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# Detailed Soil Mapping and Fertility Potential at the Borotou-Koro Integrated Agricultural Unit (Northwest Côte d'Ivoire)

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## Abstract

As soil mapping is an essential tool for sustainable agriculture, the aim of this study was to draw up maps of the different soil classes, taking morphopedology into account, with view to precise management of amendments and fertilizers in sugarcane cultivation, at the Borotou-Koro integrated agricultural unit. To this end, descriptive field and analytical laboratory data from 249 soil profiles were grouped into cartographic units and geostatistically processed using Geographic Information System software (Qgis). A total of five major soil classes were identified, namely Cambisols (74.8%), Gleysols (17.8%), Arenosols (6.5%), Plinthosols (1.4%) and Leptosols (0.6%). With regard to the nutritional standards of sugarcane cultivation, the analytical results indicate that all these soils are capable of meeting the demand for carbon, at very high levels (> 50 $g.kg^{-1}$). For the other parameters, they showed partial levels of satisfaction. Phosphorus demand was met with average levels in Plinthosols and Leptosols, then high levels in Cambisols and Arenosols. Magnesium demand is met with average levels in Cambisols and Leptosols. Calcium levels are considered average in Plinthosols, then high in Cambisols and Leptosols. Potassium levels are high in Cambisols and Plinthosols, then average in Arenosols and Leptosols. Nitrogen and cation exchange capacity are below the required threshold on all these soils. Deficits are lower for Cambisols, but relatively high for all other soil types, especially Gleysols. This justifies the need for measures to restore soil fertility levels, accompanied by maintenance fertilization in line with yield objectives.

***Keywords:*** Mapping; Cambisol; Fertility potential; Borotou-Koro; Ivory Coast

## Introduction

Sustainable development objectives call for a type of agriculture oriented towards respect for the environment with the best possible yields (Molina-Maturano et al., 2021). This means abandoning concepts such as topsoil without taking into account the full soil profile; the use of regional fertilization rates based on NPK, without taking into account soil diversity; and the application of amendments and other agricultural inputs without accurate diagnosis. Detailed information on soil profile and spatial distribution is essential to promote sustainable agriculture, with precise inputs in quantity, space and time (Alemán-Montes et al., 2019; Taghizadeh-Mehrjardi et al., 2014). In particular, accurate and up-to-date soil attributes enable better and more efficient fertility management, to the benefit of crop productivity and sustainability (Bautista, 2021; Hernández et al., 2018; Nangah et al., 2012).

Soil is a prerequisite for maintaining the normal functioning of terrestrial ecosystems (Chen et al., 2020; Wagg et al., 2019). Soil quality directly or indirectly affects plant growth (Dai et al., 2020), food production (Grumbine et al., 2021; Gomiero, 2016), and human health (Bünemann et al., 2018). For this reason, the UN (2013) declared that "...soils are the foundation of agricultural development, essential ecosystem functions and food security, and are therefore essential to sustaining life on Earth".

In practice, precision agriculture is not practiced in developing countries for several reasons, such as excessive division of land into small plots, lack of data generation capacity to produce plot maps, insufficient technical capacity of producers to make diagnoses, and scarcity of laboratories, among others (Molina-Maturano et al., 2021; Lowenberg-DeBoer and Erickson 2019). Faced with this situation, the generation of methodological strategies is necessary to achieve better soil fertility diagnostics.

In Côte d'Ivoire, the agricultural sector accounted for 28 p.c. of the country's GDP and 40 p.c. of its exports in 2018 (World Bank Group, 2023). These lands have been used for sugarcane cultivation for almost forty years. Today, the area is not immune to the problems of soil degradation linked to overexploitation, resulting in yield losses. Most crops are grown on the plains. In the hills, the main crops are rice, manioc, citrus fruits and many others. However, there is a variety of soils in both plains and hills according to WRB (2015); notably, Gleysols (GL), Fluvisols (FL), Vertisols (VR), Histosols (HS), Technosols (TC)... generally on the plains. Then there are Ferralsols (FR), Cambisols (CM), Acrisols (AC), Plinthosols (PL), Leptosols (LP), Umbrisols (UM)... on plateaus and hills. These soil groups present two main agricultural problems, excess moisture (GL, FL, VR), low chemical fertility (AC, UM), low pH values and low base saturation (López-Castañeda et al., 2022).

Soils and crops are different, but fertilization varies very little, and is mainly focused on nitrogen, phosphorus and potassium (Tinal-Ortiz et al., 2020; Aguilar-Rodríguez et al., 2017). Knowledge of landforms is insufficient to achieve agriculture in line with sustainable development objectives. It is necessary to improve the accuracy of land use.

In recent years, remote sensing has been generated to express soil properties in surface units of square meters or hectares (Gayegoz-Tavera et al., 2016). The study of soil profile for agricultural improvement goes beyond the so-called topsoil. Soil is measured from the surface downwards, but not from the surface upwards.

Geostatistics is the main discipline used in studies of soil spatial heterogeneity, which has helped popularize precision or site-specific agriculture. Geostatistics is used to create maps and thus estimate soil property values for unsampled sites (Bautista, 2021), leading to cheaper and faster plot mapping (Delgado et al., 2010; Goovaerts, 2001). One of the main weaknesses of plot maps produced using geostatistical techniques lies in the use of the topsoil (0-30 cm depth), arguing that this is where crop nutrition takes place, which is partially true. However, most soils used in agriculture have a depth of 1 m or more; in other words, a large amount of fine soil is ignored, which also influences crop nutrition and support.

The aim of this work is to develop a methodological strategy for creating digital soil maps taking into account soil profiles.

## Materials and Methods

### *Presentation of the study area*

The Unité Agricole Intégrée de Borotou-Koro is located in the northwest of Côte d'Ivoire, in West Africa, and is one of the main sugarcane production areas. Formerly the Borotou-Koro sugar complex, the Unité Agricole Intégrée de Borotou-Koro is located 840 km from Abidjan. It is geographically located between coordinates 8°36'11" and 8°21'33" latitude North, and 7°17'41" and 7°5'49" longitude West (Fig. 1). The climate is Sudano-Guinean, tropical humid, with two seasons: the rainy season, the longest, from April to October, and the dry season, from November to March. The dominant vegetation in Borotou-Koro is shrub and herb savannah, separated by patches of forest and gallery forest along the watercourses (Yao, 2017). The fauna is highly diverse. Indeed, this wild fauna includes many species harmful to sugarcane. These include duikers and rodents. Borotou-Koro's relief is generally made up of flat plateaus, 200 to 400 m high. The relief is fairly flat, monotonous and includes large plains (Yao, 2017). From a water point of view, Borotou-Koro is drained by two rivers, the Bagbè and the Boa, which join the Sassandra River, of which they are two tributaries. Sugar cane is grown here by Sucrivoire, cooperatives and small growers.

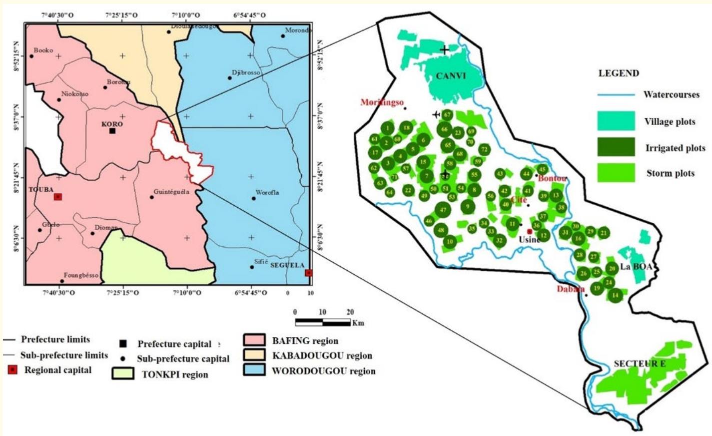



***Figure 1:*** Location of study area.

## *Field data*

Field activities consisted in locating toposequences according to the variation in topography and in a representative manner in order to cover the whole of our study area. Subsequently, soil pits 1m20 deep, 1m long and 80cm wide were opened and described. A total of 249 soil pits were opened over the entire study area (Fig. 2).

## *Satellite data sets and pre-processing*

Sentinel (S-2) multispectral optical data were used to map the spatial distribution of *land use* and *land cover* and soil types in the study area. Designed to carry out continuous measurements for the next 20 years, the Sentinel sensors were developed as part of the European Union Commission's Copernicus program (ESA, 2017). S-2 carries an innovative wide-swath high-resolution multispectral imager with 13 spectral bands (down to 10 m) and has improved information retrieval compared with previous sensors such as Landsat (Drusch et al., 2012; ESA 2017). All data are freely available on the ESA Data Hub (scihub.copernicus.eu). These multispectral data were used to map the spatial distribution of land use, land cover and soil types in the study area.

A total of 21 bands were used in this study, covering the period from October 2020 to April 2021. They are composed of the mean value of 11 spectral bands, 7 vegetation indices and 3 spectral indicators, namely the packed cap (humidity, brightness and greenness) (Table I). The images were automatically atmospherically corrected and resampled to 10 m in the Google Earth Engine cloud computing system.

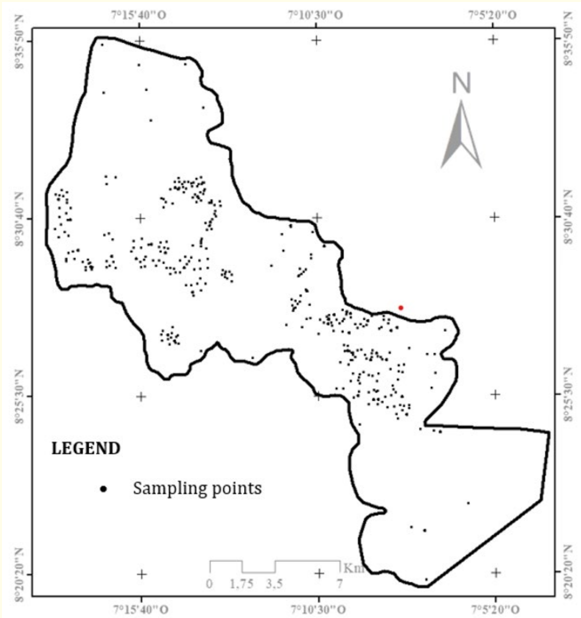



***Figure 2:*** Spatial distribution of sampling points.

## *Image classification*

In image classification with the Random Forest (RF) algorithm, as described by Breiman (2001), classes are assigned in a hierarchical system of rules and decisions. Binary decisions are used to assign a certain pixel to a certain class. This is done by inheriting properties from the highest (i.e. coarsest) decision levels to the lowest (i.e. finest) decision levels (Friedl and Brodley 1997). RF uses a set of training data to build several decision trees, each tree being constructed on the basis of a set of basic data. The training data is typically an array of values obtained by superimposing reference field data (e.g. polygons) on a set of satellite images (e.g. spectral bands and predictor indices) and extracting the corresponding values.

A two-stage classification approach, similar to the methodology described in Ouattara et al. (2020), was implemented to map the classes of interest. This approach improved the accuracy of soil classification. Reference data were randomly divided into training (training sets) (70%) and testing (validation) (30%). This was done to ensure class representativeness in both datasets (Millard and Richardson 2015).

## *Soil analysis methods*

Analytical determinations were carried out using the classic techniques described by Pauwels et al. (1992).

## *Determining particle size*

Particle size fractions were determined using a Robinson-Köhn pipette.

## *pH measurement*

pH was determined by the electrometric method, with a soil/solution ratio of 1/2.5.

### *Determination of soil carbon content*

Soil organic carbon content was determined using the Walkley and Black (1934) method.

### *Determination of soil total nitrogen content*

The Kjeldahl method was used to determine the total nitrogen content of the soil.

### *CEC measurement*

Cation exchange capacity (CEC) was determined using the pH 7.0 buffered ammonium acetate method (Peech, 1945).

### *Determination of exchangeable bases*

Exchangeable bases are extracted from the soil with an ammonium acetate solution buffered at pH7, then determined by atomic absorption spectrophotometry.

### *Determination of assimilable phosphorus*

Assimilable phosphorus was determined by the Olsen method.

### *Determination of total phosphorus*

Total phosphorus was determined by extraction with boiling nitric acid, followed by determination by molybdenum blue spectrophotometry.

| *Vegetation indices* | *Equation* | *References* |
|---|---|---|
| **EVI 2** : Improved two-band vegetation index | *G ((NIR – Red) / (NIR + 2,4 * Red + 1))* | Jiang et al., 2008 |
| **MNDWI** : modified standardised water index | *(Green – SWIR2) / (Green + SWIR2)* | Xu, 2006 |
| **SAVI** : Ground-adjusted vegetation index | *1 + L ((NIR – Red / (NIR + Red + L))* | Qi et al., 1994 |
| **GOSAVI** : Optimised ground-adjusted vegetation index green | *(NIR – Green) / (NIR + Green + Y)* | Qi et al., 1994 |
| **NDRE** : Normalised difference Index Red-Edge | *(NIR – Red Edge) / (NIR + Red Edge)* | Gitelson and Merzlyak, 1996 |
| **NDVI** : Normalised difference vegetation index | *(NIR – Red) / (NIR + Red)* | Rouse et al., 1973 |
| **NDWI** : Normalised water difference index | *(Green – NIR) / (Green + NIR)* | McFeeters, 1996 |
| **Humidity** | *(Blue * 0,1509) + (Green * 0,1973) + (Red * 0,3279) + (NIR * 0,3406) + (SWIR1 * (-0,7112)) + (SWIR2 * (-0,4572))* | Kauth and Thomas, 1976 |
| **Luminosity** | *(Blue * 0,3037) + (Green * 0,2793) + (Red * 0,4743) + (NIR * 0,5585) + (SWIR1 * 0,5082) + (SWIR2 * 0,1863)* | Kauth and Thomas, 1976 |
| **Greenery** | *(Blue * (-0,2848)) + (Green * (-0,243)) + (Red * (-0,5436)) + (NIR * 0,7243) + (SWIR1 * (-0,0840)) + (SWIR2 * (-0,1800))* | Kauth and Thomas, 1976 |

G=2.5 (gain factor), t = 1 (Soil adjustment factor), Y = 0.16 ; NIR : near-infrared band ; Red : red band ; SWIR : Short wave.

***Table 1:*** Vegetation indices used and their mathmatics formula.

## Results

### *Soil type classification*

A general classification of land use and land cover was first carried out, comprising three classes (soil, rock and water) (Fig. 3a). In a second step, the classification was restricted to only the soil areas mapped in step 1, masking non-soil areas. At this stage, five major soil classes were considered (Fig. 3b). The results of the sequential classification achieved an overall accuracy of 77.88 p.c.

Field work, including the description of profiles and test pits, is an important step in soil mapping. Borotou-Koro is characterized by a great diversity of soil types. This diversity is inherited from differentiated geological formations and a hydrographic network with major rivers (Boa and Bagbè). The morphopedological study and soil inventory revealed five (05) major soil classes throughout the study area, namely Cambisols, with a surface area of 20036.6 ha, covering 74.2 p.c. of the total surface area, are the most widespread soil classes. Next come Gleysols, a soil class covering an area of 4810.76 ha, accounting for 17.8 p.c. of the total surface area. Arenosols, with a surface area of 1757.45 ha, account for 6.5 p.c. of the total surface area. Plinthosols, with a surface area of 384.42 ha, represent 1.4 p.c. of the total surface area. Leptosols, with 0.07 ha, account for 0.1 p.c. of the total surface area (Fig. 4).

### *Soil morphology and agronomic value*

### *Morphopedological characteristics of Cambisols*

Most of the soils have a brownish character, caused by altered rocks dominated by ferromagnesites (Fig. 5). These soils are generally dark reddish brown (5YR3/4) on the surface, or reddish brown (2.5YR4/4). Hydromorphic patches, reddish yellow (7.5YR6/8) when wet, pink and yellow (2.5YR8/3, 10YR8/8) when dry, are common. Overall, the soils are poorly drained at depth (drainage class: imperfect to moderate). Their average cation exchange capacity is between 4.1 and 12.9 cmol.kg$^{(-1)}$. The texture of these soils is predominantly sandy to sandy-loam. Morphologically, the dominant units observed are characterized by gravelly material (cuirass debris and gravel, pebbles and quartz sand), resting on gneissic alterite with ferromagnesian concretions. The coarse elements are mainly nodular and coarse in size. These soils are widespread at the top, upper and mid-slopes of the study area. With saturation levels of up to 85%, most of these soils are subsaturated. These are deep to shallow soils, with depths of up to 150 cm. The clays are generally swollen, marked by crusting. They contain four times more calcium than magnesium and much less potassium than calcium. It is therefore important to take this into account in your next chemical input recipe recommendation.

### *Morphopedological characteristics of Gleysols*

The Gleysols observed are generally brown to very dark grayish-brown (2.5Y 3/3; 2.5Y 3/2) on the surface, to gray (Gley1 6/N) at depth, with red (10R 4/6) and reddish-yellow (5YR 5/8) patches, moist to drowned (Fig. 6). Overall, the soils observed are poorly draining (drainage class: poor). Water withdrawal is so slow that the water table rises to the surface most of the time. The water retention capacity, texture and depth of these soils vary greatly. Their cation exchange capacity ranges from 1 to 5.33 cmol.kg$^{-1}$. Morphologically, the dominant units of Gleysols observed are characterized by perched nappes, resulting in strong iron reductions (anoxic conditions). These soils are sticky and difficult to work, with a predominantly sandy-loamy-clay texture. These soils are found in depression zones and low-lying landscape positions, with shallow groundwater. With saturation levels of up to 66%, most Gleysols in the study area are mesosaturated. They contain twice as much calcium as magnesium and much less potassium than calcium.

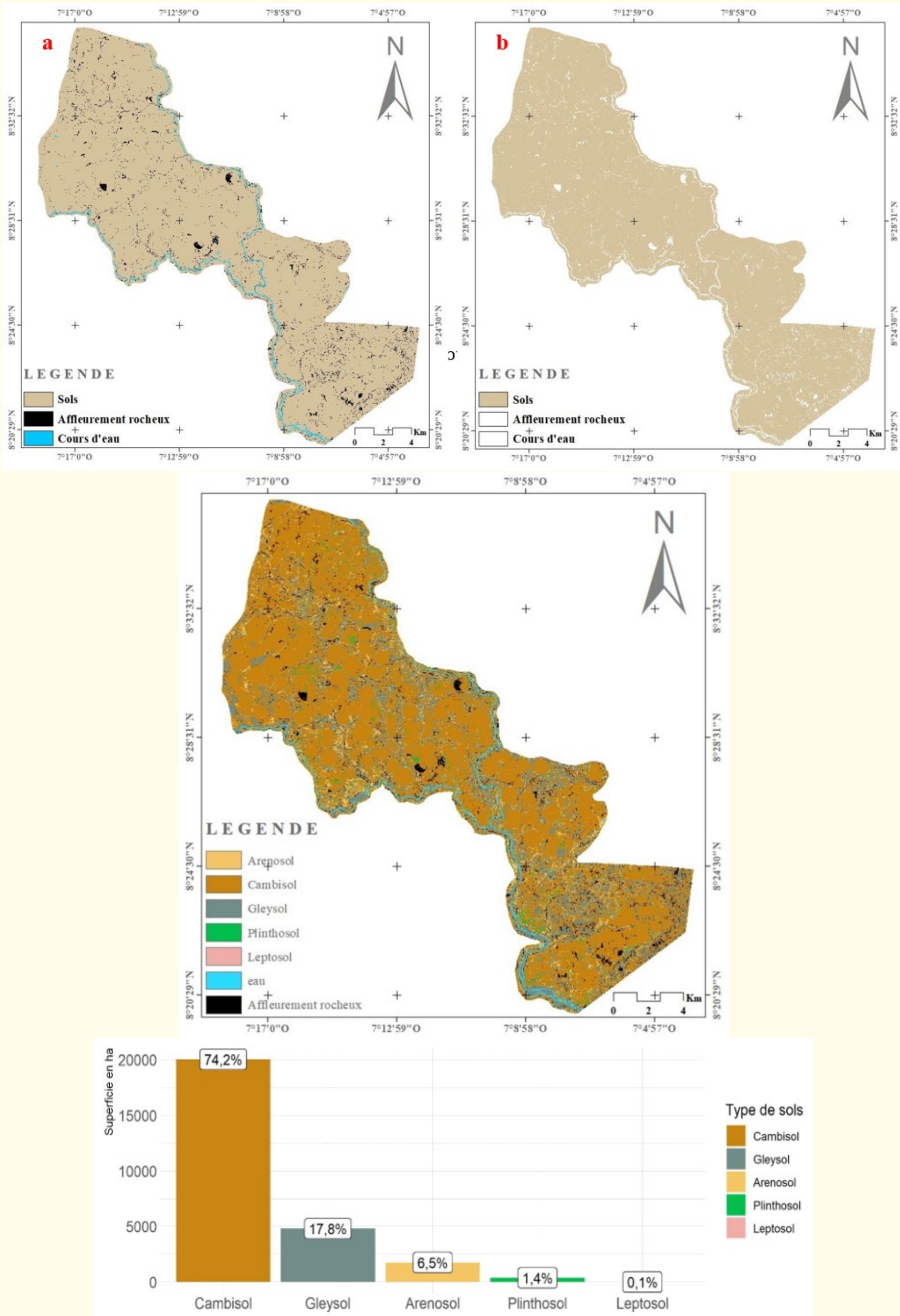
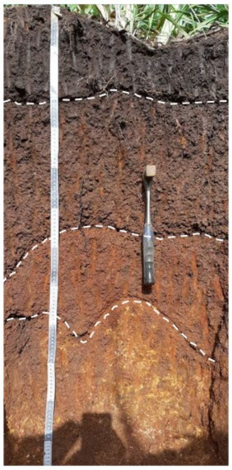



***Figure 4:*** Borotou-Koro soil map.



**Ap 0** - 23cm, ploughed horizon, sandy-loamy, dark reddish-brown (5YR3/4), moist, polyhedral structure with lumpy tendency, few fine roots, gradual transition.

**Bw** 23 - 55/69cm, sandy-loamy, reddish brown (2.5YR5/3), slightly moist, medium sub-angular structure, very fine and few roots, numerous ferromagnesian concretions, clear transition.

**BCtg** 55/69 - 75/88, sandy-loamy, light reddish brown (2.5YR6/3), slightly moist, medium-weak sub-angular structure, a few small ferromagnesian concretions, clear transition.

**Cg** 75/88 - 118**,** sandy-loam, light reddish brown (2.5YR6/3), slightly moist, sub-angular structure, numerous pink (2.5YR8/3) and yellow (10YR8/8) hydromorphic patches.

***Figure 5:*** Pseudogleyic Manganiferric Eutric Cambisol (Cutanic).

### *Morphopedological characteristics of Arenosols*

Arenosols are generally gray to very dark gray (10YR 5/1; 10YR 3/1) on the surface, to dark yellowish brown (10YR 4/3) at depth (Fig. 7). These soils are derived from colluvial materials, with sandy textures. They are slightly moist, with low particle structure, very few roots and rapid drainage. Water withdrawal is rapid in relation to water input. Soils have low water retention capacity. Their cation exchange capacity is between 2 and 5.5 cmol.kg$^{-1}$. Morphologically, the dominant Arenosol units observed are characterized by their particle structure and permeability. They are sandy soils, at least 100 to 120 cm thick. Highly permeable, they are little or not affected by excess water. These soils are relatively undifferentiated (very similar textures and colors). Their average contents of organic carbon (C), total nitrogen (N) and assimilable phosphorus (Pa) are, respectively, 5.6 g.kg$^{-1}$, 0.57 g.kg$^{-1}$ and 41.25 mg.kg$^{-1}$ of soil. With saturation levels not exceeding 45 p.c., most Arenosols in the study area are unsaturated. These are poorly developed soils with depths of up to 150 cm. They contain as much calcium as magnesium and much less potassium than calcium.

### *Morphopedological characteristics of Plinthosols*

Plinthosols are generally gray (10YR 5/1) on the surface, to reddish (2.5YR 5/6) at depth. Hydromorphic patches, reddish yellow (7.5YR 6/8) when wet, yellow (10YR 8/6) when dry, are common (Fig. 8). Compacted on the whole, these soils are moderately draining (drainage class: moderately good). Soil water withdrawal is fairly slow compared with water input. Soils have an average to high water retention capacity. Their texture is generally sandy-loamy. Their cation exchange capacity ranges from 3.6 to 9.9 cmol.kg$^{-1}$. Morphologically, the dominant units of Plinthosols observed are characterized by shallow, continuous plinthite, rich in ferromagnesian elements. However, the most obvious distinguishing feature of plinthite is, of course, that it hardens spontaneously on contact with water and other elements. The coarser elements are essentially gravel-sized, nodular pisolites. These soils are widespread at the top of the study area. With saturation levels of up to 78%, most Plinthosols in the study area are mesosaturated. These are shallow soils, with depths of up to 80 to 100 cm. They contain four times more calcium than magnesium and much less potassium than calcium.

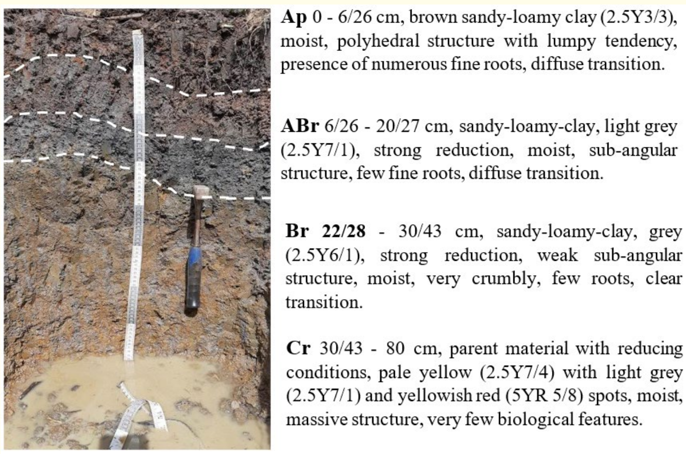



***Figure 6:*** Reductic Arenic Gleysol (Eutric, Endostagnic).

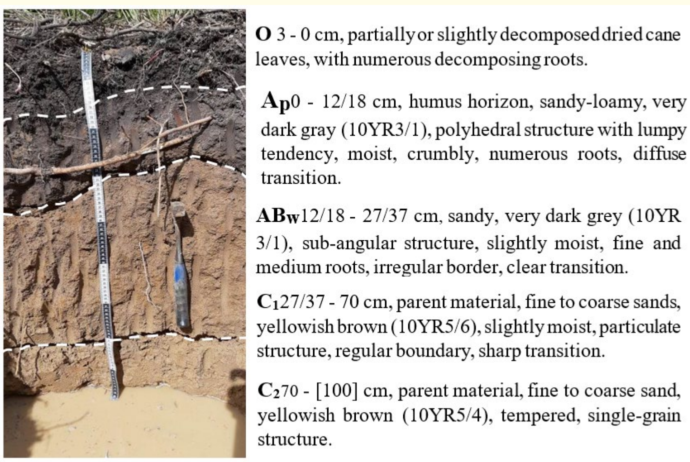



***Figure 7:*** Endostagnic Cambic Arenosol (Distric, fluvic).

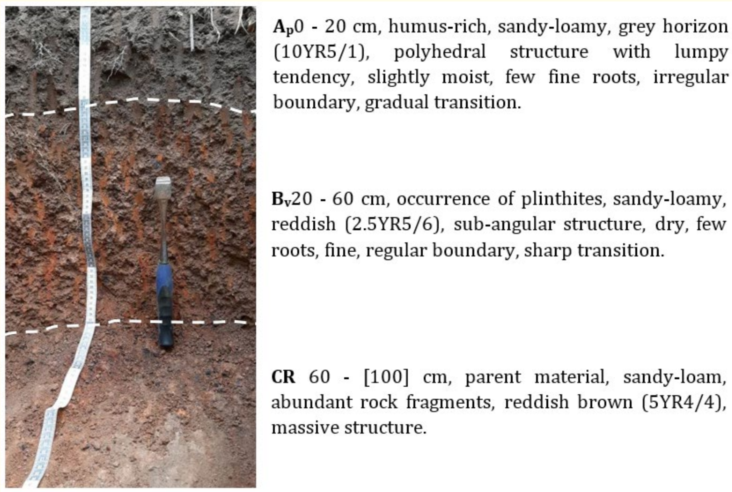



***Figure 8:*** Manganiferric Leptic Plinthosol (Eutric, Cambic).

### *Morphopedological characteristics of Leptosols*

Leptosols are generally reddish-brown in color (2.5YR 5/3) (Fig. 9). These are young, poorly developed soils with a very shallow profile, often containing large quantities of fragmented rock (abundant, angular coarse fragments), with minimal development, generally formed on hard rock. Due to limited pedogenetic development, these soils have weakly expressed horizons, and are well drained (drainage class: good). These soils have an average water retention capacity. Their cation exchange capacity ranges from 3.2 to 13.6 $cmol.kg^{-1}$. Morphologically, the dominant units of the Leptosols observed are characterized by irregularly-shaped rock fragments and high porosity. The texture of these soils is sandy-loamy. These soils are less widespread in the study area. With saturation levels reaching 87%, most Leptosols in the study area are subsaturated. They contain three times more calcium than magnesium and much less potassium than calcium.

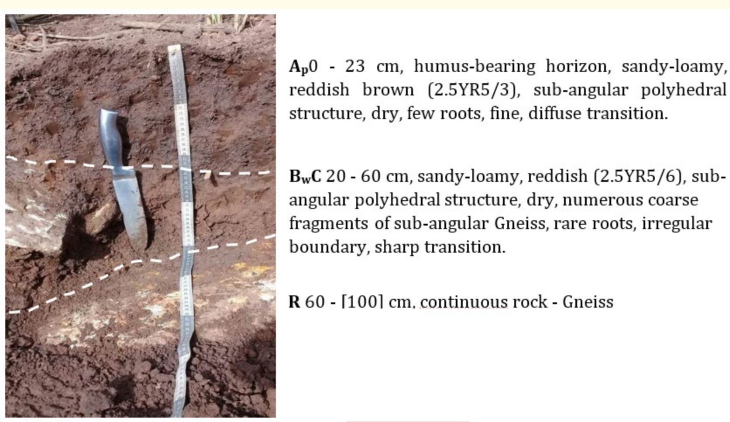
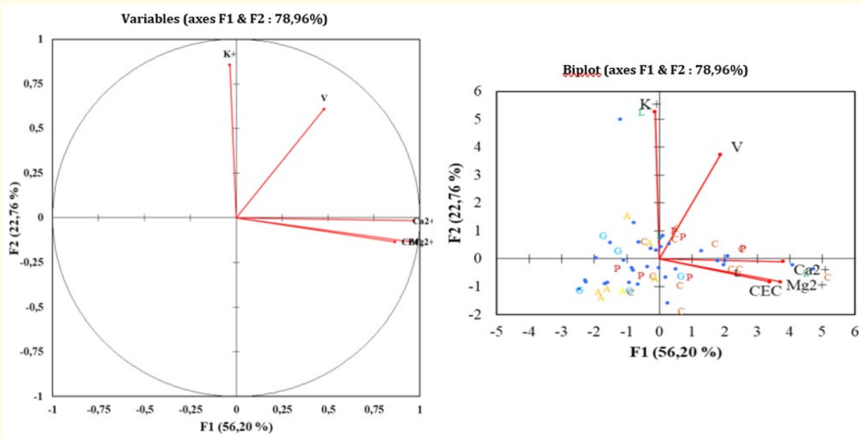



***Figure 9:*** Eutric Cambic Leptosol.

### *Relationship between physical, chemical and physico-chemical parameters of Borotou-Koro soils*
### *Relationship between the parameters of the adsorbent complex*

The correlation circle formed by the F1 and F2 axes (fig. 10a) gives 78.96 p.c. of the total information. The F1 axis (56.20 p.c.) is mainly linked to calcium, magnesium and CEC, which correlate well with each other. This axis thus defines a mineralization gradient linked to calciums and magnesiums. This axis therefore represents the influence of calciums and magnesiums on the quality of exchangeable bases in Borotou-Koro soils. The F2 axis (22.76 p.c.) is positively correlated with potassium. This axis defines a mineralization gradient mainly due to potash. The right angle between calcium and potassium tells us that these two elements are not linked. On the other hand, the obtuse angle between potassium and magnesium represents a negative correlation between these two elements.

The typological structure revealed by the F1 x F2 factorial plane (fig. 10b) shows a positive correlation between Cambisols (C), Leptosols (L), Plinthosols (P) and Magnesium and Calcium, indicating a certain abundance of these minerals in these soils on the F1 axis. Leptosols (L) also correlate positively with Potassium on the F2 axis.



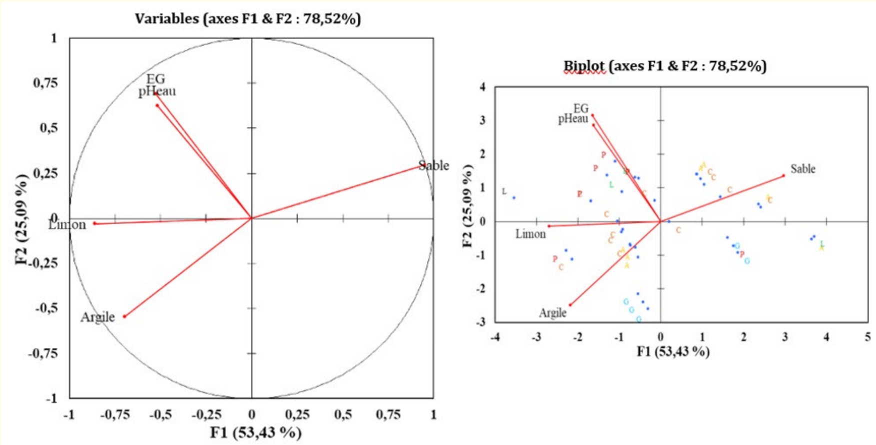

(a: correlation circle on the F1 x F2 factorial plane of exchangeable bases; b: typological structure revealed by the F1 x F2 factorial plane).

***Figure 10:*** PCA of exchangeable bases.

### *Classification based on physical parameters and pH*

The correlation circle formed by axes F1 and F2 (fig. 11a) gives 78.52 p.c. of the total information. The F1 axis (53.43 p.c.) correlates positively with sand and negatively with silt and clay. This axis thus defines a positive concentration linked to sands and a negative one to silts and clays. This axis also represents the influence of sand on the textural quality of Borotou-Koro soils: as sand increases, silt and clay decrease. The F2 axis (25.09 p.c.) is positively correlated with pH and coarse elements. This axis defines an abundance of coarse elements and a pH tending towards basicity.

The typological structure revealed by the F1 x F2 factorial design (fig. 11b) shows a positive correlation between Cambisols (C), Arenosols (A) and sand, while silt and clay correlate negatively with Cambisols (C), Arenosols (A) and Plinthosols (P) on the F1 axis. On the other hand, pH and coarse elements are positively correlated with Plinthosols, Leptosols (L) and Cambisols (C) on the F2 axis.




(a: correlation circle on the F1 x F2 factorial plane for physical parameters; b: typological structure identified by the F1 x F2 factorial plane).

***Figure 11:*** PCA of physical parameters.

## Discussion

The morphopedological description shows that the soils studied are characterized, for the most part, by gray chromium in various shades (2.5YR 3/1; 10YR 5/1, 3/1) on the surface for Cambisols, Arenosols and Plinthosols, and brown chromium in various shades (2.5YR, 3/3, 3/2 and 5/3) on the surface for Gleysols and Leptosols. At depth, however, the chromium is brown with a reddish tinge (2.5YR 4/4) for Cambisols, brown with a yellowish tinge (10YR 5/4) for Arenosols, pale yellow (2.5Y 7/4) for Gleysols and reddish (2.5YR 5/6) for Plinthosols. Physically, the soils on the study site are predominantly sandy-loam, with fine, medium and coarse sand. Their structure is polyhedral with a lumpy tendency in the surface horizons, and polyhedral with a nuciform tendency in the deeper horizons. They are not very porous, and not very cohesive to loose. The boundary between surface and deep humus-bearing horizons is more or less regular. They are moderately rich in coarse elements (<50%). Reworking and rejuvenation can be observed. Reworking can be observed from the first 30 cm downwards. Rejuvenation is characterized by gray, yellow, yellow-ochre, pink, red and rusty patches (10YR 8/8; 10YR 8/6; 10R 4/6; 7.5YR 6/8; 5YR 5/8; 2.5YR 8/3; Gley1 6/N). Rejuvenation and gleyfication are the dominant phenomena and processes, respectively, at mid-slope and in the lowlands, due to the quasi-permanent irrigation of the study site.

Soil classification results revealed an overall accuracy of 77.88 p.c. and reasonable confusion between soil classes. According to Van Genderen and Lock (1977), the interpretation of satellite images is always accompanied by errors of all kinds. Errors recorded during manual interpretations result, among other things, from misidentification of features, over-generalization, variations in interpretation details, and data recording and integration procedures. In digital processing, on the other hand, the above-mentioned errors are essentially due to interactions between the spatial structure of the landscape under consideration, the resolution of the sensor, the image pre-processing algorithm and the classification procedures (Mama and Oloukoi, 2003; Story and Congalton, 1986). Although the stepwise approach implemented, and the use of high temporal sequence multi-sensor data, improved class separability, the residual challenges, mainly associated with feature identification, meant that overall accuracy should have reached 90 p.c., although Ouattara et al. (2020) find that overall accuracy once above 70 p.c. proves to be a fairly satisfactory result.

The results of soil analysis at the Borotou-Koro Integrated Agricultural Unit indicate that the soil is capable of meeting the carbon demand of plants, with levels in excess of 5 $g.kg^{-1}$. This ability is partly linked to the total or partial annual renewal of the sugarcane root system after each harvest (Poser, 2002). By counting the restitutions made to the soil by roots and straw left in the field after a harvest, Cabidoche et al. (2003) specify that a large quantity of organic matter is reorganized in the soil during each cycle. Similar observations have shown that in Borotou-Koro, on harvested plots, there are residues of various kinds, in high proportions, made up of whole canes, cut canes, leafy stalk ends, poorly/or not incinerated. Bouadou (2014), in Zuénoula, estimated the average quantitative value of these residues at 2.270 t/ha, whose burial could considerably increase the soil's organic matter content.

As far as nitrogen is concerned, the average level in Borotou-Koro soils is relatively average compared with the nutritional norm (Pouzet et al., 1997). As in most tropical soils, losses of nitrate nitrogen are common to Borotou-Koro soils. Leaching is thought to be one of the major causes (Bouadou, 2014; Ranaivomanana, 2008). In fact, sugarcane plantations in Borotou-Koro are regularly and abundantly watered. According to Cousin and Therond (2017), nitrogen leached in nitrate form causes acidification of soils, particularly water, leading to eutrophication of the latter in the presence of sufficient phosphorus concentration ($PO_4$ions), and a reduction in biodiversity. Long-term experiments show that agricultural yields are multiplied by 2 or 3 when fertilizers are added (Spiertz, 2010). Mineral fertilizers remain the main source of soil-applied nutrients for crop production, even though organic fertilization is not negligible (Spiertz, 2010). Nitrogen is the second most absorbed macronutrient by sugarcane, extracting around 94 to 260 kg.ha$^{-1}$, varying according to genotype, soil and fertilization (Oliveira et al., 2010). Despite the high N uptake, plant responses to nitrogen fertilization have varied widely. Azeredo et al. (1986) observed that in 80% of cases, sugarcane in the first crop cycle (plant-cane) did not respond to N fertilization in evaluations carried out in 135 experiments in different regions of the country. However, Oliveira (2012) found an increase in sugarcane agricultural productivity with increasing N in three production environments in northeastern Brazil. Oliveira et al. (2013) also observed a positive variation in sugarcane dry matter production in response to increased N.

In terms of assimilable phosphorus, Cambisols and Arenosols had high levels, while Plinthosols and Leptosols had medium levels, while Gleysols had low levels on average. In addition, some plots, such as P37/A, had high levels of phosphorus, while P14/B and P26C had relatively low levels, which would require the use of phosphate fertilizers. Phosphorus is an essential element for plant growth. However, when applied in excess, it accumulates in the soil and causes losses, which can lead to chemical imbalances. Knowledge of the bioavailability of phosphorus to plants in the soil is of great agronomic interest, with the aim of improving agricultural production. Several factors could influence the variation of this bioavailability. Assessing the bioavailability of phosphorus (P) in soils is essential for establishing fertilizer recommendations (Lafond and Ziadi, 2013). The highest dose of phosphorus should be applied to the bottom of planting grooves (De Oliveira et al., 2018). Such a deeper application increases nutrient uptake by plants, since water availability in the subsoil varies less than at the surface. Phosphorus mobility in the soil is low, and its diffusion is influenced by several factors, including precipitation by cations such as iron, aluminum and calcium; volumetric water content in the soil; phosphorus adsorption by soil colloids; complexity of environmental structure; soil compaction; distance to reach roots; and soil element content (Novais and Smith, 1999). In general, very low values are recorded for phosphorus transport due to its strong interaction with soil colloids, particularly in highly weathered soils. According to (Novais and Smith, 1999), it can be estimated that transport averages 0.013 mm per day.

Average soil calcium and magnesium contents are relatively good for Cambisols, average for Leptosols and Plinthosols, and low for Gleysols and Arenosols. In terms of chemical properties, S: 7.09 cmol.kg$^{-1}$ and CEC: 8.58 cmol.kg$^{-1}$ for Cambisols were average, in contrast to those of the other soil types, namely S: 1.48 cmol.kg$^{-1}$ and CEC: 3.33 cmol.kg$^{-1}$ for Gleysols, S: 1.35 cmol.kg$^{-1}$ and CEC: 4.15 cmol.kg$^{-1}$ for Arenosols, S: 4.72 cmol.kg$^{-1}$ and CEC: 6.58 cmol.kg$^{-1}$ for Plinthosols and S: 6 cmol.kg$^{-1}$ and CEC: 7.93 cmol.kg$^{-1}$, all of which are relatively low (CIRAD, 2002; Pouzet et al, 1997). These results are contrary to those of Bouadou (2014), who obtained good chemical properties and high Ca and Mg contents on Zuénoula soils. The importance of Ca and Mg in crop production has been underestimated in recent decades (Cakmak and Yazici 2010). Indeed, compared to other nutrients, agronomists and scientists have paid little attention to this mineral nutrient in recent decades (Cakmak and Yazici 2010). As a result, there are significant chemical imbalances: for Ca/Mg, 4/1 in Cambisols and Plinthosols, 3/1 in Leptosols and 2/1 in Gleysols; for Mg/K, 3/1 in Cambisols, Gleysols and Leptosols, and 2/1 in Arenosols.

Potassium, for its part, is deficient, with a K< 5 p.c. of CEC in Cambisols, Gleysols and Leptosols, then a K< 8 p.c. of CEC in Arenosols and Plinthosols, even though it represents the essential element in crop production, and cane sugar in particular (De Resende et al., 2006). In studies carried out by Oliveira et al. (2002) using lysimeters, K losses were mainly due to leaching. These results were confirmed by (Sampaio and Salcedo, 1991), who also observed that K losses by percolation below 100 cm depth were 9.0 $kg.ha^{-1}$, fully compensated by K input from rainwater (18 $kg\ ha^{-1}$). Although potassium uptake and removal varies between sugarcane cultivars, it can be considered that for each tonne of natural matter harvested, there is an average removal of 1.5 kg of K (De Oliveira et al., 2018).

Calcium, magnesium and CEC correlate well with each other, while calcium and potassium do not. There is also a negative correlation between potassium and magnesium. In fact, calcium and magnesium are key elements in the quality of exchangeable bases in Borotou-Koro soils. On the other hand, Cambisols, Leptosols and Plinthosols correlated positively with magnesium and calcium, hence the abundance of these minerals in these soils.

In terms of granulometry, we note a positive concentration linked to sands and a negative one to silts and clays. Sand influences the textural quality of Borotou-Koro soils: as sand increases, silt and clay decrease. There is also an abundance of coarse elements and a pH tending towards basicity. Soil texture profoundly affects soil drainage, water retention capacity, soil temperature, soil erosion, fertility and productivity. Numerous studies have reported that soil internal erosion potential is mainly controlled by soil particle size distribution (Indraratna et al., 2011; Kenney, and Lau, 1985). Various studies (Fukue et al., 1986; Boutin et al., 2011) have indicated that the compressibility of compacted clay-sand mixtures is governed by the sand fraction when it reaches a threshold and forms a sand skeleton. With regard to percolation behavior, Watabe et al. (2011) found that increasing the sand fraction leads to a slight increase in hydraulic conductivity below a certain threshold, followed by a sharp increase above the threshold. Shayea (2001) studied the effect of different clay contents on sand permeability. Their results revealed that the ability of sand with low clay content to reduce the coefficient of permeability is significantly greater than that of sand with high clay content.

There is a positive correlation between Cambisols, Arenosols and sand, and a negative correlation between silt, clay and Cambisols, Arenosols and Plinthosols. However, pH and coarse elements are positively correlated with Plinthosols, Leptosols and Cambisols.

## Conclusion

Small-scale, reconnaissance or general soil surveys only give an overview of the dominant types and distribution of soils occurring over relatively large areas. The landscape may in fact include fairly large areas of different soils that are not identified on the map. As such, detailed soil reconnaissance studies are best suited to making general comparisons of soil capacities and limitations on a regional, national or even global scale. Borotou-Koro is an agro-industry with around 15,000 ha of soil area, of which 8,000 ha is cultivated. The soil map available dates back to ORSTOM. The aim of this study was to update the soil maps according to the new WRB classification.

A total of 5 soil classes were observed, namely Cambisols, with a surface area of 20036.6 ha, covering 74.2 p.c. of the total surface area, were the most widespread soil classes. Gleysols, with a surface area of 4810.76 ha, accounted for 17.8 p.c. of the total surface area. Arenosols, with a surface area of 1757.45 ha, accounted for 6.5 p.c. of the total surface area. Plinthosols, with 384.42 ha, accounted for 1.4 p.c. of the total surface area. Finally, Leptosols, with 0.07 ha, accounted for 0.1 p.c. of the total surface area.

The nutrient content of these soils was determined. Nitrogen levels are generally average. Assimilable phosphorus in Cambisols and Arenosols is highly available, in contrast to Plinthosols and Leptosols, which recorded average levels, and Gleysols, low levels. Average calcium and magnesium levels were good in Cambisols, average in Leptosols and Plinthosols, but low in Gleysols and Arenosols. Potassium is deficient, with K< 5 p.c. of CEC in Cambisols, Gleysols and Leptosols. K< 8 p.c. of CEC in Arenosols and Plinthosols.

Detailed mapping has enabled us to identify the different soil classes in the Borotou-Koro integrated farming unit and their fertility potential, thus enabling better decision-making.

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