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Characterization of soil fertility in Coffee (*Coffea* spp.) production areas in Côte d'Ivoire

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Abstract

With the depletion of forest reserves, coffee growing based on extensive and shifting cultivation mode is no more reproductive. Thus, soils of different coffee growing areas were studied in order to diagnose the fertility level, their potential for productivity of new varieties of coffee (Coffea canephora Pierre, var. Robusta) and their sustainable managements. In total, 156 soil samples were collected and analyzed in the laboratory using standard methods to determine their physicochemical statutes. The results obtained show a low nitrogen content of less than 0.27% in all soil mapping units, a base saturation percentage lower than 60% for the vast majority of soils and crucial presence of organic matter on distribution of physicochemical properties. Clustering of results identified two main components, which accounted for 88.69% of the variability of the data and the grouping into three communities by similarity of features. In view of these results, a sustainable production of the coffee trees requires a fertilization program for the improvement of soils under coffee trees.

Keywords: Characterization, Chemical potential, soil, coffee orchard, Côte d'Ivoire.

Introduction

The current context of coffee production is marked by low yields in peasant environment, about of 325 kilogram of market coffee per hectare per year, against yields of more than 2 tons per hectare per year in research station[1,2].

These low yields are due, on the one hand, to the use by coffee growers of unselected plant material and, on the other hand, to aging coffee orchards[1,3]. Moreover, with the depletion of forest reserves, traditional itinerant and extensive farming systems, based on the conquest of fertile pioneer forest fronts for high production, are no longer reproducible[4,5]. One of the alternatives to mitigate the decline in productivity during fifty years of operation, is the recommendation of the fertilization of coffee plantations. However, the use of fertilizers must meet strict criteria to optimize their use, in order to obtain the greatest productivity with the lowest production costs possible. Thus, the diagnosis of limiting factors, especially the level of fertility of coffee soils, is an important prerequisite for the objective of sustainable agricultural, economic and environmental production. Several studies focusing on coffee production diagnosis were carried out in Côte d'Ivoire, but very little information has been reported on the chemical and physical indicators of coffee soils[6,7,1]. Also, the variability of soils and agro-climatic conditions associated with the lack of sufficient data further complicates their sustainable management after fifty years of operation[8,9]. The constraints to the fertility of cultivated soils remain unknown in the main producing regions of the country and the few existing information remain rather general and old. It is therefore necessary to determine the fertility potential of coffee soils in order to improve productivity. This is the goal assigned to this work. In order to achieve this, it will be necessary, at the specific level: (a) to determine the current physicochemical properties of the coffee soils of the Robusta coffee production zones in Côte d'Ivoire; and (b) to identify the main constraints to the productivity of these soils.

Materials and methods

Study area: Study was conducted in the East, Southeast, South, Southwest, Central West and West zones of Côte d'Ivoire. The climate is hot and humid sub-humid. Amonomodal rainfall pattern is located in the west and bimodal in the other zones. Average rainfall ranging from 1100 to 2300mm per year[10]. Mean annual temperatures range between 24 and 32°C[11]. The average insolation duration is greater than 1900 hours per year[10]. Relative humidity (over 80%) is high throughout the year[12]. The majority of the soils of the Ivorian coffee zone are ferrasols[13]. There are characterized by an exchangeable base sum of less than 8meq/100g of soil, a saturation of the adsorbent complex of less than 80% and an oscillating pH between 4.5 and 6.5[8].

Sampling: A total of 156 soil sample were collected from adult coffee plantations between September and December 2014. In each plot, 30 elemental surface samples of 0-20cm horizons, distributed over two diagonal lines, were collected using a cylindrical auger on an average area of 1 ha. The chosen depth corresponds to the horizons where 90% of the absorbent roots are located as described by Hatert[14]. The samples were then mixed to form a 1kg composite sample representative of the field. The GPS coordinates of each parcel were recorded using a GPS (garmin 62) to connect the samples to the corresponding map units.

Physical and chemical measures: The samples were dried and screened on 2 mm mesh before being crushed and analyzed at the Laboratory of Plant and Soil Analysis (LAVESO) in Yamoussoukro. Soils were analyzed following methodology outlined by Pansu and Gautheryou[15]. Particle sizes was separated with “international Robinson pipette method”. The pH was determined pH-meter after addition of 50 ml of ionized water to 20g of soil followed by stirring and decantation. Organic carbon content was determined by the Walkley-Black method. The nitrogen (N) was measured using the Kjeldahl method. Available phosphorus was quantified using the modified Olsenmethod Dabin. The exchangeable bases (K, Ca and Mg) were determined after extraction with an ammonium acetate solution (NH_4OAC) at pH 7 (Metson method). Potassium was measured using a flame spectrophotometry, whereas Ca and Mg were quantified using atomic absorption. The CEC at pH 7 is determined after displacement of the $NH4^+$ ions by KCl on the pellet of the saturated sample remaining after extraction of the bases.

Statistical analysis: Statistical analyzes were carried out according to methods described by Pages, Hussonand Lê with free software R 3.0.2[16]. View the large number of criteria (quantitative variables) to qualify an "individual" factorial analyzes were used. Plots located on the same map unit constituted an average person. Principal component analysis (PCA) was using to analyze measured parameters and visualize in the form of a cloud the map units with similar physicochemical profiles. Then the Ascending Hierarchical Classification (CAH) was carried out on the results of the ACP to group and describe the types of soils presenting the same physicochemical characteristics.

Results and discussion

Overview of soil mapping units: Table-1 and Table-2 show the average physicochemical values of soil mapping units according to geological provenance. The CS (clay + silt) index varies according to the soil units (from 19 to 35%). The total nitrogen content(N) in all soils was less than 0.27%. Soil organic matter (OM) varied between 2.0 and 4.76% with an average of 2.87%. The C/N ratio varied between 7 and 12 with an average of 9.5. The soil pH is slightly acidic. The soil reaction range is between 5.1 and 6.3 with an average soil pH of 5.7. The average value of the available phosphorus (Pav) was 70.42 $mg.kg^{-1}$. Potassium (K) average was 0.22 $cmol(+).kg^{-1}$ in the range of 0.15 to 0.54 $cmol(+).kg^{-1}$. Calcium (Ca) was ranged from 1.95 to 6.89 $cmol(+).kg^{-1}$. Magnesium was ranged from 0.8 to 2.81 $cmol(+).kg^{-1}$. Soil cation exchange capacity (CEC) varied between 10 and 18 $cmol(+).kg^{-1}$. Bases saturation was between 27 and 88%. (Ca + Mg)/K ratios were variable (15 to 30).

Characterization of the fertility of soil mapping units: The first two principal components account for 85.44% of the total inertia. The percentage of information explained by each axis is 61.95% for component 1 and 23.49% for component 2 (Figure-1). The first component (Dim 1) is bonded on the positive side to high values of OM, exchangeable bases K, Ca, Mg, Total cation and bases saturation percentage (BSP). The variable "Pav" is related to component 1 on the negative side opposite to the first variables. The second component (Dim 2), on the upper side is linked the variable CEC and N of the soil. This component is not related to any variable on the lower side. On the correlation circle, positive correlation between soil OM, N and CEC was observed. Exchangeable bases and bases saturation percentage are positively correlated. Also, negative correlation was observed between available phosphorus and exchangeable bases while there is no correlation between available phosphorus, CEC, N and OM.

Figure-2 shows the distribution of individuals in the factorial plane. Soils from Granite FS_SRA, Granite SF_mR FMD, Granite SF_maRT, Basic rocks FS_MA are related to the first component on the negative side and soils from Schists FS_IA on the positive side. On the second component, soils from Granite FS_MFOA, Basic rocks FS_SRT, Granite FS_IA, Granite FS_MHFA, Granite FS_Complex, Tertiary sands FS_M contribute to the formation of this factor on the negative side and on the positive side the soils from Schists FS_SRA, Schists FS_HA, Schists FS_MA and Schists FS_MHFA.

It is more particularly observed that the soils from the Schists FS_IA geological formation are those which have relatively high contents of organic compounds and exchangeable bases. Soils from Granite FS_SRA, Basic rocks FS_MA, Granite SF_mR FMD, Granite SF_maRT, are the most depleted in mineral and organic elements but have high levels of available phosphorus. Soils from Schists FS_SRA, Schists FS_HA, Schist SF_mR FMD and ShistSF_mfiR FMD have a relatively high cation exchange capacity and nitrogen content. In addition, soils from Granite FS_MHFA, Granite FS_MFOA, Basic rocks FS_SRT, Granite FS_IA, Granite FS_Complex, Tertiary sands FS_M have high bases saturation percentage.

It is noted that the first dimension of variability is between soils relatively rich in mineral elements and with relatively low levels of available phosphorus in soils with low levels of mineral elements. The second dimension of variability opposes soils with a relatively larger adsorbent complex than the others. Soils from shale are relatively more physicochemical than other types of soils.

The hierarchical tree was constructed with Euclidean distance and Ward's criterion (Figure-3). The inertia gain diagram distinguishes a division into 3 classes. The Chi 2 test was significant, with a critical probability less than 0.05 (P.value = 0.02<0.05). The variable "types of geological substratum" is related to the class division that was constructed. In class 1, there has been no geologic substratum that is significantly over or under-represented (NULL). In class 2, the Schist geological substratum was significantly overrepresented (P. value = 0.003 and positive test value: v. Test = 2.90). The results showed that 80% of the soils (MU) of the Schist geological substratum are in class 2. The Shale represented 100% in class 2 whereas it accounted for only 33.33% (global) of the set of measures. In class 3, the Granite geological substratum was significantly overrepresented (P. value = 0.018 and positive test value v. Test = 2.35) and the Schist geological substratum was under-represented (P. value = 0.0003 and value negative test: v. test = -3.58). The results showed that 100% of the soils (MU) of the Granite geological substratum are in class 3. Granite represents 70% of class 3 whereas it represents only 46.66% (overall) of all measures. No soil (MU) of the Schist geological substratum is represented in class 3. It should be noted that no basic Roche or Tertiary sand geologic substratum is significantly over or under-represented in any class.

Table-1: Mean values of soil chemical properties by map unit (clay + silt; carbon; nitrogen; organic matter; carbon/nitrogen rate and available phosphorus).

Names of map units (MU)	FAO Correspondence	%				C/N	pH (H_2O)	mg.kg^{-1}Pav
		CS	C	N	OM			
Granite FS_IA	Fluvic Cambisol	21	1,21	0,16	2,09	7	5,8	43
Granite FS_Complex	Ferric Acrisol	23	1,23	0,18	2,12	8	5,7	60
Granite FS_SRA	Ferric Acrisol	29	1,82	0,16	3,13	12	5,3	94
Granite FS_MFOA	Haplic Acrisol	19	1,17	0,13	2,01	9	5,8	78
Granite FS_MHFA	Ferric Acrisol	25	1,26	0,15	2,17	9	6	93
Granite FS_MA	Ferric Acrisol	24	1,54	0,16	2,64	10	5,6	92
Granite FS_MIAT	Haplic Acrisol	25	1,57	0,17	2,7	10	5,8	82
Basic rocks FS_SRT	Haplic Acrisol	22	1,43	0,2	2,45	7	5,8	72
Basic rocks FS_MA	Haplic Ferrasol	35	1,85	0,19	3,17	9	5,3	79
Tertiarysands FS_M	Xhantic Ferrasol	21	1,35	0,14	2,32	9	5,1	79
Schists FS_IA	Haplic Acrisol	35	2,77	0,23	4,76	12	6,2	11
Schists FS_SRA	Fluvic Cambisol	35	2,22	0,26	3,82	9	6	75
Schists FS_HA	Fluvic Cambisol	27	2,05	0,19	3,52	11	6,6	58
Schists FS_MA	Ferric Acrisol	32	2,04	0,2	3,51	10	5,6	84
Schists FS_MHFA	Plintic Acrisol	28	1,69	0,2	2,9	9	5,9	80
Mean		27	1,6	0.18	2,9	9,4	5,7	72
Standard Deviation		5	0.5	0.03	0.8	1,5	0.4	21
CV %		20	27	18	26	16	6	30

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. CS: clay + silt; C: carbon; N: Nitrogen; OM: Organic matter; C/N: carbon/nitrogen ratio, Pav: available phosphorus.

Table-2: Mean values of soil chemical properties by map unit (potassium; calcium; magnesium; cation exchange capacity; total cations and bases saturation percentage).

Names of map units (MU)	FAO Correspondence	Cmole(+).kg^{-1}					(Ca+Mg)/K	%
		K	Ca	Mg	CEC	TC		BSP
Granite FS_IA	Fluvic Cambisol	0,22	1,95	1,38	10	3,55	15	37
Granite FS_Complex	Ferric Acrisol	0,15	3,23	1,08	11	4,46	30	39
Granite FS_SRA	Ferric Acrisol	0,23	2,54	0,92	12	3,69	17	34
Granite FS_MFOA	Haplic Acrisol	0,18	2,52	0,89	10	3,58	20	41
Granite FS_MHFA	Ferric Acrisol	0,24	2,32	1,66	12	4,22	19	39
Granite FS_MA	Ferric Acrisol	0,19	1,94	1,08	11	3,21	17	32
Granite FS_MIAT	Haplic Acrisol	0,19	2,69	1,24	12	4,11	22	34
Basic rocks FS_SRT	Haplic Acrisol	0,16	2,28	1,21	9	3,65	22	42
Basic rocks FS_MA	Haplic Ferrasol	0,13	2,21	0,82	11	3,16	23	29
Tertiarysands FS_M	Xhantic Ferrasol	0,16	2,61	0,8	10	3,57	21	42
Schists FS_IA	Haplic Acrisol	0,54	6,89	2,81	12	10,24	22	88
Schists FS_SRA	Fluvic Cambisol	0,24	2,28	1,4	18	3,92	15	21
Schists FS_HA	Fluvic Cambisol	0,18	3,5	1,57	17	5,24	29	33
Schists FS_MA	Ferric Acrisol	0,2	3,62	1,35	15	5,17	25	36
Schists FS_MHFA	Plintic Acrisol	0,22	2,69	1,58	13	4,49	22	35
Mean		0,21	2,88	1,31	12,2	4,41	21	39
Standardeviation		0.09	1,21	0.5	2,6	1,72	4	14
CV %		44	42	37	21	40	21	37

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. K: potassium; Ca: calcium; Magnesium; CEC: cation exchange capacity; TC: total cations;(Ca + Mg)/K ratio andBSP: bases saturation percentage.

Characterization class by class: A test based on analysis of variance indicates the quantitative variables that differ significantly between the three classes (Table-3). The parameter Eta2 is the measure of the magnitude of the correlation ratio between a quantitative variable and the class variable (qualitative variable). It highlights all the quantitative variables (physicochemical parameters) that differ significantly between classes (P-value <5%). Only the critical probabilities associated with the additional variables (CS and TC) have been interpreted. Base saturation was strongly related to the geological substratum. For each class, the characteristic variables either by their especially high average (positive test value) or by their especially low average (negative test value) were evaluated. Thus, for class 1, the physicochemical parameters K, TC, BSP, Ca, Mg and OM each have a |test value| ≥2 and a mean that is particularly high that the overall average, whereas the Pav has an average particularly weak (P. value<5%) but a |Test-value| ≥2. For class 2, the physicochemical parameters CEC and N have a positive test value (respectively v. CEC test = 3.19 and v. Test N = 2.11). The class average is statistically higher than the general average (P.value=<5%). For class 3 all the physicochemical parameters (Ca, TC, Mg, CS, N, OM and CEC) have a negative test value. The average physicochemical values of the class are statistically lower than the general average (P.value<5%).

Description of individuals (map units): For each class, 5 individuals closest to the class if possible were ranked according to their proximity to the center of the class. The analysis of the individual closest to the class makes it possible to characterize on average this class according to the values of the physicochemical parameters. For class 1, this type of soil (MU) is derived from Schist FS_IA. Soils of this class are particularly dominated by relatively high saturation, high exchangeable base (K, Ca and Mg) and organic matter relative to average values of other soil types. On the other hand, the values of assimilable potassium content are low.

Class 2 includes four types of soils based on shale. These are the soils from Schist FS_MA, Schists FS_HA, Schist SF_mfiR FMD and SchistSF_Fraj FMD. Since the Schist FS_MA is the paragon of this, the general characteristics of this class reflect the physicochemical characteristics of this type of soil. Excluding the CEC for which the value is high compared to the general average, soils of this class have average values in exchangeable bases K, Ca and Mg relatively low. The contents of N and the saturation rate also remain low.

Class 3 brings together basic soils, tertiary soils and granite soils. Granite SF_maRT being the paragon of this, the general characteristics of this class reflect the physicochemical characteristics of this type of soil. The soils have an Mg, CS content, CEC, organic matter and N values below the overall average.

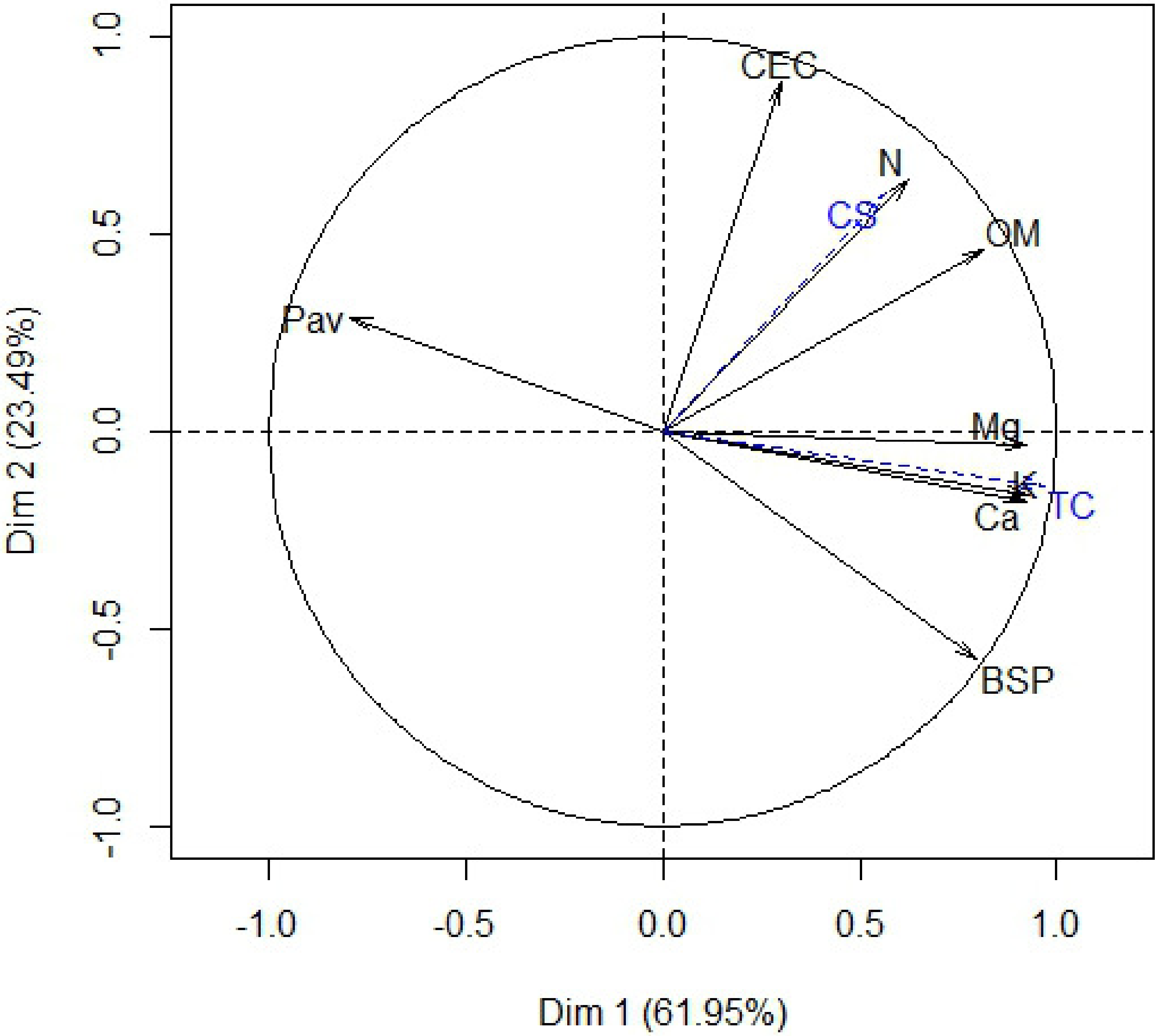

Figure-1: Distribution of the variables in relation to the main components.

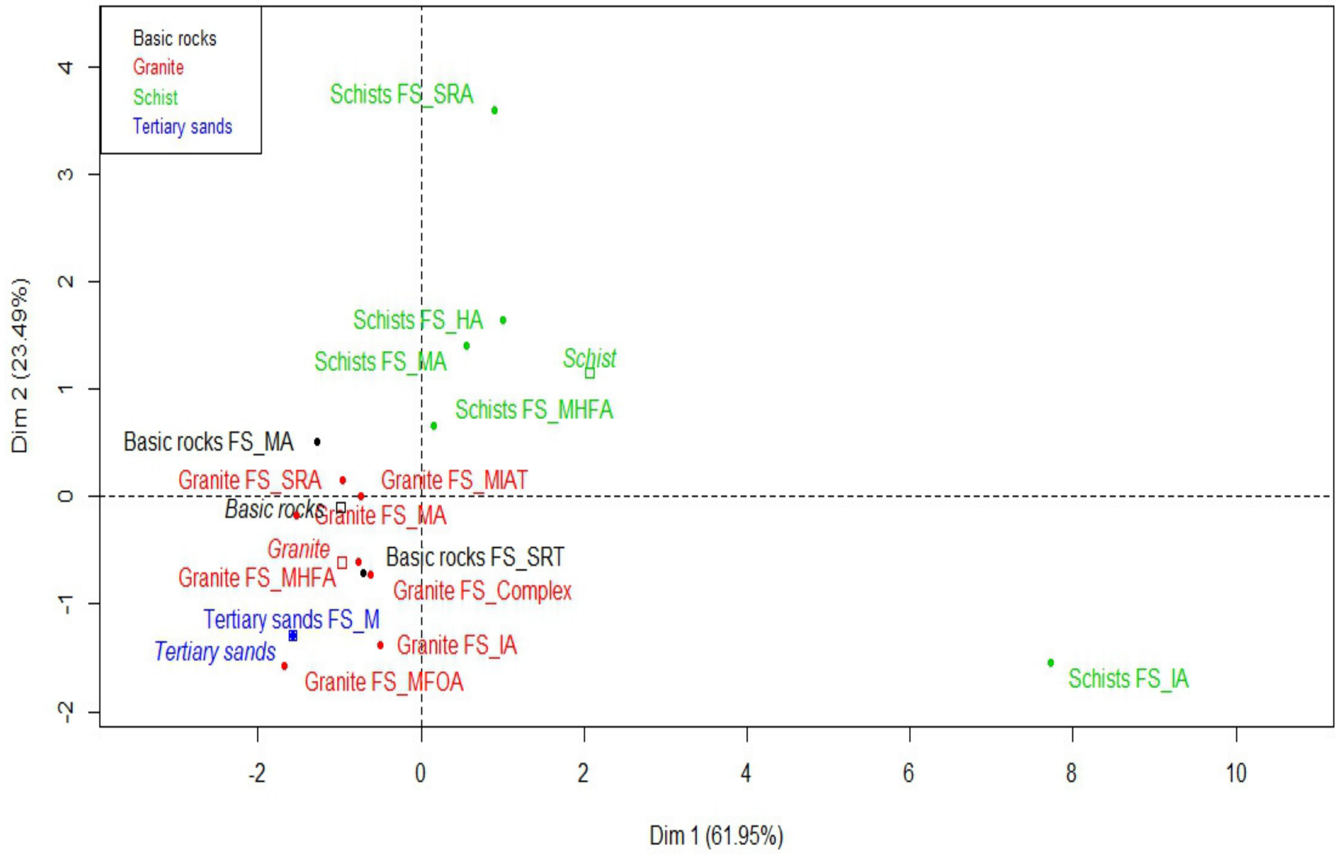

Figure-2: Distribution of individuals in relation to the main components.

Table-3: Class characterization variable.

Quantitative variables		
	Eta2	p.value
TC	0.9339477	8.304757e-08
K	0.8922794	1.562404e-06
BSP	0.8918250	1.602364e-06
Ca	0.8766324	3.525384e-06
Mg	0.7957069	7.269785e-05
OM	0.7571716	2.050204e-04
CEC	0.7420551	2.945519e-04
Pav	0.6007263	4.051580e-03
N	0.5586283	7.393104e-03
CS	0.4326799	3.334025e-02

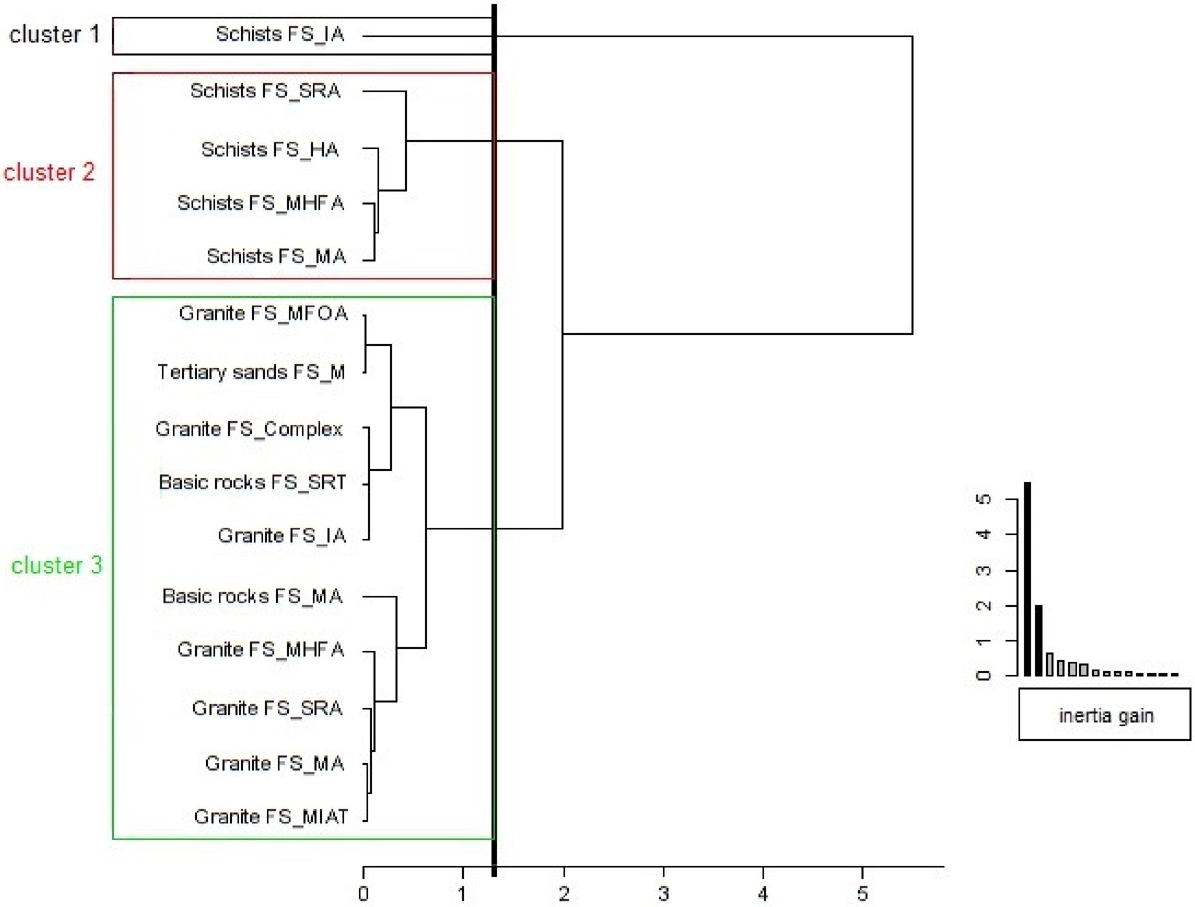

Figure-3: Hierarchical classification of 15 soil types according to physicochemical profiles.

Discussion: Analysis of the physicochemical properties of soils: Granulometric fractions are suitable for coffee cultivation in all the areas surveyed. The soil textures sampled are included in the range of clay and silt (CS) content for which the mineral requirements of coffee soils can be evaluated and improve; between 13 and 41%[17,18]. The contents of carbon and organic nitrates are very variable. This variability's are explained by very different agricultural practices over the extent of the coffee production area and also the previous crop[1]. The coefficient of variation of the high C/N also indicates that decomposition processes are variable and fast overall. Similarly, highly variable levels at large scales where agronomic and pedological differences are important, as our work indicates were reported[19]. Referring to the clay and silt indices, the organic matter contents of some soils are in the standards suggested, while other grades deviate from them. On the other hand the nitrogen contents are below the recommendations for all the soils sampled, therefore considered as low. The explanation that follows is that nitrogen is hardly adsorbable on the cation exchange complex. And it also remains the only source of nutritive supply of coffee trees that have a great affinity for nitrogen since farmers bring no soil fertilizer[1]. The degree of pH dispersion around the average is relatively low. These values are close to those obtained by another author[20]. A soil pH of 5.5-6.5 is considered the most appropriate for coffee growth[18]. Soil pH averaged 5.7 ± 0.4, and thus largely within this range. On the other hand, the phosphorus contents have a greater variability; their coefficient of variation (30%) is of the same order of magnitude as those quoted by Augusto[21]. However, few soils showed levels of available phosphorus below the threshold established by references. They established at 15ppm the value below which coffee soils need phosphorus input.

Analysis of the spatial distribution of soil units and diagnosis of their fertility: The variability of the chemical parameters of the absorbed complex of sampled soils is due to the diversity of agropedological conditions. More specifically, for some authors, it comes from the primary alteration of minerals: biotite, muscovite, mica, orthoclase and microcline; chlorite and feldspar[22,23]. Another author confer this on the biomass cycle, releasing cations and silica in the upper soil[24]. In our study, the average K:Ca:Mg ratio (5:65:30%) derived from the percentages of exchangeable bases, was found to be out of balance with the references. This can be attributed to the removal of minerals by coffee cultivation or caused by erosion or leaching after more than 50 years without the addition of external nutrients. It also observed soil's exchangeable bases change in South Sumatra after 20 years of coffee cultivation[25].

Although the characteristics of soil organo-mineral constituents are partly dependent on factors acting at shorter time scales (seasonal variations of climate, anthropogenic factors), for these same constituents, their vertical stratification and their lateral variations are intimately linked to pedogenesis. Therefore, the spatial variability of physico-chemical properties has been evaluated at the map units level.

Analysis of the spatial distribution of map units showed two main components that explain the variability of soil characteristics. Dimension 1, which opposes soils from shale to soils derived from granites, tertiary sands and basic rocks, reflects the relative richness of soils from shale compared to other types of soils. Dimension 2 shows that the cationic exchange capacity of shale-derived soils remains relatively high compared to soils from granite. The comparison of the observations on the study area with the surveys carried out by Perraud[8] on the same study areas shows that the soils have retained their main characteristics[8]. Soils resulting from shists remain relatively well stocked in organo-mineral matter and in clay unlike soils from granites. Such a remark was reported in the Central African Republic[17]. In fact, OM and finest fractions (clays) combine and form the clay-humic complex, thus increasing the fixing capacity of the mineral elements[26,27]. In addition, the association of fine elements-organic materials develops, by their colloidal properties, a significant load on their surface allowing the adsorption of minerals. The coffee soils with the highest organic matter content had a relatively high content of nitrogen and exchangeable bases K, Ca and Mg. Such correlations have beneficial effects on the characteristics of the adsorbent complex[28,29]. In fact, humus derived from organic matter protects the clay, stabilizes the soil structure and promotes the maintenance of mineral elements. Organic matter thus illustrates the role of physical protection on these particle size fractions, as already pointed out by some authors, but also by chemical protectors as demonstrated by our results[30,31].

Based on the index of the sum of clay and silt and by comparison with the appropriate levels proposed, different nutritional diagnoses of soil under coffee have been reported[17,32,18].

For Class 1 soils, the nitrogen content (0.23%) and the available phosphorus (11 mg.kg-1) are the most limiting compared to the proposed levels (1.85% and 12.5%, respectively). CEC, exchangeable bases and saturation are higher than optimal levels.

For the Class 2 soils, except for the available potassium for which the content is high compared to the reference value (84 $mg.kg^{-1}$ against 12.5 $mg.kg^{-1}$), the other nutrients showed levels limiting for coffee tree nutrition. However, the CEC (15 $cmol(+)kg^{-1}$) is above the reference value (10 $cmol(+)kg^{-1}$) and the saturation level (36%) is well below the reference value (60%).

For soils of class 3, except for available phosphorus (82 $mg.kg^{-1}$) and magnesium ($1.24 cmol(+).kg^{-1}$) which have high levels compared to reference values ($13 mg.kg^{-1}$ for available phosphorus and $0.80 cmol(+).kg^{-1}$ for magnesium). Nitrogen, potassium and calcium are the most limiting nutrients. The saturation rate (34%) is well below the reference value (60%).

Conclusion

The present work has revealed the current physicochemical status of coffee soils. The spatial distribution of the physicochemical parameters allowed to determine a set of soil variables used as indicators of the fertility level of coffee soils. The analysis of the selected variables highlighted the grouping into three types of soils with dissimilar physicochemical profiles. In addition, soils have low nitrogen content, more than 90% of soils are desaturated and present a chemical imbalance for coffee tree nutrition. At this stage, it is essential to provide soil nutrients to support sustainable coffee production. Soils that have become poorer after several decades of cultivation should be amended to meet the nutritional requirements of coffee trees.

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