Research Article

Soil Organic Carbon Distribution in a Humid Tropical Plain of Cameroon: Interrelationships with Soil Properties

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Soil organic carbon (SOC) determination is very important in the assessment of agronomic potential of a soil. The objective of this study was to determine SOC contents and stock distribution with depth in relation to selected soil properties. Five types of soils, namely, Mollic Endoaquents, Oxyaquic Paleudalfs, Oxyaquic Udifluvents, and Mollic Udifluvents from a humid tropical plain and Typic Eutrudepts from an adjacent foot slope, were studied. The soils have all developed from fluvial sediments. Morphological and physicochemical characteristics of the soils were obtained using standard methods. Soil texture varied across the different sites and within soil profiles with textural classes of genetic horizons ranging from sandy loam to heavy clay. The soils are generally young soils under development as indicated by their high silt/clay ratios which ranged between 0.23 and 2.45. All the soils were generally acidic with pH-H₂O values ranging from 4.5 to 6.2. Exchangeable H⁺ and Al³⁺ ranged from 0.5 to 2.3 and 0.2 to 3.3 cmol_ckg⁻¹, respectively. SOC contents are generally higher in surface horizons and decrease with depth. In general, SOC correlated significantly with bulk density (BD) ($r = -0.648$, $p < 0.01$), water holding capacity ($r = 0.589$, $p < 0.01$), exchangeable Al³⁺ ($r = 0.707$, $p < 0.01$), and exchangeable H⁺ ($r = 0.456$, $p < 0.05$). The correlation between SOC and exchangeable Al³⁺ was strongest in the Mollic Endoaquents ($r = 0.931$, $p < 0.01$). SOC contents correlated significantly with Munsell soil color attributes, explaining between 40 and 57% of SOC variation. Total SOC stocks at a depth of 100 cm varied between 260.1 and 363.5 t·ha⁻¹, and the variation in SOC stocks across a profile appears to be controlled by genetic horizon depth, while land use type influences SOC stock variations across genetic surface horizons.

1. Introduction

Soil organic carbon (SOC) is a major indicator of soil quality and productivity and also a key driver of most soil processes and functions. It influences nutrient retention, micro-aggregate formation and soil structure, water retention/storage and infiltration, microbial activity, and pH buffering [1]. SOC is also fundamental to the role played by soil in providing ecosystem services such as regulating services (e.g., carbon sequestration, climate and greenhouse gas regulations), provisioning services (e.g., food, water, fuel, fiber), cultural services (e.g., ecotourism and recreation), and supporting services such as nutrient cycling [2]. Soils play a very important role in climate change adaptation and mitigation by regulating the global carbon cycle and have

been identified as the largest pool of terrestrial organic carbon in the biosphere, with a carbon storage capacity surpassing that contained in plants and the atmosphere combined. According to Batjes [3], the top meter of the world's soils stores about 2200 Pg of C, with about two-thirds (66%) of it stored as soil organic matter. This amount of C is almost thrice that found in the atmosphere. Under natural conditions, the storage of OC in soil is controlled by the balance of C inputs from plant production and outputs through decomposition [4]. However, anthropogenic disturbances, mainly agricultural activities and forest clearance for fuel and timber, greatly contribute to the emission of large quantities of the stored carbon into the atmosphere [5]. On the other hand, improved cultivation practices such as addition of biochar [6], incorporation of crop residues [7, 8],

and conservation tillage [9–11] can significantly increase soil carbon sequestration. Apart from the influence of human activities, many biophysical factors influence SOC storage and distribution patterns (Table 1).

In general, SOC exists in three distinct fractions, namely, passive, intermediate, and active [35]. The active and intermediate fractions are found in the top 1 meter of soil and are often collectively known as labile SOC [36]. The SOC found in this fraction is biologically available and more susceptible to changes at the soil surface [37]. The labile fraction is the smallest pool of SOC and is estimated at 250–350 Pg [36]. This fraction originates from fresh organic residues and living organisms, and its turnover ranges from days to few decades. On the other hand, the passive or more stable fraction of SOC (chemically stable in the form of humus) is often found concentrated below 1 m and is not readily accessible to microorganisms for decomposition [36].

This stable fraction includes fine-sized organic matter that is physically protected (e.g., clay mineral-protected or contained within soil aggregates) or chemically persistent (humus) in soil. The turnover period of this fraction ranges from centuries to millennia [35]. The subsoil contains the largest pool of SOC and is the least likely to be influenced by changes in management practice and different environmental conditions than top soil [50].

Monitoring and quantifying SOC contents and stocks across landscape units and over time are crucial for the assessment of spatial and temporal variations in SOC pools and fluxes. More specifically, SOC stock estimates are important for global climate change predictions [51]. This is also very useful in understanding changes in soil fertility/productivity levels, soil deterioration/amelioration, water quality, environmental degradation, etc., hence necessitating the adoption of sustainable soil management practices for enhancing SOC storage and increased ecosystem services. However, data availability for assessing environmental changes is a major constraint, especially in most developing countries of tropical environments. This is mainly associated with a lack of adequate research facilities and too much generalization about tropical soils [52], confirming the assertion that much is still unknown about the soil resources in tropical environments compared to those in temperate regions [53]. Inventories of SOC stocks at local scales are useful and can readily be used to assist most countries in achieving the goals of the United Nations Framework Convention on Climate Change (UNFCCC).

The nonexistence of a national SOC database for Cameroon [54] could limit its ability to access funds from the Clean Development Mechanism (CDM) as proposed under article 12 of the Kyoto Protocol of the UNFCCC. The CDM allows developing countries to establish emission reduction (or emission removal) projects that can earn certified emission reductions (CERs), each equivalent to 1 t of CO₂, that can then be traded and sold, and used by industrialized countries to meet some of their emission

reduction targets under the Kyoto Protocol. Thus, estimation of SOC stocks at local scales constitutes baselines for large-scale inventories that would significantly improve the accuracy of national SOC databases. In Cameroon, a dearth of information exists on the C sequestration potential of plain soils. Like in most areas worldwide, plains in Cameroon constitute areas of intensive agricultural production that would significantly impact on the soil carbon storage potential. The objective of this study was to determine SOC contents and their distribution with depth in relation to selected soil physicochemical and morphological properties in five dominant soil types within the Mbo plain.

2. Materials and Methods

2.1. Location and Characteristics of the Study Area. The Mbo plain is located within longitudes 9° 45' E and 10° 07' E and latitudes 5° 07' N and 5° 25' N. The plain has an average altitude of 720 m above sea level and extends over a surface area of about 30,000 ha. It lies between the Bamiléké plateau (1400–2000 m) in the north and east, the dorsal part of the Ekomané Mountain (about 1800 m) in the west, and the Manengouba volcanic massif (2400 m) in the south (Figure 1). Geomorphologically, the Mbo plain is an ancient lake depression on a granite-gneissic base, resulting from deposits of the first volcanic eruptions of Mount Manengouba [55]. A lava flow of this eruption blocked the plain in the north, favoring the creation of a lake. This was followed by the draining of this lake by the Nkam River, causing its disappearance [55]. The northern and eastern parts of the Mbo plain are dominated by the Bamiléké plateau comprised of granite and gneiss, with very steep escarpments. The southern part of the plain is dominated by basalt lava flow from Mount Manengouba which descends progressively towards the plain [56]. Between these borders is a vast depression occupied by swamps containing a dense hydrographic network of many streams and the Nkam River.

The vegetation distribution in the Mbo plain is conditioned by hydrologic and edaphic factors [57]. The remaining semideciduous forests are mostly found at the peripheries of the plain, on the flanks of the mountains which dominate it. It is on glacia that most of the forest in the Mbo plain has been destroyed for the establishment of farmlands and plantations. On relatively nutrient-poor zones, *Hyparrhenia* sp. and some teak (*Tectona grandis*) plantations abound. On well-drained areas gallery forests having considerably reduced in size following clearing for the establishment of farmlands and settlement. Vast areas within the Mbo plain are either permanently or seasonally flooded, especially in depressions. These depressions are covered by fern (*Pteridium aquilinum*), raffia (*Raphia farinifera*), oil palm (*Elaeis guineensis*), and screw pine (*Pandanus* sp.). The dominant farming system in the Mbo plain consists of intensive cultivation of both annual and perennial crops for both subsistence and commercial purposes. The dominant crops cultivated include cassava (*Manihot*

TABLE 1: Major biophysical factors influencing SOC storage and distribution patterns.

Biophysical factors	References
Vegetation type	[12]; [13]; [14]
Soil biodiversity	[15]
Soil texture	[13]; [16]; [17]; [18]
Soil pH	[19]; [20]; [21]
Soil microaggregates	[22]; [23]; [24]
Temperature (sensitivity of SOC decomposition)	[25]
Climate	[12]; [17]; [26]; [27]; [28]
Precipitation	[29]
Leaching of carbonates	[30]; [31]
Mineralogy	[21]; [32]; [33]; [34]
Soil erosion	[1]; [38]; [39]; [40]
Topography	[12]; [40]; [41]; [42]
Soil depth	[3]; [26]; [43]; [44]
Soil type (reference group)	[12]; [27]
Vegetation fires	[45]; [46]; [47]
Accelerated SOM decomposition caused by global warming	[31]; [48]; [49]

esculenta), cocoyam (*Colocasia esculenta*), sweet potatoes (*Ipomoea batatas*), maize (*Zea mays*), plantain and banana (*Musa* spp.), cocoa (*Theobroma cacao*), coffee (*Coffea arabica*), ginger (*Zingiber officinale*), and a wide variety of vegetables and fruits. Vast untapped arable lands in the Santchou and Mbomi areas of this plain have high potential for developing large-scale rice production.

Following the Köppen–Geiger classification, the climate in the Mbo plain is described as Am (tropical monsoon climate), occasionally known as a tropical wet climate or tropical monsoon or trade-wind littoral climate. Mean monthly temperatures are generally above 18°C in every month of the year, with two distinct seasons prevailing—the rainy (wet) season which runs from March to October and the dry season which runs from November to February (Figure 2). The difference in rainfall between the driest and wettest month is about 420 mm. Mean annual temperature is about 23.6°C with an annual temperature variation of 2.7°C, and mean annual rainfall is about 2500 mm. The hottest month is March, with a mean monthly temperature of 24.8°C, while the coldest month is August with a mean monthly temperature of 22.1°C. Average relative humidity is high throughout the year (>70%) and highest in the months of July and August (>90%). Winds are relatively high during the months of December and January.

2.2. Field Methods and Laboratory Analyses. A survey was conducted on five soil profiles representing the major land use/cover types and geomorphological features (Table 2, Figure 3). Major environmental characteristics, physiography, and soil profiles were described in the field following standard procedures [60]. Bulk soil samples from each genetic horizon were collected and stored in polythene bags. In addition, undisturbed core samples for bulk density determination were collected from each genetic horizon using stainless steel Kopecky rings.

Soil samples from the field were air-dried and crushed using a porcelain mortar and pestle and then sieved

through a 2 mm sieve to remove coarse fragments, roots, and plant residues. The <2 mm soil fraction was used for the various physicochemical analyses. Soil pH was measured in distilled deionized water, 1 M KCl, and 0.01 M CaCl₂ in a 1:2.5 soil-to-solution ratio as described by Kome et al. [61]. Soil electrical conductivity was determined in a 1:5 soil-to-solution ratio using distilled deionized water and a conductivity meter as described by Kome et al. [61]. Soil organic carbon was determined using the Walkley–Black method [62]. Bulk density was calculated as the oven dry (105°C) mass of undisturbed core sample per volume. Particle size analysis was conducted using the hydrometer method as described by Bouyoucos [63]. Effective dispersal of the soil samples was achieved using a 2.5 N solution of sodium hexametaphosphate. The relative proportions of sand, silt, and clay were used to calculate the sand/silt and silt/clay ratios, while the clay ratio was calculated using the formula

$$\text{clay ratio} = \frac{\% \text{ clay}}{(\% \text{ sand} + \% \text{ silt})}. \quad (1)$$

Water holding capacity (WHC) was determined following procedures described by Pansu and Gautheyrou [64].

2.3. Estimation of SOC Stocks. Soil organic carbon stocks per horizon were estimated using the genetic horizon equation [65] as follows:

$$\begin{aligned} \text{SOC stock}(\text{t ha}^{-1}) &= \left(\frac{\text{mg SOC}}{\text{g soil}} \right) \times \left(\frac{\text{g soil}}{\text{cm}^3 \text{ soil}} \right) \\ &\times \left(\frac{\text{cm}}{1} \right) \times \left(\frac{\text{t}}{10^9 \text{ mg}} \right) \times \left(\frac{10^8 \text{ cm}^2}{\text{ha}} \right) \\ &\times (1 - \delta_{2\text{mm}} \%). \end{aligned} \quad (2)$$

Total SOC stock per soil profile to a depth of 1 m was estimated by summing the SOC stocks per genetic horizon:

FIGURE 1: Location of the Mbo plain in Cameroon. (a) DEM (b) and topographic (c) maps of the Mbo plain showing location of the study sites.

$$\begin{aligned}
 \text{total SOC stock (t ha}^{-1}\text{)} &= \sum_i^n \left(\frac{\text{mg SOC}}{\text{g soil}} \right) \times \left(\frac{\text{g soil}}{\text{cm}^3 \text{ soil}} \right) \\
 &\times \left(\frac{\text{cm}}{1} \right) \times \left(\frac{\text{t}}{10^9 \text{ mg}} \right) \\
 &\times \left(\frac{10^8 \text{ cm}^2}{\text{ha}} \right) \times (1 - \delta_{2\text{mm}} \%),
 \end{aligned}
 \tag{3}$$

where mg SOC g soil⁻¹ is SOC concentration, g soil cm soil⁻³ is bulk density, cm is soil horizon thickness, and $\delta_{2\text{mm}}\%$ is fractional percentage (%) of >2 mm coarse fragments by volume.

Genetic soil horizons of entire soil profiles were used to estimate SOC stocks rather than soil control sections because the latter has been proven to overestimate SOC stocks [44].

2.4. Statistical Analyses. The relationships between soil properties were established using correlation and regression analyses. Statistical analyses were performed using Microsoft Excel 2007 and SPSS (Version 23) for Windows.

FIGURE 2: Climatic diagram of study area.

3. Results and Discussion

3.1. Morphological Properties

3.1.1. Soil Color. Morphological characteristics of the various soils (Table 3) show a wide range of colors in terms of value and chroma. Profile 1, with a cambic (Bw) horizon, has a moist hue of 10YR throughout the profile except in the Bw₂ horizon where the moist hue is 2.5YR. The Bw₂ horizon also has a moist hue of 5Y as inclusions. From the Ap to the Bw₁ horizon, the colors change from dark brown through brown to yellowish brown. The heterogeneity in terms of color observed in the Bw₂ horizon (grayish red, pale orange, dull yellow orange, and bright yellowish brown) is associated with the influence of chemical weathering on the parent material, while that of the surface horizon is mainly due to organic matter. The Bw₃ and Cr horizons are dominated by a bright yellowish brown color. In the dry state, profile 1 has hues of 5YR, 7.5YR, and 10YR from surface to subsurface horizons, with generally higher values and lower chroma compared to the corresponding horizon colors in moist state.

All the other profiles located within the plain (profiles 2, 3, 4, and 5) have a moist hue of 7.5YR and a dry hue of 10YR. However, the colors in the various horizons were greatly influenced either by organic matter accumulation or mottling. The mottles were observed to have a very wide range of colors within a particular soil profile. Profile 2, classified as a Humic Gleysol, has an abrupt moist color change from the surface Ah horizon (black) to subsurface horizons (brownish gray (E) and bright brown (Bt)), in conformity with soils of this reference soil group. Compared to the moist colors of profile 2, the color values in the dry state are generally higher. The gleyic color patterns of profile 2 are mainly due to oxidation-reducing conditions resulting from the fluctuations of the water table, mostly in subsurface layers. In the E horizon of profile 2, soil color changes instantaneously from gray to reddish brown when exposed to air, giving rise to oximorphic colors. Oximorphic conditions in profile 2 are observed in the dry season during which the water table drops and surface soil cracks, giving way for oxygen to freely circulate in parts of the profile. Profile 3, classified as a Gleyic Luvisol, shows a

uniform color change from brown in the A horizon to dull brown and bright brown in subsurface horizons. The surface color appears to be influenced by organic matter from the forest vegetation, while the subsurface horizon colors show a gleyic pattern in the Btg and BCtg horizons; this as a result of water movements within this part of the soil profile. In profile 4, color is less influenced by gleyic conditions. Instead, the color pattern appears to be influenced by the presence of buried horizons. The moist color values did not follow any regular pattern from surface to subsurface horizons. Profile 5 surface (Ap) horizon has a brownish black moist color apparently associated with the accumulation of soil organic matter. The AB horizon has a bright brown moist color, while the BCt horizon has a brown color (moist). The underlying Cg horizons show gleyic color patterns with color values generally higher in the dry state compared to corresponding horizons in the moist state.

3.1.2. Soil Structure and Consistence. Profile 1 has granular structure in the Ap horizon and subangular blocky in subsurface horizons. The granular structure of surface horizons is associated with bioturbation by soil fauna and plant roots, especially where biological activity is high. Some parts of the Bw₃ horizon of profile 1 show a blocky structure, associated with its expanding clay contents. The consistence (moist) varies from friable in the A and AB horizons to firm in the cambic (Bw) horizons and then to weak in Cr horizons where the soil is very friable. Consistence (wet) is very sticky and very plastic in horizons with blocky structures, and nonsticky and nonplastic in horizons with granular structures. Occurrence of krotovinas in the first five horizons of this profile and their dominance in the Bw₃ horizon indicate transportation and accumulation of material (mainly organic matter) from one horizon to another. Weathered quartz veins traverse from Bw₂ to Cr₂ horizons in a NW to SE direction, with pressure faces of roots visible throughout the profile. Profile 2 structure is granular in the Ah horizon; blocky in the E, Bt, and Btg horizons; and granular in the C horizons. The consistence ranges from hard to very hard (dry) and friable to firm (moist). Field observations reveal that the soil surface of this profile cracks during the dry season forming medium (1–2 cm) to wide (3–5 cm) cracks, giving rise to a very hard structure, a kind similar to that of Vertisols which makes tillage with common tools such as hoes difficult. This cracking phenomenon is apparently associated with the presence of swelling-type clay minerals formed through neosynthesis processes, favored by the prevailing environmental conditions (in a depositional basin environment). Profile 3 has structure and consistence in the moist and dry states similar to those of profile 2. However, the consistence (wet) of profile 3, mostly very sticky and very plastic, is associated with the high contents of its swelling clays. Structure and consistence in profiles 4 and 5 do not show any regular pattern from surface to subsurface horizons. Here texture is more determinant as sandy horizons (mostly BC and C) generally have a granular, weak, or a subangular blocky structure that easily fragments in the moist

TABLE 2: Description of study sites and classification of representative soil profiles.

Site characteristics	Bamia series	Santchou series	Lelem series	Ntengie series	Bamengwi series
Geographical coordinates	Lat: 05° 17' 51.5" N, Long: 09° 55' 00.9" E	Lat: 05° 16' 23.5" N, Long: 09° 58' 26.0" E	Lat: 05° 12' 02.5" N, Long: 09° 59' 54.0" E	Lat: 05° 21' 59.1" N, Long: 10° 00' 27.9" E	Lat: 05° 15' 03.09" N, Long: 10° 05' 22.77" E
Land use/ vegetation	Intensely cultivated farmland dominated by mixed crops, including cocoa, cocoyam, plantain, oil palm, and maize	Uncultivated grassland	Uncultivated patch (relics) of gallery forest, having wild palms, lianas, mixed trees, shrubs, and grass	Cultivated farmland with mixed crops, including maize, sweet potato, cowpea, okra, huckleberry, and pepper	Cultivated farmland with mixed perennial crops, including oil palm, cocoa, coffee, banana, and plantain
Soil management -Tillage type -Fertilization	Minimum tillage Occasional fertilization	None None	None None	Conventional tillage Regular fertilization	Minimum tillage Occasional fertilization
Physiography	Foot slope, 2–5 % (strongly sloping), medium-gradient hill on straight concave slope, good external drainage and moderate internal drainage. Piedmont of the escarpment which limits the plain	Plain, 0 % (flat terrain), poor external drainage and moderate internal drainage	Plain, almost flat terrain (0–1%), good external drainage and moderate internal drainage	Plain, flat terrain (0–1%), good external and internal drainage	Plain, flat terrain (0–1%), good external drainage and moderate internal drainage
Relief/elevation	Foot slope, 751 m asl	Plain, 711 m asl	Plain, 716 m asl	Plain, 723 m asl	Plain, 740 m asl
Erosion	Signs of slight geologic erosion with presence of gentle rills on soil surface	No signs of erosion	No signs of erosion	No signs of erosion	No signs of erosion
Parent material	Granite	Alluvial sediments (for subsurface soil) and organic matter (for surface layer)	Alluvial sediments	Alluvial sediments	Alluvial sediments
Soil moisture regime	Udic	Udic/aquic	Udic/aquic	Udic/aquic	Udic/aquic
Soil temperature regime	Isohyperthermic	Isohyperthermic	Isohyperthermic	Isohyperthermic	Isohyperthermic
Soil classification: IUSS working group WRB, [58]	Eutric Cambisol	Abruptic Gleysol (Humic)	Endoclayic Luvisol (Gleyic)	Humi-Dystric Fluvisol	Gleyi-Humic Fluvisol (Eutric)
Soil classification: Soil survey staff [59]	Typic Eutrudepts	Mollic Endoaquents	Oxyaquic Paleudalfs	Oxyaquic Udifluvents	Mollic Udifluvents

state. The consistence of the Cg horizons of profiles 4 and 5 was either loose or friable (moist) and nonplastic (wet).

3.2. Physical Properties

3.2.1. Bulk Density. Bulk density (BD) distribution within the different profiles shows erratic functions (Figure 4), associated with the differences in the nature and composition of the sedimentary parent materials and the variation in SOC contents. A negative and significant correlation exists between BD and SOC ($r = -0.648$, $p < 0.01$), indicating that BD increases with

decrease in SOC contents. The highest BDs ($>1.30 \text{ Mg m}^{-3}$) occur in subsurface horizons of profiles 1 (Bw horizon), profile 2 (Btg and C horizons), and profile 5 (BCt and Cg horizons), while the lowest BD (0.66 Mg m^{-3}) occurs in the surface (Ah) horizon of profile 2 resulting from its high organic matter contents. All the other profiles have surface bulk density of about 1 Mg m^{-3} .

3.2.2. Particle Size Distribution (Texture). Soil texture varies across the different sites and within some profiles (Table 4, Figure 4). Profile 1 has textures ranging from clayey to loam. Profile 2 with textures ranging from heavy clay to loam

FIGURE 3: Landscapes and vegetation of different sampling sites and their corresponding soil profiles.

indicates that it originates from different parent materials. The surface Ah horizon has a loamy texture with a high silt/clay ratio of 1.23, while the underlying 2Bt/E horizon has an abrupt texture of heavy clay with a very low silt/clay ratio of 0.23 indicating that it has formed from a more advanced weathered material [66] compared to the Ah horizon, apparently dominantly formed from the accumulation of OM originating from the prevailing grassland vegetation. The high sand/silt ratios and very high sand contents (>46%) at >90 cm depths are indicative of differential sedimentation following Stokes' law. Profile 3 with clayey textural class throughout the profile is in agreement with the advanced weathering stage of the profile as indicated by the low silt/clay ratio (≤ 0.76) corroborated by the development of argillic (Bt) horizons. The textures in profile 4 range from clay loam in the surface horizon to sandy clay loam in the AB, Cg, and 2AB horizons, and clay loam in the 2Btg and 2BC horizons. Stratigraphic breaks indicative of different provenance of the parent materials are indicated by sand contents, sand/silt ratios, and BD. Textures in profile 5 vary from loam through sandy loam to clay loam.

This profile is the one developed from the most varied parent material as indicated by erratic depth functions of sand, sand/silt ratios, and silt/clay ratios. The very high silt/clay ratios (>1.4) in all (except the BCt) horizons of this soil indicate that the deposited materials in the different horizons are of recent age with a low degree of weathering. There was a significant and negative correlation between sand and clay content ($r = -0.855$, $p < 0.01$) and also between sand and clay ratio ($r = -0.784$, $p < 0.01$), confirming the classical relationship existing between sand and clay. The sand/silt ratio had a similar trend to sand content with a strong and significant correlation observed between them ($r = 0.855$, $p < 0.01$). This shows that the sand/silt ratio can be used as an index in qualifying weathering trends in these soils, whereby high sand/silt ratios indicate low weathering intensities (less developed soils), while low sand/silt ratios indicate materials

with high weathering intensities (more developed soils) [67]. On the other hand, the silt/clay ratio gives an indication of the degree of weathering of parent materials [66–68], whereby soils with silt/clay ratios < 0.15 are reported to have developed from highly weathered parent materials, while those with ratios > 0.15 are reported to have developed from young parent materials with low degree of weathering [67]. Silt/clay ratios in the soils studied ranged between 0.23 and 2.45 for all horizons, indicating that they have developed from parent materials still at an initial weathering stage. However, the sharp differences in silt/clay ratio observed between different horizons of a particular soil profile are indicative of differences in the provenance and nature (composition) of the parent materials.

3.3. Chemical Characteristics

3.3.1. Soil Acidity and Electrical Conductivity. All the soils studied were generally acidic and have a net negative charge on the soil exchange complex. The trend in pH values is $\text{pH-H}_2\text{O} > \text{pH-CaCl}_2 > \text{pH-KCl}$ (Table 5). Profiles 2 and 3 are the most acidic with $\text{pH-H}_2\text{O}$ values ranging between 4.5 and 5.0, followed by profiles 1 and 4 with $\text{pH-H}_2\text{O}$ values of 5.2 to 5.8, and lastly by profile 5 with $\text{pH-H}_2\text{O}$ values 5.7 and 6.4. Profiles 1 and 2 do not exhibit any depth functions. However, in profiles 3, 4, and 5, pH values generally increase from surface to subsurface horizons. Exchangeable Al^{3+} and H^+ concentrations are highest in profile 2 followed by profile 3. Profile 2, with the humic Ah horizon, is strongly acidic with a $\text{pH-H}_2\text{O}$ value of 4.8 and exchangeable Al^{3+} of 3.3 cmol.kg^{-1} , consistent with the high solubility of Al^{3+} at low pH values.

The electrical conductivity of all the soils is very low ($< 0.05 \text{ dSm}^{-1}$), indicating that these soils are nonsaline. The highest EC value was observed in surface horizons of profile 4, apparently associated with addition of salts from fertilizers inputs.

TABLE 3: Morphological characteristics of the soils.

Horizon	Depth (cm)	Color		Structure	Consistence			Voids	Roots and biological features	Nodules/ concretions	Boundary characteristics
		Moist	Dry		Dry	Moist	Wet				
Profile 1. Bamia series											
Ap	0–10	10YR 3/3	5YR 5/2	GR	SHA	FRF	VST and VPL	Few F and M	Common F, M, C, E, and T	VF quartz grains	C and S
AB	10–24	10YR 4/6	7.5YR 6/6	SB	HA	FRF	VST and VPL	Few F and M	Few F and M, E, and T	VF quartz grains	D and S
Bw ₁	24–42	10YR 5/6	7.5YR 6/4	SB	HA	FI	VST and VPL	Few M	Few M and C, T	F quartz grains	D and S
Bw ₂	42–72/ 90	2.5YR 5/2 (Matrix) 5Y 8/3 (inclusions) 10YR 6/8 (Inclusions) 10YR 6/4 (inclusions)	10YR 7/3 (Matrix) 10YR 7/6 (inclusions) 10YR 7/2 (inclusions)	SB	HA	FI	ST and PL	Few C	Very few C, T	M quartz grains	D and W
Bw ₃	72/ 90–102	10YR 6/8	7.5YR 7/2	SB → GR, BL in places	HA	FI	SST and SPL	Few C	Very few C	M quartz grains	D and W
Cr ₁	102–157	10YR 6/8	10YR 8/3	SB → GR	VHA	WE → FR	NST and NPL	Very few C	Very few M	Common	D and S
Cr ₂	157–215	10YR 6/8	10YR 8/3	SB → GR	VHA	WE → FR	NST and NPL	Very few C	Very few F	Common	D and S
Profile 2. Santchou series											
Ah	0–12	7.5YR 2/1	10YR 2/3	GR	HA	FR	SST and NPL	Many F and M	Common F, M, C, E and T	N	A
2Bt/E	12–38	7.5YR 6/1 (E) 7.5YR 5/6 (Bt)	10YR 6/3 (E) 10YR 7/6 (Bt)	BL	VHA	FI	VST and VPL	Few C	Very few C, T	VF quartz grains	C and S
2E/Bt	38–58	7.5YR 5/6 (matrix) 7.5YR 6/1 (mottles)	10YR 7/3 (matrix) 10YR 3/2 (mottles)	BL	VHA	FI	VST and VPL	Few C	Very few F	VF quartz grains	D and S
2Btg2	58–90	7.5YR 5/6 (matrix) 7.5YR 6/2 (mottles)	10YR 5/6 (matrix) 10YR 6/3 (mottles)	BL	VHA	FI	VST and VPL	N	Very few F	N	D and S
2Btg3	90–115	7.5YR 5/6 (matrix) 7.5YR 6/2 (mottles)	10YR 7/2 (matrix) 10YR 7/6 (mottles)	BL	VHA	FI	VST and VPL	N	N	N	D and S
2C1	115–167	7.5YR 5/8 (matrix) 7.5YR 4/3 (mottles)	10YR 7/2 (matrix) 10YR 7/6 (mottles)	GR	HA	WE → FR	SST and SPL	N	N	N	D and S
2C2	167–205	7.5YR 5/8 (matrix) 7.5YR 6/2 (mottles)	10YR 7/3 (matrix) 10YR 7/6 (mottles)	GR	HA	WE → FR	SST and SPL	N	N	N	D and S

TABLE 3: Continued.

Horizon	Depth (cm)	Color		Structure	Consistence			Voids	Roots and biological features	Nodules/ concretions	Boundary characteristics
		Moist	Dry		Dry	Moist	Wet				
Profile 3. Lelem series											
A	0–18	7.5YR 4/4	10YR 5/4	SB → GR	HA	FR	ST and PL	Many F, M and C	Many F, M, C, T	N	C and S
Bt1	18–43	7.5YR 5/4	10YR 5/6	SB → GR	VHA	FI	VST and VPL	Common F, M and C	Many F, M, C, T	N	D and S
Bt2	43–73	7.5YR 5/4	10YR 5/6	AB	VHA	FI	VST and VPL	Common F, M and C	Few F, M, C, T	N	D and S
Btg	73–118/ 134	7.5YR 5/4 (Matrix) 7.5YR 3/3 (mottles)	10YR 6/4 (Matrix) 10YR 4/2 (mottles)	SB	VHA	FI	VST and VPL	Few M and C	Very few F, M, C, T	N	D and W
BCtg	118/ 134–175	7.5YR 6/2 (matrix) 7.5YR 3/2 (mottles) 7.5YR 5/6 (mottles)	10YR 6/4 (matrix) 10YR 5/6 (mottles) 10YR 6/8 (mottles)	SB → GR	VHA	FI	VST and VPL	Few M and C	Very few F, M, C, T	N	D and W
Profile 4. Ntengie series											
Ap	0–27	7.5YR 3/3	10YR 4/4	SB	VHA	FI	SST and SPL	Many F, M and C	Many F, M, T	N	G and S
AB	27–50	7.5YR 5/6	10YR 4/4	SB → GR	HA	FI	SST and SPL	Many F and M	Many F, M, C, T	N	D and S
Cg	50–82	7.5YR 4/6 (matrix) 7.5YR 5/8 (mottles)	10YR 4/6 (matrix) 10YR 5/6 (mottles)	GR	LO	LO	NST and NPL	Many F and M	Few F and M	N	C and S
2AB	82–116	7.5YR 4/3	10YR 3/4	SB	HA	FI	ST and PL	Few M and C	Few F and M	N	D and S
2Btg	116–160	7.5YR 5/4	10YR 4/6	AB	HA	FI	ST and PL	Few M and C	Few F and M	N	C and S
2BC	160–210	7.5YR 5/6	10YR 5/6	SB → GR	HA	FI	SST and SPL	Few M and C	Few F and M	N	D and S
Profile 5. Bamengwi series											
Ap	0–25	7.5YR 3/2	10YR 5/4	SB → GR	VHA	FR	ST and PL	Many F, M and C	Many F, M, T and few E	N	G and S
AB	25–44	7.5YR 5/6	10YR 6/4	GR	SSH	FR	SST and SPL	Many F and M	Many F, M, C, T, and few B	N	G and S
BCt	41–66	7.5YR 4/4	10YR 6/3	BL	VHA	FI	VST and VPL	Many F and M	Few F and M	N	C and W
2Cg1	66–102	10YR 7/6 (matrix) 7.5YR 7/8 (mottles) 7.5YR 6/3 (matrix)	10YR 7/3 (matrix) 10YR 6/8 (mottles) 10YR 6/4 (matrix)	WE SB	SHA	LO	NST and NPL	Few M and C	Few F and M	N	C and W
3Cg2	102–134	7.5YR 6/6 (mottles)	10YR 7/8 (mottles)	SB → GR	VHA	FR	ST and PL	Few M and C	Few F and M	N	D and S

TABLE 3: Continued.

Horizon	Depth (cm)	Color		Structure	Consistence			Voids	Roots and biological features	Nodules/concretions	Boundary characteristics
		Moist	Dry		Dry	Moist	Wet				
4Cg3	134–162	7.5YR 6/4 (matrix) 7.5YR 5/8 (mottles)	10YR 7/3 (matrix) 10YR 7/8 (mottles)	SB → GR	SSH	FR	SST and SPL	Few M and C	Few F and M	N	D and S
5Cg4	162–205	7.5YR 6/2 (matrix) 7.5YR 5/8 (mottles)	10YR 7/3 (matrix) 10YR 7/8 (mottles)	SB → GR	VHA	FR	SST and SPL	Very few F	Few F and M	N	D and S

Note. BL blocky, SB subangular blocky, GR granular, AB angular blocky, SB → GR subangular blocky parting to granular, SHA slightly hard, HA hard, VHA very hard, SSH soft to slightly hard, WE weak, FR friable, FI firm, FRF friable to firm, LO loose, ST sticky, SST lightly sticky, PL plastic, SPL slightly plastic, VST very sticky, VPL very plastic, NST nonsticky, NPL nonplastic. For boundary, G gradual (5–15 cm), A abrupt, (0–2 cm), C clear (2–5 cm), D diffuse (>15 cm), S smooth, W wavy. For roots and biological features, F few, M many, C common (for abundance of roots), E earthworm channels, B burrows, T ant channels. For voids, F fine, M medium, C coarse, N none. For nodules and concretions, N none, F few, VF very few. Source: FAO [60].

FIGURE 4: Continued.

FIGURE 4: Variation of selected soil physical and chemical properties with depth.

3.3.2. Soil Organic Carbon Distribution. Soil organic carbon contents were generally higher in surface horizons and decreased with depth (Table 5, Figure 4). The surface Ah horizon of profile 2 has the highest SOC content of 5.74% contributed by the prevailing grassland vegetation. Generally, OM accumulation in the Ah horizon is largely dependent on the influx of litter-layer decomposition products and in situ accumulation of root decomposition products [69]. All the profiles recorded the lowest SOC contents in the C horizons, except for the Bt₂ horizon of profile 3. Despite the dominance of clay and clay loam textures in the surface horizons, SOC did not show any significant relationship with texture. The variation of SOC stocks with depth is

consistent with the stratifications observed with depth in the soils derived from alluvium as corroborated by BD, sand, and sand/silt depth functions. The SOC stocks at a depth of 1 m were highest in profile 2 (under grassland vegetation) with an estimated value of 363.5 t·ha⁻¹, while the lowest values were recorded in profile 4 (farmland) (260.1 t·ha⁻¹) and profile 5 (264.0 t·ha⁻¹). Both soils with very high porosities and high sand contents would favor faster mineralization of OM, compared to the more rich clay soils [70], though increased tillage activities play a complementary role. Reports indicate that grassland soils store significant amounts of SOC and about 34% of the global terrestrial carbon [28].

TABLE 4: Physical properties of the soils.

Horizon	Depth (cm)	BD (Mg m ⁻³)	Porosity (%)	WHC (%)	Sand (%)	Silt (%)	Clay (%)	Clay ratio	Sand/silt ratio	Silt/clay ratio	Textural class*
<i>Profile 1. Bamia series</i>											
Ap	0–10	1.07	59.62	40.22	33	35	32	0.47	0.94	1.09	CL
AB	10–24	1.16	56.23	40.07	30	23	47	0.89	1.30	0.49	C
Bw1	24–42	1.20	54.72	40.40	27	27	46	0.85	1.00	0.59	C
Bw2	42–72/90	1.32	50.19	30.74	37	27	36	0.56	1.37	0.75	CL
Bw3	72/90–102	1.25	52.83	30.46	36	29	35	0.54	1.24	0.83	CL
Cr1	102–157	1.01	61.89	30.97	50	23	27	0.37	2.17	0.85	SCL
Cr2	157–215	1.23	53.58	30.54	46	35	19	0.23	1.31	1.84	L
<i>Profile 2. Santchou series</i>											
Ah	0–12	0.66	75.09	49.02	42	32	26	0.35	1.31	1.23	L
2Bt/E	12–38	1.13	57.34	31.85	20	15	65	1.86	1.33	0.23	HC
2E/Bt	38–58	1.11	58.11	32.21	24	16	60	1.50	1.50	0.27	C
2Btg2	58–90	1.15	56.60	34.90	17	17	66	1.94	1.00	0.26	HC
2Btg3	90–115	1.30	50.94	36.55	46	15	39	0.64	3.07	0.38	SC
2C1	115–167	1.34	49.43	33.48	56	14	31	0.44	4.00	0.45	SCL
2C2	167–205	1.40	47.17	28.02	65	19	16	0.19	3.42	1.19	SL
<i>Profile 3. Lelem series</i>											
A	0–18	1.15	56.60	31.75	28	31	41	0.69	0.90	0.76	C
Bt1	18–43	1.19	55.09	35.15	19	35	46	0.86	0.54	0.76	C
Bt2	43–73	1.19	55.09	31.22	15	25	60	1.50	0.60	0.41	C
Btg	73–118/134	1.09	58.87	31.40	16	33	51	1.04	0.48	0.65	C
BCtg	118/134–175	1.14	56.98	29.98	15	26	59	1.44	0.58	0.44	C
<i>Profile 4. Ntengie series</i>											
Ap	0–27	0.92	65.28	35.68	39	33	28	0.39	1.18	1.18	CL
AB	27–50	0.78	70.57	42.64	54	20	26	0.35	2.70	0.77	SCL
Cg	50–82	1.11	58.11	35.05	64	12	24	0.32	5.33	0.50	SCL
2AB	82–116	0.80	69.81	38.88	47	24	29	0.41	1.96	0.83	SCL
2Btg	116–160	1.11	58.11	27.12	33	32	35	0.54	1.03	0.91	CL
2BC	160–210	1.18	55.47	36.34	36	26	38	0.61	1.38	0.68	CL
<i>Profile 5. Bamengwi series</i>											
Ap	0–25	1.03	61.13	35.01	29	44	27	0.37	0.66	1.63	CL
AB	25–44	1.01	61.89	37.61	38	40	22	0.28	0.95	1.82	L
BCt	41–66	1.30	50.94	28.06	43	24	33	0.49	1.79	0.73	CL
2Cg1	66–102	1.30	50.94	32.82	59	29	12	0.14	2.03	2.42	SL
3Cg2	102–134	1.31	50.57	33.08	28	42	29	0.41	0.67	1.45	CL
4Cg3	134–162	1.32	50.19	33.74	64	24	12	0.14	2.67	2.00	SL
5Cg4	162–205	1.29	51.32	35.16	62	27	11	0.12	2.30	2.45	SL

*Textural class according to FAO [60]. WHC water holding capacity, CL clay loam, C clay, SCL sandy clay loam, L loam, HC heavy clay, SC sandy clay, and SL sandy loam.

3.3.3. Relationship between SOC and Physicochemical Properties. Correlation analysis indicates that SOC and SOC stocks have significant relationships with some physical and chemical soil properties (Table 6, Figure 5). A negative and significant correlation exists between SOC and BD ($r = -0.648$, $p < 0.01$), reflecting the classical relationship that exists between them and further confirming that BD across the soil profiles is largely influenced by OM content. The positive and significant relationship between SOC and water holding capacity (WHC) ($r = 0.589$, $p < 0.01$) indicates that increase in SOM increases the soil's ability to retain water. However, there was a negative and significant relationship between SOC stocks and WHC ($r = -0.451$, $p < 0.01$) and also a negative and significant relationship between BD and WHC ($r = -0.636$, $p < 0.01$). A multiple linear regression equation between WHC as the dependent variable with SOC

and BD as independent variables was established as follows: $WHC = 44.51 + 1.47 \times SOC - 11.96 \times BD$ ($R^2 = 0.460$, $p < 0.05$). This indicates that SOC and BD can explain 46% of the variance associated with WHC, and thus this equation could be used to estimate WHC from SOC and BD data. Soil organic carbon had a positive and significant correlation with exchangeable Al^{3+} ($r = 0.707$, $p < 0.01$) and exchangeable H^+ ($r = 0.456$, $p < 0.05$) when the data were pooled together. The relationship between SOC and exchangeable acidity would only be valid for profiles 2, 3, and 4 with pH-H₂O values < 5.5 . However, the relationship between SOC and exchangeable Al^{3+} was strongest in profile 2 ($r = 0.931$, $p < 0.01$). A linear regression between SOC and exchangeable Al^{3+} in profile 2 gave an R^2 value of 0.867 (Figure 6), indicating that SOC can be conveniently estimated from exchangeable Al^{3+} in this soil type. The

TABLE 5: Chemical properties and SOC stocks.

Horizon	Depth (cm)	pH-H ₂ O	pH-CaCl ₂	pH-KCl	EC (dSm ⁻¹)	SOC (%)	SOC stocks (t ha ⁻¹)	SOC stocks at 100 cm depth (t ha ⁻¹)	Al ³⁺ (cmol _c kg ⁻¹)	H ⁺ (cmol _c kg ⁻¹)
<i>Profile 1. Bamia series</i>										
Ap	0–10	5.8	5.1	4.5	0.03	2.53	27.1		–	–
AB	10–24	5.6	4.8	4.2	0.01	2.53	41.1		–	–
Bw ₁	24–42	5.5	4.4	4.0	0.01	2.40	51.8		–	–
Bw ₂	42–72/90	5.4	4.4	4.0	0.01	2.50	128.7		0.9	0.0
Bw ₃	72/90–102	5.5	4.6	4.1	0.01	2.0	45.0	295.7	–	–
Cr ₁	102–157	5.6	4.5	4.1	0.01	2.0	111.1		–	–
Cr ₂	157–215	5.6	4.5	4.2	0.01	1.87	133.4		–	–
<i>Profile 2. Santchou series</i>										
Ah	0–12	4.8	4.3	3.8	0.02	5.74	45.5		3.3	2.2
2Bt/E	12–38	4.8	4.5	4.1	0.01	3.91	114.9		1.8	2.3
2E/Bt	38–58	4.5	4.1	3.6	0.01	2.78	61.7		0.5	2.0
2Btg2	58–90	4.5	4.0	3.8	0.01	3.00	110.4		1.7	1.4
2Btg3	90–115	5.0	4.8	4.4	0.01	2.39	77.7	363.5	0.8	0.7
2C1	115–167	4.7	4.2	4.0	0.00	1.35	94.1		0.6	0.5
2C2	167–205	4.9	4.5	4.2	0.00	1.30	69.2		0.5	0.0
<i>Profile 3. Lelem series</i>										
A	0–18	4.5	4.0	3.5	0.01	3.26	67.5		0.7	1.6
Bt1	18–43	4.7	4.1	3.6	0.01	3.35	99.7		0.5	1.5
Bt2	43–73	4.8	4.3	3.5	0.00	1.17	41.8		0.6	1.9
Btg	73–118/ 134	4.8	4.4	3.6	0.00	2.22	128.2	274.2	0.7	1.4
BCtg	118/ 134–175	4.9	4.3	3.8	0.01	1.57	87.7		0.4	1.3
<i>Profile 4. Ntengie series</i>										
Ap	0–27	5.3	5.0	4.3	0.04	3.00	74.5		0.2	0.0
AB	27–50	5.2	4.7	4.3	0.02	3.65	65.5		0.2	0.0
Cg	50–82	5.2	4.8	4.3	0.02	2.48	88.1		0.2	0.0
2AB	82–116	5.4	5.0	4.8	0.02	2.22	60.4	260.1	0.3	0.0
2Btg	116–160	5.5	5.1	4.6	0.02	1.57	76.7		0.3	0.0
2BC	160–210	5.5	4.9	4.4	0.02	1.17	69.0		0.3	0.0
<i>Profile 5. Bamengwi series</i>										
Ap	0–25	5.7	5.1	4.2	0.02	3.39	87.3		–	–
AB	25–44	6.0	5.6	4.6	0.01	2.61	50.1		–	–
BCt	41–66	6.0	5.3	4.5	0.01	2.22	72.2		–	–
2Cg1	66–102	6.2	5.8	4.7	0.01	1.30	60.8	264.0	–	–
3Cg2	102–134	6.1	5.6	4.9	0.01	2.09	87.6		–	–
4Cg3	134–162	6.4	5.8	5.1	0.01	2.11	78.0		–	–
5Cg4	162–205	6.2	5.8	4.9	0.01	1.08	59.9		–	–

relationship shows that exchangeable Al³⁺ forms strong complexes with OM as best observed in the humic surface horizon of profile 2. Low pH soils such as those in this study are reported to have Al³⁺-OM complexation as well as Al³⁺ toxicity as the main OM stabilization mechanisms [20, 71]. In view of the role played by soil pH in controlling soil OM stabilization mechanisms, Clarholm and Skjellberg [20] indicate that soil pH values between 6.2 and 6.8 constitute a “window of opportunity,” whereby SOM stabilization controlled by cations such as Al is not strong. Variations in soil pH in these soils would thus be attributed to both SOM type and clay content, given that a positive correlation exists between clay content and exchangeable H⁺ ($r = 0.708$, $p < 0.01$). The positive relationship observed between OC and exchangeable H⁺ indicates that soil acidity increases with increase in SOM content. Given that H⁺ is part of the

humus carboxyl (–COOH) under acidic conditions, when the soil’s acidity decreases, there is a greater tendency for the H⁺ to be removed from humic acids and to react with hydroxyl (OH[–]) to form water. The carboxyl groups on the humus develop negative charges as the positively charged H⁺ is removed. When the soil pH is increased, the release of H from carboxyl groups helps to buffer the increase in pH and at the same time creates the CEC (negative charge). Thus, when OM increases, the soil recovers its natural buffer capacity, thereby increasing soil pH and hence increasing the soil’s capacity to retain cations.

In general, there was no significant relationship between SOC and texture. Observations by Hassink [16] indicate that SOC contents varied considerably between soils with similar clay and silt contents. However, the latter found highly significant positive correlations between the clay and silt

TABLE 6: Correlation matrix of the soil properties.

	Clay	Sand	Silt	Sand/silt	Silt/clay	Clay ratio	WHC	BD	SOC	pH-H ₂ O	pH-CaCl ₂	pH-KCl	Exch. Al ³⁺	Exch. H ⁺
Clay	1													
Sand	-0.855**	1												
Silt	-0.262	-0.277	1											
Sand/silt	-0.814**	0.855**	-0.086	1										
Silt/clay	-0.801**	0.505**	0.543**	0.764**	1									
Clay ratio	0.963**	-0.784**	-0.327	-0.664**	-0.692**	1								
WHC	-0.115	0.076	0.072	-0.019	0.045	-0.149	1							
BD	-0.031	0.116	-0.160	0.247	0.095	0.003	-0.636**	1						
SOC	0.172	-0.230	0.108	-0.317	-0.171	0.152	0.589**	-0.648**	1					
pH-H ₂ O	-0.667**	0.442*	0.407*	0.555**	0.730**	-0.634**	0.010	0.191	-0.333	1				
pH-CaCl ₂	-0.658**	0.474**	0.329	0.614**	0.738**	-0.591**	0.036	0.130	-0.295	0.902**	1			
pH-KCl	-0.683**	0.603**	0.135	0.624**	0.617**	-0.618**	0.067	0.124	-0.305	0.843**	0.912**	1		
Exch. Al ³⁺	0.173	-0.177	0.039	-0.148	0.057	0.238	0.480*	-0.301	0.707**	-0.381	-0.376	-0.291	1	
Exch. H ⁺	0.708**	-0.682**	0.067	-0.603**	-0.390	0.702**	0.073	-0.089	0.456*	-0.788**	-0.700**	-0.762**	0.606**	1

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed). SOCS: SOC stock.

FIGURE 5: Relationships between SOC content and selected soil properties.

FIGURE 6: Relationship between SOC and exchangeable Al^{3+} in profile 2 (Mollic Endoaquents).

contents of some soils and the amounts of C associated with these fractions; in some cases, lower amounts of C were associated with the fine-sized particles. These observations indicate that the amount of SOC that can be bound or adsorbed is a function of the type of clay minerals present (phyllosilicates versus sesquioxides) and their corresponding specific surface area and charge characteristics which impact on this behaviour [32]. With the diversity of soil types observed in this study, having a wide range of silt/clay ratios, apparently these soils exhibit wide mineralogical differences with corresponding differences in their binding capacity with SOC. Thus, other factors, apart from soil texture, such

as land use type and management (C additions) would likely be responsible for SOC storage [72, 73].

3.3.4. Relationship between SOC and Soil Color. Soil organic carbon contents had a negative correlation with soil value and/or soil chroma in both moist and dry states (Table 7). These results indicate that, based on the correlation coefficients, Munsell soil color attributes explain between 40 and 57% of the variance associated with SOM. This has important implications for application as Zelenak [74] reported that soil color could successfully be used to estimate SOM

TABLE 7: Correlation matrix between SOC and Munsell color attributes.

	VM	CM	VM + CM	VD	CD	VD + CD	SOC
VM	1						
CM	0.338	1					
VM + CM	0.670**	0.925**	1				
VD	0.659**	0.425*	0.601**	1			
CD	-0.125	-0.052	-0.091	-0.471**	1		
VD + CD	0.545**	0.379*	0.519**	0.564**	0.463**	1	
SOC	-0.573**	-0.402*	-0.549**	-0.515**	-0.021	-0.537**	1

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed). VM: value (moist), CM: chroma (moist), VM + CM: value (moist) + chroma (moist), VD: value (dry), CD: chroma (dry), VD + CD: value (dry) + chroma (dry).

contents as it could explain approximately 50% of the variance associated with SOM. Pretorius et al. [75] reported that, based on a high coefficient of determination ($R^2 = 0.91$) for coastal plain soils of South Africa, when the sum of dry and wet value and chroma values is 9 or more, carbon content will be $\leq 4.79\%$. From the results of this study, soil color attributes, notably value and chroma, can be conveniently used to estimate organic matter contents, where cost constraints are an important factor in laboratory analyses.

4. Conclusion

In this study, SOC contents and stocks in five major soils types of the Mbo plain were estimated, and SOC distribution along soil profiles presents erratic depth functions. SOC had significant correlations with exchangeable Al^{3+} and H^+ , bulk density, water holding capacity, and Munsell soil color attributes. The correlations indicate that soil SOC can be conveniently estimated from exchangeable Al^{3+} in the Mollic Endoaquents. The results obtained in this study serve as baseline information that can be used for monitoring soil quality changes in this humid tropical environment, especially in areas subjected to intensive agricultural practices. Future studies to investigate detailed biological, chemical, and mineralogical properties are recommended in order to acquire more knowledge on soils of the Mbo plain. Additionally, detailed studies on the spatial variability of SOC are recommended in order to guide decision-making on sustainable soil management in the plain.

Data Availability

The data used in this paper are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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