

Evaluation of Soil Quality under Cocoa Trees in the Marahoué Region (Central-Western Côte d'Ivoire)

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How to cite this paper: Zro, F.G.B., Yeo, L., Toure, B., Guei, M.A., Soro, D. and Bakayoko, S. (2024) Evaluation of Soil Quality under Cocoa Trees in the Marahoué Region (Central-Western Côte d'Ivoire). *Open Journal of Soil Science*, **14**, 537-553.
<https://doi.org/10.4236/ojss.2024.149028>

Received: August 25, 2024

Accepted: September 22, 2024

Published: September 25, 2024

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Abstract

This study, which assesses the quality of soils under cocoa trees in the Marahoué region of Côte d'Ivoire, is being carried out against a backdrop of declining crop yields due to a number of factors, including the loss of soil fertility. The aim was to identify homogeneous groups of soils in terms of fertility and propose sustainable management methods for each group. The study was carried out on twenty-four cocoa orchards belonging to the SCOOP KAPATCHIVA cooperative, spread over eight sectors. A morphological characterisation of the soils was carried out in the field, followed by physico-chemical laboratory analyses of soil samples taken in the field. Soil fertility was analyzed on the basis of these two groups of data. The results showed that soil depths were generally high, except in some high altitude areas, where soils were often enriched in ferromagnesian elements and compacted. The texture of the soils varied between loamy and sandy-loamy, influencing cocoa production. Indeed, the soils of the plots with high production were looser and without ferromagnesian concretions, while those of the plots with low production were more gravelly and compact. Biological activity in the upper soil layer (0 - 30 cm) was notable with an abundance of termites and earthworms. The organic matter and nitrogen content varies considerably between sectors, directly impacting soil fertility. The soils were slightly acidic and showed significant differences in the levels of exchangeable magnesium and potassium, and not at all for phosphorus which appeared at very low doses. Chemical analysis also revealed that nutrient balance was a key factor in orchard productivity, with varying ratios of calcium, magnesium and potassium. Knowledge of these results made it possible to make recommendations for soil management with a view to improving cocoa yields in the study area.

Keywords

Soil, Chemical Balances, Fertility, Cocoa Farming, Marahoué Region

1. Introduction

Cocoa and coffee were at the root of the ivorian economic miracle of the 1970s. Since then, Côte d'Ivoire has remained the world's leading cocoa producer. Cocoa alone feeds thousands of families and is a strategic product for the ivorian economy [1]. However, cocoa farming faces a number of difficulties that are at the root of yield losses, including ageing orchards, pest pressure due to swollen shoot, global warming and the ongoing loss of soil fertility [1]. However, increasing cocoa production is a necessity and a challenge for the main producing countries, particularly Côte d'Ivoire, the world's leading producer [2] [3].

To meet this challenge, Côte d'Ivoire is taking a number of steps, including: organising the industry, guaranteeing a large part of the CIF (Cost, Insurance, Freight) price to producers, extending the area under fallow land and scientific research [4]. Stakeholders in the sector are constantly striving to improve production quality, which, according to [5], requires regular monitoring of soil quality. To this end, [6], having noted that most of the current recommendations made to Ivorian producers are based on a single formula of NPK 0-23-19 fertiliser combined with small quantities of calcium and magnesium, proposed a soil diagnosis in order to adapt mineral fertiliser inputs to the chemical quality of the soil under cocoa trees. Their work was carried out in the east of the country.

This research is set in the same context. Its aim is to assess the soil fertility of the cocoa farmers of SCOOP KAPATCHIVA, a cooperative society of farmers based in Bonon, in the Marahoué region of central-western Côte d'Ivoire, one of the country's largest cocoa-producing areas, which is currently facing yield declines.

2. Materials and Methods

Study Area

The SCOOP KAPATCHIVA intervention zone is located in the Marahoué region in central-western Côte d'Ivoire. It covers the departments of Bonon and Bouaflé (**Figure 1**) and is subdivided into 8 sectors: Blaizekro, Bozi, Grâce, Gonanfla, Katana, Koffikro, Ndouffoukankro and Solidarité. Each sector covers several villages and therefore several producers' plantations.

It is a transition zone between dense forest and wooded savannah, two types of plant formation which, depending on the dominance of one over the other, are distributed to the south and south-west for the dense forest, then to the north and north-east for the wooded savannah [7].

The area straddles the sub-equatorial Atean climate and the humid tropical Baulean climate. There are two main seasons, alternated by two shorter ones. The

long rainy season begins in March and ends in June, while the short rainy season runs from mid-August to October. Between the two rainy seasons, there is the short dry season from July to mid-August and the long dry season from November to February. Annual rainfall is between 1800 and 2000 mm, with an average annual temperature of around 25.30°C and an average humidity of 75 pc. The area is drained by the Bandama rouge or Marahoué and Bandama blanc rivers and their tributaries [8].

The region's relatively flat topography consists of low plateaux with a few low-lying areas in the plains and hills with an average altitude of 260 m. The soils are generally Ferralsols (Eutric) with slightly different characteristics, depending on whether they are in forest or savannah. There are also pockets of Acrisols in the north and north-east and Gleysols along the rivers [9].

In short, the physical characteristics of the zone give it many agricultural advantages, both for food production and cash crops. As a result, it is one of Côte d'Ivoire's main production bases for food crops and cocoa.

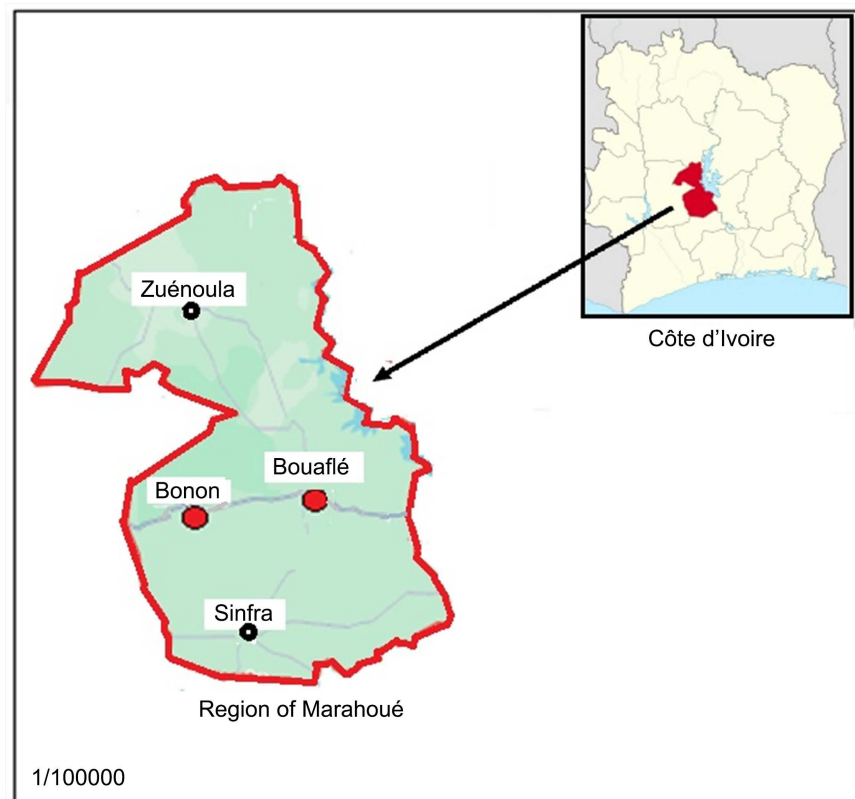


Figure 1. Map showing the location of the study area.

3. Materials and Methods

The study covered twenty-four cocoa orchards evenly distributed between the eight different sectors of the SCOOP KAPATCHIVA intervention zone. It consisted of a morphological characterization of the soil in the field, followed by a physico-chemical analysis of soil samples in the laboratory. Soil fertility was

assessed using data collected both in the field and in the laboratory.

3.1. Morphological Characterization of the Soil

In each plantation, three soil pits (F1, F2 and F3) (**Figure 2**) were established according to the state of vigour of the cocoa trees and/or the production level of the cocoa trees, to take into account the fact that when the topography of the soil is almost flat (slope ≤ 8 pc), as was the case in almost all the plantations explored, it is the level of crop development (growth, health status, infestation, yield) that better reflects the nature of the underlying soil [10]. Thus, pits F1, F2 and F3 corresponded, in this order, to the soils of high, medium and low production subplots.

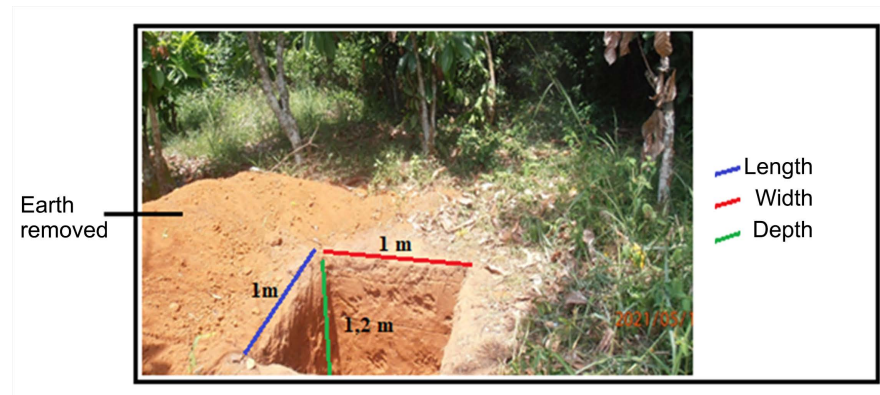


Figure 2. Example of an installed soil pit.

The observations at each pit consisted of identifying the different horizons and determining, for each horizon: the thickness, the texture, the general structure of the soil and that of the flow, the compactness and cohesion, the presence of organic matter, porosity and permeability, the natural drainage quality of the soil, the depth of appearance of the hydromorphic roof, and above all, the approximate proportion of the soil volume occupied by coarse elements, estimated visually.

3.2. Physico-Chemical Analysis of Soil in the Laboratory

The physico-chemical properties of the soil measured are listed in **Table 1**, together with the methods used. These analyses were carried out at the plant and soil analysis laboratory of the Polytechnic Institute Félix Houphouët-Boigny (Yamoussoukro, Côte d'Ivoire) and involved samples taken from the top 30 cm of pits F1, F2 and F3 in each plot. Most of the lateral roots that provide the cocoa tree with mineral and water nutrition are concentrated in this upper part of the soil, although the plant prefers well-drained soils that are at least 1.5 m deep. Clearly, the layer being evaluated is the main site for the absorption of water and mineral elements by plant roots; it is also the site of biochemical reactions involving the transformation of organic matter by soil microorganisms [11]. Understanding its properties is therefore of vital importance in making recommendations for sustainable soil management.

Table 1. Physico-chemical properties of the soil determined.

Types of variables	Variables	Methods
Chemical	pH	pH glass electrode meter [12]
	Organic carbon (C)	Walkley & Black [13]
	Organic matter (OM)	OM = 1724 × C
	Total nitrogen (N)	Kjeldahl modified [12]
	Total phosphorus (P)	Olsen modified [14]
	Exchangeable calcium (Ca ²⁺)	Atomic absorption spectrometry [15]
	Exchangeable magnesium (Mg ²⁺)	
	Exchangeable potassium (K ⁺)	
	Sum of Exchangeable Bases (SEB)	
	Cation exchange capacity (CEC)	Kjeldahl modified [12]
Base saturation (V)	V = SEB/CEC	
Physical	Sand	Robinson pipette [16]
	Silt	
	Clay	

3.3. Analysis of Soil Quality

Based on the soil variables measured, an analysis of variance was carried out to identify homogeneous groups of soils and to compare the average characteristics of these groups with existing threshold values. A full hierarchical clustering analysis (HCA) was then used to divide the soils into homogeneous subsets of equal fertility. Finally, a principal component analysis (PCA) of the soil variables was carried out to determine the determining variables in the functioning of each soil fertility subset identified, after these variables and the individuals had been projected onto the same factorial plane (1 × 2). These analyses were carried out using XLSTAT software.

4. Results

4.1. Soil Morphology

While the depth of the soil appeared to be very great (>120 m) in most of the plots (**Figure 3**), it was restrictive in some of the plots explored in the hill zone, mainly in the Bozi and Koffikro sectors. In these areas, at depths of between 50 and 70 cm, the soil was generally enriched with coarse ferromagnesian elements and was often compacted. In the other sectors, only the soils in the low production sub-plots (F3) showed a similar gravelly state, occupying around 50pc of the soil volume and often associated with compaction. In contrast, the soils in the high production sub-plots (F1) were generally loose and almost devoid of concretions (**Figure 2**). In the illustration in **Figure 3**, the F1 pit was observed in the Grâce sector, while F3 was observed in Koffikro, where the soils appeared to be more clayey on the surface (16.58 pc on average), although this difference does not significantly distinguish the soils from one another. The same is true for sand levels

and for cumulative clay and silt levels (**Table 2**). The silt content, on the other hand, shows differences between the soils, which have either a silty texture or a sandy-silty texture (**Table 2**).

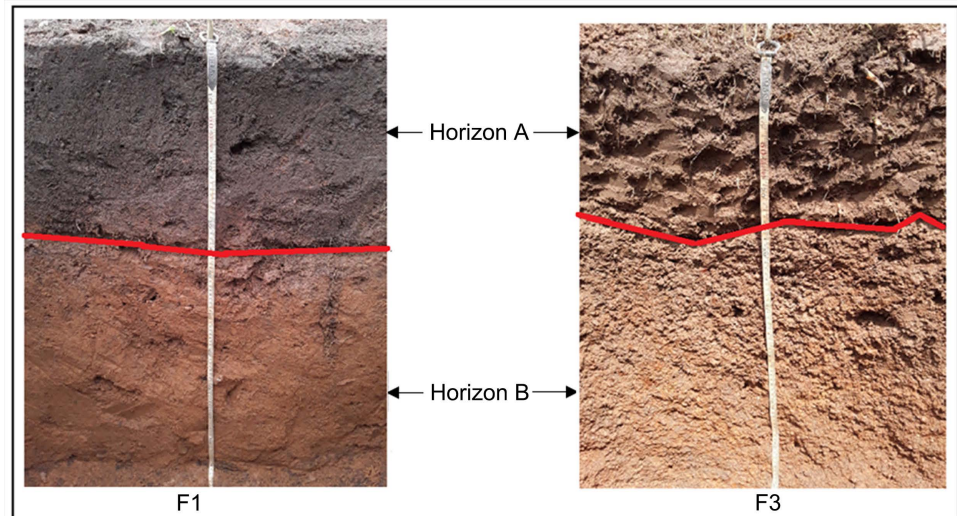


Figure 3. Representative profiles of soils from high production plots (F1) free of ferromanganic concretions and low production plots (F3) with horizon B rich in these coarse elements.

Table 2. Granulometry of the first 30 cm of soil.

Secteur	Clay (pc)	Silt (pc)	Clay + Silt (pc)	Sand (pc)	Texture
Blaisekro	13.11 ^a	37.16 ^{ab}	50.28 ^a	48.14 ^a	Silty
Bozi	13.42 ^a	28.30 ^{ab}	41.72 ^a	56.10 ^a	Silty-sandy
Gonanfla	10.00 ^a	33.95 ^{ab}	43.95 ^a	45.64 ^a	Silty
Grâce	14.55 ^a	31.10 ^{ab}	45.65 ^a	52.92 ^a	Silty-sandy
Katana	10.79 ^a	42.04 ^a	52.84 ^a	46.01 ^a	Silty
Koffikro	16.58 ^a	34.40 ^{ab}	50.98 ^a	48.03 ^a	Silty
Ndouffoukankro	11.25 ^a	32.22 ^{ab}	43.47 ^a	55.45 ^a	Silty-sandy
Solidarité	14.82 ^a	24.93 ^b	39.76 ^a	58.81 ^a	Silty-sandy
CV	0.172	0.159	0.103	0.098	
P	0.466	0.0244	0.289	0.329	
Effect	ns	s	ns	ns	

Means assigned the same letter following a column are not significantly different at the 5pc level; P: Probability; s: Significant difference; ns: Non-significant difference; CV: Coefficient of variation.

4.1.1. Soil Biological Quality

The 0 - 30 cm layer of the soil was generally the site of good biological activity, with an abundance of termites and earthworms. Many other faunal groups apart from earthworms and termites were also observed, including Myriapoda, Coleoptera, Gastropoda, etc. In addition, a thick litter of dead leaves covering the ground was observed at all the sites.

4.1.2. Soil Organic Matter and Nitrogen

Organic carbon (C) levels in the 0 - 30 cm soil layer ranged in the study area from 0.57 pc at Koffikro to 1.25 pc at Bozi (**Table 3**). The average equivalent organic matter (OM) content ranged from 0.98 pc in Koffikro to 2.16 pc in Bozi. For total nitrogen (N), the rates observed in the different sectors varied from 0.040 pc in Koffikro to 0.082 pc in Bozi. As a result, the C/N ratio is between 10.93 (Solidarité sector) and 15.02 (Grâce sector).

Table 3. Soil organic matter and nitrogen.

Sector	C (pc)	N (pc)	C/N	OM (pc)
Blaisekro	0.912 ^a	0.069 ^a	12.99 ^a	1.56 ^a
Bozi	1.25 ^a	0.082 ^a	13.69 ^a	2.16 ^a
Gonanfla	1.001 ^a	0.075 ^a	12.92 ^a	1.72 ^a
Grâce	0.828 ^a	0.060 ^a	15.02 ^a	1.42 ^a
Katana	0.665 ^a	0.050 ^a	12.92 ^a	1.14 ^a
Koffikro	0.570 ^a	0.043 ^a	12.56 ^a	0.98 ^a
Ndouffoukankro	0.622 ^a	0.048 ^a	13.10 ^a	1.07 ^a
Solidarité	0.826 ^a	0.072 ^a	10.93 ^a	1.42 ^a
CV	0.269	0.224	0.087	0.269
P	0.402	0.323	0.608	0.403
Effect	ns	ns	ns	ns

Means assigned the same letter following a column are not significantly different at the 5pc level; P: Probability; s: Significant difference; ns: Non-significant difference; CV: Coefficient of variation.

4.1.3. Soil Acidity

Table 4 shows soil acidity by sector. The soils are all slightly acidic, with a pH in the range 4.98 - 5.63. There are no significant differences between the soils in the different sectors.

Table 4. Soil acidity.

Sector	pH
Blaisekro	5.63 ^a
Bozi	5.68 ^a
Gonanfla	5.37 ^a
Grâce	5.08 ^a
Katana	4.98 ^a
Koffikro	5.05 ^a
Ndouffoukankro	5.25 ^a
Solidarité	5.22 ^a
CV	0.049
P	0.293
Effet	ns

Means assigned the same letter following a column are not significantly different at the 5pc level; P: Probability; s: Significant difference; ns: Non-significant difference; CV: Coefficient of variation.

4.1.4. Soil Adsorbent Complex

The characteristics of the adsorbent complex of the soils studied are reported in **Table 5**. Of all the variables determined, only exchangeable magnesium (Mg^{2+}) and potassium (K^+) levels show a significant difference between the soils ($P < 0.01$). According to the levels:

- three groups of soils, including two homogeneous groups and an intermediate group, can be identified in terms of Mg^{2+} . The first homogeneous group comprises the soils of the Bozi sector, which are the most abundant with an average level of $1.48 \text{ cmol}\cdot\text{kg}^{-1}$ while the soils of the Grâce, Gonanfla, Koffikro, Blaisekro and Katana sectors, with levels of between 0.49 and $0.68 \text{ cmol}\cdot\text{kg}^{-1}$, are the least abundant and form the second homogeneous group. The intermediate group comprises the soils of the Solidarité sector, characterized by an average level of $0.92 \text{ cmol}\cdot\text{kg}^{-1}$;
- there are two homogeneous groups with regard to K^+ , the first group being the soils in the Solidarité sector with an average level of $0.136 \text{ cmol}\cdot\text{kg}^{-1}$ and the second group comprising all the other soils. The levels in these soils vary between 0.103 and $0.116 \text{ cmol}\cdot\text{kg}^{-1}$;
- all the soils have a Ca^{2+} supply of between 1.12 and $2.20 \text{ cmol}\cdot\text{kg}^{-1}$. Total phosphorus remained below 100 ppm , while the sum of exchangeable bases (SEB) varied between 1.83 and $3.83 \text{ cmol}\cdot\text{kg}^{-1}$. The saturation level of the adsorbent complex (V) is close to 50 pc in almost all sectors. The cation exchange capacity (CEC) remains below $8 \text{ cmol}\cdot\text{kg}^{-1}$.

Table 5. Characteristics of soils adsorbent complex.

Sector	Ca^{2+} ($\text{cmol}\cdot\text{kg}^{-1}$)	K^+ ($\text{cmol}\cdot\text{kg}^{-1}$)	Mg^{2+} ($\text{cmol}\cdot\text{kg}^{-1}$)	P (ppm)	CEC ($\text{cmol}\cdot\text{kg}^{-1}$)	SEB ($\text{cmol}\cdot\text{kg}^{-1}$)	V (pc)
Blaisekro	1.26 ^a	0.114 ^b	0.603 ^b	36.42 ^a	4.61 ^a	2.02 ^a	45.88 ^a
Bozi	2.20 ^a	0.115 ^b	1.481 ^a	64.42 ^a	5.92 ^a	3.83 ^a	55.83 ^a
Gonanfla	1.17 ^a	0.108 ^b	0.679 ^b	50.92 ^a	5.63 ^a	2.00 ^a	37.03 ^a
Grâce	2.12 ^a	0.110 ^b	0.493 ^b	89.83 ^a	7.96 ^a	2.78 ^a	38.33 ^a
Katana	1.12 ^a	0.116 ^b	0.685 ^b	48.42 ^a	4.61 ^a	1.98 ^a	49.06 ^a
Koffikro	1.26 ^a	0.110 ^b	0.619 ^b	74.92 ^a	4.10 ^a	2.03 ^a	52.74 ^a
Ndouffoukankro	1.36 ^a	0.103 ^b	0.325 ^b	74.00 ^a	3.88 ^a	1.83 ^a	49.90 ^a
Solidarité	1.75 ^a	0.136 ^a	0.925 ^{ab}	81.07 ^a	5.17 ^a	2.86 ^a	58.03 ^a
CV	0.283	0.085	0.481	0.281	0.249	0.285	0.157
P	0.388	0.008	0.004	0.53	0.377	0.305	0.291
Effect	ns	s	s	ns	ns	ns	ns

Means assigned the same letter following a column are not significantly different at the 5pc level; P: Probability; s: Significant difference; ns: Non-significant difference; CV: Coefficient of variation.

4.1.5. Soil Chemical Equilibrium

Table 6 shows the chemical equilibria in the soils. Certain balances, namely Ca^{2+}/K^+ , K^+/CEC , N/P , $(Ca^{2+} + Mg^{2+})/K^+$ and $(SBE + 6.15)/N$ do not distinguish

the soils significantly ($P > 0.05$), unlike others, namely Mg^{2+}/K^+ and Ca^{2+}/Mg^{2+} ($P < 0.05$).

For the last two ratios mentioned, starting with the Mg^{2+}/K^+ ratio, the values obtained ranged from 3.21 (Ndouffoukankro sector) to 12.78 (Bozi sector), making it possible to distinguish two homogeneous groups of soils and an intermediate group. The first homogeneous group is made up of the soils of the Bozi sector, where the ratio is 12.78, while the soils of the Katana, Koffikro, Blaisekro, Grâce and Ndouffoukankro sectors form the second homogeneous group, with ratios of between 3.21 and 5.92. The intermediate group is made up of the Gonanfla sector, where the ratio reaches 6.23. As before, the Ca^{2+}/Mg^{2+} ratio values identify two homogeneous groups and an intermediate group. The first homogeneous group is made up of soils in the Ndouffoukankro and Grâce sectors, with ratios of 4.15 and 4.14 respectively. The Gonanfla and Katana sectors, which had the lowest ratios (1.66 and 1.65), form the second homogeneous group. Soils in the Solidarité, Bozi, Bla and Koffikro sectors form the intermediate group. Their ratios range from 2.10 to 2.41. In all the soils studied, the N/P , $(SEB + 6.15)/N$ and $(Ca^{2+} + Mg^{2+})/K^+$ ratios ranged from 10.23 to 34.26, 92.27 to 163.87 and 15.59 to 31.89 respectively, with no significant difference between soils.

Table 6. Chemical balances in soils.

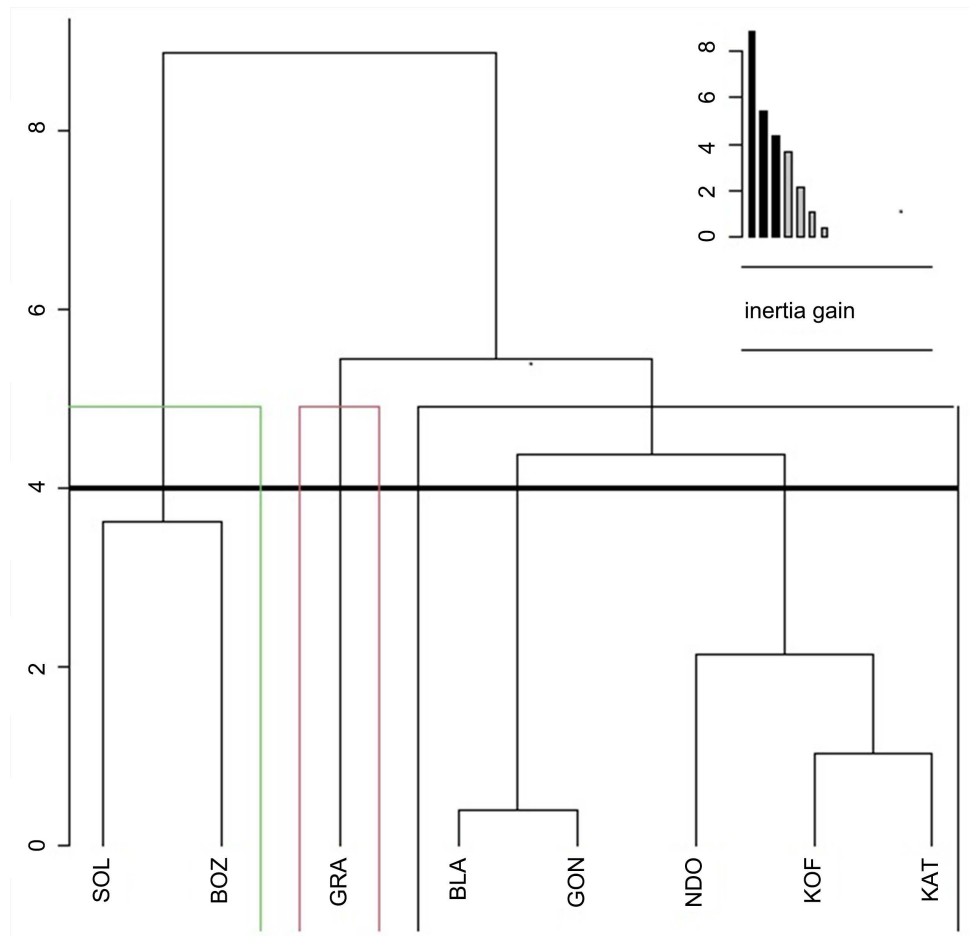
Sector	Ca^{2+}/K^+	Ca^{2+}/Mg^{2+}	K^+/CEC (pc)	Mg^{2+}/K^+	N/P	$(Ca^{2+} + Mg^{2+})/K^+$	$(SBE + 6.15)/N$
Blaisekro	11.03 ^a	2.144 ^{ab}	2.6 ^a	5.28 ^b	21.13 ^a	16.31 ^a	124.22 ^a
Bozi	19.10 ^a	2.22 ^{ab}	2.5 ^a	12.78 ^a	23.20 ^a	31.89 ^a	106.14 ^a
Gonanfla	10.55 ^a	1.66 ^b	2.00 ^a	6.23 ^{ab}	34.26 ^a	16.79 ^a	128.01 ^a
Grâce	19.10 ^a	4.14 ^a	2.1 ^a	4.45 ^b	15.09 ^a	23.55 ^a	152.43 ^a
Katana	9.67 ^a	1.65 ^b	3.00 ^a	5.92 ^b	22.29 ^a	15.59 ^a	134.46 ^a
Koffikro	11.35 ^a	2.10 ^{ab}	2.9 ^a	5.63 ^b	9.08 ^a	16.98 ^a	163.87 ^a
Ndouffoukankro	13.37 ^a	4.15 ^a	3.00 ^a	3.21 ^b	10.23 ^a	16.58 ^a	154.15 ^a
Solidarité	13.10 ^a	2.41 ^{ab}	2.7 ^a	7.60 ^{ab}	12.63 ^a	20.70 ^a	92.27 ^a
CV	0.277	0.395	0.143	0.451	0.454	0.282	0.186
P	0.445	0.00807	0.469	0.04006	0.301	0.426	0.742
Effect	ns	s	ns	s	ns	ns	ns

Means assigned the same letter following a column are not significantly different at the 5pc level; P: Probability; s: Significant difference; ns: Non-significant difference; CV: Coefficient of variation.

4.1.6. Soil Fertility Groups and Their Characteristics

Figure 4 shows the hierarchical grouping diagram used to organize the soils studied into a tree structure according to their similarities in terms of fertility. There are three groups of soils:

- Group 1 includes soils from the Blaisekro, Gonanfla, Ndouffoukankro, Koffikro and Katana sectors;
- Group 2 comprises the soils of the Grâce sector alone;
- Group 3 includes soils from the Bozi and Solidarité sectors.



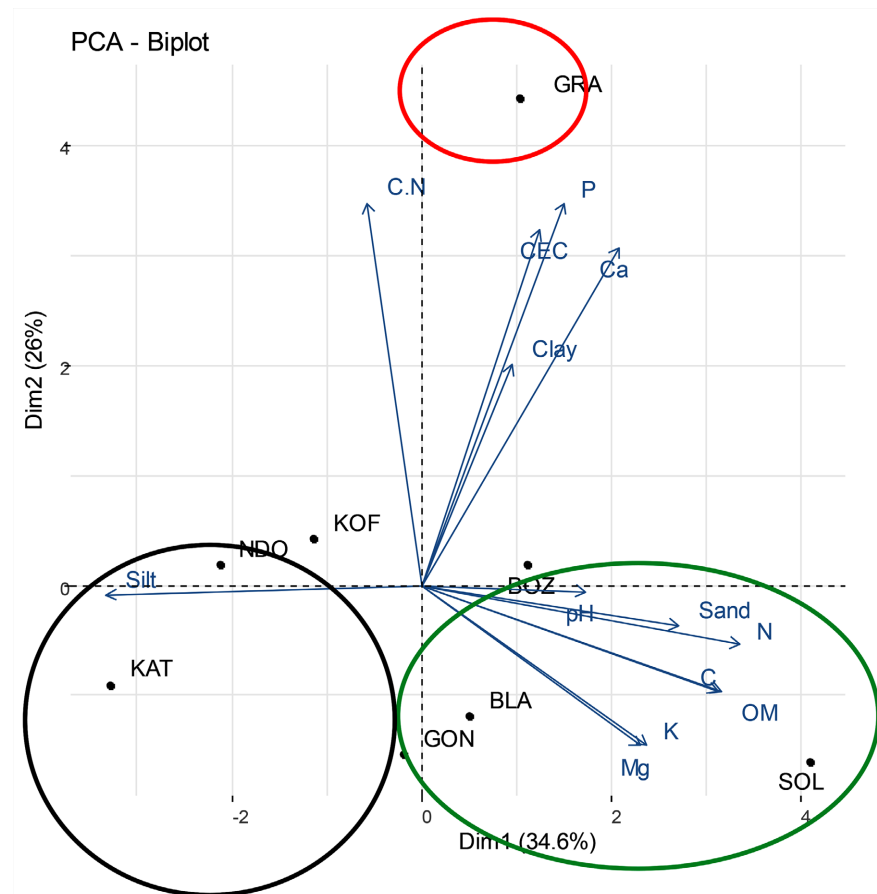
BLA: Blaisekro; BOZ: Bozi; GON: Gonanfla; GRA: Grâce; KOF: KAT: Katana; Koffikro; NDO: Ndouffoukankro; SOL: Solidarité.

Figure 4. Soil fertility groups.

Figure 5, result of the PCA, links the soil groups with the characteristics that best distinguish them. It can be seen that:

- The Blaisekro, Gonanfla, Ndouffoukankro, Koffikro and Katana sectors are characterized by soils containing the highest levels of fine elements (silt, clay + silt) and have a better balance between exchangeable bases and nitrogen;
- soils in the Grâce sector stand out for their higher levels of total phosphorus and better balance between Ca^{2+} and Mg^{2+} ions;
- in the Solidarité and Bozi sectors, the soils have relatively higher levels of OM or C, N, Mg^{2+} and Ca^{2+} , coupled with lower acidity and a high SEB;
- Blaisekro and Gonanfla soils are negatively correlated with axis 1 of the biplot, which determines the best P levels and the best balance between Ca^{2+} and Mg^{2+} ions, and are therefore essentially constrained by these two properties. Similarly, the soils of Ndouffoukankro, Koffikro and Katana, which are negatively correlated with axis 2 of the biplot, which determines the best nutritional conditions in terms of OM, N, Mg^{2+} and Ca^{2+} , are constrained in relation to these four properties. The main constraints on the Solidarité and Bozi soils are their

low levels of fine elements (silt and clay + silt) and a poor balance between exchangeable bases and N. The Grâce sector soils do not have any major constraints as indicated by the biplot.



BLA: Blaisekro; BOZ: Bozi; GON: Gonanfla; GRA: Grâce; KOF: KAT: Katana; Koffikro; NDO: Ndouffoukankro; SOL: Solidarité.

Figure 5. Soil fertility groups and their characteristics.

4.2. Discussion

In physical terms, the soils in the study area generally have a texture that varies from silty to sandy-loam, which gives them good internal drainage, good air circulation and easy root penetration. For the most part, these soils are deep and therefore suitable for cocoa production, except that in some places this great depth is limited by a large volume of ferromanganic concretions. In fact, the high rate of ferromanganic concretions in soils under cocoa trees is often linked to the different microclimates developed on the plots following the replacement of the initial forest cover by crops and when the soil is exposed to high levels of sunlight. In fact, when the previously mobilized and entrained iron precipitates, it first forms an amorphous ferric hydrate gel ($\text{Fe}(\text{OH})^{2+}$ or $\text{Fe}(\text{OH})^{2+}$), which is no longer associated with clay, but rather with colloidal silica and fulvic acids, whose insolubilization and polymerization into humic acid it encourages. This form of iron

characterizes spodic horizons and rusty patches (pseudogley) in soils with temporary hydromorphy [17]. According to [18], it is rich in organic matter and forms easily friable flakes or granules. If the proportion of organic matter decreases as a result of an increase in the proportion of ferric oxide, the amorphous iron evolves towards a crystalline form as the soil dries out (high insolation). The amorphous iron then hardens to form concretions.

From a biological point of view, the 0 - 30 cm layer of the soil was generally the site of good biological activity, marked by an abundance of termites and earthworms, followed by many other faunal groups such as Myriapoda, Coleoptera, Gastropoda, etc. [19] associate this massive presence of fauna in the soils of perennial crops such as cocoa with the fact that these crops produce a lot of litter, which acts as a habitat and food source for many species of soil invertebrates. As well as being produced naturally by the leaves and branches that fall to the ground, the litter is also the result of the practice of pruning to maintain the cocoa trees, observed in more than 80 per cent of the plantations visited.

Chemically speaking, the organic status observed throughout the study area is low in relation to the cocoa tree's need which are estimated at more than 3 pc organic matter in the humus layer of the soil [20]. These low levels are generally the result of a balance resulting from three processes: organic inputs (aerial and root litter, soil improvers), the decomposition of these inputs by soil biological activities and the stabilization of organic matter by the soil mineral matrix (clay particles) [21] [22]. In the present case, it is the third of these processes that seems to be lacking, given the low clay levels observed.

As with organic matter levels, nitrogen levels are low in the soils studied, given that average levels of this element are below 0.2 pc, which is the minimum threshold required for cocoa production [23]. However, the C/N ratio, which indicates the dynamics of organic carbon and nitrogen in the soil, between 10.93 and 15.02, reflects good carbon mineralization due to the action of fauna and soil microbes, particularly for C/N ratio values ranging from 9 to 12 [24].

Soil acidity (pH ranging from 4.98 - 5.63) is not a constraint for the cocoa tree because, although the optimum pH is 7, the plant can also grow well in soils with an acid pH (pH = 4.5 - 6) or a slightly basic pH (pH 6.7 - 7.5) [25] [26]. However, production is severely limited below a pH of 4.5 or when the pH is above 8 [23]. Under these conditions, the activity of fauna and microbes is affected, leading to a number of constraints, including: inhibition of nitrification reactions, phosphorus deficiency, aluminium and manganese toxicity, high availability of certain minor elements and, finally, limited plant growth.

The adsorbent complex has a satisfactory saturation state (around 50 pc) and a sum of exchangeable bases which, by varying from 1.83 to 3.83 cmol·kg⁻¹, is in line with the range of 2 to 6 cmol·kg⁻¹ recommended for cocoa farming [24]. On the other hand, the CEC in these soils, which varies between 3.88 and 7.96 cmol·kg⁻¹ and is therefore far from the 12 cmol·kg⁻¹ recommended for cocoa farming [24], is low and unfavorable, especially as the CEC is a measure of the soil's ability to

fix cations. The higher it is, the more cations are stored by the soil and the more fertile it is. Its level depends on the mineralogical characteristics of the soil (clay content and type) and the level of organic matter, which contributes 4 to 5 times more than clay [27]. The low CEC observed is therefore probably linked to the low levels of organic matter buried in the soil. These low CECs explain the fact that most soils in the area are deficient in Mg^{2+} , K^+ , Ca^{2+} and especially P, if we take into account the thresholds set at $2.45\text{ cmol}\cdot\text{kg}^{-1}$ for Mg^{2+} , $0.7\text{ cmol}\cdot\text{kg}^{-1}$ for K^+ , 5 to $8\text{ cmol}\cdot\text{kg}^{-1}$ for Ca^{2+} and 150 to 700 ppm for P [24] [28]-[31].

Despite these deficiencies, most of the soils studied, particularly those in the Katana, Koffikro, Blaisekro, Grâce and Ndouffoukankro sectors, appear to have a good nutritional balance between Mg^{2+} and K^+ . In fact, the optimum range for the Mg^{2+}/K^+ ratio, which is 3 to 4 for many plants, is in line with the results obtained [32]. For other soils, this Mg^{2+}/K^+ ratio is too high and thus indicates a K^+ deficiency, probably due to the strong fixation of this element on the adsorbent complex expressed by K^+/CEC ratios evolving in the range of 2 to 3 pc, a sign of a good level of saturation of the K^+ fixation sites on the adsorbent complex [32]. With regard to the balance between Ca^{2+} and Mg^{2+} , only the soils of Ndouffoukankro and Grâce have ratios within the acceptable limit of between 3 and 5 [33]. The soils in the other six sectors may be Ca^{2+} deficient because their Ca^{2+}/Mg^{2+} ratios are too low.

On the other hand, all the soils studied showed low availability of P, with N/P ratios ranging from 10.23 to 34.26, well above the target range of 1.5 to 2 [24]. As a reminder, the levels of this element had already appeared to be low, below 150 ppm [31]. These findings are very typical of tropical soils, which make up the majority of the 5.7 billion hectares of soil in the world considered to be problematic in terms of limiting plant phosphate nutrition [31]. During pedogenesis, P content decreases, with the proportion present in organic form increasing to the detriment of inorganic forms [34]. In this context, at the earliest stages of soil development, soils are mainly limited by low nitrogen content and availability, whereas at the most advanced stages of their evolution, they become more limited by P [35]. This is particularly true of tropical soils, which, except in volcanic or sedimentary regions, are often characterized by a high degree of weathering and hence low P content. In addition, in these soils, the abundance of secondary minerals such as iron and aluminium oxides is conducive to a high retention of phosphate ions, limiting their availability [31]. On the contrary, according to their ratios ($\text{SEB} + 6.15)/\text{N}$ and $(Ca^{2+}+Mg^{2+})/K^+$ greater than 8.9 and 11.5 respectively, all the soils explored show a good balance between exchangeable bases and nitrogen on the one hand, and between the Ca^{2+} - Mg^{2+} binomial and K^+ on the other [32].

5. Conclusions and Recommendations

Most of the soils explored are deep and therefore suitable for cocoa farming. Their texture varies from loamy to sandy loam, all of which suggests good internal drainage, good air circulation and easy root penetration. However, their depth is

limited in places by a large volume of ferromanganic concretions. To prevent this process from progressing in the area, the cocoa plantation should be shaded by agroforestry. This prevents certain harmful solar rays from reaching the soil. The low clay content in the surface horizons of these soils is also a major chemical constraint, as clay plays a number of functions that contribute to soil fertility. To compensate for this lack of clay, the soil would have to contain more organic matter. Unfortunately, this other major soil constituent is also lacking. Organic matter is rapidly mineralized by soil fauna and microbes. Exchangeable bases are then released regularly into the soil, hence the low overall base total. The low acidity of the soil, which generally slows down the activity of fauna and microbes, has almost no constraining effect on soil organisms. However, this low soil acidity has a negative impact on the retention of bases on the adsorbent complex. As a result, the CEC is low on all the sites surveyed. However, the low CEC of these soils may also be linked to their low clay and organic matter content. Farmers should therefore opt for farming practices that help to extend the residence time of carbon in the soil, in particular: pruning cocoa trees to increase litter, practicing agroforestry to maintain shade on cocoa farms and reducing tillage, which avoids removing the organic matter protection provided by the soil.

Despite the constraints caused by the low levels of clay and organic matter in the soils, the chemical balances are generally acceptable, particularly the ratios of Mg^{2+}/K^+ , $(SBE + 6.15)/N$ and $(Ca^{2+} + Mg^{2+})/K^+$.

For soils where the Mg^{2+}/K^+ ratio was too high, indicating a potassium deficiency, potassium fertilizer should be applied. Also, for soils where the Ca^{2+}/Mg^{2+} ratio was too low, indicating a Ca^{2+} deficiency, calcium fertilizer was recommended. In addition, for all the soils studied, phosphorus fertilizer should be added to overcome the low availability of phosphorus. For all these inputs, growers have a choice of several fertilization methods: mineral, organic or organo-mineral.

Available in liquid or soluble form, chemical fertilizers are directly assimilated by plants. However, these fertilizers are still in the spotlight because of the sharp rise in their prices on world markets, which can increase cocoa production costs. Also, while these fertilizers improve crop yields in the short term, they are detrimental to soil fertility in the long term. We therefore recommend biological practices for renewing soil fertility, which are increasingly diversified and adapted to all farming systems. The cocoa tree is a plant that exports phosphorus and potassium, some of which is found in the leaves from pruning and in the shells of the pods after denting, generating numerous residues with fertility potential. These residues can be recycled by composting. The technique of combined crops should also be encouraged, particularly legumes, which are traditionally grown by cocoa farmers on other plots. If grown under cocoa trees, legumes could provide an effective means of combating soil nitrogen deficiencies.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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