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Soil Characterization and Classification of the Koutango Watershed in the Semi-Arid Southern Peanut Basin of Senegal

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Authors' contributions

This work was carried out in collaboration between all authors. Authors MD and FD designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author KS managed the analyses of the study. Author MS managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The study was conducted to determine the potential of soil units composing the watershed for agriculture. The methodological approach was based on a soil profile description and sampling of soil units in different depths. The soil physical and chemical properties such as soil texture, soil pH, electric conductivity (EC), soil organic carbon (SOC), total nitrogen (N), extractible phosphorus (P), cation exchange capacity (CEC), were measured using standard methods. Results showed differences for SOC at the surface (2.9-5.85 g kg^{-1}), N at the surface (0.3-0.45 g kg^{-1}) and (P) at the surface as well (12-58 g kg^{-1}). Soil characteristics have allowed to come up with a soil classification. Results also showed that the lowland soil unit presented higher soil properties contents, followed by colluvium and terrace soil units, the upland unit had the lowest soil contents. With reference to soil

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nutrient ratings, except for extractible phosphorus, value contents of chemical properties were below critical values, leading to the lowest soil fertility level and therefore emphasizing the need to include agricultural management practices that can influence soil variability.

Keywords: Characterization; level of soil fertility; soil physical and chemical properties; watershed.

1. INTRODUCTION

Since the drought of the 1970s, there has been deterioration in agricultural areas in Senegal and a general decline in land productivity [1,2]. This situation, prejudicial to the living conditions of the populations, is currently very noticeable in the south of the Peanut Basin. Indeed, population growth in recent decades has significantly exceeded agricultural production, resulting not only from strong pressure on land but also forcing people to exploit marginalized land [3,4,5]. The cropping system, which was based on peanut-cereal rotation, followed by a long period of fallow, disappeared because of both a deficit and a rainfall irregularity [6]. Moreover, agricultural lands are undergoing soil degradation with a combination of erosion and a lack of vital nutrients [7,8]. A number of farming organizations are working to improve the soil for peanut cultivation, as well as for other crops, and to help small farmers secure their livelihoods [9]. These various issues have led to persistent soil degradation, which is the major obstacle to the practice of agriculture on slopes [10]. The decline in soil mineral content is the most important factor in the equation of land degradation. Unlike sudden disasters such as drought and earthquakes, the reduction of soil fertility is a gradual but steady process [5]. For nations whose livelihoods depend on agricultural production, a decline in soil fertility is a serious threat to economic development [11]. Investigations carried out [12,13] in the northern peanut basin, confirmed the low availability of straw residues, per hectare with a slight decrease in 2000, compared to 1978. According to [14,15], the fertilizer value of manure produced in rural areas varies according to its nature and decreases rapidly over time due to the action of termites and drying out of the sun, hence the value of composting techniques. Findings have improved the manure produced for more efficient organic fertilization. More than ten years after these investigations, satisfying the organic needs of farms remains an issue that still challenges research [8]. In this context, the lowlands of the continental valleys could constitute new agricultural lands as they have the potential of good quality soil [5]. However, lack of information on these environments has often been the main obstacle to their development. Few studies have been devoted to these ecosystems. In addition, there is a need to improve cropping practices, land management methods and sanitary and socio-economic conditions for the preservation of the environment. The development of watersheds whose lowlands constitute places of convergence and preferential flow of rainwater thus confers a water regime that buffers the vagaries of the climate. Improved water supply favors a long and staggered use of seasons of traditional culture). The objective of this study was to characterize the soil units of the watershed, then classify them for a better soil management and agricultural development.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Geographical location, climate and vegetation

The Koutango watershed is located between latitudes 13°66' and 13°82' N and between longitudes 15°9' and 16°09' W. It is located in the Nioro du Rip area of the Southern Peanut Basin Agroecological zone (Fig. 1). It covers an area of 173.3 km^2 and the backwater of Koular, a tributary of the Gambia River, drains it. The climate of this Kaolack region is of the North Sudanian type. It is marked by the alternation of a long dry season, which runs from November to May, and a rainy season that extends from June to October. Over the past 30 years, annual rainfall averages have varied between 417.5 mm and 999.9 mm for the Nioro du Rip zone. These are very aggressive rains: the Fournier soil degradation index, calculated for the Nioro station, is 1730 t/km^2/year. The thermal regime is very much contrasted with maximum temperatures in April of 35°C and minima in December-January of 20°C. The natural vegetation of the southern peanut basin area is a degraded light forest, but bush fires, clearing and overgrazing has transformed it into a park of *Cordyla pinnata* and *Pilostigma reticulatum* from the *Crestaceae* and *Cesalpiniaceae* families.

2.1.2 Geomorphology, geology and pedology

The region owes its model to morphogenetic processes that took place from the end of the Ternary to the Quartenary. The landscape of the Nioro area offers four main units: a plateau which is about 40 meters above sea level, a connecting glaze between the plateau and the terraces, flooded levels and a shoal. The geological substratum consists of the Pliocene deposits of the Continental terminal, the dominant facies of which is a heterometric, clayey and mottled sandstone [16]. These deposits contain locally Miocene alteration products consisting of sand lenses, kaolinitic clay banks and iron gravel pass. Like most sedimentary formations in the Senegal-Mauritanian basin, the formations of the study area strongly mark pedogenesis. Soils developed on clay sands of the Continental Terminal have characteristics that they inherited from these materials (sandy texture, low exchange capacity, lack of mineral reserves, low clay and silt content, kaolinitic nature of the clay). The soils with sesquioxides, halomorphic soils and hydromorphic soils are the most represented in the Nioro zone. A relatively low level of fertility characterizes them. Their strong anthropization and the aggressiveness of the rains have affected their physicochemical properties. Previous studies have shown that these soils have evolved towards acidification, an increase in the exchangeable aluminum content and a decrease in organic status [17].

2.2 Methods

In this watershed, soil profiles were dug using the transect method, based on a laminated plane along the toposequence. The watershed toposequence was divided into morphological units composed of lowlands, terraces, colluviums and upland. This layered approach had allowed to identify 12 transects distributed on both sides of the watershed. A soil profile was dug in each transect taking into account the variability of morphological units. 156 soil samples were hence collected from 46 soil profiles at xyz depths (cm) described according to the Duchaufour method [18]. The soil classification used by French pedologists [19] in tropical environments was adopted. In Senegal, there are seven classes out of the twelve proposed by the Commission for Pedology and Soil Mapping (CPCS). These include raw mineral soils, poorly developed soils, vertisols, isohumic soils, sesquioxide soils, halomorphous soils and hydromorphic soils. The other three classes (calcimagnesian soils, brown soils and podzols) are easily represented in Senegal. The soil characterization of the Koutango catchment was carried out by measurements of soil and geomorphological parameters.

A survey was first carried out on the entire catchment area for knowledge of the surface conditions, in particular the physiognomy of the vegetation, which reflects the soil conditions. Twelve transects were thus carried out on the whole of the two slopes at the rate of six transects per bank (Fig. 2). The 1: 25,000 othophotographs served as a working support. This has allowed positioning the soil profiles, using a GPS (Global Position System, Laser Technology, Inc. Centennial, Connecticut, USA). The soil profiles were then dug based on a 1.5 m long, 1.0 m wide and about 2.0 m deep dimensions for each.

2.2.1 The description of soil profiles

A number of equipment were used to describe the soil profile, including a Munsell code, 3rd edition (Munsell Color Company, Inc. Baltimore 18, Maryland, USA, 2010) to determine soil colours. The other soil properties were determined following indicated methods.

2.2.2 Soil sampling and laboratory analysis

Soil samples were taken from the identified genetic horizons of each soil profile described. A composite sample was taken from samples representative of the indicated horizons. Soil analysis was then run accordingly to each of the soil properties. Particle size distribution was determined by the hydrometer method [20]. Soil pH was determined in duplicate in distilled water, using a soil/liquid ratio of 1:2.5 [21]. Electric conductivity (EC) was measured by soil water ratio of 1:5 [22]. The soil organic carbon (SOC) was obtained by the wet dichromate acid oxidation method [23]. Total nitrogen was determined using the Kjeldhal distillation method as described by [24]. Extractible phosphorus was obtained using Bray11 bicarbonate extraction method as described by [25]. Cation Exchange Capacity (CEC) was measured, using 1N NH_4OAc at pH7 [26].

After having analyzed the soil samples for the above soil physical and chemical properties, data were plotted on XY axes using SigmaPlot, version 11 (2008), X representing the variation of the soil property content between the geomorphologic units, within the watershed;

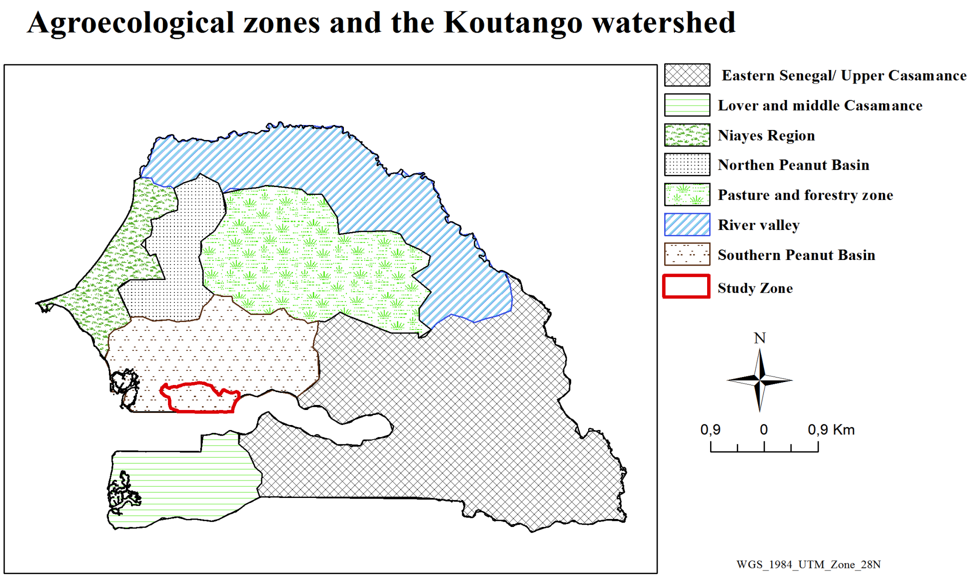

Fig. 1. Agro-ecological zones and the Koutango watershed

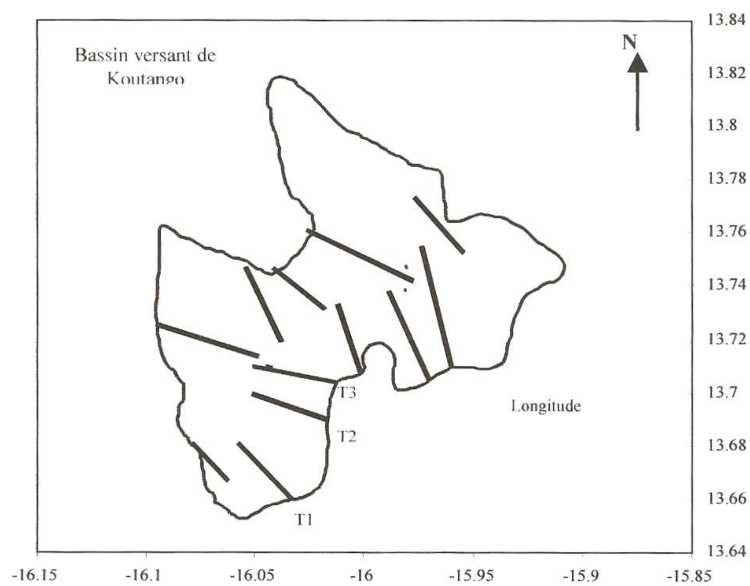

Fig. 2. Positions of the 12 transects and the soil sampling points in the Koutango watershed

Y representing the different soil horizons (from surface to bottom) from which samples were taken.

3. RESULTS AND DISCUSSION

The survey revealed four soil units presented in a Table 1. These are: 1) poorly developed soils with alluvial and hydromorphic soils (lowland soils); 2) weakly leached tropical ferruginous soils (terrace soils); 3) leached tropical ferruginous soils (colluvium soils) and 4) raw mineral soils of input and erosion, developed on breastplates (upland soils). As the boundaries between pedological units have not been observed in the field, the morphopedological approach used was to look for relationships between soil units and landscape units. In the context, this approach allowed to identify the most important units for agricultural development and areas of cropping orientation.

3.1 Poorly Developed Soils with Alluvial and Hydromorphic Soils (Lowland Soils)

These soils are circumscribed at the bottom. The structure of these soils is essentially massive on the surface and particulate in depth. However, some soils have an aggregate structure on their surface. These soils are deep and inconsistent; they have a low gravel load and the biological activity is medium to high. The shallows have hydromorphic soils that show rusty, yellow spots.

3.2 The Weakly Leached Tropical Ferruginous (Terrace Soils)

These soils or red soils are found on the slope. They have a massive structure with low angularity, a small compactness on the surface but which increases in depth. Biological activity is manifested by the presence of termites and earthworms (tubules, turricules). A cuirass within a meter of depth sometimes limits the depth of the ground. The soils then show an important gravel load (Table 1).

3.3 Tropical Ferruginous Soils and Poorly Beige Soils (Colluvium Soils)

The beige soils are located on the slope. They have a massive structure and their cohesion, weak on the surface, increases slightly in the mineral horizon, which presents rust patches and concretions. Beyond 1 m deep, it remains on a cuirass.

3.4 Raw Mineral Soils Developed on Breastplates (Upland Soils)

These soils are located in the exposed area. Their profile presents a red superficial horizon, which remains without transition on a yellowish red mineral horizon. The latter has a heavy gravel load and rests 30-50 cm deep on a lateritic breastplate.

3.5 Soil Particle Size Distribution

In the first 40 cm, a rooting zone that holds most of the crops, the clay contents (Fig. 3) vary between 5.5 and 23.0%, while the total sand contents are between 65.0 and 92.0% (Fig. 4). In the lowlands, soil texture is mainly sandy with sand contents ranging from 65.0 to 90.0%. Hydromorphic soils have a variable texture: sandy loam, loam or silt-clay loam. On the slope (colluviums), soils appear constantly sandy at the surface and sandy-clay at depth. For beige soils (terrace), the texture is sandy on the surface and sandy-clay and sandy in depth; the grades vary between 7.0 and 20.0% for the clay; 2.0 and 10.0% for silt and 76.0 and 88.0% for sand. As for the soils developed on cuirass (upland), the clay contents vary between 5.5 and 15.0%, while the sand contents vary from 88.0 to 90.0%. The transition between horizons is always progressive. Fine sands occupy a significant proportion of the soil in the watershed [27]. The high proportion of sands explains the coarse (sandy) texture of poorly developed soils. This texture is related to the process of alluvium and colluvium on the minor bed, which alternate with phases of relative calm. The colluvio-alluvial embankment constituting the lowlands is fed laterally by the erosion of the slopes and longitudinally by the floods associated with the runoff on the interfluves [28,29]. Results show a dominance of sands on clays and silts in the bottom. This is related to the nature of the original material, the extent of colluvium and the sandy texture of the elements transported on the adjacent slopes. The collapse and climatic aggressiveness of the zone reinforces the sandy texture of the coarse material in place and results in sand enrichment. Consequently, the presence of sandy allogeneous horizons with a massive particle structure covers the sandy loamy and clayey horizons of the shoal. These horizons alter the agronomic qualities of lowland soils. Regarding the soil physical properties, the soils are characterized, among other things, by a sandy texture, which greatly reduces their ability to retain water and results in a low CEC concentration. There is little clay content and clay present is Kaolinite, which is a highly weathered 1:1 layer clay mineral with a low CEC. On the colluviums, the predominantly sandy texture from the uplands is linked to an oblique drainage on the surface, which leads the fine elements towards the bottom. This lateral dynamics is certainly associated with another vertical dynamics, which explains the accumulation of the clay elements in the deep horizons of the soils developed on cuirass. This accumulation increases in red soils to a maximum (40%) in beige soils. In the latter, a pronounced leaching of the fine elements of the surface horizons towards deep horizons would be at the origin of the sandy loam texture of the B horizons [28], which gives to the horizon, a coarse texture. Under such conditions, shallow horizons are depleted of clays and sesquioxides.

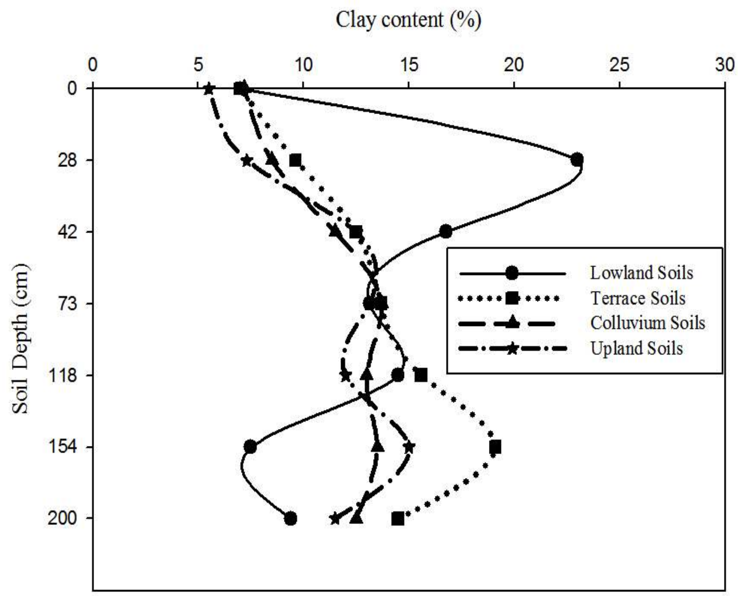

Fig. 3. Variation of the clay content between the geomorphologic units within the watershed

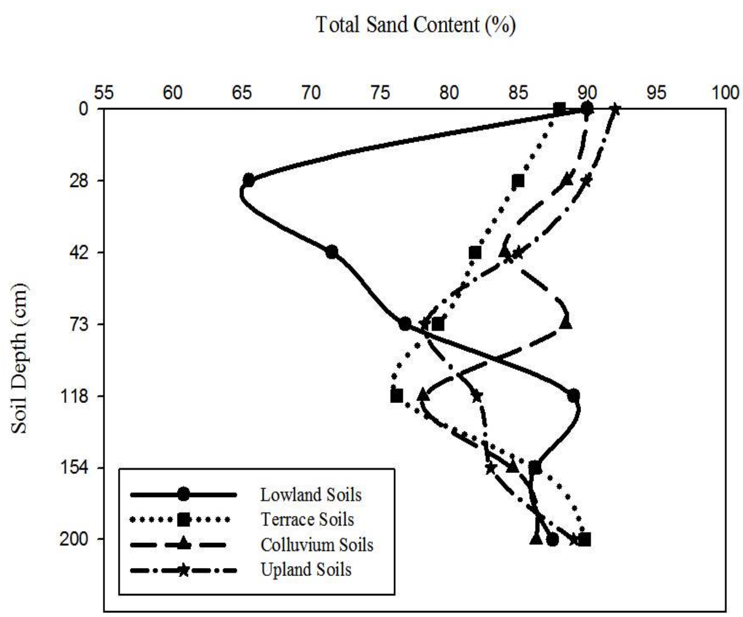

Fig. 4. Variation of the total sand content between the geomorphologic units within the watershed

3.6 Soil pH

The bottom soils are slightly acidic on the surface, ($5.3 \leq pH \leq 6.4$). For the majority of the profiles described (Fig. 5), the pH decreases in the rooting zone before increasing in depth. The terrace soils are as slightly acidic ($5.7 \leq pH \leq 5.9$) as the upland ($5.3 \leq pH \leq 5.7$). The soil pH increases in depth on most of the slope soils in relation to a much coarser texture.

3.7 Soil Electric Conductivity

The results of electric conductivity (Fig. 6) show that the soils are slightly saline ($EC \leq 0.5$ dSm^{-1}) to saline ($0.5 \leq EC \leq 1.0$ dSm^{-1}) according to the

1974 classification of the Mémento de l'Agronomie. Except the lowland soils, all other soil units soils are widely non-saline [30,31].

3.8 Soil Organic Matter

Soil organic carbon (SOC) contents vary from the soil surface (5.81 gkg^{-1}) to the bottom (4.62 gkg^{-1}) under lowland conditions (Fig. 7). In the colluvium soils, SOC varies between 3.34 and 2.83 gkg^{-1} whereas under terrace condition, it varies between 3.45 and 2.72 gkg^{-1}, while it changes from 2.90 to 2.20 gkg^{-1}. Compared to the terrace, colluvium and upland soils, the lowland soil presents greater value for total SOC contents at the soil surface and even the rooting zone, within the watershed. Data from the upper soil units are similar to most of the soils of the Sudano-Sahelian zones which contain low levels of soil organic carbon, between 0.3% and 1.0% [32,33]. With high soil moisture content from rainfall and the presence of diverse vegetation, the SOC content tends to accumulate over time, which contributes to an establishment of a good soil fertility level [34]. The evolution of the soil organic carbon as a function of depth differs from one geomorphological unit to another [15]. If on the slope, the SOC decreases with depth, in the bottom and for the majority of the soils, it increases first in the second humiferous horizon; it then gradually decreases with depth. SOC is depleted in the soils of sub-Saharan Africa due to anthropogenic activities such as deforestation and burning of biomass [35]. This results in an inadequate replenishment of nutrients, contributing to unsustainable and low-yield agriculture [7,36]. The recovery of inorganic nutrients from fertilizers by crops is very low in the Sahel. Loamy sand soils of Senegal's Peanut Basin are inherently low in soil organic matter, limiting yields of mainly cereal crops and threatening the food security of smallholders [2].

3.9 Soil Total Nitrogen

As for SOC in the first 40 cm depth, total soil N content varied between 0.17 and 0.45 gkg^{-1} (Fig. 8). At the soil surface, within the four soil units, total soil N changes from 0.28 to 0.45 gkg^{-1}. For the colluvium soils, it varied between 0.24 and 0.30 gkg^{-1} while under terrace conditions, soil total N varies between 0.18 and 0.36 gkg^{-1}. Similar to the soil organic carbon, total soil nitrogen had the highest content under lowland conditions as compared to colluvium, terrace and upland soil units. For almost all the soil units, the nitrogen content decreased with depth. In the bottom, it increased in the second horizon to decrease in depth on most profiles [37,4].

3.10 Soil Extractible Phosphorus

Soil extractible phosphorus levels were low in soil samples from which it was determined with values ranging from 12.0 to 112.0 gkg^{-1} in the first 40 cm depth (Fig. 9). In the lowland, the extractible phosphorus content went up to 112.0 gkg^{-1}. On the slope, it varied between 15.0 to

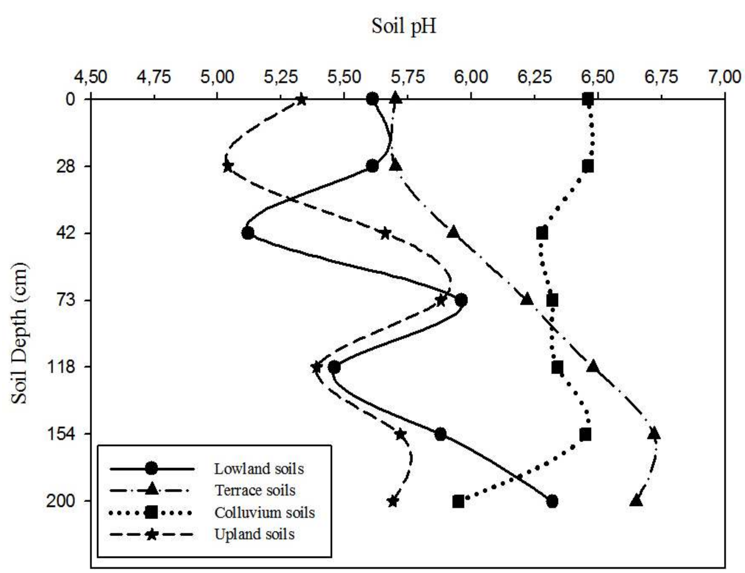

Fig. 5. Variation of the pH_{water} between the geomorphologic units within the watershed

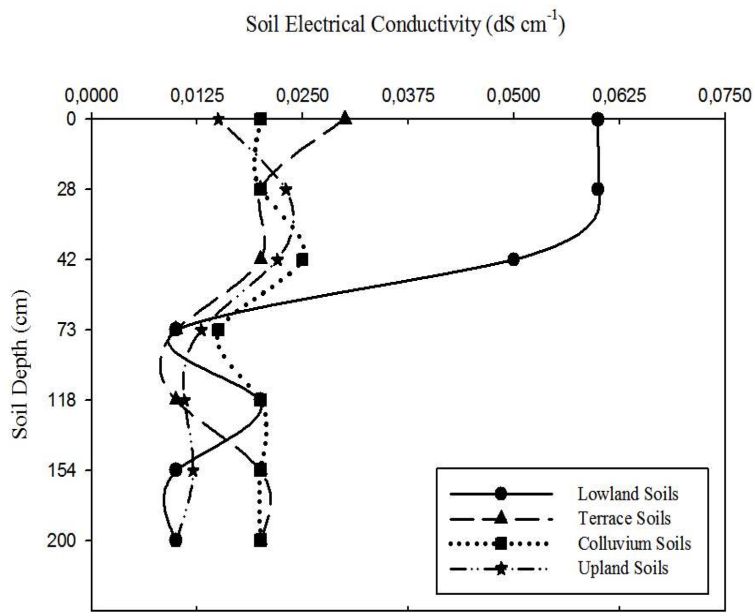

Fig. 6. Variation of the soil electrical conductivity between the geomorphologic units within the watershed

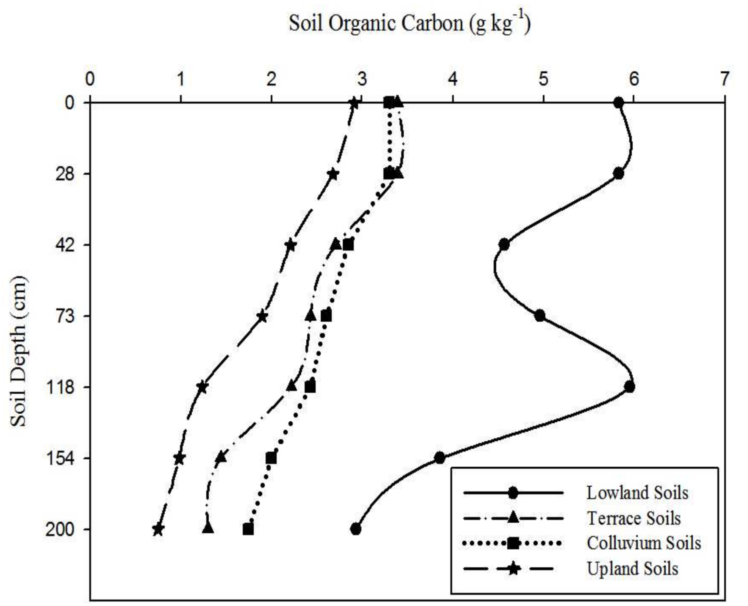

Fig. 7. Variation of the soil organic carbon content between the geomorphologic units within the watershed

38.0 gkg^{-1}. In the upland soils, it varies between 8.0 and 12.3 gkg^{-1}. These data showed fairly good levels of extractible phosphorus throughout the watershed, probably due to the relatively low soil acidity and therefore a low phosphorus fixing capacity for the soil units [4]. The widespread phosphorus deficiency in most Senegalese soils, when soil pH is low, greatly hampers agricultural productivity.

Table 1. Description of the koutango watershed soil profiles

Morphological units	Soil classification	Depth (cm)	Horizon	Colour	Texture	Structure
Lowland	Poorly developed soils with alluvial and hydromorphic soils	0 - 28	A_1	7.5YR 6/2	Sandy	Particular
		28 - 42	A_2	2.5YR 2/0	Loamy	Particular
		42 - 73	A_3	10YR 3/2	Loamy	Massive
		73 - 118	AB	7.5YR2/0	Clay loam	Polyhydric to sub-angular
		118 - 154	BC	2.5YR 6/0	Loamy	Polyhydric
		118 - 200	C	2.5 YR 8/0	Sandy	Particular
Terrace	The weakly leached tropical ferruginous	0 - 42	A_1	5YR 4/2	Sandy	Particular
		42 - 78	A_2	7.5YR 5/6	Sandy	Massive
		78 - 156	AB	5YR 5/6	Loamy	Massive to sub-angular
		156 - 200	B	2.5YR 5/4	Silt clay	Angular
Colluvium	Tropical ferruginous soils (poorly beige soils)	0 - 28	A_1	10YR 3/2	Sandy	Massive
		28 - 60	A_2	10YR 4/4	Loamy	Massive
		60 - 145	AB	7.5YR 5/4	Sandy loam	Polyhydric
		145 - 200	B	5YR 6/3	Clay loam	Polyhydric
Upland	Raw mineral soils (soils developed on breastplates)	0 - 22	A_1	5YR 4/3	Sandy	Massive
		22 - 56	A_2	7.5YR 4/4	Sandy	Massive
		56 - 130	AB	5YR 5/6	Loamy	Massive
		130 - 200	Bw	2.5YR 4/6	Loamy	Massive

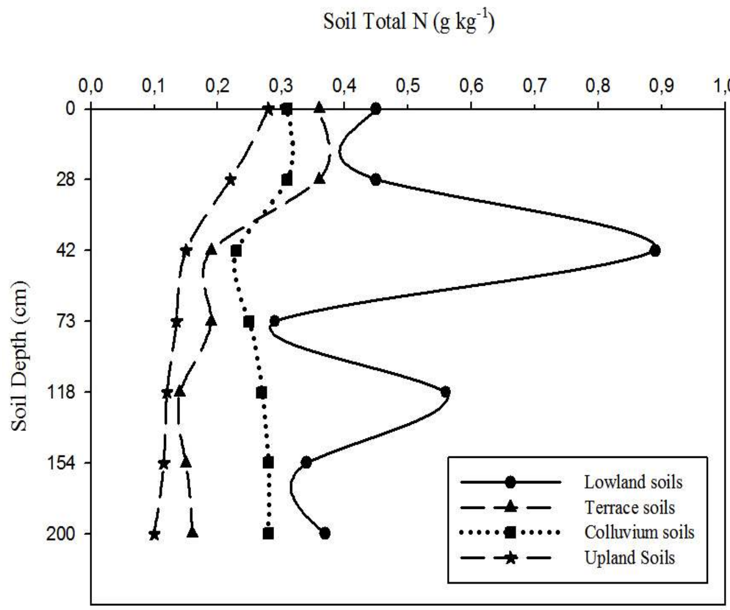

Fig. 8. Variation of the total soil nitrogen between the geomorphologic units within the watershed

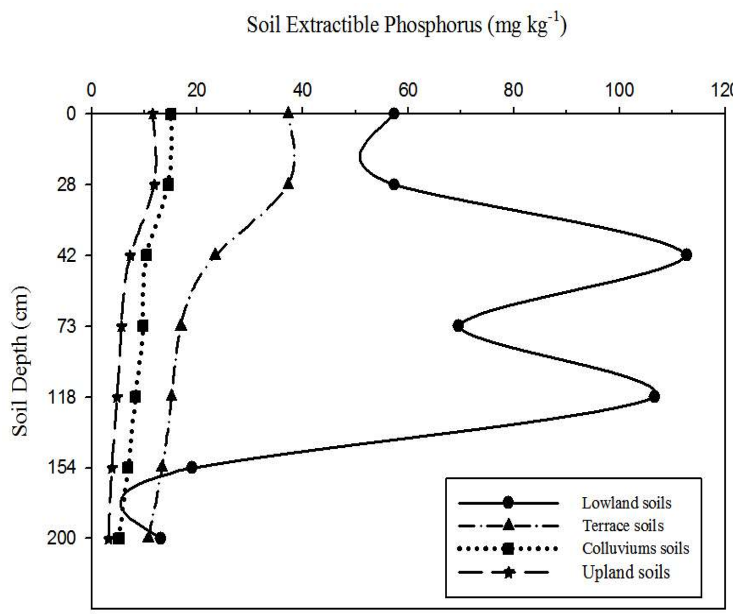

Fig. 9. Variation of the soil extractible phosphorus content between the geomorphologic units within the watershed

3.11 Cation Exchange Capacity

The cation exchange capacity (Fig. 10) varies between 3.7 and 7.6 cmolkg^{-1} soil in the lowlands. On the slope, it varies between 2.8 and 3.4 cmolkg^{-1} soil for red soils; between 2.4 and 2.9 cmolkg^{-1} soil for beige soils and between 1.9 and 2.3 cmolkg^{-1} soil for soils developed on breastplates. The highest grades are found in lowland soils and particularly in clay and/or organic-rich horizons. This variation of the CEC has decreased in content from the lowland soils

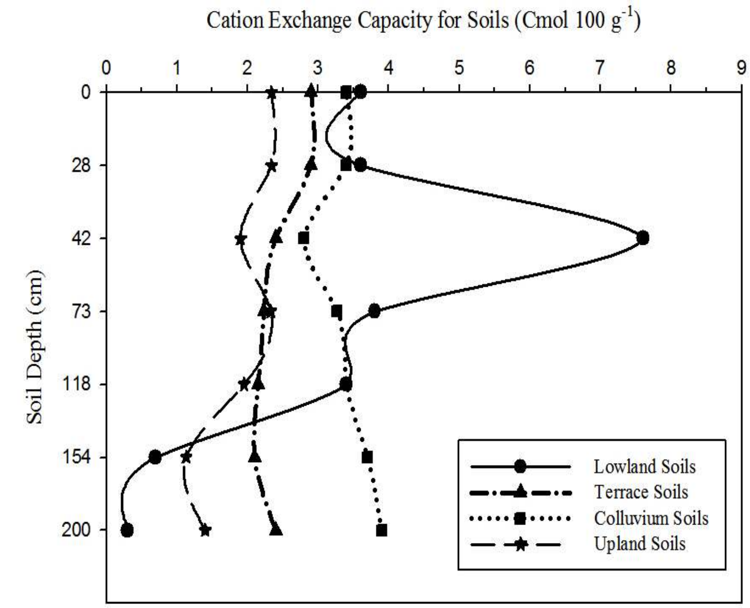

Fig. 10. Variation of the cation exchange capacity content between the geomorphologic units within the watershed

up to the upland soil, through the terrace and colluvium soils. This is due to an established already known and positive relationship between CEC and SOC.

4. CONCLUSION

The characterization of the Koutango catchment has allowed classifying four soil units with different soil physical and chemical properties. With reference to soil nutrient ratings, values of chemical properties, determined from the first 40 cm soil depth, present slightly acidic to neutral level for all morphological units within the watershed. Values are very low and below critical level for soil EC however. All soil units present relatively low value contents, with the exception of soil extractible phosphorus that has relatively high value contents for all soils units mainly due to low acidity levels. As the watershed is located in a semi-arid zone of the Sahelian region, high temperatures and low vegetation density are predominant. Furthermore, soil physical properties that are mainly texture (sandy to loamy) and structure (particular to massive) as described from soil profiles, when combined with low SOC and consequently low total N, throughout the watershed, contribute remarkably to an indication of low soil fertility and therefore low quality soils, which will need strategies for better management for greater soil productivity.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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