating the decline of soil structural aggregation (Bufebo et *al.*, 2020, Molla et *al.*, 2022). These findings alignwith several others studies (Tellen and Yerima, 2018, Elias, 2019; Bufebo et *al.*, 2020, Molla et *al.*, 2022). For instance, Tellen and Yerima (2018) reported similar results northwest region of Cameroon.

Analysis of particle size revealed significant differences among the study sites, indicating that soil texture was affected by intensive agricultural activities. This result corroborates findings from several prior studies (Molla and Yalew, 2018, Molla et *al.*, 2020, Buruso et *al.*, 2023). Relatively higher clay content was observed in cropland compared to the Control site, likely due to the disturbance of soil aggregates during agricultural activities, which promote to a selective removal of clay particles via erosion (Molla and Yalew, 2018). Similar results were reported by Agoume and Birang (2009) in Cameroon. The observed increase in the clay content with soil depth may be explained by the translocation of clay particles from the surface to deeper layers (Warra et *al.*, 2015, Molla and Yalew, 2018, Gebeyaw, 2019). Comparable trends have been observed in other studies in Ethiopia (Admasu et *al.*, 2014; Gebeyaw, 2019; Tufa et *al.*, 2019), which indicated that prolonged agricultural activities accelerate (sedimentary processes, such as erosion, weathering, eluviation and deposition, ultimately affecting soil particle size distribution. Soil pH was also influenced by intensive agricultural activities, with the lowest pH values recorded at sites cultivated for extended periods (35 years and 50 years). These findings align with previous studies by (Negasa et *al.*, 2017; Alemayehu and Sheleme, 2013, Gebeyaw, 2019), which documented reduced pH in cultivated soils in Central and Southern Ethiopia. Similarly, Amusan et *al.* (2006) reported significantly lower soil pH under continuously cultivated areas in Nigeria. The higher pH values observed at the subsoil layers could be attributed to the leaching of basic cations and soil erosion caused by tillage (Kumar et *al*. 2012, Gebeyaw, 2019, Molla et *al.*, 2021).

The SOC was affected by intensive land use, with lowest SOC values observed after 35 years and 50 years of cultivation. Conversely, no significant impact on SOC was detected after 25 years of cultivation, likely due to the shorter duration of intensive land use. his supports findings from earlier studies (Kidanemariam et *al.*, 2012, Elias, 2016; Tellen and Yerima, 2018, Bufebo et *al.*, 2020, Buruso et al., 2023; Chukwuebuka et *al.*, 2023; Okolo et *al.*, 2023), which reported a decline in SOC content under continuous cultivation. Our results are in line with studies with studies from south-eastern Nigeria (Okolo et *al.*, 2023; Okebalama et *al.*, 2017; Nwite et *al.*, 2018), which noted higher SOC content in clay-textured soils. Consequently, our hypothesis of reduced SOC and TN stocks following prolonged cultivation was confirmed, with most losses occurring in the 0–40 cm topsoil layer. Similar conclusions were drawn by Girmay et *al*. (2008) and Okolo et *al.* (2023) in their respective studies in northern Ethopian**.**

Interestingly, Darasna exhibited the highest SOC and TN stocks, suggesting that 25 years of framing practices may have led to improvements in these stocks due to the site's higher clay content. Numerous studies have demonstrated the role of clay in enhancing SOC storage (Hassink, 1997; Arrouays et *al.*, 2006; Dexter et *al.*, 2008; Schmidt et *al.* 2011; Kleber et *al.*, 2021; Schweizer et *al.*, 2021; Johannes et *al.*, 2023). SOC stabilization in the clay fractions is largely attributed to the adsorption mechanisms provided by clay surfaces (Kaiser and Guggenberger, 2003; Curtin et *al.*, 2015; Matus, 2021). In this study, smectite was identified as the dominant clay mineral across sites (Figure *3*), and its surface area showed positive correlation between SOC and clay content (Mayer, 2004, Wagai et *al.*, 2015). However, the significant negative correlations between clay content and both SOC ($r = -0.66, p = 0.018$) and the C/N ratio ($r = -0.58, p = 0.047$) indicate that clay does not contribute to the stabilization of SOM but may instead facilitate its mineralization (Table 2). These results align with the findings of Tsozué et *al*. (2020), who reported similar trends and contrast with previous findings (Hassink, 1997; Kaiser and Guggenberger, 2003; Mayer, 2004; Arrouays et *al.*, 2006; Dexter et al., 2008; Rabot et *al.*, 2024). This suggest that cultivation time is the primary factor controlling SOC, TNS and CO_2eq.

Table 2 : Pearson correlation matrix between soil physicochemical properties. Bolt values are significant at p < 0.05

	Bd	Clay	Silt	Sand	pH	SOC	TN	C/N
Clay	0.05							
Silt	-0.1	-**0.89**						
Sand	0.05	-0.8	0.45					
pH	**0.81**	-0.05	0.07	0				
SOC	-0.25	-**0.66**	0.55	**0.59**	-0.41			
TN	-0.55	0.03	0	-0.05	-**0.84**	0.54		
C/N	0.52	**-**	0.54	0.44	**0.61**	0.22	**-**	

0.58	**0.63**

The impact of intensive agriculture on TN stocks was evident in soils cultivated s for 25 and 50 years of cropping, years respectively, but no significant changes were observed at the 35 years of cultivation. TN stocks increase increased with soil depth in the 25 and 50 years sites, a trend contrary to previous studies (Gebeyaw, 2019, Bakhshanded et *al*., 2019, Soleimani et *al*., 2019, Bufebo et *al*., 2021, Buruso et *al*., 2023). Subsoil was contained higher clay content and clay minerals such as smectite, which likely limited the degradation of organic matter and enhanced the soil'nutrient and carbon storage capacities (Buruso et *al*., 2023).

4.2 Effect of land use on SOC, TN stocks and CO_2 emissions

The lowest SOC and TN were observed after 35 and 50 years of cultivation, while the highest SOC and TN stocks was recorded 25 years of cultivation These findings are consistent with previous studies (Abagaz et *al*., 2016; Biazin et *al*., 2018). Prolonged cultivatio increases the exposure of physically preserved particulate organic matter to rapid oxidation, leading to significant reductions in SOC and TN (Post and Kwon 2000; Lal 2002; Demessie et *al*., 2013; Li et *al*., 2013). Similar results reported by Gelaw et *al.* (2014) in a semi-arid watershed in Northern Ethiopia, highlighting the adverse effects of long-term cultivation on soil quality.

Significant losses of SOC and TN were observed after 35 and 50 years of cultivation. These rates of loss align with those reported by Don et *al.* (2011) and Aticho (2013), who found SOC and TN losses of 25% and 33-37%, respectively, for tropical regions and in southwestern Ethiopia. However, our results are lower than the highest rate of loss reported by Assefa et *al.* (2017),in northwest of Ethiopia, where the conversion of forest to croplands reduced C stocks by 70% over30 years of cultivation. These losses of soil C and N in intensively cultivated croplands can be attributed to topsoil erosion (Assefa et al., 2017), the removal of organic materials from fields (Abegaz et *al*., 2016), accelerated decomposition rates (Deng et *al*., 2014; Abegaz et *al*., 2020), and increased weathering and microbial activity (Smith, 2008; Lal, 2005). The loss of SOC and TN stocks was most pronounced in topsoil and subsurface, which is in agreement with findings from several studies (Don et *al*., 2011; Assad et *al*., 2013; Demessie et *al*., 2013; Lozano-Garcia and Parras-Alcantara, 2014; Yu et *al*., 2014; Biazin et *al*., 2018). The highest SOC and TN were recorded in subsoil layer across the study sites. These findings are supported by numerous works (Yimer et *al*., 2007; Assad et *al*., 2013; Demessie et *al*., 2013; Braz et *al*., 2013; Biazin et *al*., 2018) and can be attributed to the rapid turnover of long and fine roots (Asaye and Zewdie, 2013; Biazin et *al*., 2018). This result is aligns with findings of Biazin et *al.* (2018), who demonstrated that the effects of agricultural practices are more pronounced in the upper soil layers. Additionally, the restoration of the carbon and nitrogen in the topsoil layer through the cultivation of vegetables may explain these dynamics (Roa-Fuentes et *al*., 2015). Agricultural soils possess a significant capacity to act as sinks CO_2 and other greenhouse gases (GHGs) (Mirzaei et al., 2022; Mohammed et *al*., 2022; Lal, 2022). In recent years, research on GHG mitigation and adaptation in agricultural soils has garnered considerable attention (Guo and Liu, 2022; Lal, 2022). Compared to intensively managed croplands, statistically significantCO_2 accumulation was observed in soils cultivated for 25 years of cultivation and subsequently left uncultivated. These findings were in agreement with several works (Krisnawat, 2015; Shiraishi et *al*., 2023; Wang 2024). In this study, the mean rate of CO_2 emissions was significantly higher than the range (0.37 Gt CO_2 to 0.54 Gt CO_2) reported by Wang (2024). Wang (2024) attributed this increase in carbon emissions to land use changes in Brazil. Similarly, Shiraishi et *al*. (2023) estimated CO_2 emissions of 0.13 Pg CO_2.year^{-1} in 2016 in Borneo. Our results suggest that elevated CO_2 emissions are associated with prolonged intensive agricultural. The study also revealed a decline in CO_2 emissions with soil depth, corroborating findings by Okolo et *al.* (2023), who reported decrease similar trend in croplands of semi-arid regions in northern Ethiopia. Furthermore, our results indicated that soils cultivated for 25 years of cultivation functioned as CO_2 sinks, whereas subsoil acted as source of CO_2 emissions, suggesting topsoil contributed to CO_2 sequestration.

4.3 Implications for land use policy and sustainable agriculture in Sudano-Sahelian zone

Land degradation, low water productivity and high rainfall variability- often associated with climate change- are among the primary challenges faced by many countries of Sub-Saharan Africa (Karanja Nganga et *al*., 2016; Woldearegay et *al*., 2018; Gora, 2021). Araya (2011) reported that extensive cultivation has led to decline in soil productivity. To address these challenges, numerous scientific investigations and cultural practices have been developed, refined and recommended to sustain agriculture production in these regions (Golla, 2021). Sustainable agricultural practices, including no-tillage, manure application agroforestry, mulching, cover cropping and crop rotation, can be implemented to improve soil fertility and enhance carbon sequestration.

5. Conclusions

The present study was conducted to evaluate the effect of cultivation duration on SOC, TN stocks and CO_2 emissions. Our findings demonstrate that cultivation duration influences soil physico-chemical properties, SOC, TN stocks and CO_2 emissions. The most pronounced impacts were observed after

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35 and 50 years of cultivation. In contrast, sites cultivated for 25 years of cultivation appeared less sensitive to land use changes, exhibiting higher SOC and TN stocks in the topsoil layers and functioning as CO_2 sinks. This result suggests that in the Sudano-Sahelian zone, minimally exploited sites can serve as potential carbon sinks, contributing to climate change mitigation.

Nevertheless, further research is required to better understand the factors that promote carbon accumulation at these sites.

Acknowledgements
This research is part of a PhD thesis project funded by the TarsPro. The authors express their gratitude to IRD laboratory for their administrative support, with special thanks to staff UMR 242 iEES Paris Centre IRD Île-de-France in Bondy (Paris, France) for their assistance in sample preparation and analysis. We also extend our thanks to the Laboratory for Management of Natural Resources and the Environment at the University of Douala for their valuable support.

Credit authorship contribution statement
Mouaromba Wavel: Sample collection and analysis, formal data analysis, cartography, early draft, manuscript revision. Mabicka Obame Rolf Gaël: Writing original draft, formal data analysis, manuscript revision. Musadji Neil-Yohan: Writing original draft, statistical analysis formal data analysis, manuscript revision. Adoum Abdramane: Manuscript revision. Ngon Ngon Gilbert François: formal data analysis, manuscript revision. Etame Jacques: formal data analysis, manuscript revision.

All authors have read and approved the submitted version of the manuscript.

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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