Original Research Article

The Soil Diagnostic Method to Formulate Fertilizer Requirements for Coffee Trees in Côte d'Ivoire

ABSTRACT

Coffee is a crop that exports significant amounts of minerals from the soil, particularly through crop and pruning products. Maintaining sustainable productivity requires good knowledge and rational management of factors related to soil fertility and plant nutritional status, which would limit production. The objective of this study was to diagnose the mineral requirements of coffee plants in different production regions in order to recommend nutrient quantities adapted to the characteristics of each soil type for sustainable coffee production. Chemical analysis of 156 soil samples representative of the soil units of the coffee growing areas using a soil diagnostic model specific to coffee fertilization was used to determine the nutrient requirements of each soil unit studied. The results generally indicate that soil fertility levels were below the reference threshold values. Nutrient inputs are essential for all soils under coffee in large production areas. Nitrogen inputs are required in all soil units studied. The majority of the soils also showed a very pronounced potassium and calcium deficiency, while the phosphorus deficiency was not very pronounced. Magnesium, although generally in sufficient quantity in soils, has been readjusted to respect the balance in exchangeable bases. The amounts of nutrients to be supplied varied from one soil unit to another. Soils with low organic matter content showed relatively high requirements. Recommendations for appropriate soil fertility management per soil unit were presented in this work.

Key words: Soildiagnosis; nutrients; soils; Fertilization ; Coffea canephora; Côte d'Ivoire.

1. INTRODUCTION

Coffee growth has always played an important role in the growth of the Ivorian economy. Coffee production employs nearly 400,000 coffee farmers[1], almost all smallholders with plots not exceeding 2 ha[2]. The coffee sector continues to generate nearly 1.5% of Côte d'Ivoire's export earnings [3], playing a key role in Côte d'Ivoire's economic and social stability.

The expansion of coffee orchards has taken place in the southern half of the country through the exploitation of primary forests. Nowadays, this cropping system is no longer reproducible due to the decline in forest cover[4].The production area covers the entire southern half of the country and extends from west to east. This area presents a diversity of agropedoclimatic conditions and fertility potentials vary from one region to another [5]; [6].The productions that have been recorded in recent years have always been low compared to the productions obtained at the research station[2].

Coffee cultivation can thrive on a wide variety of soils [7]. However, the right chemical characteristics to meet the nutrient needs of the coffee plant are essential for good orchard productivity. Furthermore, studies in the Central African Republic [8], Côte d'Ivoire [9],and Costa Rica [10] have shown that beyond systematic fertilizer applications, the most important factor determining the best performance of the coffee plant is the balance of exchangeable bases K, Ca, and Mg in the soil.

Although soil fertility under coffee trees is not sufficient to maintain optimal productivity [6], most coffee orchards do not receive any fertilizer, not even to compensate for nutrients removed from previous harvests [2]. Furthermore, the need for fertilization of the coffee tree is high and the availability of financial resources for this purpose is scarce. The high price of fertilizers requires that inputs be used efficiently by determining which nutrients should be supplied to the plant in optimum quantity and quality [11].Therefore, sustainable management strategies for orchard productivity are essential.

This study uses the soil diagnostic model developed to help the agronomist easily understand and interpret soil chemical analysis bulletins (nutrient levels, K-Ca-Mg ratios) to be able to make adequate fertilizer recommendations for coffee cultivation to farmers without the need for time-consuming and expensive fertilizer trials [9];[12].

The objective was to identify factors related to coffee soil fertility in coffee-growing regions for fertilizerrecommendations that could limit coffee growth, development, and production.

2. MATERIALS AND METHODS

2.1 Study areas

In Côte d'Ivoire, the coffee growing areas extend over the entire southern half of the country; that is, from longitudes 2°40'W to 8°34'W and latitudes 4°16'N to 8°00'N. They cover the following districts: Lacs, Comoé, Gôh-Djiboua, Lagunes, Mountains, Sassandra-Marahoue, and Bas-Sassandra. Rainfall varies between 1100 and 2300 mm/year [13]. The western part of the country has an average temperature that varies from 18°C to 24°C while the rest of the central, south-western, and eastern zones vary between 24 and 32°C [13]. The average relative humidity of the air over the whole country decreases progressively from the south (85%) to the north (71%). Concerning soils, soil and geological maps (scale = 1/500 000) from the Institut de Recherche pour le Développement[14];[15], were obtained in the form of geo-located raster maps. They were digitized withQuantum GIS software. Other optional digital maps (e.g. administrative, road, river, lake, etc.) were obtained from free websites. These maps were used to identify the different soil types under coffee trees after positioning the georeferenced coffee plots.

2.2 Materials

The 'coffee soil diagnosis' software was developed in Côte d'Ivoire from the results of numerous fertilization trials supplemented by vegetation vase trials, some of which lasted more than 20 years [9];[12]. It is a computer program developed to facilitate the interpretation of chemical analyses to help agronomists in the management of mineral nutrition of coffee trees.

2.3 Methods

Physical and chemical parameters of the soil were carried out according to standard procedures [16]. Granulometry was determined by the international Robinson pipette method. Organic carbon (C) was determined by the Walkley-Black method after oxidation with a mixture of sulphuricacid and potassium dichromate. Total nitrogen (N) has been established by the Kjeldahl method based on wet oxidation. Available phosphorus (Pav) was determined by the Dabin method based on the use of very dilute acid, 0.001N sulphuric acid. Cation exchange capacity (CEC) and exchangeable bases, such as potassium (K), calcium (Ca), and magnesium (Mg) were determined by the Metson method. K was determined using the flame photometer, while Ca and Mg were measured by atomic absorption flame spectrophotometry. The pH of the water was measured using a pH meter after adding 50 ml of ionized water to 20 g of soil followed by stirring and decanting.

To determine the nutrient requirements suitable for coffee, the 'coffee soil diagnostic' tool was used to perform calculations of the fertilizer requirements of 156 soil samples distributed in the 15 soil units identified according to their physicochemical properties [6]. The software compares the values measured in the laboratory with those of references recorded in its matrix. Then, depending on the intrinsic quality of the soil (pH, OM, level of base saturation, and exchangeable base equilibrium), the model proposes quantities of N, P, K, Ca, and Mg to be applied to the coffee plants [17].The different quantities are coded from 0 (low need) to 4 (very high need) according to the level of fertilizer needs of the different soils. The results are given in the form of formulas and fertilizer dosages, allowing them to be correlated with other soil characteristics. The corresponding quantities to be applied to each coffee plant were then determined.

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2.4 Statistical analysis

Descriptive statistics were carried out on the data collected, using R software (version 2.0-2).

3. RESULTS

3.1 Soil unit suitability for amendment

The projection of the GPS positions of the 156 plots (Figure 1)visited confirmed that the coffee plantations are located on 15 soil units according to the CPCS 1967 classification (Commission de pédologieet de cartographie des sols). These plantations are also distributed on five major soil groups according to the World Reference Base for Soil Resources (WRB)classification[18]: Acrisol 59%, Alisol 17%, Cambisol 3%, Ferralsol 12%, and Plinthosol 9% (Table 1). The average physicochemical values of the top 20 cm of soil under coffee in the various soil units are presented in Table 1. Values in bold are those below the reference thresholds. The AL index (clay + silt) varies according to the soil units from 19 to 35%. The pH of the soil is slightly acidic. The range of soil reaction varies between 5.1 and 6.3 with an average soil pH of 5.7. Soil pH analysis confirms the moderately acidic character of the soils.

3.2 Diagnosis of soil units

3.2.1 Carbon, nitrogen, and C/N ratios

Carbon contents were below threshold levels in three soil units [19]. These were the Granite soil units FS_IA, Granite FS_Complex,and Granite FS_MFOA. The soil diagnosis revealed that the total nitrogen contents were all below the reference thresholds. Concerningthe C/N ratio, the low C and N contents destabilize the C/N ratio, which falls below 12 for some soil units (Table 1). To achieve a target yield of at least 2 tons of merchantable coffee per hectare, it was necessary to apply quantities of nitrogen according to the needs of the soil. Thus, inputs of 173 g/ha were required to cover the needs of all soil units. Referring to the data grid of the coffee soil diagnostic model (Tables 2 and 3), this need was qualified as level 1.

3.2.2 Phosphorus

Concerning available phosphorus, only two soil units (Granite FS_IA and Schists FS_IA) showed levels below the reference threshold of 45 ppm. Most of the other soil units had P contents well below the reference threshold. In addition, the Granite FS_IA soil units had a very high content compared to the Schists FS_IA soil units. Based on the target yields of 2 kg, inputs of 20 g/tree were required to cover the needs of the Granite FS_IA soil units and 40 g/tree on the Schists FS_IA soil units. Referring to the data grid of the coffee soil diagnostic model (Tables 2 and 3), these needs were qualified as level 1 for the Granite FS_IA soils and level 2 for the Schists FS_IA soils.

3.2.3 Cation exchange capacity CEC and exchangeable bases K, Ca, and Mg

In general, CEC was relatively higher in the schists soil units than in the other soil types (Table 1). This is consistent with the clay-silt indices (AL) and C contents. CEC was generally close to the optimum value of 10 meq/100 g soil in all the soil units studied. These soils had Ca and K contents below the reference thresholds [19].The Mg contents were all above the reference values. The Mg/K and (Ca + Mg)/K ratios were close to standard. As the saturation rates were almost all below 40%, the quantities of nutrients should be calculated in such a way as to reach 60% while keeping the ratios between K, Ca, and Mg at the optimum recommended by the coffee soil diagnostic software, which is 6: 76: 18%.

To achieve a target yield of at least 2 tons of merchantable coffee per hectare, it was necessary to apply K, Ca, and Mg according to the needs of the soil for each of these nutrients. Thus, for K, inputs of 78 g/ha, 155 g/ha, and 233 g/ha were required to cover the different levels of need. Referring to the data grid of the coffee soil diagnostic model (Tables 2 and 3), these needs were qualified as level 1, level 2, and level 3 respectively. The Ca inputs that allowed the 60% saturation rate to be reached and the triple ratio to be approached were 528 g/tree corresponding to a level 1 need; 1056 g/tree equivalent to a level 2 need and 1584 g/tree corresponding to a level 3 need (Tables 2 and 3). Mg intakes were recommended to maintain the balance between the triple K: Ca: Mg ratio of 6:76: 18%. Intakes were 65 g/tree corresponding to a level 1 requirement and 131 g/tree equivalent to a level 2 requirement (Table 2 and 3).

The highest sum of exchangeable bases (SEB) is 10.2 meq/100g for the Schists FS_IA soil units. This results in high saturation rates of 85 %. In contrast, all other soil units had exchangeable base sums ranging from 3.2 to 5.3 meq/100g, thus a saturation rate below 60%.

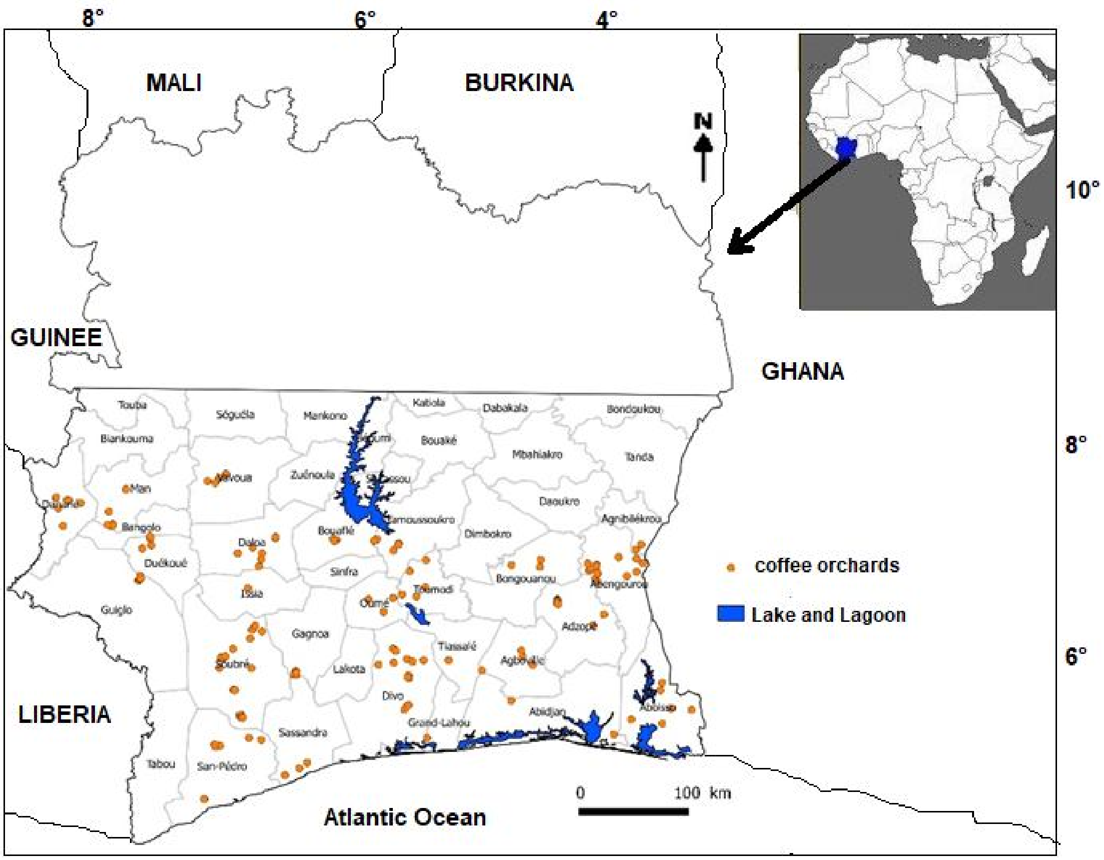

Figure 1: Coffee production area in Côte d'Ivoire

Table 1: Chemical properties of soils under coffee trees in 15 soil units

Heading	**AL**	**C**	**N**	**C/N**	**P_{av}**	**K**	**Ca**	**Mg**	**CEC**	**pH**	**K%**	**Ca%**	**Mg%**	**V %**	**SEB**	**Mg/K**	**Ca+Mg/K**
G FS_IA	21	**1.21**	**0.16**	**8**	**43**	0.22	**1.95**	1.38	10	5.8	6.2	**54.9**	38,9	**36**	3.55	6.3	15
G FS_Complex	23	**1.23**	**0.18**	**7**	60	**0.15**	**3.23**	1.08	11	5.7	**3.4**	**72.4**	24,2	**41**	4.46	7.2	30
G FS_SRA	29	1.82	**0.16**	11	94	0.23	**2.54**	0.92	12	5.3	6.2	**68.8**	24,9	**31**	3.69	4.0	17
G FS_MFOA	19	**1.17**	**0.13**	9	78	**0.18**	**2.52**	0.89	10	5.8	**5.0**	**70.2**	24,8	**36**	3.58	4.9	20
G FS_MHFA	25	1.26	**0.15**	**8**	93	**0.24**	**2.32**	1.66	12	6.0	**5.7**	**55.0**	39,3	**35**	4.22	6.9	19
G FS_MA	24	1.54	**0.16**	10	92	**0.19**	**1.94**	1.08	11	5.6	**5.9**	**60.4**	33,6	**29**	3.21	5.7	17
G FS_MIAT	25	1.57	**0.17**	9	82	**0.19**	**2.69**	1.24	12	5.8	**4.6**	**65.3**	30,1	**34**	4.11	6.5	22
BR FS_SRT	22	1.43	**0.20**	**7**	72	**0.16**	**2.28**	1.21	9	5.8	**4.4**	**62.5**	33,2	**41**	3.65	7.6	22
BR FS_MA	35	1.85	**0.19**	10	79	**0.13**	**2.21**	0.82	11	5.3	**4.1**	**69.9**	25,9	**29**	3.16	6.3	23
TS FS_M	21	1.35	**0.14**	10	79	**0.16**	**2.61**	0.80	10	5.1	**4.5**	**73.1**	22,4	**36**	3.57	5.0	21
S FS_IA	35	2.77	**0.23**	12	**11**	**0.54**	**6.89**	2.81	12	6.2	**5.3**	**67.3**	27,4	85	10.24	5.2	22
S FS_SRA	35	2.22	**0.26**	**9**	75	0.24	**2.28**	1.40	18	6.0	6.1	**58.2**	35,7	**22**	3.92	5.8	15
S FS_HA	27	2.05	**0.19**	11	58	**0.18**	**3.50**	1.57	17	6.6	**3.4**	**66.7**	29,9	**31**	5.24	8.7	29
S FS_MA	32	2.04	**0.20**	10	84	**0.20**	**3.62**	1.35	15	5.6	**3.9**	**70.0**	26,1	**34**	5.17	6.7	25
S FS_MHFA	28	1.69	**0.20**	**8**	80	**0.22**	**2.69**	1.58	13	5.9	**4.9**	**59.9**	35,2	**35**	4.49	7.2	22

AL: clay-silt indices; C/N: carbon/nitrogen ratio, P_{av}: available phosphorus; SEB: sum of exchangeable bases, V: saturation rate;G: Granite; BR: Basic Rock; TS: Tertiary Sand; FS: Ferrallitic soil; IA: Impoverished Altered; MA: Modal Altered; SRA: Slightly Rejuvenated Altered; MHFA: Modal Hardened Facies Altered; MFOA: Modal Facies with Overlaps Altered, MIAT: Modal Impoverished Altered Typical; HA: Hardened Altered; M: Modal; SRT: Slightly Rejuvenated Typical

Table 2: Keys to establishing levels of need and equivalent quantities (g/tree)

	N	P_2O_5	K_2O	CaO	MgO
4		80	310	2112	261
3		60	233	1584	196
2		40	155	1056	131
1	73	20	78	528	65
0	55	2	8	53	7

Table 3: Formulation of needs from the soil diagnosis model coffee

Codes	**Geologicalbedrock**	**Soil group FAO (2015)**	**Area size (%)**	**Nutrientrequirements**				
				N	P_2O_5	K_2O	CaO	MgO
FS_IA	Granite	Plinthosol	1	1	1	1	2	1
FS_Complex	Granite	Plinthosol	4	1	0	2	1	0
FS_SRA	Granite	Ferralsol	9	1	0	1	2	1
FS_MFOA	Granite	Alisol	7	1	0	1	1	0
FS_MHFA	Granite	Acrisol	6	1	0	1	2	0
FS_MA	Granite	Acrisol	25	1	0	1	2	1
FS_MIAT	Granite	Alisol	6	1	0	2	2	0
FS_SRT	Basic rocks	Cambisol	2	1	0	2	2	0
FS_MA	Basic rocks	Plinthosol	1	1	0	3	3	2
FS_M	Tertiarysands	Ferralsol	3	1	0	2	1	1
FS_IA	Schists	Alisol	4	1	2	2	1	0
FS_SRA	Schists	Cambisol	1	1	0	2	3	1
FS_HA	Schists	Plinthosol	3	1	1	2	2	1
FS_MA	Schists	Acrisol	23	1	0	2	2	1
FS_MHFA	Schists	Acrisol	5	1	0	2	2	1

FS: Ferrallitic soil; IA: Impoverished Altered; MA: Modal Altered; SRA: Slightly Rejuvenated Altered; MHFA: Modal Hardened Facies Altered; MFOA: Modal Facies with Overlaps Altered, MIAT: Modal Impoverished Altered Typical; HA: Hardened Altered; M: Modal; SRT: Slightly Rejuvenated Typical

4. DISCUSSION

The soil units had AL indices (clay + silt) above the threshold of 11%, the threshold above which the soil can meet the needs of the coffee crop [19]. Thus, all soils in the surveyed areas can be diagnosed using the Soil Diagnostic Model for Coffee. Soil pH analysis confirms the moderately acidic character of the soils with no consequences for coffee tree growth except perhaps a slight reduction in the availability of soil trace elements. Coffee plants can grow in these pH ranges without the need for liming [20].

Without the addition of organic matter and external nitrogen, the properties that can logically be associated with agronomic practices are the organic carbon content, the total nitrogen content, and the carbon-to-nitrogen ratio (C/N). Nitrogen was found to be insufficient to meet the needs of the plants during the diagnosis, even though it is the most important element for the nutrition of coffee plants. On the one hand, nitrogen is very mobile in the soil and is less stored on the adsorbent complex. On the other hand, nitrogen nutrient inputs have always been almost non-existent in coffee plots [2]. Moreover, in the absence of fertilization, the nitrogen available to the plantcomes from mineralization by microorganisms. A low C/N ratio reflects both a rapid evolution of litter and the possibility of feeding the coffee plants with nitrogen, except when this content is insufficient to meet the needs of the coffee plant. Therefore, a C/N ratio below 9 indicates a depletion of nitrogen in the soil under coffee [20]. Nitrogen requirements were found in all soil units at a dose of 73 g/tree; i.e. 143 kg/ha at a planting density of 1960 plants per ha. Much higher rates have been recommended by several authors [21]; [22]except that these high rates increase the total cost of production.

For all the soils studied, it can be seen that the soils with high C contents and AL index are those with high CEC. This can be explained by the fact that the CEC depends on both the clay fraction and the organic matter [23]. The values obtained are close to the optimum [20].They give a good capacity to retain the nutrients P, K, Ca, and Mg to be supplied to soils that are in short supply.

Most of the soil units had higher content than standard levels of available phosphorus [20]. Phosphorus P requirements were found to be low in almost all soils. According to Willson[21], the low P requirements of coffee plants can be attributed to the low P concentration in coffee plants. Furthermore, Carvajal [10]added that the uptake of phosphorus by the coffee plant does not exceed 6 g per tree in the first year. Also, less than 3 g is eliminated per ton of green coffee [24]. However, the continuous supply of other nutrients to the soil suggests that available P concentrations in coffee plantation soils may be deficient in the future if no P is added [25].

The Mg/K and (Ca +Mg)/K ratios showed equilibria close to the standards [19]. The low K and Ca contents on the one hand and the relatively high magnesium content on the other hand, destabilize the equilibrium between K, Ca, and Mg. The analysis of the ratio of K: Ca: Mg in the present work is far from the optimal ratio of 6: 78: 16 (in % of the sum of exchangeable bases) recommended for coffee soils by Snoeck and Lambot [20]. While at the level of exchangeable bases, Mg was in optimal amounts in all soil units, the main constraint was the K and Ca contents, as these were below critical levels. Soils can benefit from the addition of fertilizerscontaining K and Ca to raise their levels in the soil. However, to meet the triple ratio of K: Ca: Mg (6: 78: 16), moderate additional inputs of Mg were required.

Saturation levels were low in almost all soils following the reference values. These results are in agreement with those found by Boyer [26]who noted that in general, the sum of exchangeable bases of medium to highly desaturated Ferrasols in tropical areas is between 2 and 6 meq/100g.

5. CONCLUSION

This study presented nutrient requirements that varied according to soil types and environments. The results showed that all the soil units under the coffee tree were very deficient in major nutrients. Nitrogen inputs were required in all soil units studied. The majority of the soils also showed a very pronounced potassium and calcium deficiency, while the phosphorus deficiency was not very pronounced. Magnesium, although generally in sufficient quantity in soils, has been readjusted to respect the balance in exchangeable bases. Requirement levels have varied from environment to environment as they have been recommended based on residual mineral stocks in the soil. These new fertilization recommendations will have to be tested to adjust the nutrient recommendations proposed by the coffee soil diagnostic model to the needs of coffee trees in the real environment before being adopted.

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