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Variability of soil organic carbon and nutrient content across land uses and agriculturally induced land use changes in the forest-savanna transition zone of Cameroon

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ABSTRACT

Data expressing the effects of land use change on soil attributes is still very scarce in Cameroon as in most of Africa. In this regard, this study aimed to assess soil organic carbon (OC), nitrogen (N), phosphorus (P), and potassium (K) content across land uses and agricultural-induced land use changes in the forest-savanna transition zone of Cameroon. Nine land uses were identified in the study area showing five directions of land use changes namely the change from the native forest to cocoa agroforestry, native savannah to cocoa agroforestry, native savannah to cropland, savannah fallow to cropland, and transition zone fallow to cropland. The soil was sampled at 0–10 cm (upper layer) and 10–30 cm (lower layer) depths in three replicates for each land use and analyzed for physicochemical properties. There were significant differences across the land uses for OC ($p < 0.02$), N ($p < 0.01$), C/N ($p < 0.01$), pH ($p < 0.02$), soil organic carbon stocks (SOCS) ($p < 0.01$), and soil nitrogen stocks (SNS) ($p < 0.01$), with a relatively higher magnitude in the upper soil layer. Higher magnitudes of OC (26.1 to 22.5 g kg^{-1}), N (2.5 to 1.6 g kg^{-1}), SOCS (32.1 to 27.8 Mg ha^{-1}), and SNS (2.9 to1.9 Mg ha^{-1}) were observed in native lands and cocoa agroforestry with the highest in the native forest and the forest-based cocoa agroforestry. Meanwhile, the effect of land use change on soil properties was mainly significant in the change from native savannah to croplands at $p < 0.05$ for OC, N, SOCS, and SNS, and $p < 0.02$ for P. Therefore, agroforestry is an alternative to enhance the ecological resilience of lands affected by land use changes.

Abbreviations: C, Carbon; FAO, Food and agricultural organization; FCLU, Forest-based cocoa agroforestry land use; FLU, Native forest land use; FSTZ, Forest-savannah transition zone; FZ, Forest zone; K, Exchangeable potassium; N, Total nitrogen; OC, Organic carbon; OM, Soil organic matter; P, Available phosphorus; SALU, Savannah-based cropland land use; SCLU, Savannah-based cocoa agroforestry land use; SCZ1, Savannah-cocoa zone; SCZ2, Savannah-cropland zone; SFALU, Savannah fallow land use; SLU1, Native savannah of cocoa landscape; SLU2, Native savannah of annual crop landscape; SNS, Soil nitrogen stock; SOCS, Soil organic carbon stock; TALU, Transition zone-based cropland land use; TFALU, Transition zone-based fallow land use; WRB, World reference base for soil resources.

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1. Introduction

Expanding agricultural lands to meet the high demand for food due to the increasing population has led to a significant loss of biodiversity which is a global challenge (Bergengren et al., 2011; Thornton et al., 2014). Forests and savannahs provide numerous environmental benefits through various ecosystem services including soil fertility sustenance, soil protection against erosion, contributing to ecological sustainability, and climate change adaptation and mitigation (Gao et al., 2014; Liu et al., 2014). Forests contain about 80% of the global terrestrial aboveground C stocks (Kalambukattu et al., 2013) and 40% of below-ground carbon stocks (Dixon et al., 1994). Poor land use planning and management cause negative changes in soil properties like organic carbon (OC), nutrient content, bulk density, and infiltration rate, leading to the damage of ecosystem functions and services, and exacerbating yield gaps (Gao et al., 2014; Kassa et al., 2017).

Guo and Gifford (2002) reported an annual loss of about 59% of soil C when changing savannah to farmlands. In addition, the magnitudes of total carbon loss in Teragram (Tg) due to forest conversion to agricultural land were estimated for some countries using the data of the World Resource Institute (WRI, 2021) and the calculations of Kassa et al. (2017). Losses of 2355.29, 910.3, 847.9, and 58.4 Tg C in Brazil, Indonesia, the Democratic Republic of Congo (DRC), and Cameroon, respectively were reported. Soil C loss due to agricultural activities contributes enormously to global warming and climate change (Amundson et al., 2015; Tsozué et al., 2019). Nevertheless, findings have revealed that the rate of soil C and nutrient loss could be minimized through the adoption of appropriate farming systems such as agroforestry (Kassa et al., 2017), prolonged fallow ($\geq$ 10 years) (Abreu et al., 2009; Temjen et al., 2022), mechanized land preparation, and slash-and-char system for clearing rather than slash-and-burn (Tang and Yap, 2020), manure application, reduced tillage, crop rotation, cover crops and residue retention (Lal, 2014; Daniel, 2015). Unfortunately, these alternatives are not adopted by most farmers in Sub-Saharan Africa (SSA) because most of them are not affordable for poor farmers. So far, focus has been directed on large-scale farming using Western technology in agricultural policies for national food security and sovereignty, neglecting the context of the rural economic development of most countries within SSA (Fox and Jayne, 2020). In the meantime, there is a need for alternative solutions likely to ensure the sustainability of both smallholder farmers' livelihoods and the environment and agroforestry seems to be an alternative. Agroforestry is a system of agricultural production where trees (fruits, woody perennial plants, shrubs, palms, bamboo, etc.) are purposely maintained or introduced on the same land with food crops (Lundgren and Raintree, 1983).

In Cameroon, >70% of the population is employed in the agricultural sector (Abia et al., 2016; Drum, 2020), involving about 7.8 million people within which about 600,000 families are cocoa producers who are still faced with poverty (Drum, 2020). Cameroon is currently the fourth largest cocoa producer in the world, with a yearly production ranging between 280,000 sand 291,000 tons of cocoa beans for the previous two years (2020 and 2021) i.e. 6.5% of global production, after Ivory Coast with 33.0% (1,472,313 tons), Ghana with 19.2% (858,729 tons), and Indonesia with 14.7% (656,817 tons) (FAO, 2006). Findings revealed that 95% of cocoa farms in Cameroon are owned by smallholder farmers with farm sizes ranging from 2 to 5 ha (Sommeregger and Wildenberg, 2016). Unfortunately, cocoa yields are low, with approximately 300–400 kg of dried cocoa beans per hectare (Lanre et al., 2020) whereas the average expected quantity per hectare is 1000–2000 kg under good agricultural practices (Coulter and Abena, 2010). Poor farm management and poor soil fertility are the main causes of the low yields (FAO, 2006). Farmers instead persist in deforestation to expand farmlands and even beyond protected zones (Elorm, 2022). This is pitiful but with the joint efforts of policymakers, supporting organizations, and farmers, cocoa farming could be transformed into a potential solution to the poverty alleviation of farmers and climate change adaptation and mitigation.

A study reported that agroforestry has the potential to improve soil's physical properties (Rao et al., 1997). Other studies reported that the intercropped trees help in soil rehabilitation (Krauss and Soberanis, 2001), decrease attacks from pests (Beer et al., 1998), the stabilization of the microclimate (Sporn et al., 2009), increase cocoa life span (Jagoret et al., 2017), and minimizes the use of fertilizers, and pesticides (Magne et al., 2014). Most importantly, agroforestry can generate additional income for the farmers from the sales of agroforestry products (Jagoret et al., 2009; Cerda et al., 2014; Folefack and Darr, 2021). Cerda et al. (2014) further highlighted that intensified and diversified cocoa agroforestry systems could generate higher yields, net income, and cash flow but there's limited data to support these affirmations. Alongside the family benefits, stronger synergetic relationships are built with the ecosystem compared to the less diversified systems. However, agroforestry systems' environmental sustainability, economic productivity, and profitability are yet to be fully assessed. Therefore, research is required to support future actions about the sustainability of farmer's livelihood, climate change adaptation, and mitigation. Thus, this study aimed to (i) characterize the land uses present in the forest-savannah transition zone of Cameroon, (ii) assess soil C and nutrient (NPK) content across the land uses, and (iii) evaluate the effect of land use changes on soil C and nutrient (NPK).

2. Material and methods

2.1. Study area

The study area is located in the Mbam et Kim division in the central region of Cameroon, situated about 100 km from Yaounde in the northern part (Fig. 1a). The area lies between latitude 4°19′ and 5°00′N and longitude 11°30'and 11°50′E, covering a surface area of about 430 km^2. Ntui has a dry winter savannah climate (Aw) according to the Köppen-Geiger classification, and the area falls in the bimodal humid forest agroecological zone of Cameroon characterized by two rainy seasons and two dry seasons. The major dry season goes from mid-November to mid-March, while the minor dry season is from mid-June to mid-August. The major rainy season goes from mid-August to mid-November and the minor rainy season is from mid-March to mid-June. Annual rainfall is estimated to be 1232 mm with temperatures ranging between 23 °C and 28 °C (estimates from years 1992 to 2022). Concerning the geomorphological setting, the study area is in the Southern Cameroon Plateau, and it is characterized by an undulating relief where planes, hills, and valleys alternate with an average altitude of 600 m. The vegetation presents three distinct ecosystems namely: the semi-deciduous forest zone (FZ), the forest-savannah transition zone (FSTZ), and the savannah zone (SZ), enabling the cultivation of perennial and annual crops (Fig. 1b). The main soil types are rejuvenated and depleted orthic Ferralsols in the savannah area, and the red orthic Ferralsols soils in the forest area (Onana, 2018), following the classification of WRB (FAO, 2006). These soils are shallow, sandy, and characterized by a massive structure of very high porosity and therefore need to be protected to limit the effects of erosion and leaching. Geologically, the area is located on para-metamorphic rocks characterized by several facies namely: biotite embrechite, mica quartzite, two mica mica-schist, two mica gneiss, biotite gneiss, biotite anataxite and amphibolite (Gauss projection international meridian to 1/200.000 of S.G.A.E.F-Cameroon, 1949).

2.2. Selection of experimental plots, land use distribution, and direction of land use changes

A series of surveys were conducted in the study area to identify the different land uses present in the landscape. Agriculturally induced land uses were closely monitored for two years to have a good understanding of their background and history. Four distinct ecosystems referred to in

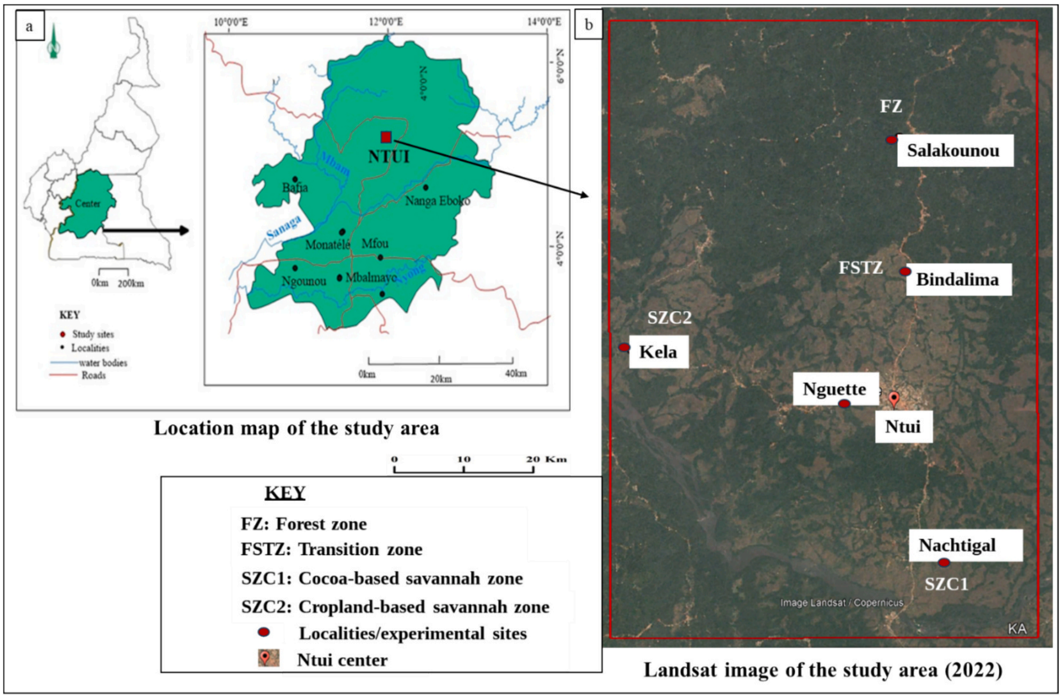

Fig. 1. Location map (a) Landsat image (2022) of the study area showing the different vegetation gradients.

this study as ecological zones exist in the study area concerning the vegetation type namely the forest zone (FZ), the savannah-cocoa zone (SCZ1), the savannah-crop zone (SCZ2), and forest-savannah transition zone (FSTZ). The study area is composed of native lands (forest and savannah), cocoa agroforestry lands, annual croplands, and fallow lands. In total, four study sites were defined in the study area corresponding to the four ecological zones (Fig. 1b). The native lands gave the possibility to assess the effects of land use changes as they were used as controls in the experiment. Thus, the different ecological zones were characterized by different land uses namely:

i) Forest zone (FZ), composed of a native forest land use (FLU) and a forest-based cocoa agroforestry land use (FCLU),
ii) Savannah-cocoa zone (SCZ1), characterized by a native savannah land use (SLU1) and a savannah-based cocoa agroforestry land use (SCLU1)
iii) Savannah-cropland zone (SCZ2), also characterized by a native savannah land use (SLU2), a savannah-based annual cropland use (SALU), and a savannah-based fallow land use (SFALU)
iv) Forest-savannah transition zone (FSTZ), characterized by a transition zone-based fallow land use (TFALU), and a transition zone-based annual cropland use (TALU)

Therefore, for this study, nine different land uses were identified in the study area as seen in Table 1 below:

The upper soil layer was characterized by a sandy-clay-loam texture in FZ (FLU and FCLU), SCZ1 (SLU and SCLU), and FSTZ (TFALU, and TALU), while all the land uses of SCZ2 (SLU2, SALU, and SFALU) showed the sandy-loam texture. The lower soil layer was marked by a sandy-loam texture in the land uses of SCZ2 (SFALU, and SALU), while FZ (FLU and FCLU), SLU1, and TALU exhibited a sandy-clay loam texture, and TFALU and the SCLU a sandy-clay texture (Fig. S1.).

Five directions of land use changes were identified in the study area across the different ecological zones:

(i) Forest zone (FZ): change of native forest land use (FLU) to forest-based cocoa agroforestry land use (FCLU)
(ii) Savannah-cocoa zone (SCZ1): change of native savannah (SLU1) to savannah-based cocoa agroforestry land use (SCLU)
(iii) Savannah-cropland zone (SCZ2):

- change of native savannah (SLU2) to savannah-based annual cropland use (SALU)
- change of savannah-based fallow land use (SFALU) to savannah-based annual cropland use (SALU)

(iv) Forest-savannah transition zone (FSTZ): change of transition zone-based fallow land use (TFALU) to annual cropland use (TALU)

2.3. Soil sampling

The soil was sampled in April 2022 at two depths namely 0–10 cm (upper layer (UL)) and 10–30 cm (lower layer (LL)) using soil augers, and 2 kg of soil was collected at each layer for laboratory analyses. The soil sampling methods in the agroforestry system and cropping systems were different. In cocoa agroforestry and the native lands, soil samples were taken from 30 random sampling points from each experimental plot to form a composite sample. The croplands were composed of either mounds or ridges and therefore soil samples were taken from 20 random points both on the mounds and in the ridges to form a composite sample, thus, a total of 54 soil samples (9 land uses x 3 replicates × 2 sampling depths) were taken and analyzed for physicochemical properties. One undisturbed soil sample was taken from each depth from each experimental plot using core cylinders of 100 cm^3 for bulk density measurement. Thus, a total of 54 samples were equally collected for bulk density measurement.

2.4. Soil analyses

Soil samples were air-dried at room temperature and passed through a 2 mm sieve. The chemical analyses included soil organic carbon (OC), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), and pH, while the physical analyses included particle size distribution and bulk density (Bd). Soil organic carbon stocks (SOCS) and soil

Table 1
Land use characteristics and land management of the studied ecosystems.

Ecosystem	Study sites	Current land use	Land use history	Land management
Forest	FSS	Native forest (FLU)	- Untouched vegetation	None
		Cocoa agroforestry (FCLU)	- Cocoa farms are aged between 40 - 60 years. - Composed of different cocoa varieties (local and hybrid) - Intercropped with a dense mixture of forest and fruit trees of different species.	- Slash-and-burn - Felling down of trees and clearing - Clearing and planting Pruning or health harvesting, - Maintenance using the anti-capsid treatment and brown rot treatment, - Harvesting,
Savannah	SSS1	Cocoa agroforestry (SCLU)	- Cocoa farms are aged between 40 - 60 years. - Composed of different cocoa varieties (local and hybrid) - Intercropped mainly with different species and lesser density of fruit trees	- No fertilizer, no fallow, no rotation - Cocoa plants mixed with various nitrogen-fixing shade trees and fruit trees. - Cocoa mixed with banana trees, pineapple, and cocoyam, - Tree litter incorporated into the soil
		Native savannah (SLU1)	- Untouched vegetation	- None
Savannah	SSS2	Native savannah (SLU2)	- Untouched vegetation	- None
		Cropland (SALU)	- Cropland under exploitation for more than 20 years - Marked by a mixed cropping system of yam-pumpkin-maize. - Cultivated for 1 year after which a mixed cropping system of groundnut-cassava-maize is put in place and can be repeated for 2 to 3 years before the land is left on fallow	- Slash-and-burn, - Conventional tillage, - Mixed cropping - Crop rotation - Crop residue retention - Fallow (2 to 5 years)
		Fallow (SFALU)	- Fallow has been under exploitation for more than 20 years. - Fallow lands of 05 years - Shortening of fallow length	- Used for livestock grazing
Transition zone	TSS	Cropland (TALU)	- Cropland under exploitation for more than 20 years - Marked by a mixed cropping system of yam-pumpkin-maize. - Cultivated for 1 year after which a mixed cropping system of groundnut-cassava-maize is put in place and can be repeated for 2 to 3 years before the land is left on fallow.	- Slash-and-burn, - Conventional tillage, - Crop rotation - Crop residue retention - Fallow (2 to 5 years)
		Fallow (TFALU)	- Fallow has been under exploitation for more than 20 years. - Fallow lands of 3 years - Shortening of fallow length	- Used for livestock grazing

FZ = Forest zone, SCZ1 = Savannah-cocoa zone, SCZ2 = Savannah-cropland zone, FSTZ = Forest-savannah transition zone, FLU = Forest land use, FCLU = forest-based cocoa agroforestry land use, SLU1 = savannah land use in cocoa landscape, SCLU = savannah-based cocoa agroforestry land use, SLU2 = savannah land use in annual cropland use, SALU = savannah-based annual cropland use.

nitrogen stocks (SNS) were calculated from OC and N respectively. For C and N analysis, soils were further ground to pass through a 0.5 mm sieve. Organic C was determined by chromic acid digestion with heating and spectrophotometric analysis (Heanes, 1984). Total N was determined from a wet acid digest (Buondonno et al., 1995) and analyzed by colorimetric analysis (Anderson and Ingram, 1993), while K was extracted using ammonium acetate at pH 7 and determined by flame atomic absorption spectrophotometry (AAS). Available P was extracted using the Bray-1 procedure and analyzed using the molybdate blue procedure described by Murphy and Riley (1962). Soil pH in water was determined in a 1:5 (*w/v*) soil: water suspension. Particle size (three fractions) was determined by the hydrometer method (Day, 1965; Boverwijk, 1967).

2.5. Calculation of bulk density (Bd), soil organic carbon stock (SOCS) and soil nitrogen stock

Bulk density (g cm^{-3}) was determined using the formula:

$$Bd = \frac{DSW}{SV} \quad (1)$$

Where DSW is the dry soil weight (g); and SV is the soil volume (cm^{-3}).

The soil organic carbon stock (SOCS in Mg ha^{-1}) and soil nitrogen stocks (SNS in Mg ha^{-1}) were assessed using Eqs. 2 and 3 (Chan, 2008).

$$SOCS = SOC \times Bd \times SD \times 100 \quad (2)$$

$$SNS = N \times Bd \times SD \times 100 \quad (3)$$

Where SOC is the concentration of soil organic carbon (%), N is the concentration of soil total nitrogen (%), Bd is the bulk density (g cm^{-3}); SD is the soil sampling depth (cm).

2.6. Statistical analyses

Data were tested for normality and homogeneity of variance using the Shapiro-Wilk normality and Levene's tests respectively. Thereafter, a one-way analysis of variance (ANOVA) was used to analyze the effect of land use changes on the measured soil variables (SOC, N, P, K, pH, BD, SOCS, SNS, sand, clay, and silt) followed by a post hoc test using "emmeans" package (Lenth, 2022). The multiple comparisons amongst the treatments were done using the "multcomp" package (Hothorn et al., 2008a, 2008b), and the *p*-value was corrected for multiple comparisons with the "Sidak" adjustment. Linear regression analysis was used to determine the relationship between SOC, N, and other soil parameters, and a student's *t*-test was applied to assess the effects of land use changes on soil properties and the variation of soil properties with depth. R (R Core Team, 2023) was used to perform these analyses.

3. Results

3.1. Variability of soil physicochemical properties across land uses

3.1.1. Trend of OC, N, and pH across land uses

Soil OC showed a significant difference ($p < 0.02$) across the land uses in the upper soil layer (Fig. 2) with the highest concentrations in the forest land uses with 26.1 g kg^{-1} in the native forest and 25.0 g kg^{-1} in the forest-based cocoa agroforestry, followed by the native savannah of cocoa landscape with 23.1 g kg^{-1}, and then the savannah-based cocoa agroforestry with 22.5 g kg^{-1}. Although there were no significant differences in the lower soil layer (Table 2), the highest concentration of SOC was noted in the savannah with 19.6 g kg^{-1} in the native savannah of the cocoa landscape and 16.6 g kg^{-1} in the savannah-based cocoa agroforestry.

Likewise OC, there was a significant difference in N ($p < 0.01$) in the upper soil layer across the land uses with the highest concentration of N in the forest ecosystems with 2.5 g kg^{-1} in the native forest and 2.3 g kg^{-1} in forest-based cocoa agroforestry, followed by the savannah-based cocoa agroforestry with 1.8 g kg^{-1}, and the native savannah of cocoa landscape with 1.6 g kg^{-1}. Still in the upper layer, the lowest concentration of N was noted in the savannah-based cropland and fallow land with 0.7 g kg^{-1} and 0.6 g kg^{-1} respectively. In the lower soil layer, the highest concentration of N was also noted in the forest ecosystems with 1.7 g kg^{-1} in the native forest and 1.5 g kg^{-1} in forest-based cocoa agroforestry, followed by the savannah ecosystem with 1.4 g kg^{-1} in the native savannah of cocoa landscape and 1.3 g kg^{-1}in the savannah-based cocoa agroforestry. Likewise, OC, the lowest concentration of N in the lower soil layer was in the savannah-based cropland and fallow land with 0.6 g kg^{-1} and 0.5 g kg^{-1} respectively (Fig. 3).

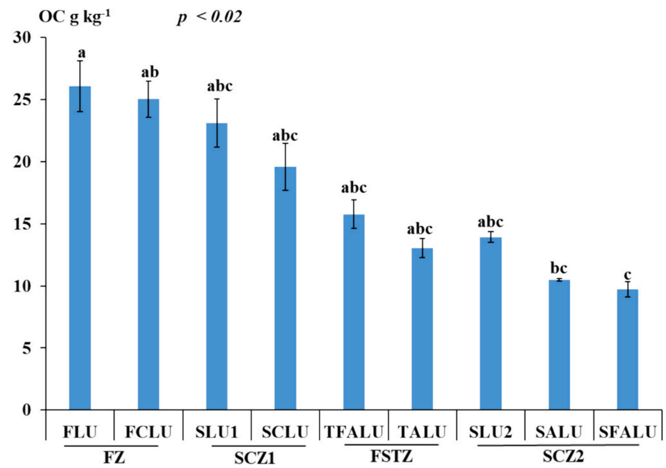

Fig. 2. Variation of soil organic carbon (OC) in the upper soil layer across different land uses.
FZ: Forest zone, FLU: Native forest land use, FCLU: Forest-based cocoa agroforestry land use, FSTZ: Forest-savannah transition zone, SCZ1: Savannah-cocoa zone, SCLU: Savannah-based cocoa agroforestry land use, SALU: Savannah-based cropland land use, SCZ2: Savannah-cropland zone, SLU1: Native savannah of cocoa landscape, SFALU: Savannah fallow land use, SLU2: Native savannah of annual crop landscape, TALU: Transition zone-based cropland land use, TFALU: Transition zone-based fallow land use, letters a, b, c etc. indicate significant differences.

There was a significant difference in soil pH ($p < 0.02$) in the upper soil layer with a similar trend to that of SOC and N with the highest value in the forest ecosystems. Results indicated a value of 7.3 in the native forest and 7.1 in the forest-based cocoa agroforestry, followed by the native savannah of the cocoa landscape with 6.2, and the savannah-based cocoa agroforestry with 6.1. The lowest pH value (5.3) was recorded in the transition zone-based cropland. Meanwhile, in the lower soil layer, the highest pH value was recorded in the native forest (6.9) and forest-based cocoa agroforestry (6.8). Thus, a positive correlation was observed between soil pH, OC, and N (Table 3).

3.1.2. Trend of P, K, and C/N across land uses

Soil P showed no significant difference between the land uses. Nevertheless, the highest concentration in the upper soil layer was recorded in the native savannah of the crop landscape (5.8 mg kg^{-1}), the native forest (5.5 mg kg^{-1}), forest-based cocoa agroforestry, (5.1 mg kg^{-1}), and native savannah in crop landscape (4.7 mg kg^{-1}) respectively. Likewise, the lowest P concentration was recorded in SCLU1 (0.9 mg kg^{-1}). Meanwhile, in the lower soil layer, the highest concentration was recorded in the forest ecosystems namely the native forest (3.6 mg kg^{-1} in), and the forest-based cocoa agroforestry (3.3 mg kg^{-1}), followed by the savannah-based cropland (2.7 mg kg^{-1}), and the native savannah of the crop landscape (2.2 mg kg^{-1}) (Table 3).

No significant difference was noted in K across the land uses. Nonetheless, higher concentrations were noted in the savannah ecosystem with 200.7 mg kg^{-1} in the native savannah of the cocoa landscape and 176.9 mg kg^{-1} in the savannah-based cocoa agroforestry, followed by transition zone-based fallow (142.1 mg kg^{-1}), and then the forest ecosystem with 112.1 mg kg^{-1} in the native forest and 111.7 mg kg^{-1} forest-based cocoa agroforestry. The lowest concentration of K in the lower layer was recorded in the savannah-based cropland (56 mg kg^{-1}) and savannah-based fallow (49.5 mg kg^{-1}). The highest concentration of K in the lower soil layer was recorded in the savannah-based cocoa agroforestry (129.3 mg kg^{-1}), and the native savannah of the cocoa landscape (126.4 mg kg^{-1}). Here also, the lowest concentration of

Table 2
Organic carbon (OC), Total nitrogen (N), soil organic carbon stocks (SOCS), soil nitrogen stocks (SNS), and bulk density (Bd) in the lower soil layer across land uses of the study area.

		OC (g kg^{-1})	N (g kg^{-1})	SOCS (Mg ha^{-1})	SNS (Mg ha^{-1})	Bd (g cm^{-3})	
Ecological zones	Land uses	LL (10–30 cm)	LL (10–30 cm)	LL (10–30 cm)	LL (10–30 cm)	UL (0 -10 cm)	LL (10–30 cm)
FZ	FLU	16.1 ± 1.87	1.71 ± 0.72	49.6 ± 4.06	5.28 ± 1.52	1.20 ± 0.21	1.49 ± 0.13
	FCLU	16.6 ± 1.76	1.52 ± 0.60	53.4 ± 3.32	4.89 ± 1.13	1.30 ± 0.06	1.60 ± 0.08
SCZ1	SLU1	19.6 ± 1.89	1.43 ± 0.51	54.3 ± 3.12	3.97 ± 0.85	1.24 ± 0.13	1.40 ± 0.10
	SCLU	16.6 ± 0.67	1.36 ± 0.17	44.5 ± 1.32	3.63 ± 0.35	1.35 ± 0.10	1.33 ± 0.06
SCZ2	SLU2	10.4 ± 0.61	0.75 ± 0.12	31.8 ± 0.94	2.29 ± 0.18	1.43 ± 0.03	1.53 ± 0.06
	SALU	10.4 ± 0.36	0.62 ± 0.03	28.6 ± 0.80	1.71 ± 0.05	1.25 ± 0.13	1.38 ± 0.06
	SFALU	8.4 ± 0.70	0.47 ± 0.14	25.6 ± 1.40	1.42 ± 0.29	1.47 ± 0.11	1.52 ± 0.05
FSTZ	TFALU	11.4 ± 0.52	0.89 ± 0.16	31.0 ± 0.95	2.05 ± 0.20	1.33 ± 0.10	1.31 ± 0.06
	TALU	11.9 ± 0.72	0.79 ± 0.16	32.6 ± 0.35	2.53 ± 0.11	1.31 ± 0.20	1.44 ± 0.13

LL = lower soil layer, FZ = Forest zone, SCZ1 = Savannah-cocoa zone, SCZ2 = Savannah-cropland zone, FSTZ = Forest-savannah transition zone, FLU = Forest land use, FCLU = forest-based cocoa agroforestry land use, SLU1 = native savannah land use in cocoa landscape, SCLU = savannah-based cocoa agroforestry land use, SLU2 = native savannah land use in annual crop landscape, SALU = savannah-based annual cropland use.

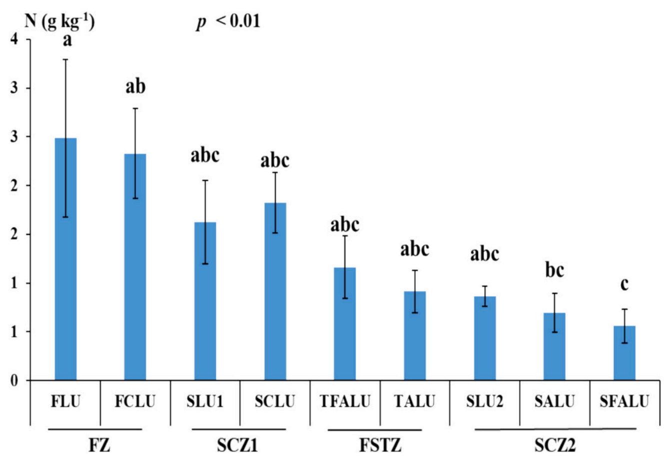

Fig. 3. Variation of total nitrogen (N) in the upper soil layer across different land uses.
FZ: Forest zone, FLU: Native forest land use, FCLU: Forest-based cocoa agroforestry land use, FSTZ: Forest-savannah transition zone, SCZ1: Savannah-cocoa zone, SCLU: Savannah-based cocoa agroforestry land use, SALU: Savannah-based cropland land use, SCZ2: Savannah-cropland zone, SLU1: Native savannah of cocoa landscape, SFALU: Savannah fallow land use, SLU2: Native savannah of annual crop landscape, TALU: Transition zone-based cropland land use, TFALU: Transition zone-based fallow land use, letters a, b, c etc. indicate significant differences.

K was noted in savannah-based cropland and fallow with 50.8 mg kg^{-1} and 37.8 mg kg^{-1} respectively.

The C/N ratio was significantly different across the land uses both in the upper soil layer ($p < 0.01$) and the lower soil layer ($p < 0.01$), and it was relatively higher in the savannah land uses (Table 3). Thus, the highest C/N value was noted in savannah-based fallow (17.4), followed by native savannah of the crop landscape (16.1), and savannah-based cropland (15.5). Meanwhile, the lowest values were noted in the forest ecosystems with 10.8 in both the native forest and the forest-based cocoa agroforestry. In the same way, in the lower layer, the lowest values were recorded in the native forest (9.7) and forest-based cocoa agroforestry (11.1) while the highest values were noted in the savannah-based cropland and fallow land with 16.7 and 17.8 respectively.

3.1.3. *Trend of SOCS and SNS across land uses*

The SOCS showed significant differences only in the upper soil layer ($p < 0.01$). The highest values were noted in the cocoa agroforestry systems with 32.1 Mg ha^{-1} in the forest-based cocoa agroforestry and 30.0 Mg ha^{-1} in the savannah-based cocoa agroforestry, followed by the native lands showing 29.8 Mg ha^{-1} in the native forest and 27.8 Mg ha^{-1} in the native savannah of the cocoa landscape. In the lower layer, SOCS was highest in the native savannah of the cocoa landscape (54.3 Mg ha^{-1}), and the forest ecosystem (53.4 Mg ha^{-1}) (Fig. 4)

Similarly, SNS showed significant differences in the upper soil layer ($p < 0.001$), with the highest concentration in the forest ecosystems starting with the agroforestry system with 2.9 Mg ha^{-1} in the forest-based cocoa agroforestry and 2.8 Mg ha^{-1} in the native forest. Meanwhile, the lowest values were recorded in the savannah ecosystem with 0.9 Mg ha^{-1} in savannah-based cropland and 1.4 Mg ha^{-1} in savannah-based fallow (Fig. 5).

Table 3
Available phosphorus (P), exchangeable potassium (K), and C/N ratio in two soil layers across land uses of the study area.

		P (mg kg^{-1})		K (mg kg^{-1})		pH		C/N	
Ecological zones	Land uses	UL (0 -10 cm)	LL (10–30 cm)	UL (0 -10 cm)	LL (10–30 cm)	UL (0 -10 cm)	LL (10–30 cm)	UL (0 -10 cm)	LL (10–30 cm)
FZ	FLU	5.52 ± 1.19a	3.57 ± 1 .42a	112 ± 5.2a	84.7 ± 5.40a	7.09 ± 0.48a	6.84 ± 0.56a	10.8 ± 0.5c	9.71 ± 0.24f
	FCLU	5.11 ± 1.79a	3.31 ± 1.48a	117 ± 5.17a	88.0. ± 5.23a	7.35 ± 0.09a	6.99 ± 0.04a	10.8 ± 0.3c	11.1 ± 0.20ef
SCZ1	SLU1	4.75 ± 1.10a	1.81 ± 0.35a	200.7 ± 5.66a	126.4 ± 5.65a	6.18 ± 0.23ab	5.76 ± 0.27a	14.0 ± 0.3abc	13.7 ± 0.07cde
	SCLU	0.90 ± 0.16a	0.62 ± 0.12a	176.9 ± 11.0a	129.3 ± 9.41a	6.13 ± 0.25ab	5.86 ± 0.11a	12.3 ± 0.13bc	12.3 ± 0.10def
SCZ2	SLU2	5.82 ± 0.41a	2.19 ± 0.29a	86.0 ± 1.67a	61.1 ± 4.6a	6.10 ± 0.08ab	5.42 ± 0.11a	16.1 ± 0.04ab	13.9 ± 0.18 cd
	SALU	3.27 ± 0.65a	2.69 ± 0.43a	56.0 ± 3.71a	50.8 ± 4.49a	6.08 ± 0.04ab	5.67 ± 0.03a	15.5 ± 0.73ab	16.7 ± 0.46ab
	SFALU	2.37 ± 0.29a	1.84 ± 0.06a	49.5 ± 4.32a	37.8 ± 4.33a	6.01 ± 0.19ab	5.56 ± 0.17a	17.4 ± 0.13a	17.8 ± 0.16a
FSTZ	TALU	1.90 ± 0.24a	1.40 ± 0.12a	76.9 ± 3.16a	69.1 ± 2.84a	5.33 ± 0.11b	5.26 ± 0.19a	14.3 ± 0.14abc	15.1 ± 0.12bc
	TFALU	2.62 ± 0.36a	1.31 ± 0.25a	84. ± 7.13a	89.9 ± 4.36a	6.03 ± 0.14ab	5.60 ± 0.11a	13.6 ± 0.17abc	12.9 ± 0.25cde

UL = upper soil layer, LL = lower soil layer, FZ = forest zone: SCZ1 = savannah-cocoa zone, SCZ2 = savannah-cropland zone, FSTZ = forest-savannah transition zone, FLU = native forest land use, FCLU = forest-based cocoa agroforestry land use, SLU1 = native savannah land use in cocoa landscape, SCLU = savannah-based cocoa agroforestry land use, SLU2 = native savannah land use in annual crop landscape, SALU = savannah-based annual cropland use, P = available phosphorus, K = exchangeable potassium, C/N = the ratio of carbon on nitrogen, letters a, b, c… = significant differences.

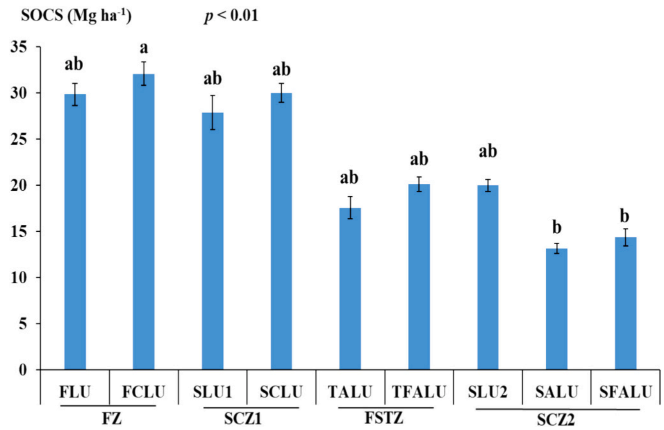

Fig. 4. Variation of soil organic carbon stock (SOCS) in the upper soil layer across different land uses.
FZ: Forest zone, FLU: Native Forest land use, FCLU: Forest-based cocoa agroforestry land use, FSTZ: Forest-savannah transition zone, SCZ1: Savannah-cocoa zone, SCLU: Savannah-based cocoa agroforestry land use, SALU: Savannah-based cropland land use, SCZ2: Savannah-cropland zone, SLU1: Native savannah of cocoa landscape, SFALU: Savannah fallow land use, SLU2: Native savannah of annual crop landscape, TALU: Transition zone-based cropland land use, TFALU: Transition zone-based fallow land, letters a, b, c etc. indicate significant differences.

3.1.4. Variation of Bd across land uses

Bulk density did not show a significant difference across the land uses but the highest value in the upper layer was noted in the savannah-based fallow with 1.5%, followed by the native savannah of the annual crop landscape with 1.4%. Meanwhile, the lowest bulk density of 1.2% was noted in the native forest and the native savannah of the cocoa landscape. In the lower soil layer, the highest bulk density was recorded in the forest-based cocoa agroforestry with 1.6% (Table 2).

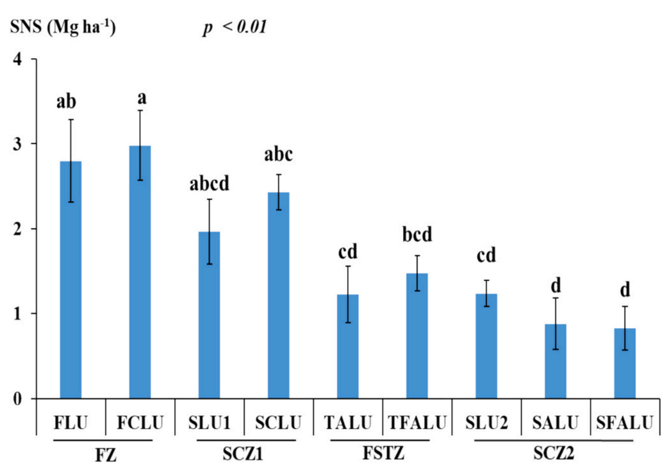

Fig. 5. Variation of soil nitrogen stock (SNS) in the upper soil layer across different land uses.
FZ: Forest zone, FLU: Native forest land use, FCLU: Forest-based cocoa agroforestry land use, FSTZ: Forest-savannah transition zone, SCZ1: Savannah-cocoa zone, SCLU: Savannah-based cocoa agroforestry land use, SALU: Savannah-based cropland land use, SCZ2: Savannah-cropland zone, SLU1: Native savannah of cocoa landscape, SFALU: Savannah fallow land use, SLU2: Native savannah of annual crop landscape, TALU: Transition zone-based cropland land use, TFALU: Transition zone-based fallow land use, letters a, b, c etc. indicate significant differences.

3.2. Variability of soil physical and chemical properties with land use change

The difference in soil physical and chemical properties with land use change was mainly significant in the change from the native savannah of the crop landscape to savannah-based croplands as described below.

3.2.1. Change of native savannah of crop landscape (SLU2) to savannah-based cropland (SALU)

The change from native savannah of the crop landscape to savannah-based cropland showed a significant difference in the concentrations of OC ($p < 0.05$), N ($p < 0.05$), P ($p \leq 0.02$), SOCS ($p \leq 0.05$), SNS ($p \leq 0.05$). Thus, soil nutrient content decreased significantly from the native savannah to the corresponding cropland with a higher magnitude in the upper soil layer in most cases. The OC concentration decreased from 13.8 to 10.5 g kg $^{-1}$ but remained the same in LL with 10.4 g kg^{-1}. The N content decreased from 0.9 and 0.7 g kg^{-1} in the upper soil layer, and 0.8 to 0.6 g kg $^{-1}$ in the lower soil layer. The concentration of P decreased by half from 5.8 to 3.3 mg kg^{-1} in the upper soil layer but with a slight difference in the lower layer. In the same way, the concentration of K decreased from 86.0 mg kg^{-1} to 56.0 mg kg^{-1} in the upper soil layer, and from 61.3 to 50.8 mg kg^{-1} in LL. Also, SOCS dropped significantly from 20.0 and 13.2 Mg ha^{-1} in the upper soil layer, and from 31.8 and 28.6 Mg ha^{-1} in the lower layer SNS decreased from 1.2 to 0.9 Mg ha^{-1} in the upper soil layer, and from 2.3 to 1.7 Mg ha^{-1} in the lower layer (Fig. 6 a and b).

3.2.2. Other land use changes

A significant difference was recorded in the concentration of P ($p < 0.05$) in the change of land use from native savannah of the cocoa landscape to savannah-based cocoa agroforestry in the lower soil layer (Fig. 6 a and b), with a decrease in the concentration of P from 0.9 mg kg^{-1} to 0.6 mg kg^{-1}. Also, a significant difference was recorded in soil pH ($p < 0.05$) and C/N ($p < 0.04$) in the transition zone with a change from the transition zone-based fallow (06) to transition zone-based cropland (5.3), while C/N was relatively higher in the transition zone-based cropland (15) than in the transition zone-based fallow (13) (Fig. 6 c, d, and e).

3.3. Correlation between soil C and N and other soil parameters

3.3.1. Correlation between soil OC and N

The SOC and N present similar trends across the different land uses as an indication of a positive correlation between the two elements both in the UL and LL as illustrated in Fig. 7 below:

3.3.2. Correlation between soil OC and N and other soil parameters

Positive correlations were also observed between C and N and other soil parameters with a relatively weaker correlation in LL than UL in most cases as seen in Fig. 8 below:

4. Discussion

4.1. Variability of soil chemical parameters across land uses

4.1.1. Soil organic carbon (OC), soil organic carbon stocks (SOCS), and soil pH

The higher soil OC and SOCS in the forest zone (native forest and forest-based cocoa agroforestry) may be due to trees and shrub litter decomposition (Worku et al., 2014; Kassa et al., 2017), and continuous leaf defoliation (Mohammed and Bekele, 2014; Lal, 2001). Meanwhile, the higher concentrations of OC in the lower soil layer can be due to the decomposition of dead fine tree and shrub roots and the mycorrhizal fungi contribution of SOM (Lemma et al., 2006; Yimer et al., 2007). The high pH and low C/N also attest to the presence of an advanced litter decomposition rate (Nsabimana et al., 2008; Adugna and Abegaz, 2015).

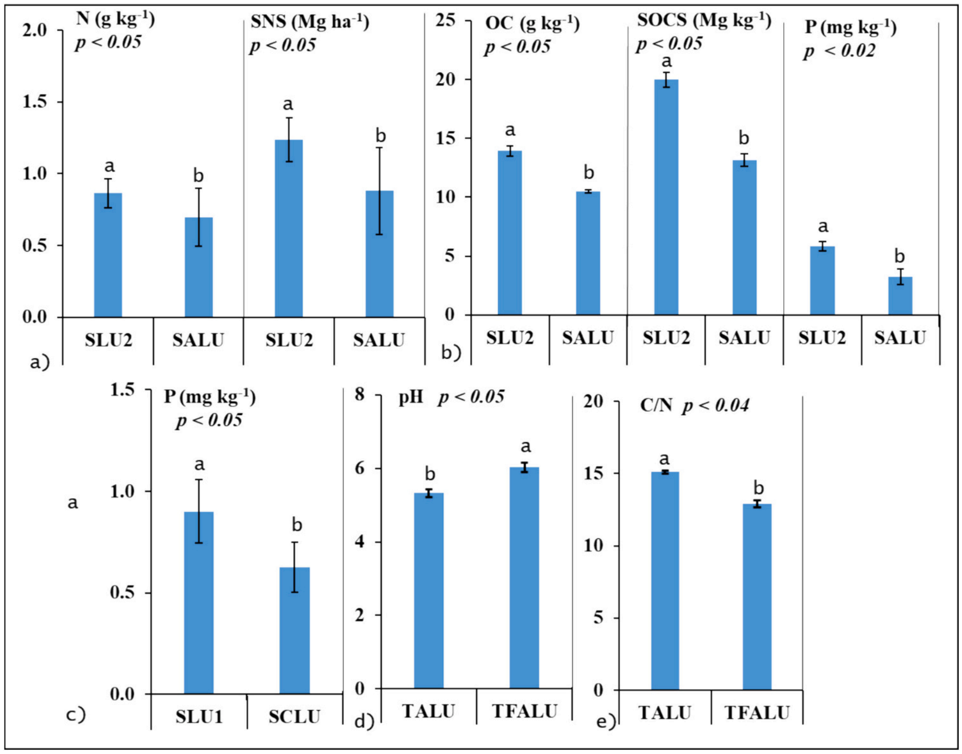

Fig. 6. Variation of soil organic carbon (OC), soil organic carbon stock (SOCS), total nitrogen (N), soil nitrogen stock (SNS), available phosphorus (P), pH, and C/N with change in land use in the upper soil layer.

FLU: native forest land use, SLU1: native savannah of cocoa landscape, SCLU: savannah-based cocoa agroforestry land use, SLU2: native savannah of crop landscape, SALU: Savannah-based cropland use, TALU: transition zone-based cropland use, TFALU: transition zone-based fallow land use, letters a, b, c, etc. indicate significant differences.

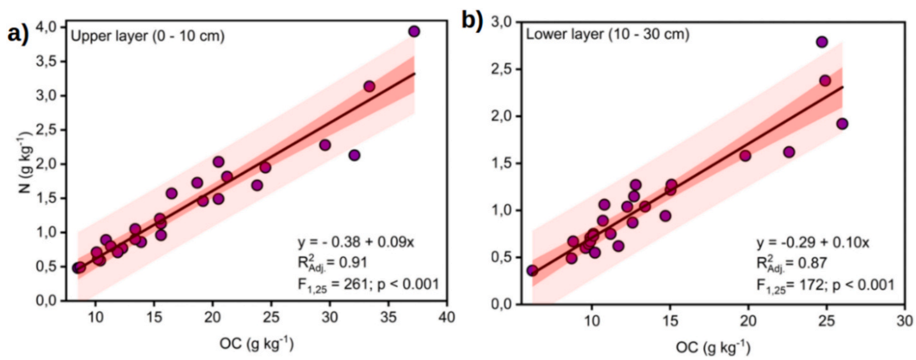

Fig. 7. Simple linear regression between soil organic carbon (OC) and total nitrogen (N) in (a) the upper soil layer and (b) the lower soil layer.

In agroforestry, the highest soil OC content was noted in the forest-based cocoa agroforestry which was characterized by an intensified and highly diverse associated forest and fruit tree species. Studies have reported that intensified highly diverse-dense cocoa agroforestry systems have more synergetic ecosystems and vice versa (Rao et al., 1997; Bayala and Prieto, 2020; Cerda et al., 2014).

In the cropland and fallow lands, the lower soil OC content may result from slash-and-burn added to shortening fallow periods (≤ 5 years). Thus, fallow is the only means of soil fertility recovery for the farmers who rely on slash-and-burn to clear their farms due to a lack of resources to pay for labor. Slash-and-burn causes loss of biodiversity, decrease in SOM content, and aggregate stability, soil nutrient depletion, increase in surface runoff, soil erosion, and leaching (Cox et al., 2000a, 2000b; Yemefack et al., 2006; Kassa et al., 2017). Slash and burn also causes high release of CO_2 gas into the atmosphere thereby contributing to climate change (Palm et al., 2004). Results also showed that soil OC was higher in the transition zone croplands over the savannah which can be explained by the frequency and intensity of tillage and the shorter duration of the rotational system due to shorter fallow lengths (≤ 3). Thus, massive crop residues are produced and incorporated into the soil during tillage, which undergoes decomposition to release soil nutrients (Bargali et al., 2015; Blanco-Canqui et al., 2017; Hornbach et al., 2021).

The transition zone is the central town study area which is highly populated and easily accessible probably causing high demand for food and land scarcity confirming the study of Jalloh (2006) and Nounamo et al. (2002) who reported that fallow length has dropped to about 5 years in rural areas and 3–4 years along major highways. Although the higher fallow length in the savannah, OC was lower in the croplands which can be explained by the higher bulk density. Thus, human actions and livestock grazing during the fallow period contribute to limiting the SOM input into the soil, causing soil compaction with a negative impact

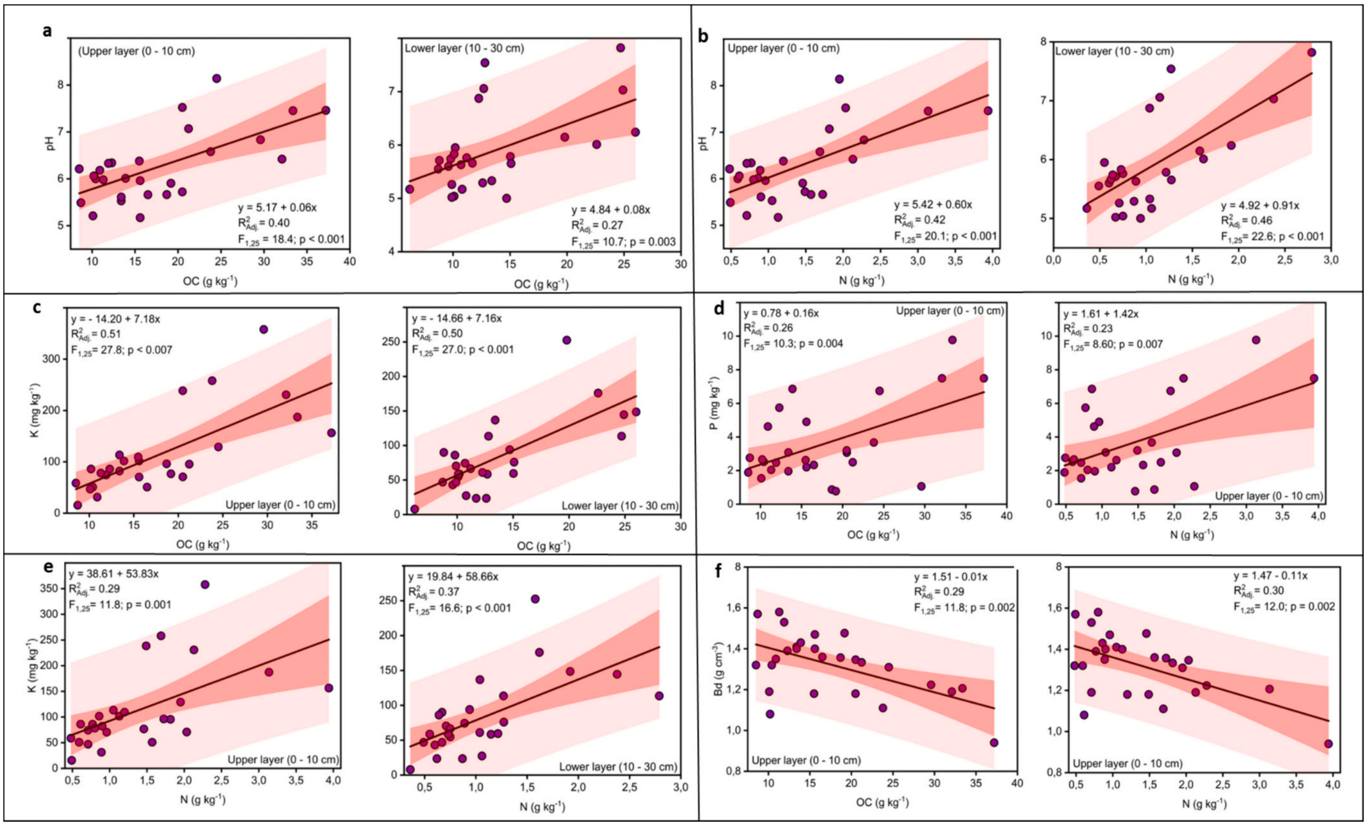

Fig. 8. Positive correlations between soil organic carbon (OC) and total nitrogen (N) and pH, phosphorus (P), potassium (K), and bulk density (Bd) in upper and lower soil layers.

on the soil bulk density (Hamza and Anderson, 2005; Don et al., 2011). Nevertheless, further investigations with more plot replications and an improved number of bulk-density samples will be required to add more reliability to this study.

4.1.2. Total nitrogen (N), soil nitrogen stock (SNS), available phosphorus (P), exchangeable potassium (K)

The relatively high concentrations of N, SNS, and P in the native lands (native forest and native savannah of cocoa landscape) and the forest-based cocoa agroforestry are probably due to the presence of leguminous and non-leguminous trees, shrubs, and herbs species playing a significant role in supplying SOM, N, and P to the soil. Binkley and Giardina (1998) further highlighted that this is a common phenomenon in tropical areas that hold leguminous trees. Survey results also indicated that most cocoa farmers in the area use foliar fertilizers which may also be potential sources of soil N and P in cocoa agroforestry although they apply them randomly due to financial constraints. Thus, further studies are needed to shed more light on the main sources of N, and P in cocoa agroforestry. The ability of cocoa agroforestry trees to fix N through the symbiotic association of bacteria and mycorrhizal fungi contributes significantly to the topsoil's levels of N and Pincrementation through decomposition (Nsabimana et al., 2008; Worku et al., 2014). Thus symbiotic association also leads to nutrient accumulation in the biomass of trees, and therefore the tree leaves contribute significantly to the topsoil's levels of N after decomposition.

On the other hand, the higher concentration of K in the savannah-based cocoa agroforestry may be due to the presence of high SOM and clay contents in the upper soil layer from which OM formed by trees and shrub litter underwent a complete microbial breakdown and decomposition releasing humic substances and exchangeable bases in their turn (Saikh et al., 1998; Nsabimana et al., 2008). Meanwhile, the SOM in the transition zone-based fallow mainly results from the decomposition of crop residues in the cropland by the findings of Jarecki and Lal (2003). Crop residues, generally composed of stalks, stubble, leaves, roots, and seed pods determine SOM content and the availability of nutrients when they undergo decomposition under favorable conditions as reported by Nicholson et al. (2014), Khan et al. (2021). This explains the perfect correlation between K with SOC and N (Fig. 8).

4.2. Effects of land use change on soil physical and chemical properties

4.2.1. Change of native forest (FLU) to cocoa agroforestry land uses (forest-based cocoa agroforestry (FCLU), and native savannah of cocoa landscape (SLU1)) to savannah-based cocoa agroforestry (SCLU)

The significantly higher concentration of P in the native savannah compared to savannah-based cocoa agroforestry was probably due to the higher tree density in the native savannah (Cerda et al., 2014), which prevents leaching, and surface erosion (Nsabimana et al., 2008; Abegaz and Adugna, 2015). Thus, the savannah-based cocoa agroforestry was characterized by very few associated fruit trees. Therefore, SOC and soil nutrient content increase with increasing density and diversity of associated trees as reported by (Cerda et al., 2014; Achille and Dietrich, 2021). The higher P in the native savannah may also be conditioned by the tree species (Jama et al., 2006; Raddad and Luukkanen, 2007; Keesstra et al., 2018). Thus, future investigations in this regard should consider assessing litter nutrient composition.

On the other hand, the similar C and nutrient content in native forest and forest-based cocoa agroforestry characterized by intensified highly diverse and dense associated forest and fruit trees indicates that agroforestry is a potential solution to enhance the ecological resilience of farms affected by land-use change. Thus, cocoa agroforestry systems have a synergetic ecosystem relationship but also, could generate remarkably higher yields, net income, cash flow, and family benefits for the farmers (Cerda et al., 2014; Achille and Dietrich, 2021). In this regard, there's a need for detailed studies putting into evidence the socioeconomic impact and trade-off of agroforestry to guide decisions on the sustainability of agriculture, livelihood, and the environment.

4.2.2. Change of native savannah of crop landscape (SLU2) to savannah-based cropland use (SALU)

The significant difference in soil C, N, P, SOCS, and SNS content in the change of land use from the native savannah of crop landscape to the croplands may be the result of the agricultural management practices. Thus, croplands are managed under slash-and-burn, conventional tillage, and shortened fallow lengths of ≤5 years (Kanmegne, 2004). Slash-and-burn may cause damage to the upper soil layer because fire hinders soil C storage, carbon allocation patterns, and plant tissue chemistry, and decreases the rate of SOM decomposition (Reich et al., 2001). The ashes produced exert a negative impact on the soil in the long run by promoting the leaching of nutrient elements, reducing SOM content, and modifying soil aggregate stability (Nounamo et al., 2002; Kanmegne, 2004; Edivaldo and Rosell, 2020). Ash may also contribute to pore blockage resulting in increased surface runoff (Pérez-Cabello et al., 2012; Bodí et al., 2011; Janvier et al., 2013). Slash-and-burn also decreases microbial biomass composition (MBC) (Wapongnungsang et al., 2021). On the other hand, tillage can lead to the modification of soil structure and result in the disruption of aggregates, enhance compaction, and disturb soil floral and faunal communities (Plante and McGill, 2002). Thus, tillage can lead to greater losses of soil C and nutrients (N, P, and K), especially in the top layer (10 cm) (Du Preez et al., 2001; Roldán et al., 2003); D'Haene et al. (2008), and the short fallow period (≤ 5 years) does not give enough time for nutrient recovery (Hervé, 1994; Abreu et al., 2009; Temjen et al., 2022).

4.2.3. Change of transition zone-based fallow (TFALU) to transition zone-based cropland (TALU) and savannah-based fallow (SFALU) to savannah-based cropland (SALU)

No significant difference was observed in terms of soil C and nutrient content in the change of land use from fallow to cropland except for soil pH ($p < 0.04$) which was relatively higher and C/N ($p < 0.03$) which was lower in the transition zone-based fallow land uses (TFALU). Meanwhile, fallow is supposed to be the best mechanism for soil nutrient recovery amongst smallholder farmer's communities but unfortunately the short fallow period (≤ 5 years) in the area is not sufficient for soil C and nutrient restoration (Masse et al., 2004). This is because shortening fallow periods reduces the regrowth and amount of vegetation, thereby decreasing the amount of soil C and nutrient (NPK) inputs (Aguilera et al., 2013). Studies reported that a minimum fallow length of ≤10 is required to obtain a significant recovery in soil C and nutrients (Abreu et al., 2009; Temjen et al., 2022).

5. Conclusion

Soil carbon and nutrient content vary across land uses and based on the direction of land use changes. The concentration of soil OC and N in the agroforestry systems were higher and similar to that of the native lands (forest and savannah) with a higher magnitude in the upper soil layer compared to the croplands. Amongst the land use changes, significant differences were mainly observed in the change from native savannah to cropland. Therefore, agroforestry is an option for enhancing the ecological resilience of lands affected by land use change, thus promoting the sustainability of ecosystem services, climate change adaptation, and mitigation. Resilience can further be enhanced by intensification and diversification of the associated trees. On the other hand, additional efforts are required to maintain soil C and nutrient storage in cropland which is possible through crop rotation with leguminous crops, crop residue retention, reduced tillage, and prolonged fallow. However, further studies with more sampling replicates are needed for better representativeness and reliability. Prolonged periods of experimentation (≥ 3 years) are also required to show quantitative evidence of the long-term effects of agroforestry and the overall benefits of intercropped trees on soil quality and ecosystem functioning. The impact of land use change could also be better appreciated if the percentage/degree of changes are evaluated.

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Funding statement

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CRediT authorship contribution statement

Viviane Pauline Mandah: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paul Tematio:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Adalbert A. Onana:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Komi K.M. Fiaboe:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Emmanuel Arthur:** Writing – review & editing, Validation, Supervision, Software, Formal analysis. **Mekonnen H. Giweta:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Rose Ndango:** Resources, Methodology. **Francis B.T. Silatsa:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Duchel D.I. Voulemo:** Resources, Investigation. **Jean Baptiste Biloa:** Software, Resources, Investigation. **Cedrick Nguemezi:** Resources, Investigation. **Cargele Masso:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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 study.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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