



Physical and Chemical Properties of Soil in the Sahelian Region: Case Study in Nioro du Rip, Senegal

**Landing Biaye^{1*}, Fary Diome², Seybatou Diop², Modou Mbaye^{2,3}, Djibril Tine²,
Dome Tine², Ndeye Penda Dione Diene⁴ and Gayane Faye²**

¹Department of Geology, Faculty of Science and Technology, Cheikh Anta Diop University, Dakar, Senegal.

²Institute of Earth Sciences, Faculty of Science and Technology, B. P. 5396, Dakar-Fann Senegal.

³Department of Physics, Faculty of Science and Technology, Cheikh Anta Diop University, Dakar, Senegal.

⁴Head of the Analysis Laboratories (GLA) group of the Mining Exploration and Promotion Directorate, Senegal.

Authors' contributions

This work was carried out in collaboration among all authors. Authors LB and FD designed the study. Author MM performed the statistical analysis. Authors Dome Tine and Djibril Tine made the maps. Authors LB, SD and GF wrote the protocol and wrote the first draft of the manuscript. Authors LB and NPDD managed the analyses of the samples. Authors LB, SD and MM managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The locality of Nioro du Rip is facing intense erosion, loss of agricultural land, soil pollution and soil degradation. Today, there is limited information about the soil physical and chemical properties in the locality. In this work, we describe the main essential factors or mechanism that control the evolution of the soil in the study area.

The physical and chemical properties of soils encountered along a NE-SW transect in are analyzed in this paper. The statistical analysis results revealed low structural stability of soils in general, due to their low organic matter content and exchangeable bases and their predominantly silty texture. A

*Corresponding author: E-mail: rhobiaye@yahoo.fr;

net trend towards acidification, which is more pronounced in the lower-bottom and terrace soils, provides information on the conditions that are increasingly unfavorable to agricultural development.

The multivariate principal component analysis (PCA) identified the preponderance of two factors among the four primarily involved in soil geochemical composition. These include a mineralization process (expressed through the first principal component (PC1), which causes soils to be rich in elements (Ca^{2+} , K^+ , C, N, MO) controlling their structure and fertility level; The PC2 axis expresses the spatial differentiation phenomenon of the soil granulometric composition: soils forming cluster poles according to their textural affinity in the projection of the plane formed by these two components, with on one side the sandy-dominated soils of the shallows and terraces and on the other the clay-dominated soils of the plateau and the slope. A clear reversal of textural polarity in the studied topo sequence that must be blamed on the strong water erosion in this area.

Keywords: Soil; physical and chemical; erosion; principal component analysis assessment.

1. INTRODUCTION

Soil degradation by erosion is the main mechanism for the loss of agricultural land worldwide [1]. This poses a real problem for socio-economic development in sub-Saharan Africa [2]. In Senegal, soil erosion has become a major concern, with 77% of degraded land being degraded through water erosion [3]. This is particularly the case in the Niore du Rip area, where until the 1950s, soils were protected by relatively dense natural vegetation. Since the 1960s, rampant population growth has led to overgrazing and significant clearing of forest areas. Apart from these changes in land use, the rainfall deficit of the 1970s has led to environmental degradation, including forest destruction and significant loss of habitable/arable land and both quantitative and qualitative deterioration of the region's soils [4]; impacts that have ended up affecting the entire local economy, which depends on agriculture. The soils of the study area (mainly sesquioxide, holomorphic and hydromorphic types) developed on the lands of the late Tertiary [5]. Their strong anthropogenic and aggressive rains have negatively impacted their physical-chemical properties. Several authors [6-9] have revealed their trend towards acidification, with an increase in their content of exchangeable aluminum and a decrease in their organic status. In addition to a classic characterization study based on their physical-chemical properties, the study uses a multivariable statistical technique such as principal component analysis to highlight the key factors or mechanisms that control soil evolution in the study area.

2. MATERIELS AND METHODES

The Niore du Rip department is in the Kaolack region. It covers an area of 2296.5 km² and is

limited to the north by the departments of Kaolack and Kaffrine, to the west by the department of Foundiougne (Fatick region), to the south and southeast by the Republic of Gambia (Fig. 1). From a geological point of view, the soils of the study area developed on the sandstones of the Continental Terminal. These are, for the most part, soils with sesquioxide, hylomorphicsoils and hydromorphic soils forming, from a geomorphological point of view: Plateau 15 to 20 meters above sea level, with armor outcropping at the periphery and border. Convex-concave convex connecting glazes noted in laterites. Terraces that are thick formations of colluvionnement and alluvial, and finally shallows that are beds of dead valleys and old beds of the tributaries of the Baobolong [10]. The study of the study area was based on the measurement of soil and geomorphological parameters.

The transect used in the study was selected after surveying the area for recognition of soil surface conditions. The path of this north-east/southwest direction transect is as materialized in Fig. 2. The height difference is 13 m for 2 km on its route. Field observations have allowed us to identify a significant phenomenon of water erosion from the ridgeline of the basin, becoming increasingly pronounced towards the southwest. A direction in which the slopes become much stronger, thus promoting an intensive runoff of rainwater. The ability to infiltrate stormwater is reduced, due to the low permeable nature of the soil and the dilapidated vegetation cover, which has been greatly undermined by agricultural practices, deforestation, and anarchic urbanization.

The fieldwork consisted first of identifying the different surface soil units (Fig. 3), then digging pits to make a description of the soil profile (Fig. 4), before taking samples for laboratory analysis.

In total, four soil pits, known as P1 to P4, were dug along the transect and a few fifteen (15) soil samples taken from sachets. The samples were carefully referenced, before being sent to the laboratory for a series of physical and chemical analyses; the determinations made on each sample are as follows [11,12]:

- pH-water, pH-KCl and electrical conductivity (CE) horizons from soil suspension solutions.
- granulometry, sifting and decanting of fines using Robinson's method.
- the tradable bases (Calcium, magnesium, sodium, and potassium), using ammonium acetate and sodium acetate methods.
- Cationic exchange capacity (CEC), by the saturation method at NH_4^+ ;
- organic carbon (C), by Anne's method,
- Nitrogen (N), by the method of Kjeldahl.

The behavior of organic matter has been studied by dosing the C/N ratio, which allows the ability of organic matter to decompose in the soil. This C/N ratio makes it possible to characterize the organic matter present in the soil [13].

2.1 Data Processing

In addition to statistical description, the interpretation of the results was based on the main component analysis (PCA) of the data, to look for possible relationships between the different parameters measured on soil samples [14]. Indeed, these parameters very often correlate with each other, due to the same control mechanism ("phenomenon or associated factor"), responsible for their dependence or inter-correlation. The PCA method is a statistical mathematical process that makes possible the search for correlation between the parameters studied and thus makes it possible to systematize the information they contain [15]. In doing so, it allows us a better understanding of their structure and thus facilitates their interpretation. It focused here on the 16 parameters (or variables) that are: the S sand content, L silt, clay A, calcium Ca^{2+} , magnesium Mg^{2+} , sodium Na^+ , potassium K^+ , total carbon-C, nitrogen N, organic matter OM, S exchangeable bases, CEC cation exchange capacity, saturation rate (V), pH water, acid pH and electrical conductivity-CE.

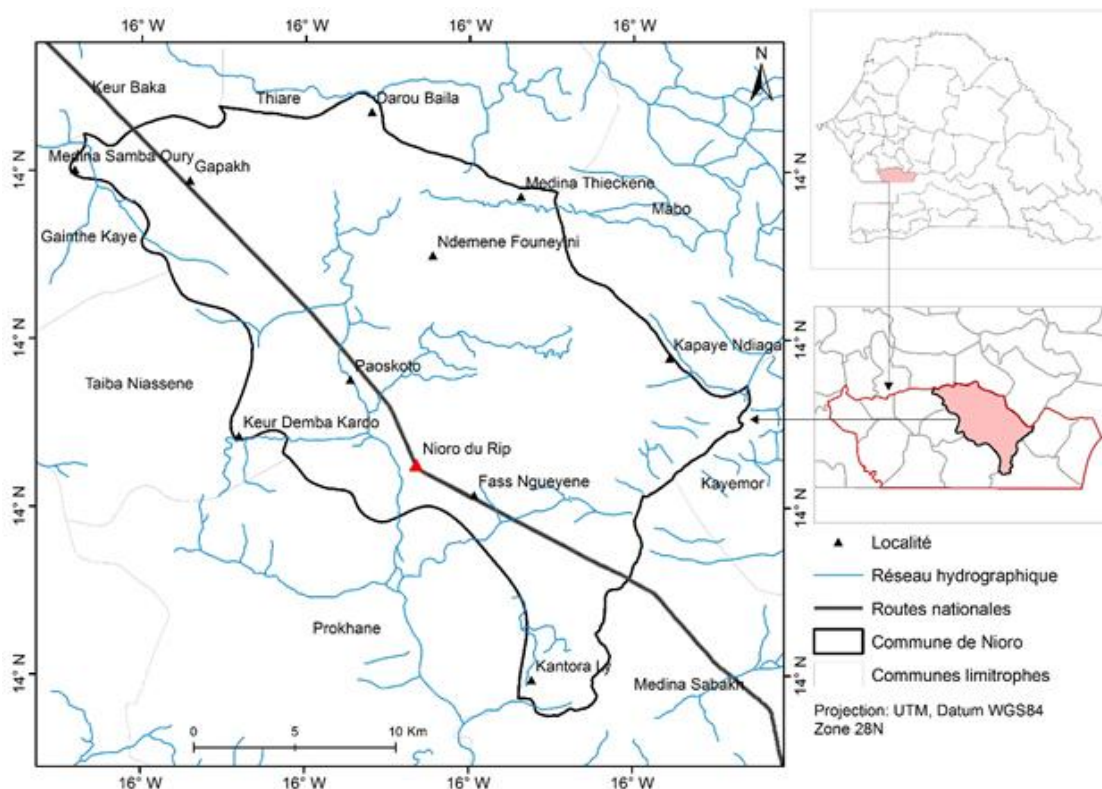


Fig. 1. Geographical location of Nioro du Rip

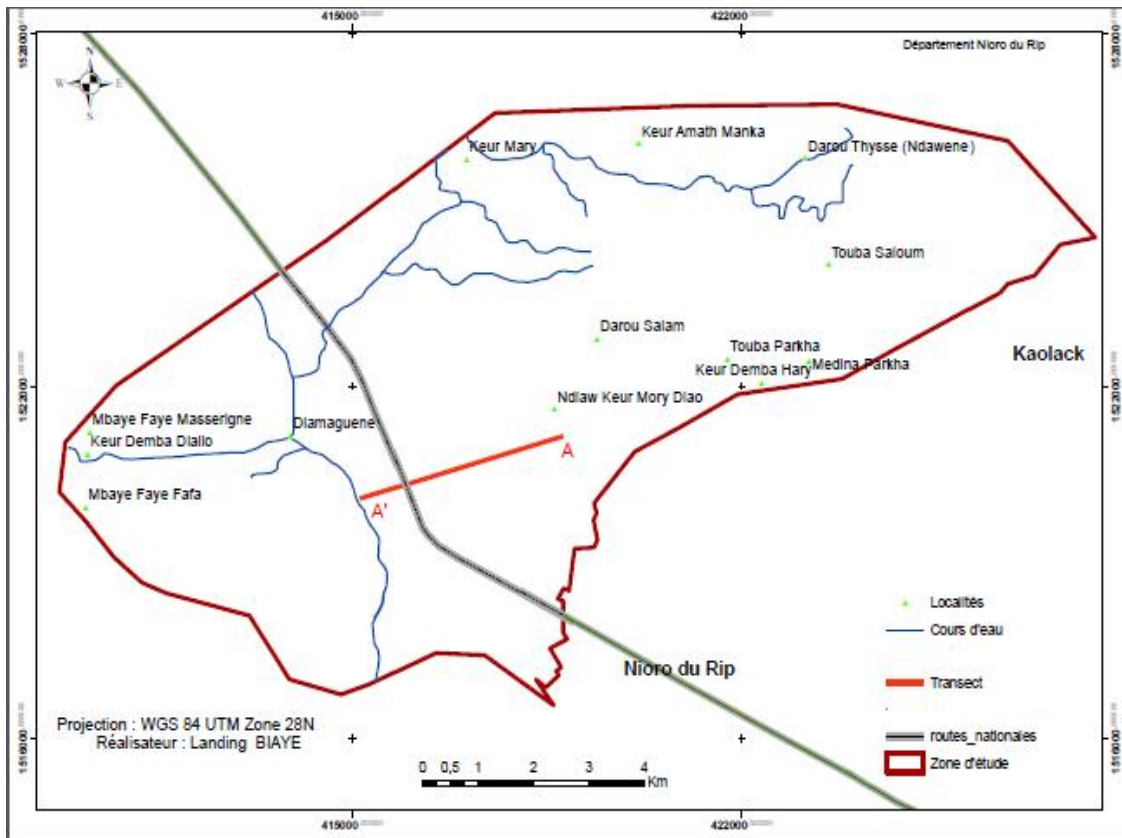


Fig. 2. Direction of the study area transect (A-A'cutting line)

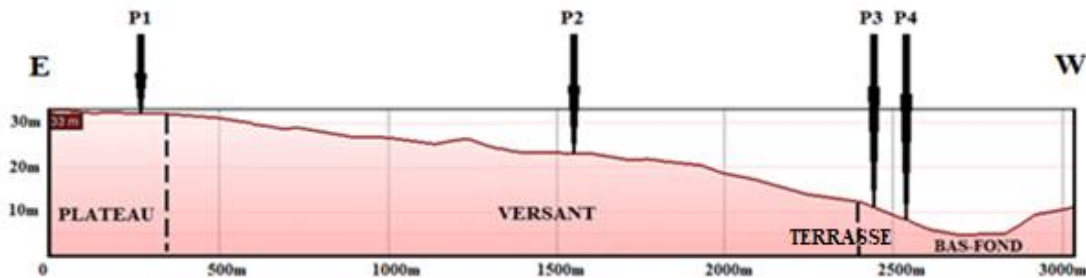


Fig. 3. Position of pedological profiles following the topography

2.2 Principal Component Analysis

To properly characterize a soil, one usually needs to measure several of its physical-chemical parameters (or properties). But very often, the different parameters measured are not independent. They show a certain level of correlation between them, due to the same control mechanism. The PCA method allows for a grouping of intercorrelated parameters (or variables) in the form of new mathematical

magnitudes, commonly referred to as "factors" or "principal components," at which each influenced variable marks or scores a weight (a factor weight) in terms of variance explained by the factor that influences it. Seen from this perspective, the PCA is a tool for synthesizing (compression) of information contained in a database [16] and the factor weight of a given variable on a factor provides an idea of its degree of correlation with it [17]. The PCA was operated here using R software [18].



Fig. 4. Position of pedological profiles following the topography

3. RESULTS AND DISCUSSION

3.1 Descriptive Analysis of Physical and Chemical Parameters

3.1.1 Granulometry

The granulometric composition of the samples taken is given in the (Table 1). The soils of the plateau are sandy-luminous in the first horizon, limono-sablo-clayey in the second and third horizon. The soils of the sandy, limono-sand and limono-sablo-clayey slope. The terrace floors are either limono-sandy or sandy. Hydromorphic soils are sandy. At the plateau and slope level, the percentage of sand decreases with depth (Table 1). The percentage of silt decreases in the second horizon, before increasing in depth. The percentage of clays increases with depth. At the terrace level, the percentages of silts, sands and clays are not constant in different horizons. Those of silts and clays increase in the early horizons, they are stable in the intermediate and lower horizons. At the bottom, the percentage of sands and silt decreases with depth while the percentage of clays increases.

3.1.2 pH

The soils of the plateau and slope show acid pH in the upper horizons, with values between 5.1 and 5.6 and between 5.2 and 5.8, respectively. Values then decrease in the second horizon, before increasing in depth (Table 1). On the

terrace, the floors are slightly acidic to neutral (6.4 (pH 7.4) while the low-bottom soils are slightly acidic (pH 6.5) acidic (pH 5.7). The pH increases deeply on most of the terrace floors, but it decreases with depth in the shallows. Along the time of the time pH values are not constant in the superficial horizons.

3.2 Electrical Conductivity (EC)

According to the classification established by Durand in 1983 (Baize, 2000), the soils of the plateau, slope, terrace, and shallows are unsalted ($EC \leq 500 \mu S/cm$). Their salinity varies between $11.08 \mu S/cm$ at the plateau and $111.8 \mu S/cm$ at the bottom. The electrical conductivity of soils varies, and it is lower at the plateau and slope ($11.08 \mu S/cm \leq EC \leq 15.51 \mu S/cm$) than at the terrace and bottom ($39,98 \mu S/cm \leq EC \leq 111.8 \mu S/cm$).

3.3 Organic Matter Content and C/N Ratio

Except for the first horizon of the terrace (having a C/N ratio - 11.4%), all the floors of the plateau, slope, terrace, and bottom, have a C/N - 12. This indicates that mineralization is slowed by conditions of anaerobic and excessive acidity [15]. The value of the C/N ratio ranging from 19.65% to 12% indicates excess carbon due to poor degradation of organic matter and lack of oxygen (anaerobic conditions). The evolution of organic matter according to depth is the same in all geomorphological units: it decreases with

Table 1. Results of physical and chemical analyses of samples

Profile cm	pH water	pH KCl	EC µS/cm	C %	P ppm	N %	C/N %	OM %	Clay %	Limon %	Sand %	Ca ²⁺ %	Mg ²⁺ %	K+ %	Na+ %	EB %	CEC %	Sat
11.5	5.4	5.1	13.5	0.4	23.9	0.027	0.7	14.4	6.4	3.8	89.7	2.5	0.2	0.1	0.1	2.8	3.3	84.5
11.5-60	5.1	5.0	11.1	0.3	13.5	0.018	0.4	13.9	12.9	3.4	83.6	1.4	0.1	0.1	0.1	1.8	3.9	45.3
60-135	5.6	5.2	14.7	0.2	8.9	0.017	0.4	13.3	17.6	4.3	78.1	1.9	0.2	0.1	0.1	2.3	5.2	44.8
18.5	5.8	5.6	17.2	0.4	136.5	0.030	0.7	12.9	3.4	2.6	93.9	2.3	0.1	0.1	0.1	2.5	3.1	82.4
18.5-60	5.3	5.1	14.9	0.2	36.1	0.012	0.4	19.6	12.9	2.8	84.3	1.7	0.2	0.1	0.1	2.1	3.6	56.1
60-125	5.5	5.4	15.5	0.2	24.2	0.013	0.4	17.6	16.9	3.5	79.5	1.6	0.4	0.1	0.1	2.3	6.5	34.8
30	6.6	6.4	56.8	0.7	8.1	0.065	1.3	11.4	8.3	4.9	86.7	2.8	0.6	0.2	0.1	3.6	6.1	60.0
30-62	7.0	6.9	48.9	0.7	8.4	0.052	1.3	14.4	10.7	6.1	83.2	3.8	0.1	0.4	0.1	4.4	7.6	57.8
62-82	6.9	6.7	39.9	0.3	6.9	0.015	0.5	17.5	3.2	1.5	95.3	1.8	0.3	0.2	0.1	2.3	2.7	88.4
82-98	6.9	6.9	41.4	0.3	12.1	0.017	0.5	14.9	3.4	1.4	95.2	2.3	0.1	0.1	0.1	2.6	2.7	96.7
98-110	6.9	6.8	63.6	0.3	5.7	0.018	0.5	17.6	3.4	1.5	95.2	2.2	0.7	0.1	0.1	3.1	3.9	78.1
110-129	7.3	7.1	48.2	0.2	4.0	0.021	0.4	11.9	5.9	3.7	90.4	2.4	0.3	0.1	0.1	2.8	2.9	95.9
129-170	7.4	7.1	47.6	0.2	4.9	0.016	0.4	12.9	7.6	4.6	87.8	2.2	0.3	0.1	0.1	2.7	3.9	69.8
25	6.5	6.4	111.8	0.4	5.4	0.022	0.7	18.9	2.6	1.9	95.5	2.4	0.3	0.1	0.1	2.9	2.9	98.8
70	5.7	5.6	42.7	0.3	3.1	0.018	0.5	14.3	3.4	1.8	94.7	1.8	0.1	0.1	0.1	2.2	2.3	94.8

depth (Table 1). This low organic matter content can result in low soil reserves, low structural stability and low biological activity.

3.4 Tradeable Base Grades and Cationic Exchange Capacity

The content of tradable bases (Table 1) is higher in the upper horizons of the plateau, slope, terrace, and shallows. This indicates according a low level of organic matter. Surface horizons have a much lower CEC than depth horizons. This could be related to the low clay content in these horizons. Mg/K reports point to a shortage of exchangeable potassium ($K \leq 0.2$ meq/100 g). The exchangeable Ca content is significantly higher than the K, Mg and Na levels and represents almost two-thirds of the tradable bases, thus demonstrating the acidity of these horizons. It varies on average between 1.4 and 3.8 meq/100 g. The Cationic Exchange Capacity (CEC) not only assesses the degree of saturation (V) which is a valuable indication for the potential fertility of soils but also gives an idea of the nature of clay minerals. Several classifications can be determined by the saturation level (S/T).

Saturation ($S/T > 95\%$) at intermediate horizons of the terrace and the horizons of the lower depth. sub-saturation » ($80\% \leq S/T \leq 95\%$) at higher horizons of the plateau and slope and the intermediate horizons of the terrace. meso-saturation » ($50 \leq S/T \leq 80\%$) at intermediate horizons of the terrace and the second horizon of the slope and Oligo-saturation ($20 \leq S/T \leq 50$) for the deep horizons of the plateau, the slope, and the terrace.

All the stages of saturation are found at the level of the terrace floors which thus form, with the deep horizons of the plateau and the slope, the areas with low saturation rate. The latter are characterized by significant acidity, low fertilizer reserves and low microbiological activity.

3.5 Phosphorus Content

On the shelf, the assimilable phosphorus content ranges from 8.9 to 23.9 g/kg. On the slope, it varies between 24.2 and 136.5 g/kg; in terraces between 4 and 12.1 g/kg and in the shallows between 3.1 and 5.4 g/kg. The soils on the slopes therefore have the highest assimilable P content. But, this content decreases with depth, with increased pH and reduced organic matter content. On the slopes, the assimilable P content may be related to the presence of Al^{3+} and Fe^{2+} cations or drainage processes.

3.6 Principal Component Analysis Results

The PCA allowed us to find the specific values of the linear correlation coefficient matrix between the different variables, to determine the specific components or variables responsible for these own values, but also to see the level of correlation between the starting variables and "associated factors." The results are shown in Table 2 which provides the specific values of the correlation coefficient matrix, as well as the percentage of variance explained by each main component of the resulting statistical model. There are 4 essential components (PC1, PC2, PC3 and PC4), totaling more than 92% of the variance described by the model; other factors (PC5 to PC14) participating only very timidly in the description of the information contained in the starting variables.

3.7 Interpretation of the Model

PC1 expressing the highest percentage of variance (42.94%) is well correlated with the variables Ca^{2+} , K^+ , C, N, MO, and S (Table 2). It can therefore be considered as the axis highlighting mineral decomposition and soil structure. PC2 (32.54% of variance) that correlates well with clay, sand, V saturation and T CEC reflects granulometric soil differentiation. With scores around 10% of the variance explained by the model, the PC3 components (10.22% of variance and grouping the variables Mg^{2+} , pH water and acid pH) and PC4 (variance 6.73% and discriminating EC variables, pH KCl) are quite poorly expressed in the model. This makes it difficult to interpret them. However, PC3 could be perceived as a factor in acidification and degradation of soil structure by magnesium salt accumulation, while PC4 could be considered a factor in soil salinization (total mineralization).

The projection of variables and individuals (soil samples) in the plane formed by the PC1 and PC2 components that are sufficient to explain nearly 75% of total inertia (Fig. 5) makes it possible to notice two things: A clear tendency of the terrace floors to distinguish itself from the soils of the plateau and the slope through the mineralization process (PC2 component) at the origin of the accumulation in MO, K, N, C and Ca^{2+} ; spatial grouping by textural affinity and degree of acidity of the lower and terrace soils on the one hand (in the upper left dial of the plot) and the floors of the plateau and slope on the other hand (in the lower left dial) linked to the

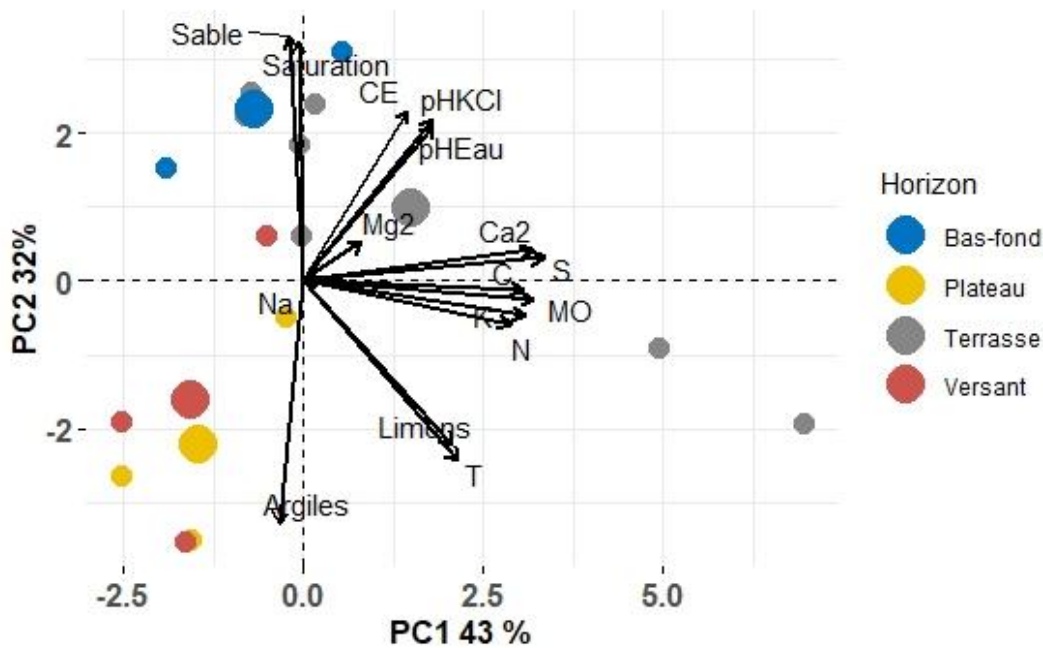


Fig. 5. Clouds of variables and individuals in the factor plane PC1-PC2

Table 2. Results of the principal component analysis

Factor	Contribution of factors			Contribution of variables				
	Eigenvalue	%Variance	% Cumulative variance	Variables	PC1	PC2	PC3	PC4
PC1	6.44	42.94	42.94	pH-water	4.16	7.45	15.17	9.77
PC2	4.88	32.54	75.48	pH-KCl	4.15	8.14	13.71	11.52
PC3	1.53	10.22	85.69	EC	2.75	9.02	4.19	43.53
PC4	1.01	6.73	92.42	C	12.13	0.02	9.12	5.84
PC5	0.39	2.63	95.05	N	12.36	0.37	3.57	5.67
PC6	0.37	2.47	97.52	OM	13.29	0.11	5.73	4.25
PC7	0.20	1.30	98.83	Clay	0.15	18.35	3.88	0.54
PC8	0.09	0.59	99.41	Limon	5.58	8.44	0.56	5.98
PC9	0.05	0.33	99.74	Sand	0.05	18.67	3.22	1.37
PC10	0.02	0.15	99.89	Ca	13.29	0.30	1.12	3.47
PC11	0.01	0.05	99.94	Mg	0.84	0.47	29.74	5.27
PC12	0.01	0.04	99.98	K	10.80	0.59	0.88	6.40
PC13	0.00	0.02	99.99	Na	0.00	0.00	0.00	0.00
PC14	0.00	0.01	100.00	S	14.48	0.18	0.34	0.04
				T	5.97	10.04	4.44	0.24
				V	0.01	17.84	4.33	1.11

effect of the PC2 factor. Contrary to what might be expected, samples collected at the plateau and watershed cover show a more argilo-limonous texture as opposed to those taken at the low-bottom level and the terrace with a

sandier texture. Through this anomaly, we find the impact of significant water erosion in the basin that appears to be responsible for this granulometric inversion.

4. CONCLUSION

This work shows that the soils studied are characterized by low structural stability because of their low organic content, exchangeable bases, and silt-dominant texture. The PCA results identified four major processes of soil evolution, two of which appear to be the most important: a primary process of decomposition of organic matter and a secondary process of deterioration of soil texture/structure. These two observations are consistent with those of Betardand Bourgeon [4]. The second process (granulometric factor) is decisive since dominant clay-limestone fraction soils have low cohesion; this facilitates their detachment and facilitates the transport of soil fertilizers. It precedes the acidification of the watershed soils and their gradual salinization. These four main factors confirm the work Cisse [2] and are consistent with the observations of authors such as Teixeira [5], and Ndiaye [6]. This study also shows a greater acidification at the terrace and shallows where acid sulphate soils with jarosite stains developed by Diop [3]. Compared to plant needs, our results indicate a serious deficiency of soils in chemical fertility (S, CEC, and OM).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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