Original Research Article

Mapping coffee tree fertilizer requirements in Côte d’Ivoire

ABSTRACT

Coffee production in Côte d'Ivoire has been declining sharply for more than twenty years due to degradation in soil fertility status. ~~as a result~~ of soil fertility degradation. The objective of this study was to map the mineral requirements of coffee trees in different production regions and to recommend immediate and long-term intervention strategies for soil management. In this study, the diagnosis of the chemical needs of 156 soil samples from major coffee production areas were used. We used a soil diagnostic model specific to coffee fertilization combined with geographic information systems (GIS). The combination of fertilizer formulas from the coffee soil diagnostic model, recent climatic data and soil units of the coffee growing areas allowed for the development and elaboration of a thematic map showing a total of five basic formulas (N-P_2O_5-K_2O-CaO-MgO) adapted to the real nutritional needs of coffee trees according to their agropedoclimatic environments. Two of these formulas cover 90% of the area studied. This study will enable appropriate soil management for sustainable productivity of coffee trees in Côte d'Ivoire.

Key words: Coffea canephora Fertilization, GIS, Ivory Coast, ~~Fertilization~~, ~~GIS~~, Nutritional needs, Sustinable productivity and Mapping

1. INTRODUCTION

In Côte d'Ivoire, coffee production in the 1990s involved nearly 400000 coffee farmers, almost all of them were belongos to ~~whom were~~ small family farmers [1]. The coffee sector could generate a turnover of about 100 billion CFA francs, making it the third largest export commodity after cocoa and cotton [2]. Since then, coffee production, which was estimated at over 200000 tones in the 1990s, is now less than 90000 tones. This decline can be explained by several factors. On the one hand, the traditional system based on extensive shifting cultivation is no longer reproducible due to declining forest reserves [3], and on the other hand, competition from other perennial crops such as cocoa, rubber and oil palm for the development of existing fallows and old orchards [4]. Nevertheless, despite the current situation, the coffee sector continues to generate nearly 1.5% of Côte d'Ivoire's export earnings [5], playing a key role in Côte d'Ivoire's economic and social stability. Although coffee farmers are aware of the reduction in available land and low productivity of their orchards, with good agricultural practices, including the use of fertilizers, remain almost nonexistent in Côte d'Ivoire [6]. And for the few farmers who practice fertilization, the formulas and doses used remain universal and not appropriate to the local situation [7]. Indeed, the coffee growing area represents a diversity of soils

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and agropedoclimatic conditions that makes soil fertility potentials vary from one region to another [7]. Therefore, poorly managed fertilization can disrupt balances between soil nutrient levels, which can become either limiting or toxic for coffee trees. This is particularly important as lack of fertilization or ~~irra~~irrigation ~~tional~~ inputs can cause or leads to ~~in the~~ long term affect on the sustainability of coffee orchards. Coffee farmers should therefore adapt their cultivation methods to the agropedoclimatic characteristics as per the ~~of~~ local agricultural conditions and adopt more sustainable production systems in their coffee fields. This study focuses on improving soil nutrient management. In particular, we studied the relationship between the nutritional needs of coffee trees and the different soil types and climatic conditions in order to map out fertilizer formulas and propose to coffee farmers the formulas and doses best suited to their soils. This work uses/d~~es~~ two complementary tools: the 'coffee soil diagnostic' and the geographic information system [8]. Soil diagnosis is a tool that was developed to help and establish the nutritional requirements of coffee from the physical and chemical parameters of one or more soil samples [9,10,11]. GIS was used to map the results so that they could be simultaneously correlated with other geo-localized information such as soil and climate data. Thus, both tools were used to delineate agro-ecological zones are favourable for coffee cultivation and the resulting information was displayed in the form of thematic maps.

2. Materials and methods

2.1 Study environment

In Côte d'Ivoire, the coffee-growing areas extended over the entire southern half of the country, i.e. from latitudes 2°40'W to 8°34'W and longitudes 4°16'N to 8°00'N. They cover the following ~~departments~~ regions : Lakes, Comoé, Gôh-Djiboua, Lagunes, Mountains, Sassandra-Marahoue and Bas-Sassandra. Three rainfall isohyets were identified in the study area. The West, South-West and South-East of the country are characterized by sufficient rainfall for coffee growing (over 1400 mm/year). The large Centre has less intense rainfall, varying between 1100 and 1400 mm/year. The least humid lands are the North and Northeast where rainfall varies between 900 and 1100 mm/year; this is insufficient for coffee cultivation [12]. Average temperatures in the southern half of the country vary between 25°C and 30°C; which is suitable for coffee cultivation. The mountainous west, which has an average temperature of 24°C, is also suitable for coffee cultivation [12]. The average relative humidity of the air over the whole country ~~decreases~~ increased gradually from south to north (from 71% to 85%). Regarding soils, soil and geological maps at a scale of 1:500000 were obtained in the form of geolocated raster maps from the ~~Institut~~Institute de ~~Recherche~~Recherché pour le Développement [13,14]. They were digitized to construct the digital soil map for use with GIS software. Other optional digital maps (e.g. administrative, road, river, lake, etc.) were obtained from free websites.

2.2 Soil data

To determine the nutrient requirements for coffee, the 'coffee soil diagnosis' tool developed in Côte d'Ivoire was used to perform the calculations [9,10]. The calculations were performed on the average physicochemical properties of 15 soil units [7]. 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, organic matter, 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 as per their requirement for optimum growth and development. The different quantities are coded from 0 (low need) to 4 (very high need) according to the levels of fertilizing elements required by the different soils. The results are given in the form of formulas and fertilizer doses, allowing them to be correlated with other soil characteristics. Then, the corresponding quantities for a coffee plot were determined.

2.3 Mapping

Soil and climate data in the form of geo-referenced image maps (raster) from the literature were vectored using the open source geographic information system and QGIS [8]. An appropriate growing area was constructed by combining soil, geological, rainfall and thermal maps according to the environmental needs of the coffee tree. Then, a connection between the Excel Soil Diagnostic database (codified soil data) and the QGIS software is established via an ODBC (Open Data Base Connectivity) connection to create vector layers. Finally, the synthesis map is created by combining the different thematic maps.

2.4 Statistical analysis

The data were analyzed using R software (version 2.0-2). Multivariate analysis was applied to the data. Principal component analysis (PCA) was used to analyze map units with similar physicochemical requirements. Then the Ascending Hierarchical Classification (AHC) was performed on the results of the PCA to group and describe the soil types with similar mineral requirements.

3. RESULTS

3.1 Delineation of ecological zones favourable to coffee cultivation

Three main rainfall and temperature zones have been identified (Figure 1). The favourable rainfall zone is the southern half of the country and is characterized by annual rainfall above 1200 mm/year. The moderately favourable zone, where annual rainfall varies between 1100 and 1200 mm/year, is more uncertain for coffee cultivation. The northern and central-eastern zone with less than 1100 mm of rainfall is too dry for coffee cultivation. Three temperature zones have also been distinguished. The first is located in the mountainous areas in the west, where the average temperature varies between 18 and 24 °C. The second is located between the center and the east with an average temperature of over 28°C. The third zone is the remaining southern half of the country, where the average temperature varies between 24 and 28 °C. Relative humidity is above 75% in the southern half

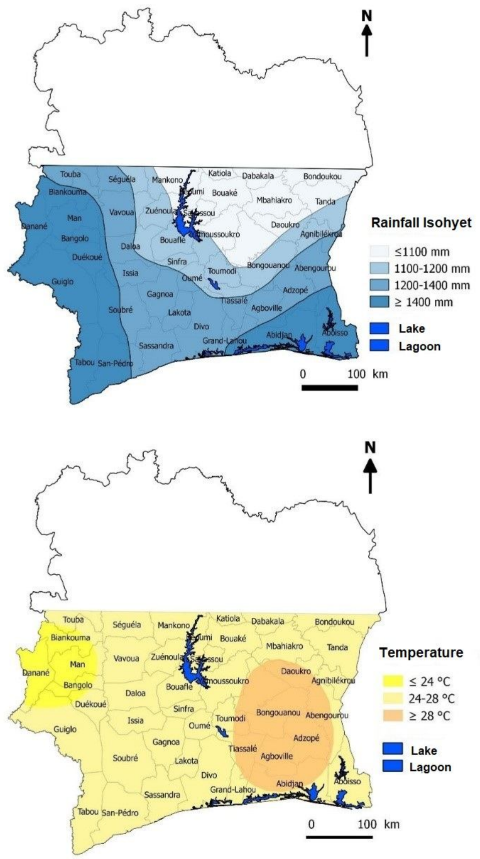

Figure 1: Rainfall and temperature maps

3.2 Major characteristics of soils

The projection of GPS positions of the 156 plots ~~visited~~ studied shows that coffee trees are grown or cultivated ~~installed~~ on 6 soil types according to the FAO classification [15] and 15 different ferralitic soils according to the French CPCS 1967 classification [14]. The French CPCS 1967 classification was used throughout this work. Thus, the seven requirement pairs were identified on the bedrock of granitic origin, two requirement pairs on the bedrock Basic Rock, one pair belonging to the bedrock Tertiary Sands and five pairs of Schist origin. The codified major characteristics of the different mineral requirements from the soil-coffee diagnostic model are described in Table 1. Nitrogen (N) requirements were recorded in all soil units or types. Only one requirement level (level 1), a low requirement, was observed in the production zone. Three levels of phosphorus requirement were observed in the coffee growing area. The level 0 requirement covers the vast majority of soil units in the study area (92% of soil units), indicating a low phosphorus requirement. Level 1, a low requirement, was located on the Impoverished Altered soils (FS_IA) and the Hardened Altered (FS_HA). The level 2 requirement, which is quite high, is located on the reworked depleted ferralitic soils (in the south). Potassium requirements were low (level 1) and fairly high (level 2). They cover 48% and 51% of the soil units respectively, while the level 3 (high) requirement covers 1% of the soil units. Three types of requirements are needed to redress the calcium content of the soil. Level 2 (high enough) needs cover most of the production area, i.e. 80% of the soil units. The Level 1 (low) requirement covers 18% of the soil units. Level 3 (high) covers a very small part of the soil units (2%). Mg requirements are level 0 (low), level 1 (low) and level 2 (fairly high). They cover 29%, 70% and 1% of the soil units respectively.

Table 1: Coded formulas for different soil units

Code	Geological bedrock	Soil group FAO (2015)	Area size (%)	Soil units mineral requirements				
				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.

3.3 Grouping of mineral element requirement pairs

In total 12 different formulas were selected (Table 1). Two of the 12 formulations cover 62% of the coffee growing areas, respectively 28% on schists and 34% on granite. The results of the principal component analysis (PCA), followed by a hierarchical bottom-up classification applied to the data from the 12 N-P_2O_5-K_2O-CaO-MgO formulations show two principal components selected according to eigenvalue criteria greater than or equal to 1. The contribution of the components to the total variation in the first and second dimensions is 73.07%; 47.32% for axis 1 and 25.74% for axis 2 (Figure 2). The first component is clearly related to the variables K_2O, CaO and MgO on the positive side. Also, there is a positive and significant correlation between the variables K_2O, CaO and MgO. On the second component, the only significant property on the positive side is P_2O_5. The factorial design of the individuals (Figure 3) was used to establish the distribution of soils under coffee trees in the geosols. Soils under coffee trees on Basic rocks FS_MA, schists FS_SRA, schists FS_MA and schists FS_MHFA are related to the first component on the positive side while on the negative side are the Granites FS_Complex, Tertiary Sands FS_M and Granites FS_MFOA. The second component is related on the positive side to the Granites FS_IA, schists FS_IA and schists FS_HA. On the negative side are the Basic Rock FS_SRT, Granites FS_SRA, Granites FS_MHFA, Granites FS_MA and Granites FS_MIAT. Referring to (Figure 2) and (Figure 3), it can be seen that the first dimension of variability (Dim 1) contrasts soils under coffee with high K_2O, CaO and Mg requirements with soils with relatively low requirements. These are Basic Rocks FS_MA soils under coffee trees, Schists FS_SRA soils under coffee trees, Schists FS_MA soils under coffee trees and Schists FS_MHFA soils under coffee trees. The second dimension of variability (Dim 2) contrasts soils under coffee with a higher phosphorus requirement than other soils under coffee. These are the soils under coffee from Schists FS_IA, Schists FS_HA and Granites FS_IA.

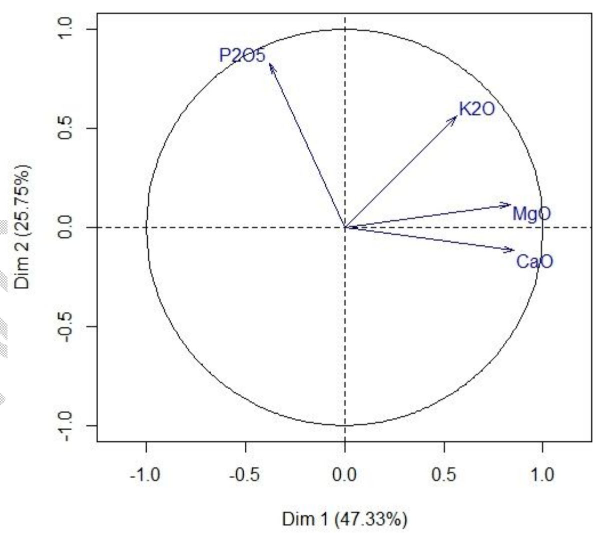

Figure 2: Representation of the variables (chemical needs) in the (1;2) factorial plane

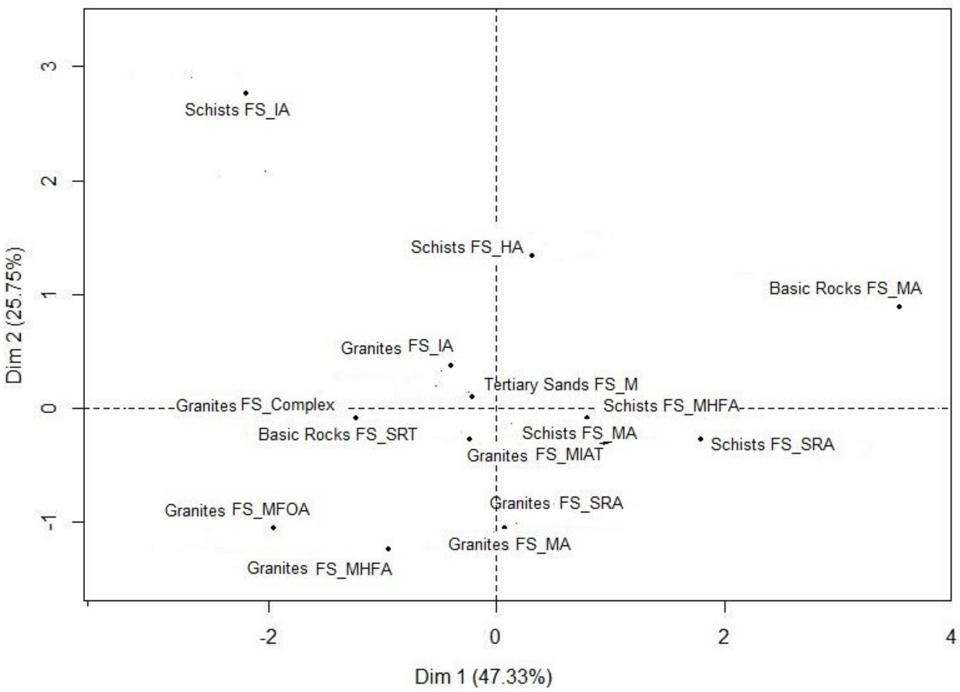

Figure 3: Representation of the individuals (soil geological origins) in the factorial plane (1; :2) :

3.4 Characterization of the needs of soil groups under coffee

3.4.1 Grouping of needs

A hierarchical ascending classification was used to construct a typology of possible formulations in the study area (Figure 4). Five groups were retained as a basis for the distribution of fertilizer quantities. For the types of geological **bedrock**, the chi2 test was significant, with a critical probability of less than 0.05 (*P=.017*). The "bedrock" variableis related to the grouping that was constructed. The needs were generally grouped according to geological bedrock.

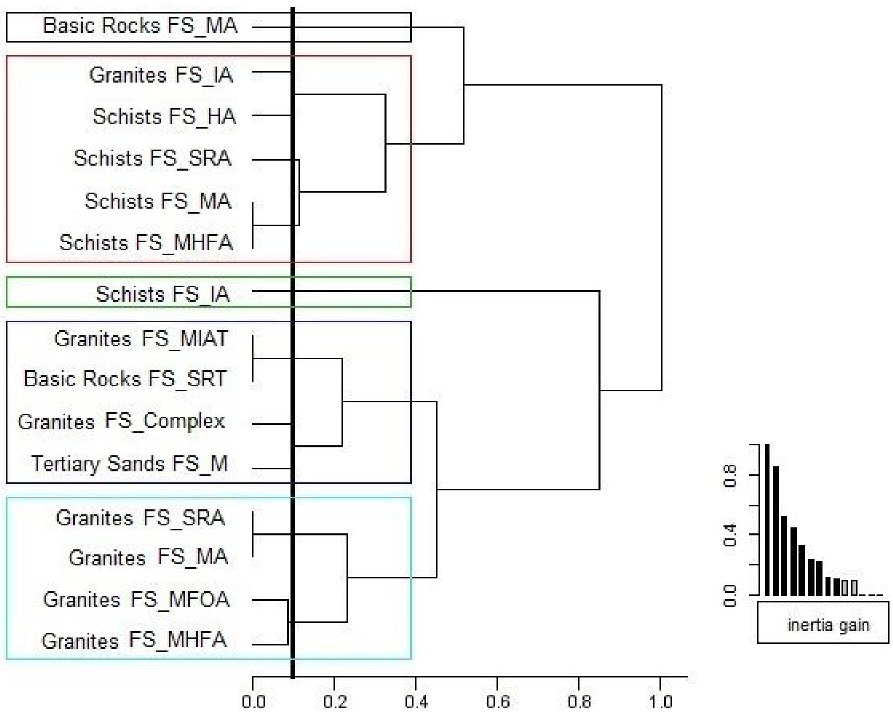

Figure 4: Classification of the 15 soils units according to the nutrient requirements of the coffee plant

3.4.2 Description of groups by quantitative variables or chemical requirements

Correlations ratio between a quantitative variable and the group variable (qualitative variable) highlights all the chemical requirements that differ significantly between the groups (P.critique < 5%). These are K_2O (*R= 0.838; P= .001*), MgO (*R= 0.709; P= .009*), P_2O_5 (*R= 0.695; P= .017*) and CaO (*R= 0.659; P= .019*). For each of these groups, the characteristic variables either by their especially strong mean (positive test value) or by their especially weak mean (negative test value) were evaluated. Thus for:

In group 1, the average (m) requirements of MgO (*m=2; P= .025*) and K_2O (*m=3; P= .027*) are particularly higher than the general average; respectively 0.66 and 1.73,

In Group 2, no chemical needs are particularly high;

In group 3, the chemical requirement average of P_2O_5 (*m=2; Pc= .002*) is higher than the overall average of 0.26;

In group 4, the chemical requirements average of CaO (*m=1.4; Pc= .045*) and MgO (*m=0.2; P= .038*) are statistically lower than the overall averages of 1.86 and 0.66 respectively;

In group 5, the K_2O requirement (*m=1; P= .004*) is statistically lower than the overall average of 1.73.

3.4.3 Description of soils units

The analysis of the closest individual to the class allowed us to characterize on average five groups according to chemical requirements:

Group 1 is the type of soil under coffee trees derived from Basic rocks FS_MA. Soils in this group have particularly high MgO and K_2O requirements,

Group 2 consists of four types of soil under coffee trees, based on Schists and one soil under coffee trees are ~~on~~ Granites FS_IA. These are soils from Schists FS_MA, Schists FS_MHFA, Schists FS_SRA and Schists FS_HA. As the Schists FS_MA is the most characteristic individual in this group, the general requirements of this group reflect the chemical requirements of this soil type,

Group 3 is the type of soil under coffee that is derived from Schists FS_IA. The soils in this group have particularly high P_2O_5 requirements,

Group 4 includes soils under coffee trees on Granites FS_Complex, Granites FS_MIAT, Basic Rocks FS_SRT and Tertiary Sands FS_M. Since Granite FS_Complex is the paragon of this group 4, the characteristics of this soil reflect the general characteristics of this group. These soils have CaO and MgO requirements. The Mg requirement is lower than in group 1,

Group 5 includes soils under coffee trees on Granites FS_SRA, Granites FS_MA, Granites FS_MFOA and Granites FS_MHFA. Granites FS_SRA is the most characteristic of this class. The soils in this class have a lower K_2O requirement than the general average.

3.5 Output of formulas to be recommended per soil unit

The formulas generated by the above calculations were linked to the soil units in QGIS software to draw a detailed map of the formulas and fertilizer rates. By grouping soils with the same physico-chemical characteristics and nutrient requirements, the number of formulas was reduced from 12 to 5 by grouping soil units with the same requirements. About 90% of coffee plantations in Côte d'Ivoire are grown on two main types of geological formations: schists and granites. Figure 5 shows the distribution map of the nutrient requirements N-P_2O_5-K_2O-CaO-MgO in the whole ~~cultivation~~ cultivated area. Nitrogen (N) is required everywhere as it is in deficit in all types of soils. The soil requirement for phosphorus (P) is particularly localized in the south. Potassium (K) and calcium (Ca) requirements are also spread over the whole growing area. Magnesium (Mg) and calcium (Ca) requirements are highest in the south-east, specifically north of Aboisso. All nutrients should be made available to the plants in specific ratios by taking into account of ~~to take into account~~ the "law of the minimum" or limiting factor. Taking into account the most characteristic individual in the class and this law, the N-P_2O_5-K_2O-CaO-MgO requirements for each class are determined. For these chemical requirements, the recommended amounts of nutrients at 100% efficiency for coffee plants at the density of 1960 plants/ha are (in kg/ha):

• Group 1: 143 of N, 4 of P_2O_5, 457 of K_2O, 3104 of CaO and 257 of MgO,

• Group 2: 143 of N, 40 of P_2O_5, 304 of K_2O, 2070 of CaO and 128 of MgO,

• Group 3: 143 of N, 92 of P_2O_5, 304 of K_2O, 1035 of CaO and 14 of MgO,

• Group 4: 143 of N, 4 of P_2O_5, 304 of K_2O, 2070 of CaO and 128 of MgO,

• Group 5: 143 of N, 4 of P_2O_5, 153 of K_2O, 2070 of CaO and 128 of MgO.

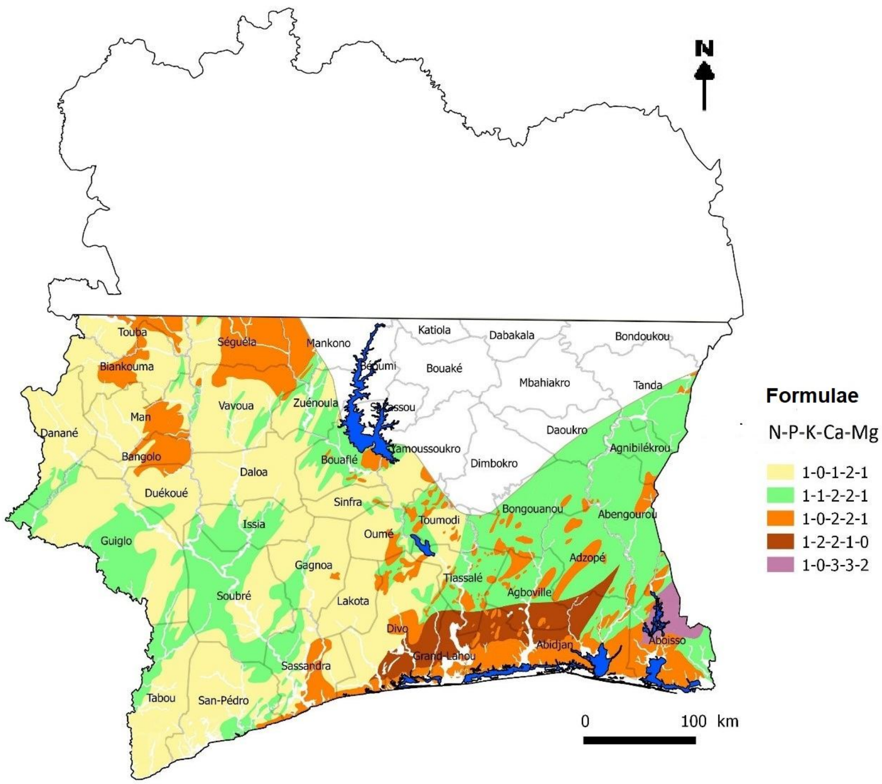

Figure 5: Nutrient requirement maps for mature coffee trees in Côte d'Ivoire

4. DISCUSSION

This work was based on the use of geographic information systems, soil analysis and statistical tools to make the results usable for potential fertilizer producers but also to facilitate the adoption of fertilizers by farmers. The study reveals that the surveyed areas present a diversity of agro-pedoclimatic conditions. The conditions of different agronomic practices have been reported by recent works [6]. Varied soil conditions were also reported in 2019 [7]. This study also highlights diverse climatic conditions. This observation was also reported by work on the same study area in relation to cocoa production [16]. The analysis of the data shows that the areas suitable for coffee cultivation depend mainly on climatic conditions, because weather conditions most affect the growth and development of coffee trees [17]. Thus, the climatic zones favourable for coffee cultivation were those polygon units with regular rainfall above 1100 mm/year. Areas with low rainfall and regular temperatures above 30°C are not suitable for growing coffee according to its requirements [18]. Although coffee trees are established in marginal areas with less than 1100 mm/year of rainfall, coffee development in these areas with low rainfall and high temperatures cannot be economically viable. Although Descroix and Snoeck [18] proposed that coffee should be grown under rainfall of more than 1100 mm/year for good development of coffee trees, rainfall is not the only condition for good development. Indeed, according to Yao et al. [12], if rainfall is above 1100 mm/year and its distribution remains essential for the development of coffee. Moreover, relative humidity is not a constraint in the southern half of the country, as it has always been above 75% throughout the study area. At the soil level, coffee trees are grown on a variety of soils. They can develop as long as there is a favourable texture, soil moisture and sufficient depth to facilitate root development [18]. The 15 soils units covering the study area, although diverse, all have textures favourable to coffee growing [7]. Indeed, the textures of the sampled soils are within the appropriate ranges of clay and silt for coffee cultivation; i.e. between 13 and 41% [19,20]. In addition, the pH values are within the range recommended by the same authors. However, these soils must have sufficient amounts of nutrients to support acceptable and sustainable coffee productivity. About 90% of coffee plantations in Côte d'Ivoire are grown on two main types of geological formations: schists and granites. The need for nitrogen (N) is essential on all soil units. Phosphorus (P) requirements are localized in the South and the Centre. Potassium (K) requirements are more frequent in the East and South-East. Calcium (Ca) requirements are heterogeneously distributed throughout the coffee cultivation area. Magnesium (Mg) is mainly required in the South-West and East. In short, apart from the low phosphorus requirement, all other soils should respond positively to fertilizer inputs due to their low mineral content. By grouping soils with the same physico-chemical characteristics and the same nutrient requirements, the general tendency is to show, on the one hand, soils with a high base desaturation as opposed to soils with a low base desaturation and, on the other hand, soils with a low phosphorus content as opposed to soils with a relatively high phosphorus content. In the first or second case, this is explained by a lack of fertilization [6] which has led to a generalized depletion of the soil. Such findings have been documented under cultivation conditions in Ghana [21]. The characterization and classification of the different mineral element requirements allowed the requirement formulations to be reduced from 12 to 5 for the whole production area. These formulations are of the complete type, thus including major mineral elements. This change in the chemical status of soils under coffee reflects an evolution in the nutrient requirements of coffee trees under different agropedoclimatic conditions. This evolution of chemical status is all the more noticeable as five complete formulas of needs have been recommended instead of the three formulas recommended by studies on the same coffee growing area [22]. The P requirement was found to be low in almost all soils. According to Willson [23], the low P requirement of coffee trees can be attributed to the low P concentration in coffee plants. Indeed, Carvajal [24] indicated 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 are eliminated per ton of green coffee [25]. 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 additional P supply is made [26]. For calcium and magnesium, the increase in levels is based on the principle of keeping the balance between K:Ca:Mg (6-78-16). For these various soils studied, whether they are of schist, granitic, basic or tertiary origin, a high rate of base desaturation has been observed [7]. This partly explains the need for exchangeable bases (K, Ca, Mg) regardless of the type of geological substratum. Previous studies confirm that for desaturated soils, complete fertilizer formulations should be applied for a better response of the coffee plants [25]. However, the different quantities needed depend on the type of bedrock and whether the soils are highly desaturated or weakly desaturated.

5. CONCLUSION

The technologies used in this work consist of a combination of the results of the coffee soil diagnostic model, geographic information systems and statistical tools. The objective is the applicability of the results by the users, i.e. the fertilizer suppliers and the end users, i.e. the farmers. This study made it possible to reconsider the areas suitable for coffee cultivation, to highlight the mineral requirements of soils under coffee and to propose fertilizer formulas adapted to the different types of soil in the various coffee-growing regions of Côte d'Ivoire. Five N-P_2O_5-K_2O-CaO-MgO formulas were identified, two of which cover 90% of the areas surveyed. Complete fertilizer requirements were recorded in all coffee growing areas. Based on this study, new fertilizer recommendations should be made. It would be interesting in future studies to test these formulations on coffee trees in the field to better adjust the recommended doses. Thus, fertilizer types, frequencies, doses and timing of application should be proposed for better management ~~of~~ sustainable orchard production and productivity.

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