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ORIGINAL PAPER

Soil organic carbon accumulation in dry tropical mountainous zone of Cameroon

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Abstract

The present work was designed to study a soil sequence in Mount Mandara, in order to identify the influence of altitude, soil characteristics, and land use on the accumulation of soil organic carbon (SOC). The study was conducted in four sites in the Far-North region of Cameroon, including Zamai, Kossohone, Sir, and Rhumsiki. Three pits were dug down to the weathering horizons in three positions (upslope, mid-slope, and footslope) along a representative toposequence in each site. Samples were taken from each pit at regular increment of 25 cm from the soil surface. The total SOC stock (T-SOCS) contents are 128.63 ± 5.25 Mg ha^{-1} in Arenosols at Zamai (608 m a.s.l.), 158.248 ± 10.52 Mg ha^{-1} in Leptosols at Kosohone (865 m a.s.l.), 158.99 ± 13.25 Mg ha^{-1} in Luvisols at Sir (970 m a.s.l.), and 144.79 ± 24.23 Mg ha^{-1} in Regosols at Rhumsiki (1050 m a.s.l.). The main secondary minerals are smectite, kaolinite, sepiolite, lepidocrocite, hematite, and calcite. Clay minerals and iron oxides are good receptacle for SOC and might constitute a major asset for the accumulation and the sequestration of SOC. Increase in elevation leads to decrease in the annual temperature which affect microbial activity, leading thus to a slow rate of soil organic matter (SOM) decomposition, which thereby affected SOCS. This is confirmed by the significant correlation between altitudinal gradient and T-SOCS ($r = 0.70$), with altitude contributing to the accumulation of SOC for 49.68%. Texture also plays a central role in carbon sequestration in the studied area, confirmed by the significant and positive correlation between silt fraction and SOM. Under Regosols, there is a decrease in T-SOCS value as a result of a reduction of the quantity of organic matter returned to the soil and more rapid SOM decomposition due to ploughing. This research provides a preliminary assessment for SOC stock at Mount Mandara. It suggests that altitudinal gradient, land use, and soil characteristics should be included in SOCS models and estimations at local and regional scales.

Keywords Soil organic carbon · Altitudinal gradient · Land use · Mount Mandara · Cameroon

Introduction

Pedogenesis involves all the processes relating to the formation and evolution of soils on the earth surface. It is the consequence of climate (temperature, precipitation), parent materials, biota, time, and topography (slope angle, slope shape, altitude) (Jenny 1941; Amundson 2014; Singer 2015). In general, there is a vertical organization of soil from the base of massifs to their summit. This variation along the altitudinal gradient has repercussions on soil characteristics and soil organic carbon (SOC) stocks (Fiener et al. 2015; Fissore et al. 2017; Tsozué et al. 2019). This is even more accentuated when the bedrock is made of volcanic rocks containing glasses which can easily be transformed into amorphous materials which further facilitate the retention of soil organic matter (SOM) (Tsozué et al. 2019). It is demonstrated that altitude alone accounted for 73% of

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the variation in SOC storage in tropical to temperate part of Indian Himalayan region (Tashi et al. 2016) and 75% in Mount Bambouto in the humid part of Cameroon (Tsozué et al. 2019).

Soil organic carbon stocks (SOCS) play an essential role in the climate regulation through atmospheric carbon dioxide (CO_2) storage (Olson et al. 2016; Greiner et al. 2017; Mayer et al. 2019; Tsozué et al. 2021). It is proved that vegetation fixes about 120 Pg of carbon (C) per year from the atmosphere through photosynthesis process and half of this C is returned to the atmosphere by plants (Bernoux and Chevalier 2013; Tsozué et al. 2021). Part of the atmospheric C drawn by plants is stored in biomass and soil which have the potential to constitute a C sink, in the form of SOM, slowing down the increase of CO_2 in the atmosphere (Mayer et al. 2019; Tsozué et al. 2019, 2021).

Soils are the largest continental reservoir of organic C (Smith 2012; Chenchounia and Neffar 2022). This reservoir contains nearly 800 GtC in the first 30 cm of soil and between 1500 and 2000 GtC over the first meter (Ciais et al. 2013; Chenchounia and Neffar 2022), representing about twice that of the atmospheric reservoir (805 GtC) and three times what is stored in vegetation (550 GtC) (Houghton 2007). Vegetation and earthly animals constitute a stock of 610 GtC (FAO 2015; Chenchounia and Neffar 2022). SOCS varies in space and time. It is in response of several biotic and abiotic factors among which the most important is the climate (Boudjabi and Chenchouni 2022; Chenchounia and Neffar 2022). Climate controls both net primary production and SOC dynamics, through the combined and synergetic effects of temperature and precipitation (Deb et al. 2015; Chenchounia and Neffar 2022). High precipitation increases soil moisture and soil microbiological community activity, which induces an increase in plant primary production and greater inputs of C in the soil (Razafimbelo et al. 2010; Chenchounia and Neffar 2022). Soil microbiological communities are key drivers of biogeochemical cycling and numerous important ecosystem processes such as decomposition and soil respiration (Xu et al. 2020), which have important effect on the sequestration of C in the soil. Temperature affects the sequestration time of C in the soil (Razafimbelo et al. 2010; Chenchounia and Neffar 2022). High temperatures stimulate soil biological activity and accelerate the SOM degradation, leading thus to a decrease in microbial biomass and dissolved SOC, which is also related to the low quantity of litter produced by plants (Boudjabi and Chenchouni 2022; Chenchounia and Neffar 2022). In fact, an increase of 10 °C in air temperature decreased the sequestration time of SOC by a factor of 2–3 (Raich and Schlesinger 1992). In addition to climate, other environmental and anthropogenic conditions which have an impact on the C cycle dynamics include soil mineralogy, soil texture and structure, chemical properties, landscape, landscape position, slope, latitude, anthropogenic factors, soil management, and natural disturbances such as wind, fire, drought, insects, and diseases (Zinn et al. 2007; Lal 2009a; Lal 2009b; Wang et al. 2010; Novara et al. 2011; Corral-Fernández et al. 2013; Cerdá et al. 2014; Fernandez-Romero et al. 2014; Lozano-García and Parras-Alcantara 2014a, b; Bruun et al. 2015; Tsozué et al. 2019, 2021).

In dry areas, SOC content is low, representing only less than 1% of the soil mass (Lehmann and Kleber 2015; Plaza et al. 2018; Tsozué et al. 2021). In the temperate zone on contrary, it reaches 4 to 5% in grassland soils or under forest (Lehmann and Kleber 2015; Plaza et al. 2018; Tsozué et al. 2021). In humid tropical mountainous zone of Cameroon, it was observed an increase in SOCS along with the altitudinal gradient from 158 Mg ha^{-1} at the base of the massif (1400 m a.s.l.) to 302 Mg ha^{-1} in its summit (2740 m a.s.l.) (Tsozué et al. 2019). This summit was characterized by the presence of market gardening crops where a wide range of European vegetables are cultivated (cabbage, sweet pepper, potato, leek, garlic, onion, tomato, pepper, parsley, beets, carrots, celery, and peas) (Tsozué et al. 2011). A similar organization is observed in the Mount Mandara that located in the dry tropical zone of Cameroon, from its base at 400 m a.s.l. to its summit at 1400 m a.s.l. There is a gradual appearance of European vegetables, largely represented by potatoes from 800 m a.s.l. The presence of European vegetables is synonymous of land use change in the area which is modifying the SOCS that will positively or negatively impact local and global climate change.

In general, works devoted to SOC in dry tropical mountainous zone are very rare. In Central Africa, works related to this environment are completely absent. The present work proposes to study the influence of altitude, soil characteristics, and land use on SOCS at dry tropical mountainous zone, particularly in the Mount Mandara. Specifically, it will involve to (1) study the mineralogical, geochemical, and physicochemical characteristics of these soils; (2) study the variation of the SOCS along the altitudinal gradient; and (3) analyze the influence of soil characteristics, human activities, and altitudinal gradient on SOC sequestration. To achieve this, the Mayo-Tsanaga Division in general and more specifically the sites of Zamai, Kossohone, Sir, and Rhumsiki in the Far-North region of Cameroon were chosen. We hypothesized that altitude, soil characteristics, and land use are main factors controlling the accumulation of SOC in the Mount Mandara. The results are expected to improve our understanding on the distribution of SOCS in Mount Mandara and provide important additional information for the scientific evaluation of SOCS at local and regional scales.

Materials and methods

Description of the study area

The Far-North region of Cameroon stretches on about 325 km from the Sudanese countries in the south to the shores of Lake Chad in the north. It is located between 10°00′ and 13°00′ North and between 13°30′ and 15°30′ East. The study took place in the Mayo-Tsanaga Division (Fig. 1). The different study sites are Zamai, Kossohone, Sir, and Rhumsiki (Fig. 1). The climate is characterized by an alternation of two seasons, a dry season from October to May and a short rainy season from June to September. The average annual precipitation varies between 800 and 1000 mm and the mean annual air temperature range between 28 and 25.8 °C (Table 1). The relative humidity is generally low, reaching 10% in the dry season. The landscape is undulate and made of a succession of hills, with altitude ranging between 600 and 1400 m a.s.l. (Fig. 1). The different soil units are developed on alluvial materials (Zamaï), gneiss (Kossohone and Sir), and granit (Rhumsiki) (Ngounounou et al. 2000; Tamen et al. 2015; Gountié Dedzo et al. 2019). The different soil types present in the region are Vertisols, Arenosols, Leptosols, Regosols, Acrisols, Lixisols, Luvisols, Fluvisols, and Gleysols (Tsozué et al. 2017; Silatsa et al. 2021). Due to the relief and the climate, the hydrographic network has two flow regimes: a low water regime in the dry season and a flood regime in the rainy season. The main collectors are Mayo-Tsanaga and Mayo-Louti. The vegetation is strongly anthropized in the whole Mount Mandara (Table 1). The most represented species are *Acacia hockii*, *Albizia-chevaleri*, *Balanites aegytiaca*, *Bauhinia rufescens*, *Combretuma culeatum*, *Dichrosta chyscinera*, *Ziziphus mauritiana*, *Piliostigma reticulatum*, *Strychnos spinosa*, *Ximenia americanass*, *Andropogon pinguipes*, *Bothriochloa bladhii*, *Chrysochloa hindsii*, *Eragrostis viscosa*, *Heteropogon melanocarpus*, *Leersia drepanothrix*, *Oryza glaberrima*, *Pogonarthria squarrosa*, *Schizachyrium nodulosum*, and *Sehima ischaemoides* (Letouzey 1985; Van der Zon 1992). The main human activities are agriculture and livestock breeding. All the upper part of the massif above 1000 m a.s.l. is cultivated.

Field work and soil sampling

A detailed study of the topographic maps of the study area help to choose four study sites. The study was carried out in the dry season. Precipitation of the year reported in the study is the mean annual precipitation according to the historic. At each site, meticulous landscape analyses were conducted. The main parameters examined are the relief,

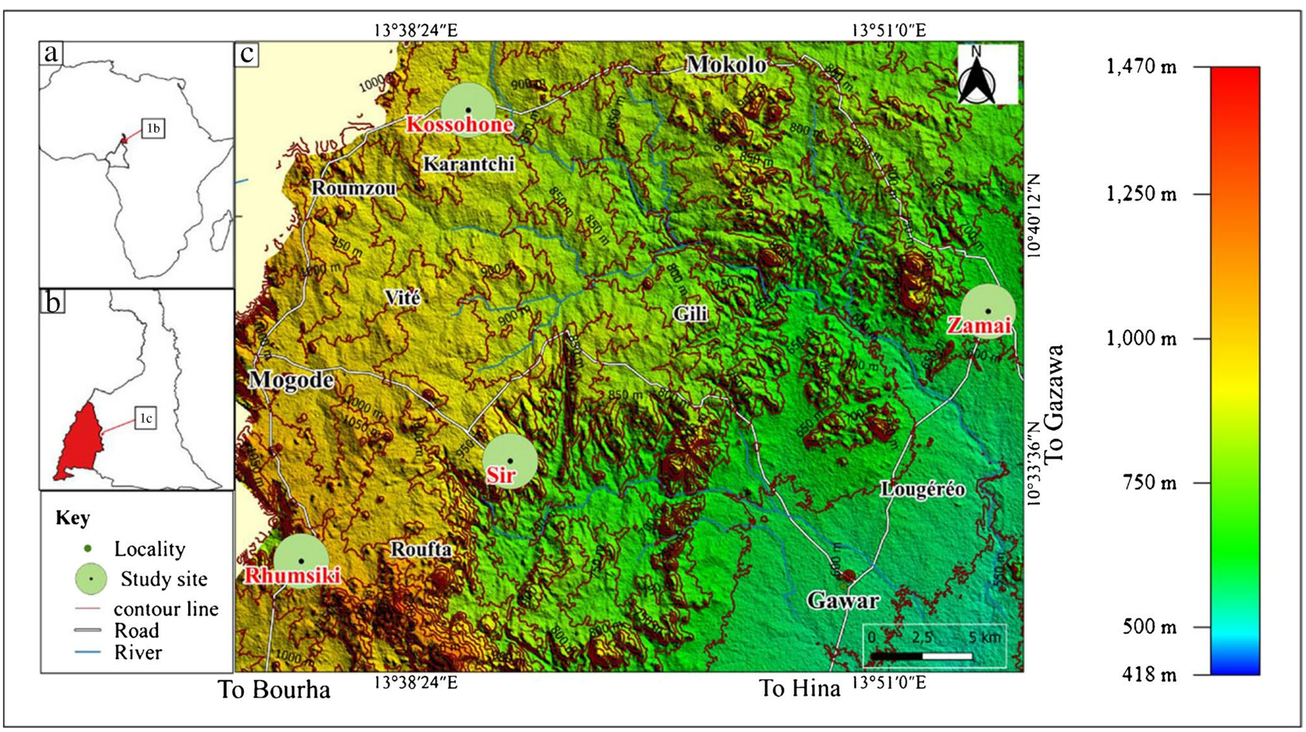

Fig. 1 Location of the study area

Table 1 Physical and mineralogical characteristics of the studied sites

Site	Altitude (m a.s.l.[a])	Climate		Bedrock	Mineralogical composition	Surface state	Soil classification	n[b]
		Precipitation (mm)	Temperature (°C)					
Rhumsiki	1050	1006.6	25.8	granite	Quartz, kaolinite, smectite, sépiolite, plagioclase, alkaline feldspar, calcite, hematite	Vegetation highly anthropogenized; cultivation of maize and sorghum but recently colonized	Eutric Regosols	12
Sir	970	829.5	26.7	gneiss	Quartz, kaolinite, smectite, sépiolite, lépidocrocite, calcite, plagioclase, alkaline feldspar	Virgin forest reserve	Haplic Luvisols	15
Kosohon	865	802	27.5	gneiss	Quartz, kaolinite, smectite, sépiolite, hematite, plagioclase, alkaline feldspar	Virgin Forest reserve	Dystric Leptosols	13
Zamai	608	800	28.0	Sandy alluvial deposits	Quartz, kaolinite, smectite, sépiolite, calcite, hematite plagioclase, alkaline feldspar, amphibole	Virgin forest reserve	Dystric Arenosols	15

[a]Meters above sea level

[b]Number of sample

bedrock, hydrography, and vegetation. Four transects were previously established in each site and one most representative toposequence was retained per site. Along each toposequence, three pits with a depth up to more than 150 cm were made, including one at the top of the interfluve, a second at mid-slope, and a third at the footslope. Twelve pits in total were dug down to the weathering horizons. Soils description was made on the walls of the profiles and the colors were determined in the field using the Munsell colors charts. Samples were thereafter taken from each pit at regular increment of 25 cm from top to bottom in each soil profile. Depth increments were used for a uniform comparison between studied soils. A total of 55 samples were collected in the polythene bags labeled with corresponding defined codes for laboratory analysis. For soil classification, the IUSS Working Group WRB (2015) was used.

Soil analysis and SOC estimation

The mineral phase analysis was carried out by X-ray diffraction (XRD) on disoriented powders and on oriented aggregates, and by Fourier transform infrared spectroscopy (FTIR) on total powder. Samples were scanned in the 2θ range from 2° to 45° with step size of 0.02° and time per step 2 s, with CuKα1 radiance, $\lambda = 1, 5418$ Å, at 40 kV, and 30 mA. Detailed identification was done through air-drying (24 h), glycolation (22 h), and heating (500 °C for 4 h) with further tests on clay fraction (Moore Duane and Reynolds Robert 1989).

Diffuse reflectance infrared spectra were recorded between 4000 and 500 cm^{-1} using a FTIR spectrometer (IFS 55). The spectrum resolution was 4 cm^{-1} and spectra were obtained by accumulation of 200 scans (Nguyen et al. 1991).

Elemental composition analysis was performed by X-ray fluorescence spectroscopy (XRF) (Beckhoff et al. 2006).

For physicochemical analysis, different methods used in this study were already used in the same laboratory by Tsozué et al. (2019, 2021). Except the bulk density, all the physical and chemical analysis were carried out after sieving the soil through 2-mm meshes. For bulk density (BD), clods were first roughly sized in order to fit into the cell (8 × 6 × 6 cm) of the clod box, and thereafter, it was measured by the paraffin-coated clods method (USDA 2004). The soil texture was determined by Robinson's pipette method using sodium hexametaphosphate [$Na_6(PO_3)_6$] as dispersing agent (USDA 2004) and the textural class was determined using the USDA texture triangle. Soil pH was carried out with a pH meter equipped with a glass electrode in soil–water suspensions (1:2.5) (Guitián and Carballas 1976). Exchangeable cations were extracted by 1 N NH_4OAc at pH 7 and their concentrations were determined by atomic absorption spectrometry Perkin Elmer for Ca and Mg, and by flame emission spectrometry for K and Na. Cation exchange capacity (CEC) was also determined using the ammonium acetate method at pH 7, by a direct continuation using a 1 N potassium chloride (KCl) saturation solution. SOC was determined by dichromate oxidation using the Walkley–Black method (Walkley and Black 1934). SOM content was obtained using a conversion factor of 1.724 (Walkley and Black 1934). Total nitrogen (TN) was determined with the Kjeldahl method (Bremner 1996) and the C:N ratio calculated by dividing the SOC concentration by the N concentration.

SOCS, expressed in Mg ha^{-1}, was calculated according to IPCC (2003) as follows:

$$\mathrm{SOCS} = \sum_{\mathrm{horizon}=1}^{\mathrm{horizon}=n} \left([\mathrm{SOC}] \times \mathrm{BD} \times \mathrm{d} \times (1 - \delta 2\mathrm{mm}\%) \times 10\right)_{\mathrm{horizon}}$$

where SOC is the organic C content (g kg^{-1}), d the thickness of the control section (m), δ_{2mm} is the ratio of gravel larger than 2 mm in size in the soil, and BD the soil bulk density (Mg m^{-3}). Total SOCS (T-SOCS), refer to the entire soil profile thickness (Mg ha^{-1}), was calculated according to IPCC (2003) as follows:

$$\mathrm{T-SOCS} = \sum\nolimits_{\mathrm{Soilsection}} \mathrm{SOCstock}_{\mathrm{Soilsection}}$$

Statistical analysis

Data were subjected to the Anderson–Darling normality test which evaluate the normal distribution of analyzed variables. Soil properties were statistically analyzed for each of the soil types, including the mean values, standard deviations (SD), and correlation for each soil property investigated in order to characterize their general trends. A Spearman rank correlation coefficient was carried out in order to assess the possible connection between the soil properties and SOC in each site. The statistical significance of the differences in each soil variable was identify using the Kruskal–Wallis statistical test. Significance was considered at $p < 0.05$. Linear regression analyses were carried out to evaluate the relationship between geochemical elements, altitude, and T-SOCS. For the regression analysis, only the mean values of each site were used. All analyses were performed using XSLSAT 2008.6.03 software for Excel.

Results

Physicochemical characteristics of soils

The texture of the soil was sandy loam to loam sandy. Sand is the most important particle size fraction. With the exception of Luvisols in which there is an increase in clay content from the surface (7.23 ± 1.15%) to the middle part of the soil profile (20.23 ± 1.52%), then a decrease to the base of the soil profile (8.23 ± 1.52%), all the particle size fractions show a zigzag evolution with depth. The highest contents of sand were observed in the Arenosols at Zamai (80.33 ± 12.01%) while the lowest were observed in the Luvisols at Sir (59.03 ± 0.77%) (Table 2). The silt and clay contents are low and vary generally within the same ranges, with 7.56 ± 4.72 to 22.36 ± 5.22% for silt and 8.10 ± 5.56 to 22.6 ± 9.19% for clay. Soil pH is weakly acidic in Regosols and Luvisols (6.10 ± 0.17 to 6.90 ± 0.26), but weakly acidic to neutral in Arenosols and Leptosols (6.3 ± 0.00 to 7.55 ± 0.91) (Table 2). The BD varies between 0.75 ± 0.00 and 2.33 ± 0.22 g/cm^3. It increases with depth in Regosols, decreases from the surface to the middle zone before increasing thereafter to the base of the soils in Luvisols, but presents a zigzag evolution in Leptosols and Arenosols. A weak and low significant positive correlation exist between bulk density and sand ($r = 0.472$, $p < 0.05$), and negative significant correlation with silt ($r = -0.418$, $p < 0.05$) and nitrogen ($r = -0.482$, $p < 0.05$). The gravel contents vary greatly at the scale of the massif. The lowest content is observed in Arenosols (3.66 ± 3.05%) while the highest is perceived in Leptosols (25.00 ± 0.00%). A weak positive and significant correlation exist between gravel and TN ($r = -0.348$, $p < 0.05$). Overall, with the exception of silt and pH which values show significant differences, no significant difference was noted between other physical parameters of the studied soil in the entire massif (Table 3). There is a significant and negative correlation between silt and sand ($r = -0.674$, $p < 0.05$), clay and sand ($r = -0.811$, $p < 0.05$), and between pH and clay ($r = -0.306$, $p < 0.05$). In addition, there is a weak significant and positive correlation between pH and sand ($r = 0.312$, $p < 0.05$) (Table 4).

SOM, TN, and C:N ratio

In each soil type, the SOM content is high in the first 25 cm, and there is no significant statistic difference between layers ($H(2) = 3.563$; $p = 0.515$) (Table 2). The highest content is observed in Leptosols (6.09 ± 1.96%) while the lowest is observed in Arenosols (2.33 ± 0.81%). These contents generally decrease with depth, but their evolution varies from one soil type to another. In the Regosols, Luvisols, and Arenosols, there is a decrease from the surface to the middle part of the soil profiles, then an increase down to the base of the soils (Table 2). No significant difference is noted in the variations of SOM content at the scale of the Mount Mandara ($H(3) = 7.815$; $p = 0.632$) (Table 3). There is a significant correlation between SOM and silt ($r = -0.406$, $p < 0.05$) (Table 4). The TN contents are very low in the studied soils. They vary between 0.12 ± 0.01 in Leptosols and 0.06 ± 0.02% in Luvisols (Table 2). There is a significant difference between the TN contents in Arenosols at Zamaï, Leptosols at Kossohone and Luvisols at Sir. However, no significant difference was noted between the TN contents

Table 2 Physical and chemical properties of the soils evaluated (mean ± SD) in Mount Mandara

Site	Section	Detph (cm)	Sand %	Silt %	Clay %	OM %	N %	C/N	pH	BD g cm^{-3}	Gravel %
Rhumsiki (Regosols)	S1	0–25	73.33 ± 5.07a	16.6 ± 5.84a	10.06 ± 0.76a	4.31 ± 3.73a	0.08 ± 0.1a	28.51 ± 26.79a	6.16 ± 0.30a	1.6 ± 1.20a	21.66 ± 7.63a
	S2	25–50	71.66 ± 2.62a	9.93 ± 3.44a	18.4 ± 3.96a	1.11 ± 1.03a	0.02 ± 0.0a	27.94 ± 20.77a	6.20 ± 0.52a	1.96 ± 0.62a	7.66 ± 6.42a
	S3	50–75	71.33 ± 6.67a	11.93 ± 3.10a	16.73 ± 4.19a	0.83 ± 0.22a	0.01 ± 0.0a	45.88 ± 6.80a	6.30 ± 0.30a	2.04 ± 0.89a	5 ± 2.00a
	S4	75–100	78.33 ± 2.28a	10.6 ± 1.38a	11.06 ± 2.02a	1.19 ± 0.55a	0.01 ± 0.0a	68.64 ± 38.79a	6.53 ± 0.23a	2.33 ± 0.22a	5 ± 2.00a
Sir (Luvisols)	S1	0–25	74.7 ± 1.00a	18.06 ± 0.57a	7.23 ± 1.15a	3.83 ± 0.70a	0.06 ± 0.02a	44.50 ± 19.69a	6.83 ± 0.25a	1.36 ± 0.22a	18.33 ± 5.77a
	S2	25–50	63.03 ± 5.77a	17.4 ± 1.00a	19.56 ± 4.93a	1.37 ± 1.02a	0.03 ± 0.02a	21.18 ± 5.88a	6.10 ± 0.17a	1.33 ± 0.55a	4.33 ± 2.30a
	S3	50–75	59.03 ± 0.77a	20.73 ± 1.15a	20.23 ± 1.52a	1.03 ± 0.90a	0.02 ± 0.00a	27.77 ± 28.11a	6.26 ± 0.40a	1.10 ± 0.05a	9.66 ± 13.31a
	S4	75–100	71.03 ± 8.62a	18.4 ± 8.88a	10.56 ± 1.15a	1.66 ± 0.22a	0.021 ± 0.01a	56.42 ± 34.85a	6.66 ± 0.15a	1.31 ± 0.30a	9.00 ± 13.85a
	S5	100–125	78.36 ± 2.30a	13.4 ± 1.00a	8.23 ± 1.52a	1.65 ± 1.36a	0.01 ± 0.01a	55.55 ± 30.76a	6.90 ± 0.26a	1.49 ± 0.58a	9.00 ± 13.85a
Koshon (Leptosols)	S1	0–25	69.2 ± 10.22a	22.36 ± 5.22a	8.43 ± 5.13a	6.09 ± 1.96a	0.12 ± 0.01a	30.36 ± 12.82a	6.53 ± 0.20a	0.88 ± 0.25a	9.00 ± 5.29a
	S2	25–50	60.33 ± 20.00a	20.9 ± 6.08a	18.76 ± 14.84a	1.31 ± 1.44a	0.05 ± 0.03a	10.99 ± 9.94a	6.76 ± 0.15a	1.01 ± 0.19a	16.66 ± 10.40a
	S3	50–75	68.13 ± 15.49a	13.43 ± 6.51a	18.43 ± 13.01	1.76 ± 0.40a	0.06 ± 0.02a	17.27 ± 10.30a	6.76 ± 0.05a	1.09 ± 0.54a	25.00 ± 5.00a
	S4	75–100	61.9 ± 4.38a	15.5 ± 4.80a	22.6 ± 9.19a	1.10 ± 0.06a	0.07 ± 0.04a	10.63 ± 9.96a	7.55 ± 0.91a	0.99 ± 0.06a	13.00 ± 16.97a
	S5	100–125	69.00 ± 0.00a	18.9 ± 0.00a	12.1 ± 0.00a	1.57 ± 0.00a	0.08 ± 0.00a	10.40 ± 0.00a	6.3 ± 0.00a	0.75 ± 0.00a	25.00 ± 0.00a
	S6	125–150	70.00 ± 0.00a	18.9 ± 0.00a	11.1 ± 0.00a	1.23 ± 0.00a	0.02 ± 0.00a	29.13 ± 0.00a	7.0 ± 0.00a	0.96 ± 0.00a	5.00 ± 0.00a
Zamai (Arenosols)	S1	0–25	75.33 ± 13.61a	14.9 ± 9.84a	9.76 ± 3.78a	2.33 ± 0.81a	0.07 ± 0.01a	19.18 ± 5.66a	6.93 ± 0.56a	1.24 ± 0.37a	7.66 ± 7.02a
	S2	25–50	83.0 ± 10.58a	8.90 ± 5.19a	8.10 ± 5.56a	1.96 ± 0.15a	0.07 ± 0.02a	19.71 ± 14.14a	6.83 ± 0.85a	1.26 ± 0.44a	11.0 ± 12.49a
	S3	50–75	80.33 ± 12.01a	7.56 ± 4.72a	12.1 ± 7.550a	0.86 ± 0.81a	0.03 ± 0.02a	12.09 ± 9.34a	7.1 ± 1.25a	1.27 ± 0.08a	11.0 ± 2.49
	S4	75–100	70.56 ± 8.50a	11.3 ± 5.15a	18.13 ± 9.30a	1.62 ± 0.24a	0.04 ± 0.05a	27.71 ± 18.99a	7.1 ± 1.21a	1.12 ± 0.37a	10.66 ± 12.50a
	S5	100–125	69.56 ± 20.15a	13.73 ± 12.94a	16.7 ± 9.18a	2.61 ± 2.43a	0.03 ± 0.00a	32.00 ± 23.19a	7.13 ± 1.06a	1.38 ± 0.79a	3.66 ± 3.05a

BD bulk density, *OM* organic matter, *SD* standard deviation. Numbers followed by different lowercase letters within the same column have significant differences ($p < 0.05$) at different depths, considering the same topographic position

Table 3 Mean soil characteristics (mean ± SD) variation along the Mount Mandara

Variables	Sites			
	Zamai (Arenosols)	Kossohone (Leptosols)	Sir (Luvisols)	Rhumsiki (Regosols)
Sand %	75.76 ± 12.69a	65.83 ± 11.93a	69.23 ± 8.47a	73.66 ± 4.85a
Silt %	11.28 ± 7.42b	18.37 ± 5.72b	17.6 ± 6.18a	12.26 ± 4.22a
Clay %	12.96 ± 7.42a	15.79 ± 10.22a	13.16 ± 6.18a	14.06 ± 4.55a
OC %	0.97 ± 0.62a	1.45 ± 1.33a	1.10 ± 0.74a	1.08 ± 1.29a
OM %	1.88 ± 1.29a	2.50 ± 2.29a	1.91 ± 1.28a	1.86 ± 2.23a
N %	0.05 ± 0.02b	0.07 ± 0.03ab	0.02 ± 0.03a	0.03 ± 0.03a
C/N	22.12 ± 15.05a	18.20 ± 11.71a	41.09 ± 26.50a	42.74 ± 28.13a
pH	7.02 ± 0.85b	6.81 ± 0.46b	6.55 ± 0.39ab	6.3 ± 0.34a
SCOS	25.72 ± 18.35a	31.53 ± 26.64a	31.80 ± 21.58a	36.20 ± 24.70a

SOCS soil organic carbon stock, *SD* standard deviation. Numbers followed by different lowercase letters within the same column have significant differences ($p < 0.05$) at different depths, considering the same topographic position

Table 4 Spearman correlation matrix for relationships between selected soil parameters in the study area

Variables	Sand	Silt	Clay	pH	OM	N	C/N	BD	Gravel	SOCS
Sand	**1**									
Silt	**−0.674**	**1**								
Clay	**−0.811**	0.197	**1**							
pH	**0.312**	−0.163	**−0.306**	**1**						
OM	−0.133	**0.406**	−0.185	−0.059	**1**					
N	−0.090	**0.280**	−0.217	−0.003	**0.525**	**1**				
C/N	0.002	0.052	-0.055	−0.127	**0.488**	**−0.377**	**1**			
BD	**0.472**	**−0.418**	−0.245	−0.029	−0.180	**−0.482**	0.261	**1**		
Gravel	0.089	0.078	−0.186	0.186	0.163	**0.348**	−0.150	0.033	**1**	
SOCS	0.043	0.259	**−0.298**	−0.177	**0.859**	**0.332**	**0.591**	0.227	0.149	**1**

SOCS soil organic carbon stock. Values in bold are different from 0 with a significance level alpha = 0.05

at Sir and Rhumsiki sites (Table 3). There is a weak positive and significant correlation between TN and silt ($r = -0.280$, $p < 0.05$) and between TN and SOM ($r = -0.525$, $p < 0.05$). The C/N ratios are very high. They vary between 12.09 ± 9.34 and 32.00 ± 23.19 in Arenosols at 608 m a.s.l., 10.40 ± 0.00 and 30.36 ± 12.82 in Leptosols at 865 m a.s.l., 21.18 ± 5.88 and 56.42 ± 34.85 in Luvisols at 970 m a.s.l., and between 27.94 ± 20.77 and 68.64 ± 38.79 in Regosols at 1050 m a.s.l. (Table 2). No significant difference is noted between the values of this ratio either as a function of the depth in each soil type or at the scale of the massif (Table 3). There is a weak significant and positive correlation between the C/N ratio and SOM ($r = -0.488$, $p < 0.05$) and negative between the C/N ratio and TN ($r = -0.377$, $p < 0.05$) (Table 4).

Evolution of SOC and SOCS contents in the studied soils

SOC always presents the highest contents in the upper part of the soils, in the 0–25-cm interval. The highest content is observed in Leptosols (35.36 ± 11.39 g kg^{-1}) while the lowest is noted in Arenosols (13.54 ± 4.69 g kg^{-1}). The evolution of the SOC content is modeled on that of the SOM (Table 2). The highest total SOC (T-SOC) value is obtained in Leptosols at 865 m a.s.l. (75.89 ± 3.74 g kg^{-1}), but the lowest is obtained in Regosols at 1050 m a.s.l. (43.27 ± 8.03 g kg^{-1}), which are entirely cultivated (Table 5). In general, the T-SOC content increases from Zamai to Kossohone, then decreases up to the summit of the massif. As for the SOCS, its evolution with depth is almost reflect that of SOC content, varying between 13.67 ± 5.65 and 38.40 ± 18.01 g kg^{-1} in Arenosols at the base of the massif, 12.81 ± 0.0 and 69.64 ± 15.90 g kg^{-1} in Leptosols at 865 m a.s.l., 15.13 ± 14.88, and 60.46 ± 3.41 g kg^{-1} in Luvisols at 970 m a.s.l., and between 23.27 ± 12.56 and 53.063 ± 31.14 g kg^{-1} in Regosols at 1050 m a.s.l. (Table 5). Overall, there were no significant differences in SOC and SOCS contents both as function of depth and at the scale of the massif (Tables 3 and 5). There is a weak negative and significant correlation between SOCS and clay ($r = -0.298$,

Table 5 Soil organic carbon content and soil organic carbon stock (mean ± SD) in the study area

Site	Section	Depth cm	SOC $g \cdot kg^{-1}$	T-SOC $g \cdot kg^{-1}$	SOCS $Mg \cdot ha^{-1}$	T-SOCS $Mg \cdot ha^{-1}$
Rhumsiki (Regosols)	S1	0–25	25.05 ± 21.63a	43.27 ± 8.03	53.063 ± 31.14a	144.79 ± 24.23
	S2	25–50	6.43 ± 5.98a		28.916 ± 31.03a	
	S3	50–75	4.84 ± 1.28a		23.27 ± 12.56a	
	S4	75–100	6.95 ± 3.23a		39.55 ± 22.19 a	
Sir (Luvisols)	S1	0–25	22.23 ± 4.10a	55.45 ± 4.9	60.46 ± 3.41a	158.99 ± 13.25
	S2	25–50	7.96 ± 5.93a		20.33 ± 11.21a	
	S3	50–75	6.01 ± 5.25a		15.13 ± 14.88a	
	S4	75–100	9.63 ± 1.28a		28.13 ± 5.21a	
	S5	100–125	9.62 ± 7.93a		34.94 ± 31.54a	
Kossohone (Leptosols)	S1	0–25	35.36 ± 11.39a	75.89 ± 3.74	69.64 ± 15.90a	158.248 ± 10.52
	S2	25–50	7.63 ± 8.39a		20.68 ± 23.85a	
	S3	50–75	10.25 ± 2.32a		28.74 ± 19.77a	
	S4	75–100	6.4 ± 0.35a		13.51 ± 3.61a	
	S5	100–125	9.11 ± 0.0a		12.81 ± 0.0a	
	S6	125–150	7.14 ± 0.0a		12.85 ± 0.0a	
Zamai (Arenosols)	S1	0–25	13.54 ± 4.69a	48.90 ± 6.12	38.40 ± 18.01a	128.63 ± 5.25
	S2	25–50	11.40 ± 6.72a		35.43 ± 26.43a	
	S3	50–75	5.0 ± 5.53a		13.67 ± 5.65a	
	S4	75–100	7.10 ± 4.90a		15.88 ± 12.69a	
	S5	100–125	11.84 ± 8.78a		25.23 ± 13.49a	

SOC soil organic carbon, *T-SOC* total SOC, *SOCS* soil organic carbon stock, *T-SOCS* total SOCS, *SD* standard deviation. Numbers followed by different lowercase letters within the same column have significant differences ($p < 0{:}05$) at different depths, considering the same topographic position

$p < 0.05$) but a significant and weak positive correlation with TN ($r = 0.332$, $p < 0.05$) and the C/N ratio ($r = -0.591$, $p < 0.05$), and strong negative correlation with SOM ($r = -0.859$, $p < 0.05$) (Table 4). The T-SOCS contents is quite important. It is 128.63 ± 5.25 Mg ha^{-1} in Arenosols at the base of the massif, 158.248 ± 10.52 Mg ha^{-1} in Leptosols at Kossohone (865 m a.s.l.), 158.99 ± 13.25 Mg ha^{-1} in Luvisols at Sir (970 m a.s.l.), and drops down to 144.79 ± 24.23 Mg ha^{-1} in Regosols at Rhumsiki (1050 m a.s.l.) (Table 5), with a marginal significant difference between Zamai and Sir. There is a strong correlation between altitude and T-SOCS ($r = 0.70$) (Fig. 4).

Mineralogical and geochemical characteristics of soils

The mineralogical composition of the studied soils slightly varied along the Mount Mandara slope. The main secondary minerals are smectite, kaolinite, sepiolite, calcite, lepidocrocite, and hematite (Table 1). They are associated with quartz, plagioclase, and alkaline feldspars. Sepiolite is observed in the summit of the interfluve. Lepidocrocite on contrary is observed in the mid- and footslope. Except the Kossohone site, calcite is present in all the three other sites. Also, hematite was not detected in Sir. In the X-ray diffractions, quartz is identified by peaks at 4.25 Å and 3.34 Å, kaolinite by peaks at 7.14 Å and 3.58 Å, plagioclase at 3.18 Å, alkaline feldspar at 3.24 Å, calcite at 3.03 Å, hematite at 2.75 Å, and smectites at 9.81 Å and 4.48 Å. In the infrared spectra, smectites are detected by his peak at 1645.58 cm^{-1}, sepiolite by peak at 527.2 cm^{-1}, and quartz by peaks at 1000.34 cm^{-1}, 461.12 cm^{-1}, and 417.23 cm^{-1}. Kaolinite which the characteristic absorption band ranges between 3600 and 3700 cm^{-1} was identified at 3695.34 and 907.81 cm^{-1}. Lepidocrocite was detected at 741.02 cm.$^{-1}$

The geochemistry of the various soil samples at the scale of the whole slope is dominated by silicon. Its content oscillates between 50.05 and 73.13% (Fig. 2). Apart from silicon, only aluminum and iron are significantly expressed and have contents range respectively between 13.56 and 23.60% Al_2O_3 and 1.88 and 8.73% Fe_2O_3. Potassium contents varied between 3.35 and 7.78% K_2O. The other alkalis and alkaline-earths contents are low, almost below 2%. The other major elements contents such as TiO_2, P_2O_5, and MnO are almost below 0.4% (Fig. 2). The Si/Al ratios varied between 2.00 and 4.6. This confirms the presence of phyllosilicates and quartz minerals already noted in the mineralogical analysis. The loss on ignition is between 2.33 and 13.71%, and might characterize the destruction of SOM in the studied sample, the dehydration, and decarbonation reactions.

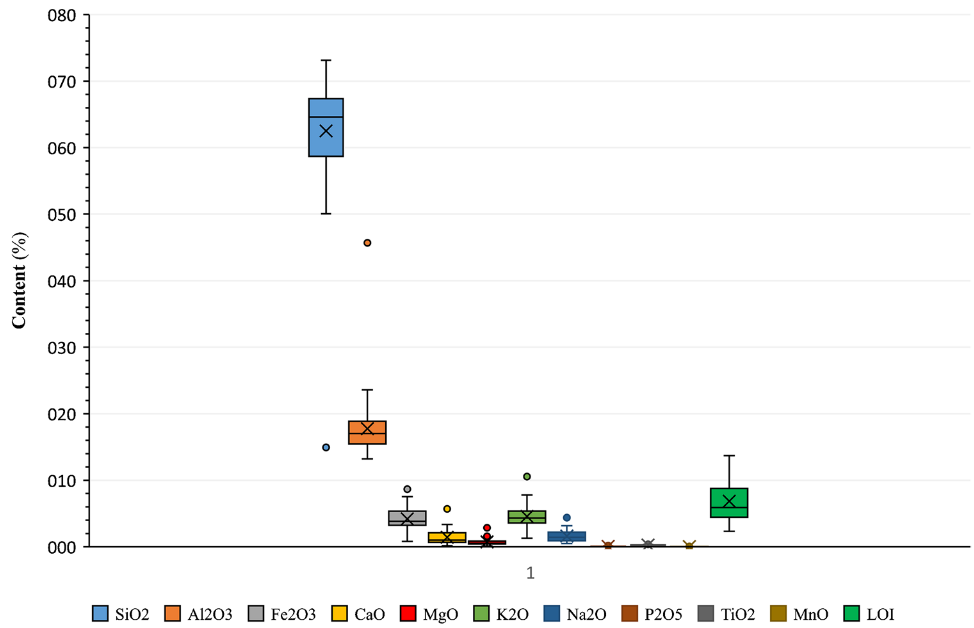

Fig. 2 Box plots showing the summary of major elements characteristics in the studied soils along the Mount Mandara slope

Discussion

Soil properties in the Mount Mandara

The studied area is composed of Arenosols, Leptosols, Luvisols, and Regosols. These soils are characterized by the sandy loam and loam sandy texture, as consequence of the large predominance of the sandy fraction which contents range between 59.03 ± 0.77% in Luvisols at Sir and 80.33 ± 12.01% in Arenosols at Zamai. The predominance of sandy texture is related to the nature of the bedrocks, constituted of sandy alluvial materials, gneiss, and granite which the mineralogy is mainly dominated by quartz mineral. pH is weakly acidic in Regosols and Luvisols (6.10 ± 0.17 to 6.90 ± 0.26) in the upper part of the Mount from 970 to 1050 m a.s.l., but weakly acidic to neutral in Arenosols and Leptosols (6.3 ± 0.00 to 7.55 ± 0.91) towards the base of the Mount from 600 to 865 m a.s.l., in line with the significant difference noted between the two groups of soil. The low soil pH value observed at high altitude might be due to the strong presence and dissociation of carboxyl functional groups below pH 7 (Boguta and Sokołowska 2020), leading thus to the acidification of the soil solution, as consequence of progressive increase in SOC content. The BD varies between 0.75 ± 0.00 and 2.33 ± 0.22 g/cm^3. High values are observed in Regosols. In Arenosols, Leptosols, and Luvisols, all values are below 1.38 g/cm^3. The low values obtained below 970 m a.s.l. are closed to those obtained by Chenchounia and Neffar (2022) in arid and semi-arid steppe rangelands of northeastern Algeria. According to Pieri (1989) and Li et al. (2006), any decrease in BD generally reflects a loosening effect of the plant against a compaction effect. High BD values at the summit of the massif might be due to their regosolic nature, in line with the significant correlation between the BD and the sand fraction. However, a low value was obtained in the topsoil (1.6 ± 1.20 g/cm^3) compared to the subsoil (2.33 ± 0.22 g/cm^3) in this Regosols. Generally, tillage which is the main management system in the upper part of the Mount Mandara is known to reduce BD in topsoils (Strudley et al. 2008; Palm et al. 2014).

N, SOC, and SOCS in the Mount Mandara

SOM is a key component of any terrestrial ecosystem, and any variation in its amount and composition has important effects on many of the processes that occur within the system (Batjes 2014). In different studied soil types, its content is high in the first 25 cm (2.33 ± 0.81 to 6.09 ± 1.96%), in line with observations already made by Plaza et al. (2018). These contents generally decrease with depth, but their evolution varies from one soil type to another (Batjes 1996; Parras-Alcántara et al. 2015; da Silva et al. 2019). A significant correlation was noted between SOM and silt. This means that a part of SOM in the studied soil is linked to the silt fraction. This might be due to the existence of expansive 2:1 clay minerals in the silt fraction (Iturri and Buschiazzo 2014; Liu et al. 2020). It is well known that expansive 2:1 clay minerals (e.g., smectite) have larger specific surface area (Yukselen-Aksoy and Kaya 2010; Tang et al. 2015; Liu et al. 2020). The TN contents are very low in the studied soils. It varies between 0.06 ± 0.02 and 0.12 ± 0.01%. Generally, the concentration of TN increases with SOM and SOC level, indicating that TN nutrition of plants greatly depends on the maintenance of SOM and SOC level (Sakin 2012; Tsozué et al. 2021). The relationship between TN and SOM is confirmed by the significant positive correlation between TN and SOM obtained from the Spearman correlation matrix between soil parameters in the studied area. Here, TN content is very low compared to that of SOM, leading thus to high C/N ratios which reach 68.64 ± 38.79 in Regosols in the upper part of the Mount Mandara, in line with the significant and positive correlation between the C/N ratio and SOM. The correlation between TN and SOC indicates that these two soil components act together along the Mount Mandara slope, contrary to observations made in the latitudinal variation of SOCS by Tsozué et al. (2021). According to Batjes and Dijkshoorn (1999), a C/N ratio above 12–14 is often considered indicative for a shortage of TN in the studied soil. The decrease in C/N ratio with depth in subsoil reflects a greater degree of breakdown and older age of the humus stored in the lower parts of the soil profile (Batjes 2014). The increase of C/N ratio thereafter until the base of each soil type might indicate the accumulation of this humus in this part of the soil profile. As for the SOCS, its evolution with is almost modeled on that of soil organic carbon content. This is confirmed by the strong negative correlation ($r = -0.859$, $p < 0.05$) between soil SOCS and soil SOM as already observed by many authors (Tsozué et al. 2019, 2021). There is a weak negative and significant correlation between SOCS and clay. This confirmed the importance of clay stabilization mechanisms on SOC in the studied soils (Parras-Alcántara et al. 2015). The T-SOCS contents is 128.63 ± 5.25 Mg ha^{-1} in Arenosols, 158.248 ± 10.52 Mg ha^{-1} in Leptosols, 158.99 ± 13.25 Mg ha^{-1} in Luvisols, and drops down to 144.79 ± 24.23 Mg ha^{-1} in Regosols. The T-SOCS values obtained here in Leptosols and Regosols are higher than those obtained by De Vos et al. (2015) and Parras-Alcántara et al. (2015) in Leptosols and Regosols (53.8 ± 18.3 to 158.0 ± 15.8 Mg ha^{-1}) in the Despeñaperros Natural Park under temperate semi-arid climate in southern Spain, in similar altitude gradient interval (607 to 1168 m a.s.l.). The high T-SOCS in the dry tropical mountainous zone where the decomposition rate is naturally low in the dry season and increases in the wet season might be due to the quality of the organic matter (OM), the soil microbial community, and particularly the soil mineralogy. It might also be due to more productive vegetation as consequence of the high precipitation in the study area (Tsozué et al. 2021). The T-SOCS obtained in Arenosols in the study area is also higher than that document by De Vos et al. (2015) in Europe (102 Mg ha^{-1}). As for Luvisols, the T-SOCS obtained in the studied area (158.99 ± 13.25 Mg ha^{-1}) is similar to that obtained under semi-arid climate in Tunisia (109.2 Mg ha^{-1}), situated in north of Africa and in south of Mediterranean Sea, but in the 0–100-cm depth (Brahim et al. 2014). Those T-SOCS values are globally below those obtained in the humid tropical mountainous zone in soils developed on volcanic rocks where T-SOCS values reached 302 Mg ha^{-1} (Tsozué et al. 2019).

Effect of soil mineralogy on SOCS

The studied soils contain several clay minerals, which include smectite, kaolinite, and sepiolite. Generally, fractions rich in kaolinite often showed less C contents and the smectite-rich fractions contain organic C within a wide (Manjaiah et al. 2010). The presence of kaolinite thus indicates the presence of low reactive clay-sized silicates which offer fewer binding site to SOC contrary to smectite which indicate the presence of high reactive clay-sized silicates (White et al. 2005; Manjaiah et al. 2010). However, both 2:1 and 1:1 clay layers contain pH-dependent charges corresponding to surface charge generated by protonation–deprotonation reactions of surface hydroxyl groups (Singh et al. 2017). Soils rich in 2:1 clay minerals, for example, smectite and sepiolite, have a greater ability to protect the C in soil than 1:1 clay minerals such as kaolinites (Six et al. 2002; Ibrahim et al. 2022), due to their higher specific surface area and cation exchange capacity (Hassink 1997; Wattel-Koekkoek et al. 2001). In addition to clay minerals, hematite and lepidocrocite are present in the studied soils. These iron oxides are reactive constituents (Singh et al. 2017). Many works show that they adsorbed more SOC in comparison to phyllosilicate clay minerals such as kaolinite and smectite (Kaiser and Guggenberger 2003; Tombácz et al. 2004; Singh et al. 2017). Clay minerals and iron oxides are good receptacle for SOC and might constitute a major asset for the accumulation and the preservation of SOC leading to thus an increase of SOCS along the Mount Mandara slope.

Effect of soil geochemistry on SOCS

Iron and aluminum are the main metal-(oxyhydr)oxides in the studied soils. Their contents range respectively between 13.56 and 23.60% Al_2O_3 and 1.88 and 8.73% Fe_2O_3. Under oxidizing conditions, these oxides play an important role in soil sorption capacity, as they usually occur as coatings on clay particles (Rieuwerts et al. 1998). It is demonstrated that the formation of oxides and oxyhydroxides of Al and Fe might play a role in the occlusion of SOC at the level of clay microstructure (Mayer et al. 2004; Reichenbach et al. 2021). When these oxides are exposed to water, their surfaces become hydroxylated, and consequently, they have variable charge (Ngole-Jeme 2019). This might increase the soil sorption capacity and subsequently the global aptitude of soil to sorb SOC. These characteristics are thus favorable to the sequestration and stabilization of SOC resulting in an increase of SOCS in the studied area (Reichenbach et al. 2021). They could be anionic, neutral, or cationic depending on the degree of protonation they undergo, which in itself is determined by the prevailing pH conditions (Ngole-Jeme 2019). They have a net positive surface charge at low pH, a net negative surface charge at high pH, and are neutral at circumneutral pH conditions (Hyun et al. 2003). These conditions are met in the study area where the pH are generally weakly acidic to neutral. The contribution of iron and aluminum oxides and even the other major oxides to the accumulation and stabilization of SOCS in the studied soils is very low (< 7%) (Fig. 3). Except SiO_2 and Fe_2O_3 whose effects on SOCS are respectively 5.92 and 6.49%, the effects of the other major oxides are less or equal to 3.60% (Fig. 3).

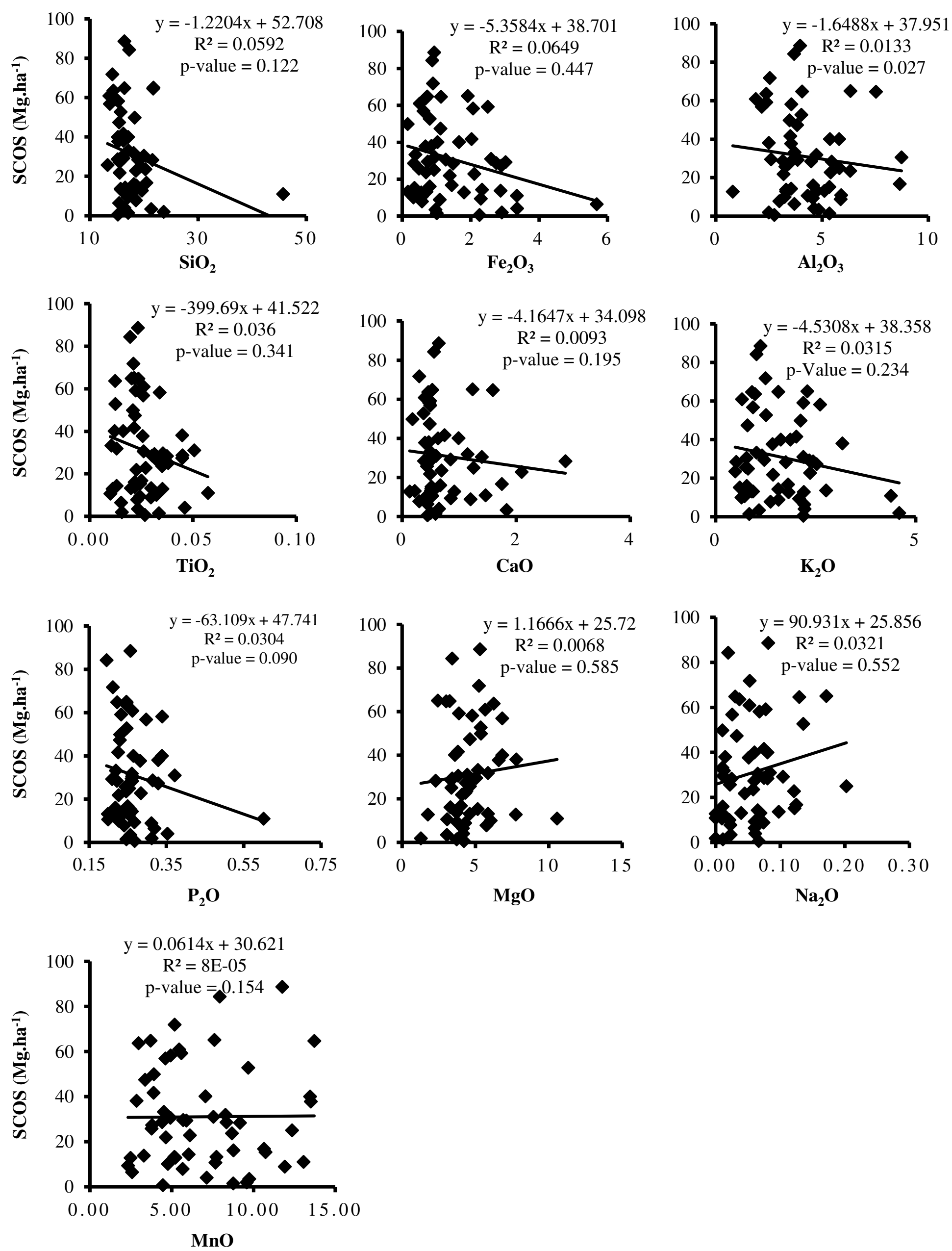

Fig. 3 Correlations between major element contents and soil organic carbon stock (SOCS)

Effect of land use and environmental factors on SOCS

Altitudinal change is very common in mountainous environments and this change influence the microclimate, which generally affect the SOC content (Parras-Alcántara et al. 2015; Chang et al. 2016; Tsozué et al. 2019). In the studied area, T-SOCS increase with altitudinal gradient from 128.63 ± 5.25 Mg ha^{-1} in Arenosols at the base of the massif to 158.99 ± 13.25 Mg ha^{-1} in Luvisols at 970 m a.s.l. Increases in elevation lead to decreases in the annual temperature as observed in the studied area, which affect microbial activity. This leads to a slow rate of SOM decomposition, which thereby affected SOCS (Trumbore et al. 1996; Garten 2004; Garten and Hanson 2006). The decrease in temperature occurs simultaneously to an increase in precipitation in the studied area. These two climate components, temperature and precipitation, are important factors affecting C sequestration in soil because both play important roles in biomass production (Singh et al. 2017). However, less microbial activity occurs in dry soils as in the Mount Mandara, and greater decomposition of SOC is observed in wetter soils, provided there is good movement of air (Chang et al. 2016). Altitudinal gradient thus affects the climatic characteristics of the studied area which in turn affect the biomass production and consequently the T-SOCS. This is confirmed by the significant correlation between altitudinal gradient and T-SOCS ($r = 0.70$), with altitude contributing to the accumulation of SOC for 49.68% (Fig. 4). Moreover, since the climatic characteristics of Zamai and Sir are not contrasting enough, it can be assumed that the climatic characteristics in response to changes in altitude are not the only principal factor of interest at these sites, the soil characteristics might be another main factor of greater importance affecting the C sequestration.

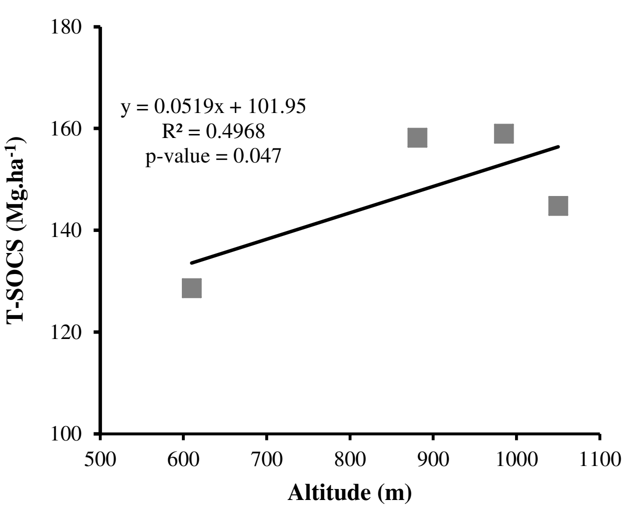

Fig. 4 Plots of the total soil organic carbon stock (T-SOCS) versus altitudinal gradient in Mount Mandara

Among soil characteristics which affect C sequestration, soil texture plays a central role in C sequestration (Singh et al. 2017). This is confirmed along the altitudinal gradient by the significant and positive correlation between silt fraction and SOM ($r = 0.406$, $p < 0.05$). It is well known that mineralization of C is highly expressed in coarse-textured soils compared to fine-textured soils (Hassink 1992; Singh et al. 2017). These results could be due to the greater ability of fine-textured soils to physically protect the SOC from microbial attack (Hassink 1995; Singh et al. 2017). It also plays an important role in C stabilization in the lower soil depths under all land uses (Fontaine et al. 2007; Albaladejo et al. 2013; Singh et al. 2017). In fact, SOC is not easily accessible to soil microbes in clay dominant soils compared with sandy soils. This is due to the chemical adsorption of C on clay minerals surfaces and also its physical occlusion within soil microaggregates (Sissoko and Kpomblekou-A 2010; Singh et al. 2017).

Under Regosols in Rhumsiki at 1050 m a.s.l., there is a decrease in T-SOCS value respectively reaching 144.79 ± 24.23 Mg ha^{-1}. All this upper part of the massif is intensely cultivated. Land use management is known to have a strong influence on SOC (Muñoz-Rojas et al. 2012; Schlüter et al. 2022). It can affect C mineralization through changes in thermal properties, water retention and consumption, and through biomass production (Schlüter et al. 2022). Conversion of natural vegetation to cropland as observed in Regosols in the upper part of the Mount Mandara is assumed to cause a decrease of SOM content (Degryze et al. 2004; Gerzabek et al. 2005). In addition, ploughing is the main management system in the upper part of the Mount Mandara. Ploughing was found to be the management that resulted in the lowest SOM levels worldwide due to the lack of vegetation and increased C emissions as a consequence of repeated ploughing (Lozano-Garcia and Parras-Alcantara 2014a; Carr et al. 2015; de Moraes et al. 2015; Parras-Alcantara et al. 2016; Tsozué et al. 2019). It might also be due to a decrease in the amount of OM returned to the soil and more rapid SOM decomposition, as a consequence of the intensification of ploughing (Dalal et al. 1991; Nweke and Nnabude 2014).

Conclusion

The present work studied the properties of a soil sequence from a dry tropical zone in Mount Mandara, Cameroon. The study area is composed of Arenosols, Leptosols, Luvisols, and Regosols. They are sandy loam to loam sandy. Soil pH is weakly acidic in Regosols and Luvisols, but weakly acidic to neutral in Arenosols and Leptosols. The C/N ratios are very high, ranging between 12.09 ± 9.34 and 68.64 ± 38.79. The T-SOCS contents are quite substantial.

It is 128.63 ± 5.25 Mg ha^{-1} in Arenosols at the base of the massif, 158.248 ± 10.52 Mg ha^{-1} in Leptosols at Kossohone (865 m a.s.l.), 158.99 ± 13.25 Mg ha^{-1} in Luvisols at Sir (970 m a.s.l.), and drops down to 144.79 ± 24.23 Mg ha^{-1} in Regosols at Rhumsiki (1050 m a.s.l.). There is a strong correlation between altitude and T-SOCS (r = 0.70). The main secondary minerals are clay minerals (smectite, kaolinite, sepiolite) and iron oxides (lepidocrocite, hematite). Clay minerals and iron oxides are good receptacle for SOC and might constitute a major asset for the accumulation and the preservation of SOC leading to thus an increase of SOCS along the Mount Mandara slope. Altitudinal gradient affects the climatic characteristics of the studied area which in turn affect the biomass production and consequently the T-SOCS. This is confirmed by the significant correlation between altitudinal gradient and T-SOCS (r = 0.70), with altitude contributing to the accumulation of SOC for 49.68%. Among the soil factors, texture plays a central role in C sequestration, confirmed in the studied area by the significant and positive correlation between silt fraction and SOM. Under Regosols in Rhumsiki at 1050 m a.s.l., there is a decrease in T-SOCS value (144.79 ± 24.23 Mg ha^{-1}) as a consequence of a decrease in the amount of OM returned to the soil and more rapid SOM decomposition due to ploughing in the upper part of the Mount Mandara. Therefore, cultivation has a negative consequence on SOCS, and if this continues at the other sites, it will increase greenhouse gas emissions contributing to global climate change. This research provides a preliminary assessment for SOCS at Mount Mandara. It suggests that altitudinal gradient, land use, and soil characteristics should be included in SOCS models and estimations at local and regional scales.

Declarations

Competing interests The authors declare no competing interests.

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