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ORIGINAL PAPER

Soil Carbon and Nutrient Trajectories Across A 52-Year Cocoa Agroforestry Chronosequence Under Low-Input Smallholder Management

Ndzana Georges Martial[1] · Zhimin Zhao[2] · Ruili Gao[3] · Mengue Mfou'ou Yvana[1] · Joseph Kabala Mubolo[1] · Amani Kagadju Napoléon[1] · Tadjuidje Armel Landry[1] · Moundjeu Evarist[1] · Abodo Thierry Mamert[1] · Bin Xue[4] · Jeroen Meersmans[5]

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Abstract

Land-use change, particularly the conversion of forests to agriculture, is a major factor contributing to soil degradation in tropical regions. This study aims to investigate the long-term effects of converting natural forests to cocoa agroforestry systems on soil organic carbon (SOC) and nutrient pools in the Oxisol of South Cameroon, addressing the issue of soil degradation due to agricultural land-use change. Using a chronosequence approach, we compared soils from natural forest with those from cocoa plantations that were 7, 41, and 52 years old. Soil samples were collected from three depths: 0–10 cm, 10–20 cm, and 20–30 cm, and were analyzed for SOC, total nitrogen (TN), available phosphorus (AP), and exchangeable bases (K^+, Ca^{2+}, Mg^{2+}, Na^+), alongside their respective stocks. The results indicated a significant decrease in SOC concentrations and stocks following the conversion from forest to cocoa cultivation, with a total loss of 18% in the 0–30 cm depth profile after 52 years. Conversely, TN and AP stocks showed increases of 44% and 11%, respectively, predominately in the deeper soil layers over the same time frame. Exchangeable potassium (K^+) levels rose with the age of the plantations, while calcium (Ca^{2+}) and magnesium (Mg^{2+}) initially peaked but then experienced a notable decline. We found strong positive correlations between SOC and TN, as well as among the exchangeable cations. The finding suggest that converting forests to cocoa agroforestry without sustainable practices can lead to substantial long-term reductions in SOC and base cation availability, ultimately compromising soil health. To mitigate soil carbon and nutrient depletion, we highlight the importance of conserving existing forests and advocate for enhanced agroforestry practices with organic amendments in established cocoa systems, thereby promoting sustainable agricultural production in these highly weathered soils.

Keywords Land-use change · Soil carbon sequestration · Nutrient depletion · Soil fertility · Chronosequence · Sustainable agriculture

1 Introduction

Land-use change, especially the conversion of tropical forests to agricultural systems, is a dominant force driving global environmental change, with profound implications for soil health, carbon cycling, and ecosystem services (Jakovac et al. 2021; Smith et al. 2016). In the humid tropics, forests are increasingly replaced by cash crops such as cocoa (*Theobroma cacao L.*), driven by economic incentives and growing global demand (Duguma et al. 2001; Schroth and Ruf 2014). While cocoa is often cultivated under agroforestry systems that retain some tree cover, its expansion

✉ Ndzana Georges Martial
ndzanageorges2006@yahoo.fr

[1] Department of Soil Sciences, Faculty of Agronomy and Agricultural Sciences, University of Dschang, Po. Box 222, Dschang, Cameroon

[2] School of Resource Environment and Life Sciences, Ningxia Normal University, Guyuan, Ningxia 756000, China

[3] School of Agriculture, Ningxia University, Yinchuan, Ningxia, China

[4] School of Ecology and Environment, Ningxia University, Yinchuan, Ningxia, China

[5] Department of Gembloux Agro-Bio Tech, University of Liège, Liège 4000, Belgium

still entails significant biomass removal, soil disturbance, and long-term alterations in biogeochemical cycles (Nijmeijer et al. 2019; Wartenberg et al. 2017).

Previous studies in understanding forest-to-agriculture conversion has highlighted consistent patterns of soil organic carbon (SOC) decline, particularly in the first decades after deforestation (Bernadin et al. 2025; Bruun et al. 2015). Meta-analyses show that converting tropical forests to agricultural land typically results in high SOC loss with the magnitude depending on management intensity, climate, and soil properties (Beillouin et al. 2023; Don et al. 2011; Guo and Gifford 2002; Huang et al. 2024).However, recent studies suggest that well-managed agroforestry systems especially those integrating shade trees and organic inputs can mitigate these losses and even enhance nutrient cycling over time (Atapattu et al. 2024; Dewangan et al. 2024). In cocoa systems, some research reports initial nutrient enrichment due to decomposition of residual forest biomass, followed by gradual depletion without external inputs.

Several studies have examined the impact of forest-to-cocoa conversion on soil properties. For instance, Dawoe et al. (2014) observed significant SOC reduction within three years of conversion in Ghana. Converting tropical forest to cocoa–based agroforestry led to a substantial total C–stock and nutrients decrease (Arthur et al. 2022; Dawoe et al. 2014), while Adiyah et al. (2023) and Tinoco-Jaramillo et al. (2024) reported SOC gains in the Ecuadorian Amazon cocoa agroforestry systems, attributing improvements to organic amendments and diversified shade tree integration. Additional evidence from the Amazon and Ecuador shows that cocoa agroforestry can enhance deep soil carbon storage and improve nutrient status under favorable management (Reyna-Bowen et al. 2025; Suárez et al. 2025). These contrasting findings underscore that SOC and nutrient responses are not inherent to cocoa agroforestry itself but depend heavily on management practices, shade tree composition, and soil characteristics (Middendorp et al. 2018).

Although several studies have examined forest-to-cocoa conversion, most have been conducted outside Central Africa or under management regimes that differ substantially from those used by smallholders in Cameroon. In Cameroon, however, existing work has focused primarily on savannah-to-cocoa transitions (Fonkeng et al. 2024), leaving a major gap regarding how forest-derived cocoa systems evolve over multiple decades under the low-input, minimally managed conditions typical of smallholder farms.

This study addresses this gap by investigating the long-term evolution of soil fertility across a 52-year cocoa agroforestry chronosequence in southern Cameroon. We examine how conversion from natural forest to cocoa cultivation affects soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), and exchangeable base cations (K^+, Ca^{2+}, Mg^{2+}, Na^+) under low-input management without fertilizers or soil conservation practices. We hypothesize that (i) forest conversion leads to an initial decline in SOC and nutrient stocks, (ii) older cocoa systems may show partial recovery through organic matter accumulation, and (iii) SOC nutrient relationships reflect long-term biogeochemical coupling shaped by management and soil mineralogy. By evaluating these trajectories under real-world farming conditions, this study provides evidence to inform sustainable cocoa production, climate-smart agriculture, and soil conservation strategies in Central Africa.

2 Materials and Methods

2.1 Description of the Study Area

The research was conducted at Nkoemvone, in the South of Cameroon, precisely between 2°48’N and 2°49’N and between 11°7’ E and 11°8’ E. It is situated at Mvila subdivision and covers an area of 8,697 km². The region experiences an equatorial Guinean climate, marked by four distinct seasons: two dry seasons alternating with two rainy seasons. Mean annual temperatures average 24.8 °C, with substantial annual precipitation reaching 2000 mm. Vegetation consists primarily of dense but degraded forest, transitioning to shrub-dominated patches in urbanized areas (Mertens & Lambin 2000). The lithology of the study area is dominated by granitoides, especially the charnockite which is a category of coarse-grained igneous rocks primarily composed of quartz, feldspar, and mica (Pouclet et al. 2007; Tchameni et al. 2000). The dominant soils include highly weathered and iron-rich soils across the landscape. They have very low nutrients stocks resulting in low native fertility and are classified as Oxisol (Soil Survey Staff 2014). These soils are acidic (pH = 4 to 5) texture changing from clay-to-clay loam (Table 1). However, these soils are broadly used for cacao cultivation in the study area and have been reported to be suitable for cocoa cultivation (Ehounou et al. 2019).

2.2 Description of Study Site Design and Soil Sampling

The study comprised four adjacent sites located at 2°48’N, 11°7’E and including a natural forest representing the initial state before turning into cocoa plantation; and three cocoa agroforestry system farms with varying ages form 7 years, 41 years and 52 years. The idea is to compare the SOC and nutrient pools from natural forest with the one in cocoa agroforestry system farms.

Table 1 Location of the study site and soil basics properties of forest and cocoa plantation at different ages

				Soil textures (%)					
System	Standard ages (Year)	Location	Altitudes (m)	Sand	Silt	Clay		pH	Soil type
Forest	0	2°49’5,2”N 11°7’15,7”E	560	31.44	23.00	45.56	Clay Loam	4.0	Oxisol
Cocoa plantation	7	2°48’57,0”N11°7’16,8”E	610	33.94	15.28	50.78	Clay	4.4	
Cocoa plantation	42	2°49’16,1”N11°7’6,1”E	510	43.61	15.67	40.72	Clay Loam	4.1	
Cocoa plantation	53	2°49’9,1”N 11°7’15,6”E	560	26.67	33.78	39.56	Clay Loam	5.0	

Table 2 Bulk Density (g cm^{-3} ± SEM), at the different depths of the soil profile in forest and cocoa plantation

Soil depth (cm)	Forest	Cocoa 7 Years	Cocoa 40 Years	Cocoa 50 Years
0–10	0.96±0.05	1.25±0.03	1.14±0.05	1.23±0.02
10–20	1.07±0.05	1.23±0.06	1.27±0.01	1.25±0.02
20–30	1.22±0.06	1.21±0.05	1.26±0.04	1.23±0.01
0–30	1.08±0.05	1.23±0.03	1.23±0.02	1.24±0.02

Among the study sites, the natural forest serving as control was not affected by any perturbation. The cocoa agroforestry system site comprises three farms plantation created in 2018 (Year 1), 1983 (year 41) and 1972 (Year 52). Farm Year 7 is the newest farm, covering an area of 1.32 ha, with a total of 1,066 trees. Farm Year 41 covers an area of 1.41 ha, with a total of 560 trees. Farm Year 52, the oldest cocoa farm in the study area, covers an area of 1.75 ha and has 709 productive plants. Although the chronosequence includes uneven temporal intervals particularly the 34-year gap between the 7- and 41-year plantations, this distribution reflects the actual availability of cocoa farms in the study landscape. Cocoa establishment in the region has historically occurred in discrete waves linked to socio-economic and demographic factors, resulting in limited representation of intermediate plantation ages (20–25 years). Chronosequence studies in tropical agroforestry systems frequently rely on such opportunistic age structures, especially where land tenure, farm abandonment, and replanting cycles constrain the availability of evenly spaced age classes. Despite the uneven intervals, the selected sites share comparable soil type, landscape position, management history, and farmer practices, allowing meaningful interpretation of long-term soil carbon and nutrient trajectories. The inclusion of the 41- and 52-year plantations still captures mature system dynamics and provides valuable insight into long-term biogeochemical changes in cocoa agroforestry systems on Oxisol.

Across all cocoa agroforestry sites, cocoa density and shade-tree composition varied with plantation age, reflecting the low-input, smallholder management typical of the region. Shade-tree density was generally low and dominated by remnant forest species retained during establishment. Common shade species included *Terminalia superba*, *Ceiba pentandra*, *Cola acuminata*, *Irvingia gabonensis*, and scattered fruit trees such as *Dacryodes edulis* and *Mangifera indica*. No deliberate shade-tree enrichment, pruning, or canopy management was reported, and shade cover tended to decline with plantation age due to natural senescence and selective removal by farmers.

Establishment practices were similar across farms. Forest conversion involved manual logging and slashing, with occasional burning of residual biomass. Cocoa seedlings were planted at variable spacing (typically 3 × 3 m to 3 × 4 m), without soil amendments or fertilization. Management remained low-input throughout the chronosequence, consisting mainly of periodic weeding and herbicide application. Farmers did not apply organic amendments (mulch, compost, manure), mineral fertilizers, or implement soil conservation measures such as cover cropping or residue retention.

Disturbed soil samples were collected at 0–10, 10–20 and 20–30 cm depth in all study sites including in natural forest and cocoa farms with different ages using soil auger. For that, three replicates sampling plots (35 m x 55 m to 75 m x 85 m) depending on the farm size were considered for each site and soil samples were collected from twenty points along an S-shaped transect for a total of sixty soil samples per soil depth (3 replicates x 20 points) and a total of 180 samples for each site considering the three layers. Along with collected soil samples, undisturbed soil samples with replicates were also collected in each depth for bulk density and carbon storage measurements. The collected soil samples were bagged in plastic bags for laboratory where they will be air-dried, passed through a 2 mm sieve prior to analysis.

3 Laboratory Analysis

Bulk density (BD) was determined using the Blake (1965) undisturbed core method. Because the standard 100 cm^3 core sampler has a height of approximately 5 cm, two separate cores were collected for each 10 cm soil increment. For the 0–10 cm layer, one core was taken from 0 to 5 cm and another from 5 to 10 cm; the mean BD of these two cores represented the full 0–10 cm increment. The same procedure was applied to the 10–20 cm (10–15 and 15–20 cm) and 20–30 cm (20–25 and 25–30 cm) layers (Table 2). Each core was oven-dried at 105 °C to constant weight, and BD was calculated as dry mass divided by core volume. The determination of SOC was carried out using the acid-dichromate wet oxidation method (Walkley and Black, 1934). The total Nitrogen was determined by the digestion with H_2SO_4 using the Kjeldahl method (Jones Jr 1991). Available phosphorus (P) was determined by Bray II methods (Sims, 2000). The ammonium acetate (1 M and pH 7.0) method was used to determine the exchangeable Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} cations (Metson 1957). The Sum of Exchangeable Bases (SEB) was calculated as the arithmetic sum of the concentrations of these four cations following the Eq. (1):

$$\mathrm{SEB} = \mathrm{ExCa} + \mathrm{ExMg} + \mathrm{ExK} + \mathrm{ExNa} \tag{1}$$

The analysis were performed into three replicates.

The Total Exchangeable Bases (TEB) represents the stock of exchangeable bases within a given soil layer and was calculated by multiplying SEB by bulk density (BD) and layer thickness (H) (Eq. 2):

$$\mathrm{TEB}\ \left(\mathrm{cmol}\diagdown m^2\right) = \mathrm{SEB} \times \mathrm{BD} \times H \times 10 \tag{2}$$

where BD is in g cm^{-3} and H is in cm. This approach ensures consistency with the stock calculations used for SOC, TN, and AP. We have used TEB in cmol/m^2. Using cmol cm^{-2} is not a replacement for the conventional unit. It is used only when to express exchangeable cation stocks per unit area, not per unit mass.

The stock of AP, TN and SOC were calculated using the following Eq. (3):

$$\mathrm{Y\,stocks} = \mathrm{Y} \times \mathrm{BD} \times \mathrm{H} \times 10 \tag{3}$$

Y signify the stocks of SOC (Mg/ha), TN (Mg/ha), or AP (g/ha) in the soil sample. The soil total nitrogen content is represented as TN (g/kg), while BD indicates the soil's bulk density (g/cm^3). SOC refers to the soil organic carbon content (g/kg), and AP represents the available phosphorus content. H signifies the thickness of the soil layer (cm) (Li et al. 2019).

For statistics, all statistical analyses were performed using SPSS 19.0, with significance set at $p<0.05$. Prior to conducting the one-way ANOVA, we verified that the data met the underlying assumptions of parametric analysis. Normality of residuals was assessed using the Shapiro-Wilk test, complemented by visual inspection of Q-Q plots and residual distribution histograms. Homogeneity of variances was evaluated using Levene's test. All variables satisfied these assumptions at $p>0.05$. In cases where minor deviations from normality were detected, ANOVA was retained because of its robustness to slight departures from normality in balanced experimental designs. One-way ANOVA was then used to test for significant differences in SOC, TN, AP, and exchangeable cations across land-use types and soil depths. When ANOVA indicated significant effects, post-hoc comparisons were performed using Tukey's HSD test to identify pairwise differences among chronosequence stages. Pearson correlation analysis was applied to examine relationships among SOC, TN, AP, exchangeable bases, CEC, and pH. All figures and tables were generated using OriginPro 2021.

4 Results

4.1 Dynamic of SOC, TN, AP Concentrations and C/N in Forest and Various Agroforestry Systems Along the Chronosequence

We assessed differences in soil organic carbon, total nitrogen, and available phosphorus between natural forest and cocoa agroforestry systems along the chronosequence.

Soil organic carbon (SOC) concentrations exhibited a consistent decline with soil depth across forest and cocoa agroforestry systems, with statistically significant ($P<0.05$) variations both between land-use types and within soil depths. The forest presented the highest SOC concentration, peaking at 5.0% in the 0–10 cm soil depth and thereafter decreased with increasing depth (Fig. 1A). Seven years after forest conversion (Year-7), the SOC concentrations declined significantly ($P<0.05$) in all soil depths. This decline of SOC concentrations was also significantly ($P<0.05$) observed 41 and 52 years after forest conversion into cocoa agroforestry farms, with the most pronounced decline in older plantations, indicating long-term carbon loss.

The concentration of total nitrogen varied in the forest from 0.15% in the 0–10 cm and 20–30 cm to near 0.28% in 10–20 cm. Seven years after forest conversion to cocoa agroforestry farms, the TN concentrations increased abruptly at the surface soil (0–10 cm) and dropped 36 years later (Year-41) and thereafter significantly increased after 11 years (Year-52) (Fig. 1B). A similar trend was not observed at the 10–20 cm soil depth, where TN concentrations increased in forest and in the Year-41 after forest conversion compared to Year-7 and Year-52, or in 20–30 cm soil depths where TN concentrations increased with ages after forest conversion (Fig. 1B).

AP concentrations in the forest were 11 mg/kg in the surface soil (0–10 cm) and decreased significantly ($P<0.05$) to 7 mg/kg and 6.5 mg/kg in the 10–20 cm and 20–30 cm soil depth, respectively (Fig. 1C). Seven (Year-7) and forty-one (Year-41) years after forest conversion to cocoa agroforestry farms, the concentration of AP at the surface soils (0–10 cm) declined significantly ($P<0.05$), to increase abruptly eleven

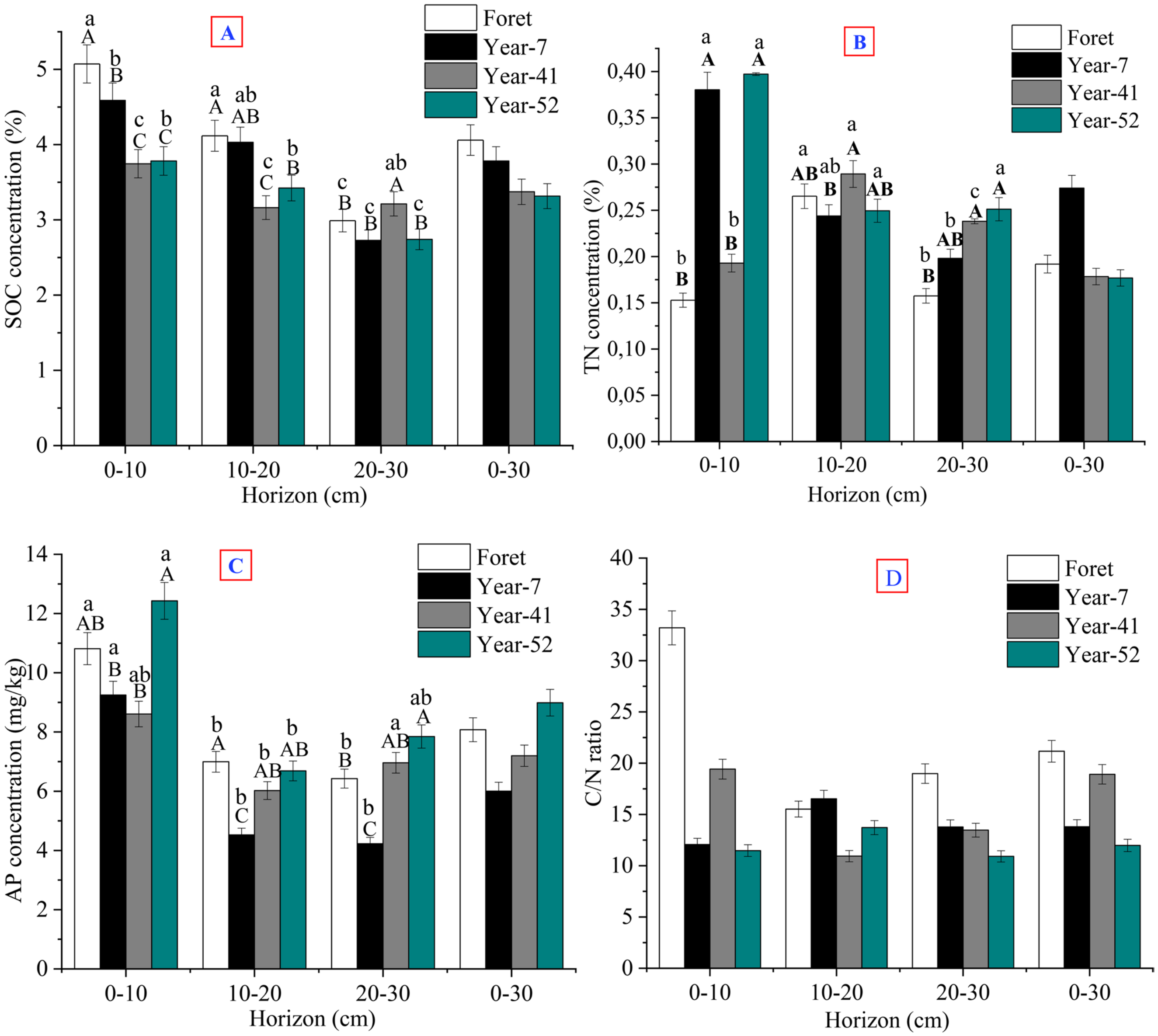

Fig. 1 The SOC (**A**), TN (**B**), AP (**C**) concentrations and C/N ratio (**D**) in soils horizons under Forest (control) and agroforestry system with cocoa with various plantation ages. Lowercase and uppercase letters indicate significant differences ($p < 0.05$) among the different cocoa plantation ages. Capital letters (A, B, C) denote statistically significant differences between treatments (i.e., Forest, Year-7, Year-41, Year-52) for the same horizon depth. Lowercase letters indicate statistically significant differences between different horizons' depth within the same treatment. *SOC* soil organic carbon, *TN* total nitrogen, *AP* available phosphorus. Error bars represent SD (n=3)

years after (Year-52) to peak at around 13 mg/kg. In the soil depth (10–20 and 20–30 cm), the AP concentrations shifted after seven years of forest conversion to cocoa agroforestry farms and then gradually increased with ages increasing.

The forest exhibited the highest C/N ratio (32.5) at the surface soil (0–10 cm), which decreased with depth as well as with age of forest conversion to cocoa farms. The change of the C/N ratio was not consistent with the age of conversion. After seven and fifty-two years of forest conversion, the C/N ratio shifted to 12.5, and to 20 after forty-one years of forest conversion (Fig. 1D).

4.2 Distribution of Cation Exchangeable Capacity in Forest and Various Agroforestry Systems Along the Chronosequence

The sum of exchangeable bases (SEB) in forest was approximately 1.5 meq/100 g in the surface soil (0–10 cm) and showed a significant decrease with increasing soil depth ($P<0.05$). Following the conversion of forest to cocoa agroforestry systems, the concentration of SEB increased over time (Fig. 2). This trend was observed across all soil depth, except for the surface soil (0–10 cm), where no such

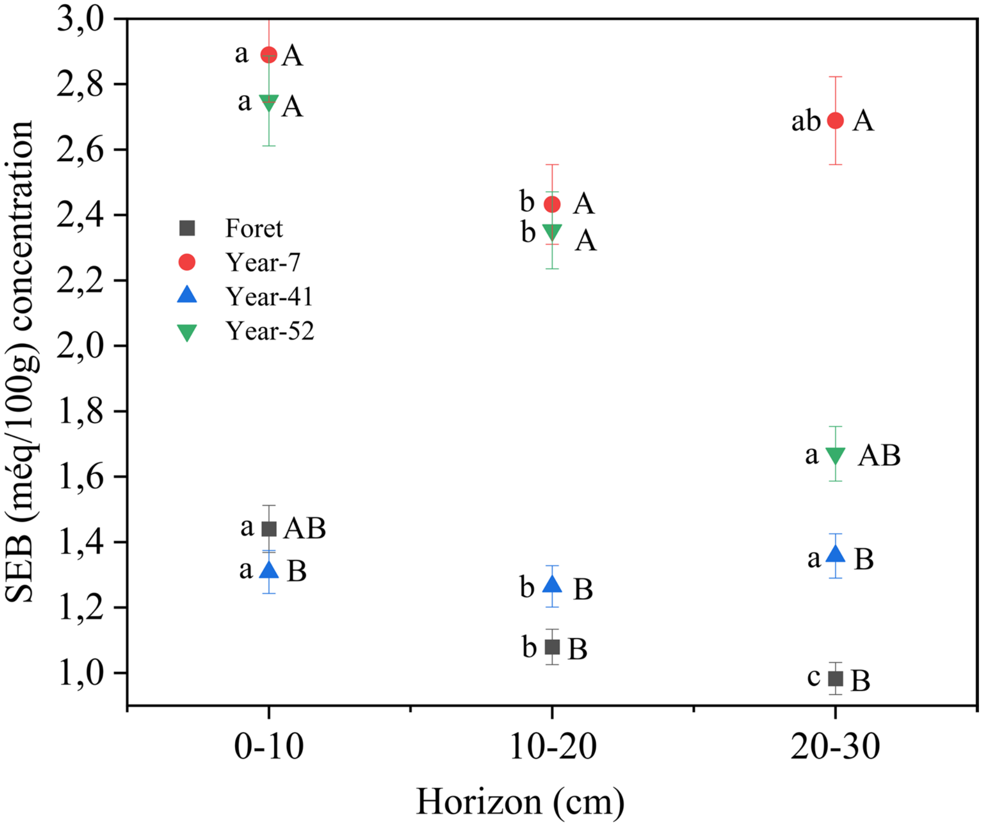

Fig. 2 The soil exchangeable base (SEB) concentrations in different horizons depth under cocoa plantations with different ages. The data means the average replicate ($n=3$) and error bars represent standard deviation. Different lowercase and uppercase letters indicate significant differences ($p< 0.05$). Capital letters (A, B, C) denote statistically significant differences between treatments (i.e., Forest, Year-7, Year-41, Year-52) for the same horizon depth. Lowercase letters indicate statistically significant differences between different horizons' depth within the same treatment

increase was noted. The enhancement in SEB concentration was more pronounced in the deeper soil (10–20 cm and 20–30 cm). Notably, the youngest cocoa agroforestry ecosystem (Year-7) exhibited significantly higher SEB concentrations ($P<0.05$) compared to older systems. Specifically, the SEB values for the Year-7 system were 2.9, 2.5, and 2.8 meq/100 g in the 0–10 cm, 10–20 cm, and 20–30 cm soil depth, respectively (Fig. 2).

The K$^+$ concentrations in the forest varied from 0.3 meq/100 g at the surface soil (0–10 cm) to 0.2 meq/100 g in the 20–30 cm. This concentration increased significantly ($P<0.05$) after the conversion of forest into cocoa agroforestry system and maintained the increasing with the prolonged age of cocoa agroforestry farms (Fig. 3A). This concentration increased with the maturity of the cocoa agroforestry farms, mostly in 10–20 and 20–10 cm soil depth.

The Ca^{2+} concentrations present the same trend as K$^+$ concentrations, increased significantly ($P<0.05$) after forest conversion. However, the concentration of Ca^{2+} declined seven years later with increasing cocoa agroforestry ages. This is clearly observed with Year-41 and Year-52 (Fig. 3B). The Na^{2+} concentrations were very low, less than 0.1 méq/100 g and its change after forest conversion is not consistent with the age of cocoa agroforestry farms (Fig. 3C).

The Mg^{2+} concentrations were low in surface soils (0–10 cm) and deep soils (20–30 cm). However, the seven first years after this forest was converted into cocoa agroforestry farms, the concentration of Mg^{2+} abruptly increased in all soil depth and thereafter started to decline significantly with the prolonged age of cocoa agroforestry farms in all the soil depth, mostly in the 10–20 cm soil depth where the concentration of Mg^{2+} was less than that in forest (Fig. 3D).

4.3 Status of SOC, TN and AP Stocks in Forest and Various Agroforestry Systems Along the Chronosequence

Conversion of natural forests to cocoa agroforestry significantly ($P<0.05$) alters soil nutrient dynamics, with distinct trends observed for soil organic carbon (SOC), total nitrogen (TN), and available phosphorus (AP) over time. SOC stocks declined following conversion, dropping from 48.70 Mg/ha in the 0–10 cm layer under forest to 44.06 Mg/ha at Year-7 and further to 35.96 Mg/ha at Year-41, with only a slight recovery to 36.32 Mg/ha by Year-52 (Table 3). A similar pattern was observed in the 10–20 cm layer, while in the 20–30 cm layer, SOC peaks at 39.19 Mg/ha in Year-41 but shifted to 33.44 Mg/ha in Year-52. As a result, the total SOC stock in the 0–30 cm profile decreases from 43.98 Mg/ha in the forest to 35.92 Mg/ha after 52 years of cocoa cultivation, indicating a net loss of 18% over time.

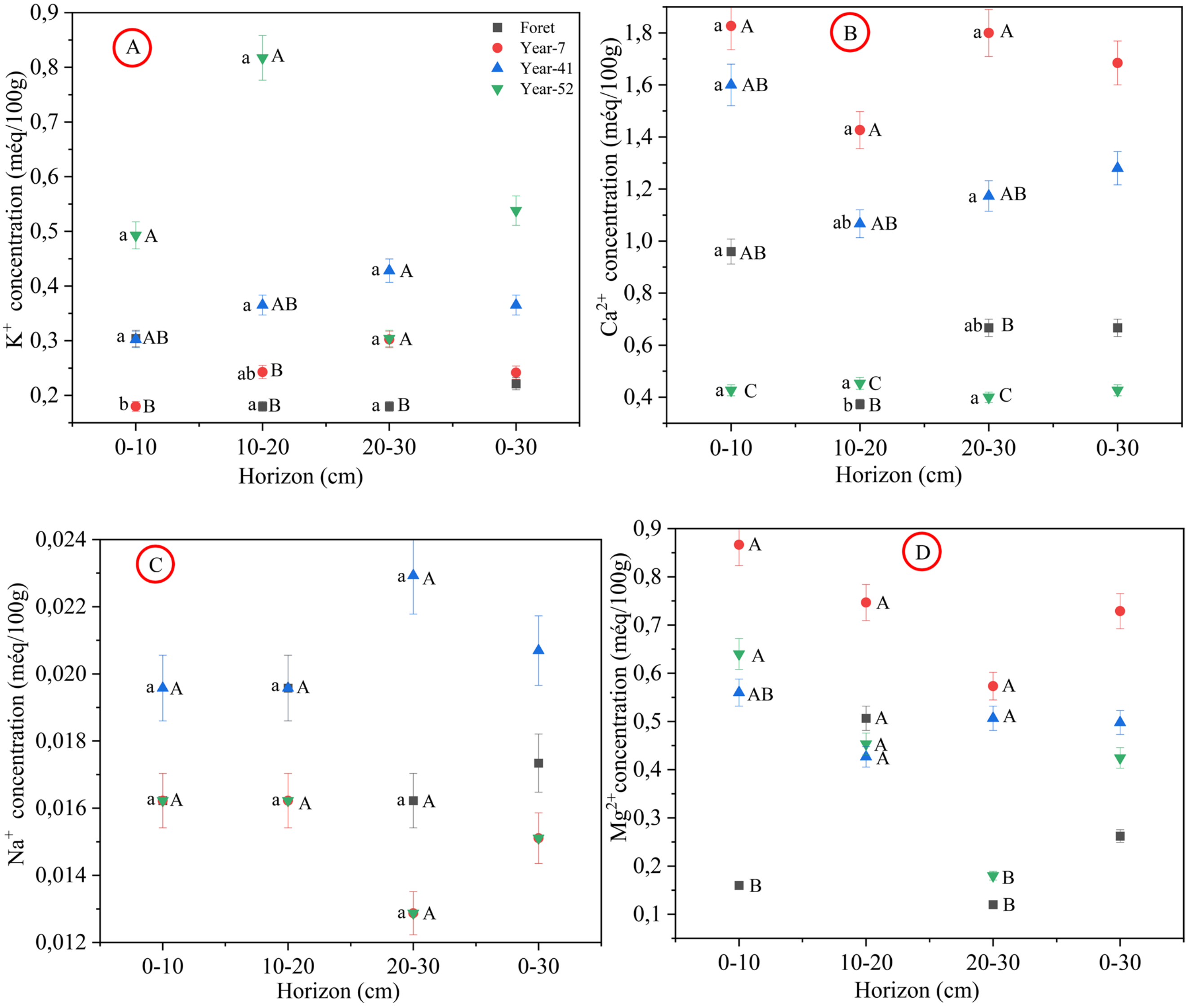

Fig. 3 Soil exchangeable potassium (K^+) (**A**), calcium (ca^{2+}) (**B**), sodium (Na^+) (**C**), magnesium (Mg^{2+}) (**D**) concentrations in different horizons depth under cocoa plantations with different ages. The data means the average replicate ($n=3$) and error bars represent standard deviation. Different lowercase and uppercase letters indicate significant differences ($p< 0.05$). Capital letters (A, B, C) denote statistically significant differences between treatments (i.e., Forest, Year-7, Year-41, Year-52) for the same horizon depth. Lowercase letters indicate statistically significant differences between different horizons' depth within the same treatment

In contrast, TN stocks increased sharply after conversion, rising from 1.47 Mg/ha in the forest's topsoil to 3.65 Mg/ha at Year-7, despite a partial decline to 1.85 Mg/ha at Year-41, recovering to 3.17 Mg/ha by Year-52 (Table 3). Subsoil TN continued to increase with age, reaching 3.06 Mg/ha in the 20–30 cm layer at Year-52 nearly 1.6 times higher than in the forest (1.92 Mg/ha). Consequently, total TN in the 0–30 cm profile raised from 2.08 Mg/ha in the forest to 3.00 Mg/ha in Year-52, representing a 44% increase.

For AP, stocks initially decreased from 10.38 kg/ha in the forest's surface layer to 8.88 kg/ha at Year-7 and 8.26 kg/ha at Year-41 but rebounded to 11.93 kg/ha by Year-52. The subsoil showed an even greater accumulation, with AP in the 20–30 cm layer increasing from 7.84 kg/ha in the forest to 9.58 kg/ha at Year-52. Total AP in the 0–30 cm profile thus raised from 8.75 kg/ha in the forest to 9.74 kg/ha after 52 years (Table 3). These results indicate that while cocoa agroforestry leads to long-term SOC depletion, it enhances nitrogen and phosphorus stocks over time, particularly in deeper soil layers, reflecting improved nutrient retention and cycling in mature systems.

Table 3 The SOC, TN and AP stocks in the different horizons of the forest and cocoa plantation with different ages

Parameters	Horizon (cm)	Foret	Year-7	Year-41	Year-52
SOC-stock (Mg/ha)	0–10	48.70±2.43Aa	44.06±2.20ABa	35.96±1.80Ca	36.32±1.82BCa
	10–20	44.06±2.20Aa	43.13±2.15Aa	33.84±1.69Bab	36.63±1.83ABa
	20–30	36.47±1.82Ab	33.29±1.66ABb	39.19±1.96Aa	33.44±1.67Bb
TN-stock (Mg/ha)	0–10	1.47±0.07Bb	3.65±0.18Aa	1.85±0.09Bb	3.17±0.16Aa
	10–20	2.84±0.14Aa	2.61±0.13ABab	3.10±0.15Aa	2.67±0.13ABab
	20–30	1.92±0.10Bb	2.42±0.12ABab	2.85±0.14Aa	3.06±0.15Aa
AP-stock (kg/ha)	0–10	10.38±0.50ABa	8.88±0.44Bb	8.26±0.41Bb	11.93±0.60Aa
	10–20	7.48±0.40Aa	4.84±0.25Bc	6.44±0.32ABb	7.15±0.36Aa
	20–30	7.84±0.40ABab	5.16±0.24Bbc	8.49±0.40Aa	9.58±0.48Aa

SOC soil organic carbon soil, *TN* total nitrogen, *AP* available phosphorus. The data mean the average of 3 replicates ± SDs. Capital letters denote significant differences between treatments (i.e., Forest, Year-7, Year-41, Year-52) for the same horizon (depth layer). Lowercase letters indicate statistical differences between horizons within the same treatment at $P<0.05$ according to Duncan's multiple range test

Table 4 Soil total exchangeable bases (TEB) and exchangeable K^+, N^{a+}, Ca^{2+} and Mg^{2+} cations stocks within horizons of soil under forest and cocoa plantation with different ages

Parameters	Horizon (cm)	Foret	Year-7	Year-41	Year-52
TBE (cmol/m^2)	0–10	13.83±0.69Ba	27.74±1.39Aa	12.56±0.63Ba	26.39±1.32Aa
	10–20	11.55±0.58Bab	26.03±1.30Aa	13.53±0.68Ba	25.18±1.26Aa
	20–30	11.99±0.60Bb	32.80±1.64Aa	16.56±0.83Ba	20.38±1.02ABa
Exchangeable K^+ (cmol/m^2)	0–10	2,92±0.15ABa	1.73±0.09Bb	2.90±0.15ABa	4.73±0.24Aa
	10–20	1.93±0.10Bb	2.60±0.13Bab	3.91±0.20Aa	8.74±0.44Aa
	20–30	2.20±0.11Bb	3.69±0.18Aa	5.22±0.26Aa	3.71±0.19Aa
Exchangeable Ca^{2+} (cmol/m^2)	0–10	9.22±0.46Ba	17.54±0.88Aa	15.36±0.77Aa	4.10±0.20Cb
	10–20	3.99±0.20Cb	15.27±0.76Aa	11.41±0.57ABa	4.85±0.24Cb
	20–30	8.13±0.40Ba	21.96±1.10Aa	14.31±0.72ABa	4.88±0.24Bb
Exchangeable Na^+ (cmol/m^2)	0–10	0.16±0.01Aa	0.16±0.01Aa	0.19±0.01Aa	0.16±0.01Aa
	10–20	0.21±0.01Aa	0.17±0.01Aa	0.21±0.01Aa	0.17±0.01Aa
	20–30	0.20±0.01Aa	0.16±0.01Aa	0.28±0.01Aa	0.16±0.01Aa
Exchangeable Mg^{2+} (cmol/m^2)	0–10	1.54±0.01Bb	8.32±0.42Aa	5.38±0.27ABa	6.14±0.31ABa
	10–20	5.42±0.27Aa	7.99±0.40Aa	4.57±0.23ABa	4.85±0.24ABa
	20–30	1.46±0.07Bb	6.99±0.35Aa	6.18±0.31Aa	2.20±0.11Bb

The data mean the average of 3 replicates ± SDs. Capital letters denote significant differences between treatments (i.e., Forest, Year-7, Year-41, Year-52) for the same horizon (depth layer). Lowercase letters indicate statistical differences between horizons within the same treatment. at $P<0.05$ according to Duncan's multiple range test. The exchangeable bases are used in cmol/m2 in order. K+ Potassium, Na+ Sodium, Ca2+ Calcium, Mg2+ Magnesium.

4.4 Soil total Exchangeable Bases (TEB) and Exchangeable K^+, Na^+, Ca^{2+} and Mg^{2+} Cations Stocks Dynamic in Forest and Various Agroforestry Systems Along the Chronosequence

Conversion of natural forests to cocoa agroforestry significantly ($P<0.05$) modifies soil base cation dynamics and total base saturation (TBE). TBE rose sharply from 12.65 cmol/kg (forest) to 28.93 cmol/kg (Year-7) then declined to 14.20 cmol/kg (Year-41) and partially recovered to 24.46 cmol/kg (Year-52), indicating an early fertility peak followed by depletion (Table 4).

Exchangeable K^+ increased significantly after forest conversion, reaching 4.73 cmol/kg (0–10 cm soil depth) and 8.74 cmol/kg (10–20 cm soil depth) at Year-52. In contrast, Ca^{2+} peaked at 17.54 cmol/kg (Year-7) but dropped to 4.10 cmol/kg (Year-52), stocks declining from 18.25 to 4.62 cmol/kg in 0–30 cm soil depth, indicating substantial loss (Table 4). Mg^{2+} rose to 7.90 cmol/kg (Year-7) but fell to 4.60 cmol/kg (Year-52), while Na^+ remained consistently low (0.16–0.22 cmol/kg). In general, cocoa agroforestry boosts initial cation availability, but long-term cultivation leads to Ca^{2+} depletion despite sustained K^+ and partial TBE recovery (Table 4).

4.5 Relationships Between Soil Nutrient Content and Stocks in Forest and Various Agroforestry Systems Along the Chronosequence

The Pearson correlation matrix reveals interrelationships among soil chemical properties (Fig. 4). Soil organic carbon (SOC) and total nitrogen (TN) exhibited a strong

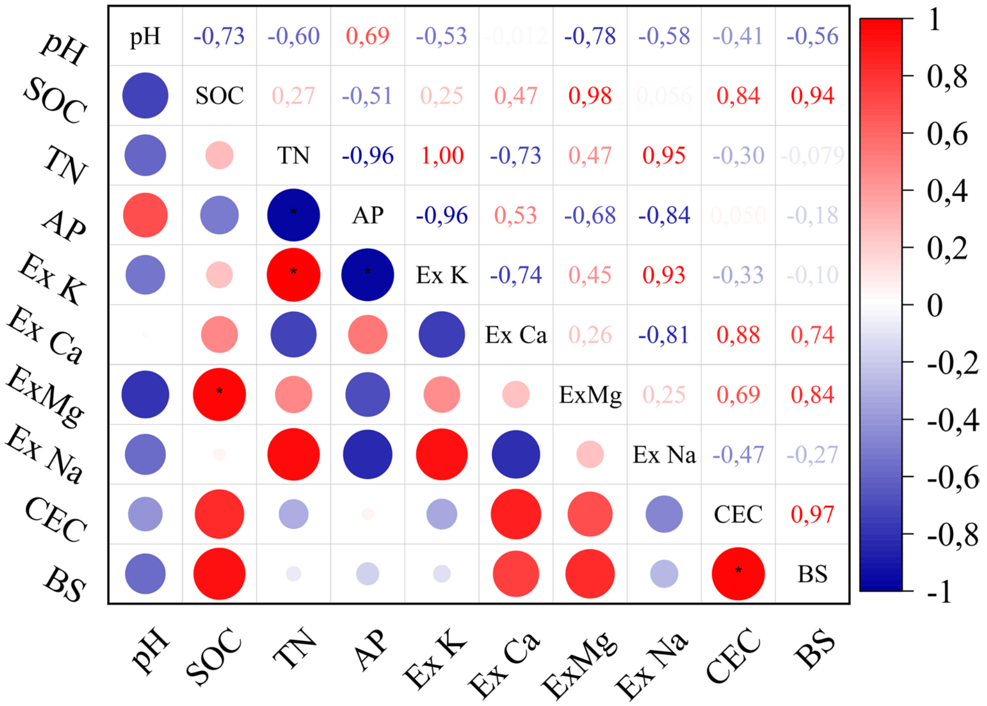

Fig. 4 Pearson correlation matrix for factors including pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), exchangeable potassium cations (Ex K), calcium (ExCa), magnesium (ExMg), sodium (ExNa), CEC, soil total exchangeable base (BS). Correlation is significant at * $p<=0.05$

positive correlation. Conversely, available phosphorus (AP) is strongly negatively correlated with TN. Exchangeable cations such as calcium (ExCa), magnesium (ExMg), sodium (ExNa), and potassium (ExK) show moderate to strong positive inter-correlations. Notably, cation exchange capacity (CEC) and base saturation (BS) were highly positively correlated, reinforcing their collective role in enhancing soil fertility. A negative correlation between pH and ExK also emerged, potentially reflecting pH-mediated constraints on potassium availability (Fig. 4).

5 Discussion

The conversion of natural forest to cocoa agroforestry systems in South Cameroon resulted in a marked and persistent decline in soil organic carbon (SOC), confirming that deforestation remains a major driver of carbon loss in tropical landscapes. In this study, SOC concentrations were highest under natural forest (5.0% in the 0–10 cm layer) and declined significantly across all soil depth following conversion, with the most pronounced reductions observed in the older cocoa plantations. After 52 years of cultivation, total SOC stocks in the 0–30 cm profile decreased by 18%, demonstrating that cocoa agroforestry systems, when managed with minimal organic inputs are unable to fully restore the carbon lost during forest clearing. These findings align with global syntheses reporting SOC losses of 20–40% after forest conversion to agriculture in the humid tropics (Bruun et al. 2015; Yang et al. 2025).

However, the broader literature reveals contrasting SOC trajectories following forest-to-cocoa conversion. Several studies report substantial SOC depletion, consistent with our findings. For example, Gusli et al. (2020) and others (Beillouin et al. 2023; Don et al. 2011; Guo and Gifford 2002; Huang et al. 2024) documented a dramatic reduction in total C stocks. In contrast, other studies, particularly from the Ecuadorian Amazon have reported SOC gains in cocoa agroforestry systems. Adiyah et al. (2023) and Tinoco-Jaramillo et al. (2024) attribute these increases to the use of organic amendments, diversified shade tree canopies, and deliberate soil fertility management. These divergent outcomes underscore that SOC responses in cocoa systems are not inherent to the crop itself but are strongly shaped by management intensity, organic matter inputs, and site-specific soil properties.

A key feature of our chronosequence is the non-linear SOC trajectory. SOC declined sharply within the first seven years after conversion, consistent with rapid oxidation of forest-derived organic matter and reduced litter inputs following canopy removal. Similar early declines have been documented in cocoa systems in Indonesia (Dawoe et al. 2014) and in other tropical agroecosystems where initial biomass removal exposes soil carbon to accelerated mineralization. However, unlike systems where SOC continues to decline monotonically, the 41- and 52-year plantations exhibited partial SOC stabilization, particularly in the deeper soils (20–30 cm), where SOC stocks temporarily peaked at Year-41 before declining again. This suggests that long-term cocoa agroforestry systems may gradually accumulate carbon through root turnover, litterfall from shade trees, and incorporation of fine organic residues, even in the absence of external inputs. Similar delayed SOC recovery has been reported in diversified cocoa agroforestry systems where shade trees and organic inputs enhance carbon cycling (Atapattu et al. 2024; Middendorp et al. 2018).

The contrasting SOC patterns across the chronosequence can be explained by several interacting mechanisms. Immediately after forest clearing, SOC declines sharply because the removal of forest biomass drastically reduces organic matter inputs while exposing previously protected carbon to rapid microbial oxidation. As shown in this study, SOC concentrations dropped significantly in all soil depth just seven years after conversion. This early decline is driven by the loss of continuous litterfall, reduced root biomass, and increased soil temperature and aeration following canopy opening conditions known to accelerate decomposition in tropical soils (Bruun et al. 2015; Dawoe et al. 2014). The absence of organic amendments and the use of herbicides in the study farms further limit carbon replenishment, allowing mineralization to outpace carbon inputs.

A critical factor that helps explain both the SOC decline and the limited recovery observed in this study is the clay content of the Oxisol, which ranged from 40 to 51%. Clay-rich soils typically have a high capacity to stabilize organic matter through mineral–organic associations, microaggregation, and physical protection of carbon within fine pores. However, the type of clay and degree of weathering are equally important. The Oxisol in our study is dominated by low-activity clays (e.g., kaolinite) (Ahanda et al. 2019; Ndzana et al. 2025) and Fe/Al oxides, which, despite their high clay percentage, have limited capacity to stabilize fresh organic inputs compared to 2:1 clays. This mineralogical constraint helps explain why SOC stocks declined sharply after forest conversion despite the relatively high clay content. The clay fraction likely slowed but did not prevent the loss of forest-derived carbon, especially in the surface soils where disturbance, herbicide use, and reduced litterfall accelerated decomposition. The temporary SOC increase observed at Year-41 in the 20–30 cm layer may reflect deeper root inputs interacting with clay minerals to form more stable carbon pools, but this stabilization was insufficient to offset long-term depletion.

These findings suggest that clay content alone cannot guarantee SOC resilience in highly weathered tropical soils. Instead, SOC stabilization depends on the interaction between clay mineralogy, organic matter inputs, and management practices. The contrasting results reported globally declines in some regions and gains in others can therefore be understood as the outcome of differing combinations of soil mineralogy, shade tree diversity, organic inputs, and disturbance regimes. In our study, the absence of organic amendments, limited shade tree diversity, and reliance on herbicides likely constrained the capacity of the clay-rich Oxisol to retain carbon over time. This reinforces the need for management strategies that enhance organic matter inputs such as mulching, compost application, and diversified agroforestry to influence the stabilizing potential of clay and promote long-term SOC recovery in cocoa systems.

The long-term SOC decline documented here has significant implications for soil fertility, given the strong positive correlation between SOC and total nitrogen observed in this study. SOC depletion reduces cation exchange capacity, impairs soil structure, and limits nutrient retention, critical concerns in Oxisol, which are inherently low in fertility and highly susceptible to degradation. From a climate perspective, the 18% SOC loss represents a substantial reduction in soil carbon sequestration potential, contributing to atmospheric CO_2 emissions. This reinforces findings from other tropical regions where forest-to-cocoa conversion has been identified as a major carbon source (Gusli et al. 2020; Schroth and Ruf 2014).

The observed increases in TN (44%) and AP (11%) along the chronosequence are not attributable to fertilizer inputs, as none of the study farms applied mineral or organic fertilizers. Instead, these increases likely reflect internal nutrient cycling processes within the cocoa agroforestry systems. Gradual nitrogen accumulation may result from biological nitrogen fixation by certain shade tree species (e.g., Albizia, Gliricidia) and from root turnover and fine root inputs that progressively enrich soil N pools (Dawoe et al. 2014; Isaac and Borden 2019). The modest rise in available phosphorus may be linked to long term mineral weathering and organic matter mineralization, processes known to release P in highly weathered tropical soils (Wang et al. 2025). Additionally, fluctuating moisture conditions can promote desorption of P from Fe/Al oxide surfaces, increasing AP availability over time (Frossard et al. 2000). These mechanisms are consistent with low input tropical agroforestry systems where external nutrient inputs are minimal but internal recycling can sustain or slightly enhance TN and AP stocks.

Our results demonstrate that forest conversion to cocoa agroforestry leads to persistent SOC depletion, with only limited recovery after five decades of cultivation. The contrasting SOC patterns across the chronosequence highlight the importance of management practices in determining carbon outcomes. While cocoa agroforestry has the potential to function as a carbon-enhancing land-use system, this potential is not realized under low-input, monoculture-leaning management. Enhancing shade tree diversity, incorporating organic amendments, and adopting soil conservation practices are essential to reverse long-term SOC losses and promote sustainable cocoa production in South Cameroon.

6 Conclusion

This 52-year chronosequence under real smallholder low-input management in southern Cameroon shows that forest conversion to cocoa agroforestry on highly weathered Oxisols leads to an 18% net loss of soil organic carbon stocks in the 0–30 cm profile after five decades, despite partial stabilization in older plantations. Total nitrogen stocks increased by 44% and available phosphorus by 11%, driven mainly by subsoil accumulation, while exchangeable base cations exhibited strong initial enrichment followed by marked depletion of calcium and magnesium.

These patterns reveal the limited capacity of low-input cocoa systems to fully restore soil fertility on such soils without external interventions. To sustain long-term productivity in Central African cocoa landscapes, management must prioritize continuous organic matter inputs, greater shade tree diversification, and practices that enhance nutrient retention. Such approaches can support smallholder livelihoods while reducing degradation risks and aligning agricultural expansion with soil conservation objectives across the region.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

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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