Imperial Journal of Interdisciplinary Research (IJIR)
Vol-3, Issue-6, 2017
ISSN: 2454-1362, http://www.onlinejournal.in

Mapping Cacao Fertiliser Requirements in Côte d'Ivoire

N'GUESSAN Kouamé Jean Claude[1] ; TRAORE Migninna Joachim*[1] ; SNOECK Didier[2] ; KASSIN Emmanuel[3] ; KOKO Louis[4] ; CAMARA Mamery[3] ; YAO-KOUAME Albert[1]

[1]Soil Sciences department, UFR STRM (Training and Research Unit), Félix Houphouët-Boigny University, Cocody (Abidjan, Côte d'Ivoire). 22 BP 582 Abidjan 22
[2]CIRAD, UPR Systèmes de Pérennes, Avenue Agropolis ; 34398, Montpellier (France)
[3]Centre National de Recherche Agronomique de Cote d'Ivoire, cacao Abidjan, Lagunes (Côte d'Ivoire)
[4]Groupe OCP : 01 BP 2056 Abidjan 01 Abidjan, (Côte d'Ivoire)

Abstract: *In Côte d'Ivoire, soils in cacao plantations are depleted due to the absence or underuse of fertilisation. A digital map of 130 land-units was created from soil and climatic parameters. A soil diagnosis software was combined with GIS (geographical information system) to convert the current unique fertiliser "Engrais cacao" into a greater number of recommendations more adapted to local conditions, thus more actual. Cacao fertiliser requirements were calculated from soil samples taken in mature cacao plantations in each land-unit. The relationships between nutrient requirements and soil chemical parameters enabled building a map of the actual cacao fertiliser recommendations. Soils with identical characteristics were compared regarding their cacao nutritional needs. Highly significant correlations between soil nutrients were found; particularly, Ca and Mg were highly correlated with K, making it possible to calculate the Ca and Mg amounts in fertiliser formulae as function of K (i.e. Ca = 8.5×K and Mg = 3×K). The final map contains 23 N-P-K-Ca-Mg fertiliser formulae. Among them, the currently recommended blanket fertiliser represents 16.5% of the cacao areas. The comparison of our results with a previous study, done 40 years ago, evidenced that the soil nutrients under cacao have significantly decreased over the period, reinforcing the need for fertilizers.*

Keywords: *Côte d'Ivoire; Fertilisation; GIS; Soil management; Theobroma cacao*

1 INTRODUCTION

Cocoa plays a key role in the economic and social stability of Côte d'Ivoire. It is therefore crucial to maintain the sustainability of the cacao (*Theobroma cacao* L.) agrosystems. Among the various parameters that influence the sustainability of cultivated lands, this study is focusing on the soil chemical status of the plantations. Although cacao growers are aware of the key role of soil properties in managing the nutrition of their cacao plots and that an adequate supply of nutrients is essential to ensure their optimisation, the fertilisation practises are still unsatisfactory in Côte d'Ivoire [1]. As a consequence, current practices favour the extension of the planted area rather than fertilisation and the authors observed that cacao plantations have been extended at the expense of forest ecosystems regardless of the environmental conditions and soil suitability. This is often done using slash and burn of the forest whose advantage is that it quickly releases nutrients that helps feed the cacao trees in the beginning; but it has only a short-term effect on cacao growth [2]. This is one of the reasons why, after decades of cacao farming, soils are becoming more and more desaturated and acidic, resulting in a drop in cocoa yields [3]. Fertilisation has also the advantage of reinforcing the effect of cultivation methods giving them a more sustainable character. For example, it can help improve disease resistance [4], [5]; in particular, a cacao deprived of Ca and Mg is less resistant to pod rot. Another advantage is that fertilisation improves the size and quality of beans [6], [7]. However, the fertiliser must be well dosed because badly managed fertilisation can disturb the balances between the levels of soil nutrients, which can become either limiting or toxic. This is particularly important in the case of nitrogen [8].

In this situation, it is important that farmers change their farming practices and start using fertilisers. Currently, the extension services in Côte d'Ivoire currently recommend one single fit-all formula for the whole country. This fertiliser, called "engrais cacao", contains 0% N – 23% P_2O_5 – 19% K_2O, 10% CaO, 6% MgO, and small amounts of S and Zn [9]. The recommended dose is 400 $kg \cdot ha^{-1} \cdot year^{-1}$. However, the use of a single fit-all formula for all types of soil is not appropriate. Indeed, each type of soil has its own fertility potential which depends on a wide range of parameters such as the origin of the soil, cultural practices, environment and associated crops [10]. More recent studies on the use of fertilisers in cacao plantations in Côte d'Ivoire confirmed that the currently recommended single fertiliser is only increasing yields in a few cacao farms [11]. Ideally, to meet the very wide range of situations, one fertiliser formula per cacao plot should be should recommended. However, this would be impractical for both farmers and fertiliser dealers.

Because cacao needs a soil adapted to its growth and has specific nutrient requirements [12], the formulation of appropriate fertiliser recommendations must be based on actual and current soil nutrients levels and balances. Indeed, the soil characteristics influence soil depth, acidity, and drainage [13], [14] which are important parameters for the determination of any agricultural programmes, and more specifically for cacao [15].

The objective of this study was to assess the influence of the diversity of soil and climate situations on the nutrient availability required by the cacao species. Once this is done, it will be possible to establish a thematic map of Cote d'Ivoire showing a reasonable amount of fertilizer formulae adapted to cacao cultivation. To achieve these goals, two complementary tools were used: 1) Geographical information system (GIS) to draw the thematic map and the fertiliser recommendation maps. 2) A soil diagnosis tool to identify the cacao nutrient requirements required to draw up recommendations for fertiliser after linking the soil data to the corresponding land units.

2 MATERIAL & METHODS

2-1 Study area

The cacao growing areas of Côte d'Ivoire extend throughout the forest area, which covers the whole southern part of the country and stretches from east to west. For this study, soil data were collected in all cacao growing regions [16]. The two main regions are Soubré and San Pédro producing more than 150,000 tons of cocoa beans per year. The other important regions are Duékoué, Vavoua, Daloa, Issia, Gagnoa, Divo and Abengourou, each of them producing 50 to 150,000 tons per year. The other cacao growing regions are also in the South; they are producing less than 50 k tons per year.

2-2 Agro-ecological zones suitable for cacao cultivation

Soil characteristics and climatic data were the two parameters used to delineate the agro-ecological zones suitable for growing cacao and defining the land units on the digital maps.

Each type of soil has different amounts and balances of nutrients whose availability for a specific crop depends on many factors, of which the geological origin of the parental material and soil development are the most important [17]. Those parameters are available from the geological and pedological maps and were used to build the GIS maps.

Pluviometry (P) and temperature (t°) are the two other main criteria used to delimit the zones suitable for cacao. For pluviometry, the areas were divided into three zones: unsuitable ($P < 1{,}200$ mm a year), average ($1{,}200 \leq P < 1{,}400$ mm a year), and suitable ($P > 1{,}400$ mm a year). For temperature, two zones were delimited: suitable (25 °C < t° < 28 °C) and unsuitable where average temperatures are lower than t° = 25 °C or higher than t° = 28 °C. Both layers were combined to build the climatic map.

2-3 Mapping and creation of land units

Based on soil and geological maps (scale = 1/500,000) obtained from [18], a soil map of Côte d'Ivoire was created with a GIS mapping software [19]. In this study, a land unit (LU) is the elementary polygonal area having identical soil type and identical climate. A total of 130 land units suitable for cacao cultivation were identified in the whole cacao growing area.

2-4 Soil sampling and chemical analyses

The soil samples were collected in mature cacao plots distributed in each of the 130 LUs.

To cover the different agro-ecological conditions of cacao per LU as accurately as possible, two to five plots of mature cacao trees (15 to 35 years old) were selected in each LU depending on its size. A total of 475 cacao plots were selected and geolocated (Figure 1).

In each selected cacao plot, one single composite soil sample was taken randomly in the top 20 cm, which corresponds to the horizon prospected by 75 to 90% of the cacao feeder roots.

The soil samples were dried, sieved to 2 mm and ground. For cacao, the following chemical analyses are required: the Walkley-Black method for organic carbon (C_{org}); the Kjeldahl method for total nitrogen (N_{tot}); the Olsen-Dabin method for available phosphorus (P_{avail}); the Metson method (at pH = 7) for cation exchange capacity (CEC) and the three cations (K, Ca, Mg); the EDTA method for Fe, Zn, Mn, Cu; hot water dilution for extraction of B; a glass electrode pH meter after dilution at 1:2.5 soil:water ratio to measure pH_{water}. The methods are detailed in the [20] manual.

2-4 Statistical analysis

The relationships between significant soil components were assessed using analysis of variance (ANOVA) and multiple linear regression with forward stepwise variable selection. The relationships and multivariate variability of the soil types were further analysed using a principal component analysis (PCA) and soil pedology or soil geological material as sub-factors. A correlation analysis was performed to assess the significant correlations between variables. Spatial variabilities of the soil properties were analysed in QGIS.

2-5 Use of soil nutrient ratios to compute cacao fertilisation requirements

To assess appropriate fertilisation formulae and doses for cacao, two steps are necessary: 1) to compare each nutrient level to thresholds specific to cacao; and 2) to compare the nutrients between them to assess their balances and avoid the limiting factors effects [21]. These two steps were performed using the soil diagnosis software developed by [22]. The software uses the optimum values and thresholds specific to the cacao species which were determined after long-term field trials supplemented by greenhouse tests [23]. The amounts of each nutrients are computed to maintain the nutrients levels as close as possible to the optima considering the local constraints caused by chemical imbalances in the plot, zone, cultural practice or soil type. In brief, to determine nitrogen requirement, the data from the soil samples are compared to the upper and lower thresholds and to both the N:P and the N:(Sum of cations) ratios. The required amounts are then calculated from the distance between the sampled point and the optimum line. The cacao soil diagnosis model uses the following optimum lines: $N = P_2O_5/2$ and the $N = \{(\text{Sum cations}) + 6.15\}/8.9$ [23]. To determine P requirement, the soil data are compared to the thresholds and the N : P ratio. To determine K, Ca and Mg requirements, the soil data are compared to both their corresponding thresholds and to the balance between the three of them. For cacao, the optimal balance is equal to 8% K, 68% Ca and 24% Mg (as a % of their sum). The amounts of cations are also calculated to bring the base saturation above 60%, which is the level at which nutrients are absorbed efficiently by the cacao [24]. The results of above calculations produce the fertiliser formula that details the amounts of N, P, K, Ca and Mg required to correct the current soil nutrient levels and ensure optimal cacao growth, provided good agricultural practices are carried out. In case of adult cacao, more nutrients are then added to take into account the nutrients exported through harvest and for basal functioning. If higher yields are targeted, the doses are increased accordingly.

Then, when more than one fertiliser formulae were linked to one LU, the soil analyses were re-evaluated and combined to get the best adjustment that gives the most appropriate fertiliser formula for this LU.

2-6 Mapping fertilisation recommendations

The soil diagnosis produced as many recommendations as land units; i.e. 130, which is too many to handle by fertiliser dealers. The number of recommendations were reduced using a fuzzy set classification [25]. This method has advantage above classic classification that it makes the classification more convenient to rank the formulae as they are made of five nutrients of equal weight. The method was used to compute the membership of each major nutrients to the formula calculated by the soil diagnosis and identify the optimal dose of each major nutrients to build the resulting average formula to be linked to the corresponding LU. The results were grouped in five classes (0 to 4) following, which were noted as follows: 0 if the nutrient is not needed; 1 if between 0 and 1/4; 2 if between 1/4 and 1/2; 3 if between 1/2 and 3/4; and 4 if between 3/4 and 4/4 of the highest dose found in our study. For each class, the recommended dose is the weighted average of the class.

The recommended formulae were linked to the LUs through their GPS points and transferred onto the digital map. This enabled providing the LUs with their corresponding fertiliser requirements. The combination of these data was used to draw the final thematic map showing the N-P-K-Ca-Mg fertiliser formulae best adapted to each LU.

3 RESULTS

3-1 Climatic zone suitable for cacao growing

Four major areas were identified using the two main climatic parameters: annual rainfall and average monthly temperature. They are presented in Figure 1.

Imperial Journal of Interdisciplinary Research (IJIR)
Vol-3, Issue-6, 2017
ISSN: 2454-1362, http://www.onlinejournal.in

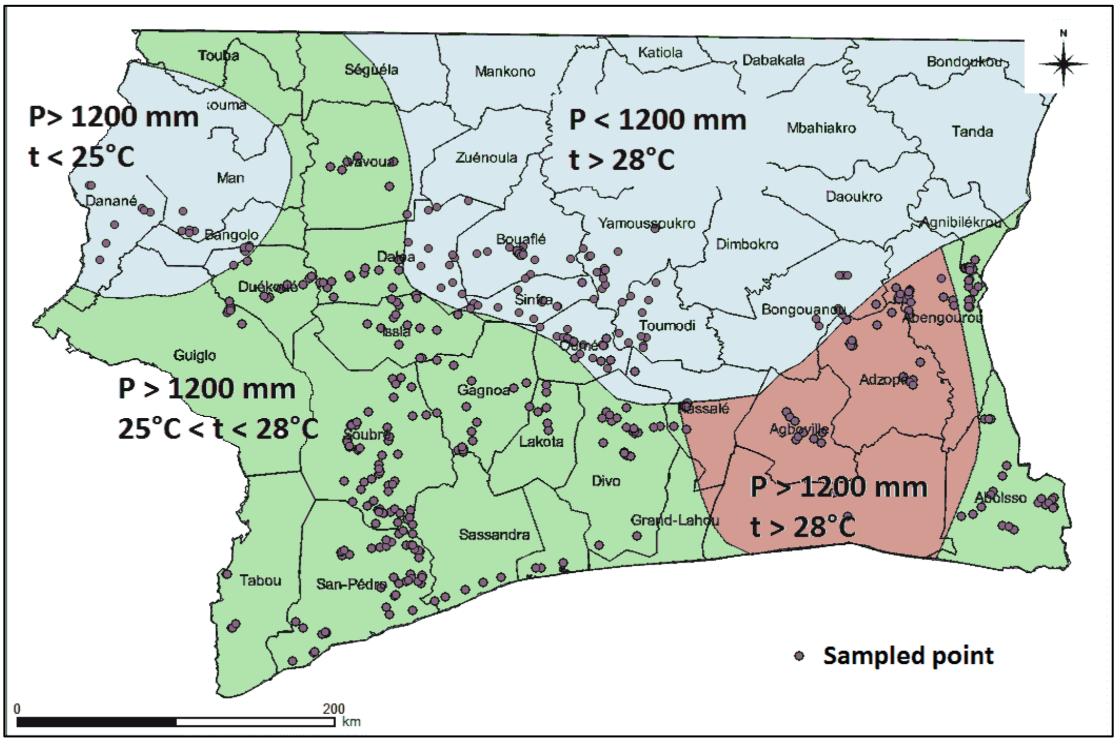

Figure 1: Cacao growing regions in Côte d'Ivoire showing the zones suitable for cacao cultivation based on pluviometry (P) and temperature (T) and the GPS positions of the sampled points.

The suitable zones are coloured in green. Actually, the areas cultivated today extend beyond the optimal areas because farmers encroach on unsuitable areas. This includes areas with average temperatures > 28 °C and the mountainous part in the western zone with average annual temperature < 25 °C. Only the northern zone that is too dry (P < 1,200 mm) was also found unsuitable by farmers and not cultivated with cacao.

3-2 Soil characteristics

Cacao trees are cultivated on seven pedological units after the WRB classification [26]. Each of them is of different geological origins. The combination of both parameters gives 9 soil units (Table 1).

The total surface area of the cacao growing regions is 145,025 km². The Ferralic Cambisol represents 41.2% of the total cacao cultivated areas. Of these, 38.2% are on schists and 3.0% on basic rocks. The Ferralic Luvisol represents 21.5%, Haplic Acrisol 18.5%, Ferric Acrisol 8.7%, Xanthic Ferralsol 5.7%, and Ferralic Arenosol 4.3% of the areas. When considering the soil origin, about 56% of the cacao plantations are cultivated on soils derived from granite, 38% on schists, 3% on basic rocks and 3% on tertiary sands.

3-3 Soil chemical analyses

The soil analysis data were grouped and calculated according to soil type and geological parent material (Table 2).

Table 1: Soil types (WRB) and geologic substratum of the cacao growing regions of Côte d'Ivoire with corresponding areas (sum of LU areas in km² and % of covered areas)

WRB classification	(Code)	Geologic substratum	Sum of LU areas (Km²)	(%)
Ferric Acrisol	(ACfr)	Granites	12,586	8.7
Haplic Acrisol	(Acha)	Granites	26,902	**18.5**
Ferralic Arenosol	(ARfl)	Tertiary sands	4,304	3.0
Ferralic Arenosol	(ARfl)	Granites	1,938	1.3
Ferralic Cambisol	(CMfl)	Basic rocks	4,281	3.0
Ferralic Cambisol	(CMfl)	Schists	55,357	**38.2**

Xantic Ferralsol	(FLxa)	Granites	8,293	5.7
Dystric Gleysol	(GLdy)	Podzolic or ferralitic soils	173	0.1
Ferralic Luvisol	(LUfl)	Granites	31,191	**21.5**
Grand Total			145,025	

Table 2: Means of the major soil nutrients data per WRB class and per soil geological origins and ranking after Tukey's test

WRB class	pH	C_{org}	N_{tot}	P_{avail}	K	Ca	Mg	CEC
ACfr	5.69 b	1.58 ab	0.14 ab	10 ab	0.32 a	3.54	1.08 b	7.23 ab
ACha	5.91 a	1.49 ab	0.12 ab	12 ab	0.29 ab	3.44	1.08 b	6.32 ab
ARfl	6.02 a	1.44 ab	0.13 ab	12 ab	0.25 ab	4.23	1.92 a	8.21 a
CMfl	5.75 ab	1.86 a	0.16 a	16 ab	0.33 a	4.14	1.49 a	8.34 a
FLxa	6.25 a	1.88 a	0.19 a	23 a	0.49 a	5.43	1.49 a	9.11 a
GLdy	5.83 ab	1.42 b	0.11 b	6 b	0.14 b	2.88	1.17 ab	6.10 b
LUfl	5.78 ab	1.70 a	0.14 ab	19 a	0.30 ab	4.20	1.36 ab	7.92 ab
Basic rocks	6.09 a	1.96 a	0.19 a	28 a	0.38 a	6.21	1.96 ab	10.93 a
Tertiary sands	6.02 a	1.54 ab	0.14 ab	17 ab	0.24 ab	4.89	3.48 a	11.80 a
Schists	5.72 b	1.85 a	0.16 a	15 ab	0.33 a	3.96	1.46 ab	8.12 b
Granites	5.87 ab	1.60 ab	0.14 ab	15 ab	0.30 ab	3.92	1.24 ab	7.23 b
Podzol	5.83 ab	1.43 b	0.12 b	6 b	0.14 b	2.89	1.18 b	6.10 b
Pr > F	0.011	0.026	0.009	0.011	0.047	0.096	< 0.001	0.001

Values with the same letters statistically similar for α = 0.05.

The results showed significant effect of the soil origin on the soil acidity and nutrient availability, except for P and Ca. CMfl and FLxa give the soil with highest nutrients. On the opposite, GLdy gives the poorest soil. Basic rocks have significantly highest pH and are richer in nutrients. Granites have lowest CEC and show high levels of N and Ca.

The soil nutrient requirements for cacao were determined using the soil diagnosis tool.

Major nutrients requirements

The comparison of the soil nutrients to their specific thresholds showed that 86% of the soils are low in both organic C and N; 85% of the soils are low in P; 34% of the soils are low in K; 67% of the soils are low in Ca; 44% of the soils are low in Mg. This indicates that the soils are generally poor in the major nutrients and will respond positively to fertilisers.

The balances between the nutrients were studied using a principal component analysis (PCA), which was done to assess both the relations between the soil parameters and their relative weight. The soil nutrients were correlated with soil pedology (Figure 2) and soil geology (Figure 3).

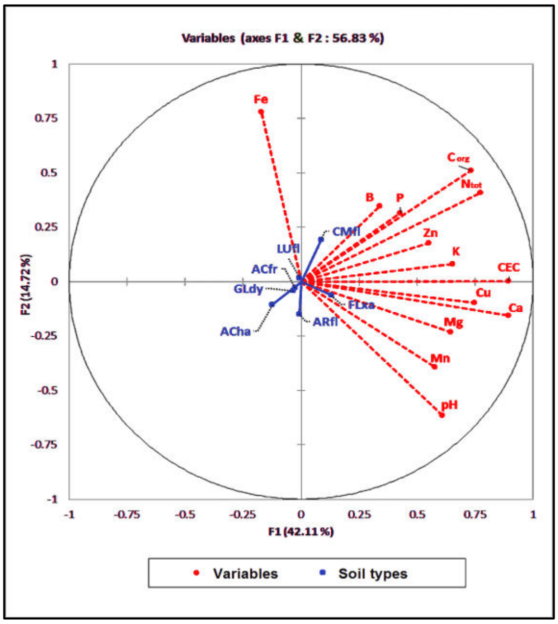

Figure 2 : PCA analysis showing the soil chemical properties as main parameters and soil pedology (WRB classification) as sub-parameter (FAO indices: ARfl = Ferralic Arenosol; FLxa = Xantic Ferralsol; ACfr = Ferric Acrisol; ACha = Haplic Acrisol; CMfl = Ferralic Cambisol; GLdy = Dystric Gleysol); LUfl = Ferralic Luvisol)

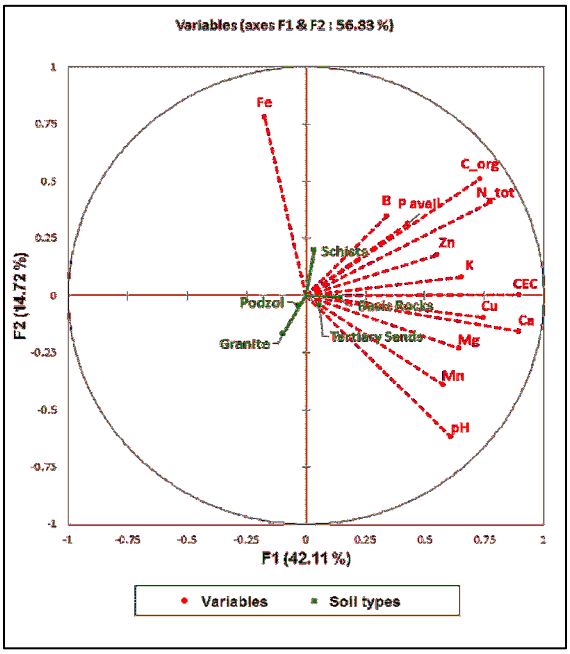

Figure 3: PCA analysis showing the soil chemical properties as main parameters and soil geological origins as sub-parameter

Looking at the soil nutrient parameters contributing to axis 1, the Ca, CEC, N and C were the more important with a contribution of respectively 15%, 14%, 11% and 10%; while Fe and pH were contributing to axis 2 for 52% (respectively by 32% and 20%). Looking at the soil pedology as supplementary variables, the effect of CMfl and FLxa on soil characteristics is confirmed (Figure 2). Looking at soil geology as supplementary variables, the influence of basic rocks on soil nutrients is confirmed (Figure 3).

The correlation analysis between nutrients revealed that the soil pH was highly significantly correlated with Ca ($r^2 = 0.45$; $p < 0.0001$); the organic C was significantly correlated with N ($r^2 = 0.88$; $p < 0.0001$), with CEC ($r^2 = 0.48$; $p < 0.0001$) and with Ca ($r^2 = 0.41$; $p < 0.0001$); the N and CEC were significantly correlated ($r^2 = 0.71$; $p < 0.0001$). Concerning cacao requirements, two ratios are used to determine whether N is required in the fertilisation, the N:P and N:(K+Ca+Mg). However, the N:P indicator was not found significant because P was below threshold ($P_{avail} < 15$ ppm) almost everywhere. Particularly, the linear regression showed a very low slope coefficient and a correlation coefficient close to zero ($N = 0.0018 \times P + 0.123$; $r^2 = 0.06$; $p > 0.20$). On the contrary, the regression analysis of the second indicator (N to the sum of cations) showed significant correlation: i.e. $N = 0.015 \times (K+Ca+Mg) + 0.07$ ($r^2 = 0.49$; $p < 0.001$). This indicates that this parameter is appropriate for calculating the fertiliser recommendations. In practical, in Figure 4, the points located to the left and above the optimum line N = {(Sum cations) + 6.15}/8.9 represent soils that will respond positively to the addition of a nitrogen fertiliser.

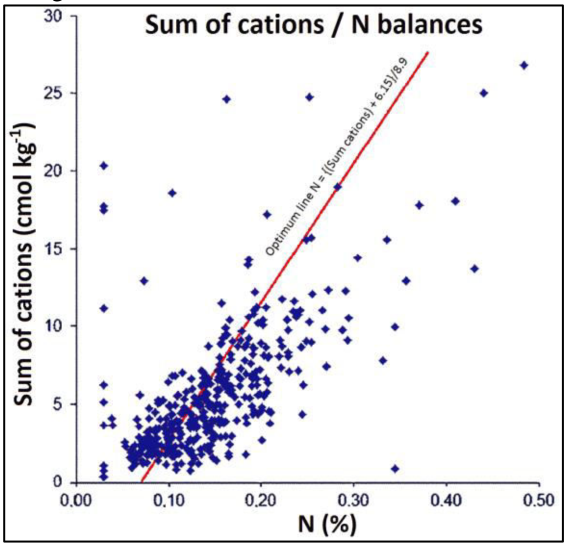

Figure 4: Balance between N and the sum of cations (K+Ca+Mg). The red line indicates the limit between soils requiring N or not

The graph shows that 23% of the points are above the optimum line; these points will definitely respond positively to N fertiliser. Among the points below the optimum line, about 32% of them are within 10% of the optimum line; these points indicate soils that must be closely monitored, even though N is not currently recommended for the soil with these ratios.

Available P was found below the 15-ppm threshold for 85% of the soils. This suggest that these soils will respond positively to P fertilisation. The N:P ratio was not used for the same reason described above for N. Thus, the calculation was done to reach the minimum amount recommended of available P (50 ppm). Statistical analysis showed significant correlation between soil available P and P required in the fertilisation ($r^2 = 0.31$; $p < 0.001$).

For K, Ca, Mg, the required amount of each of the three cations is calculated from the distance between the position of the observed point and the optimum K-Ca-Mg balance (ideally 8%–68%–24%). These points are shown in Figure 5.

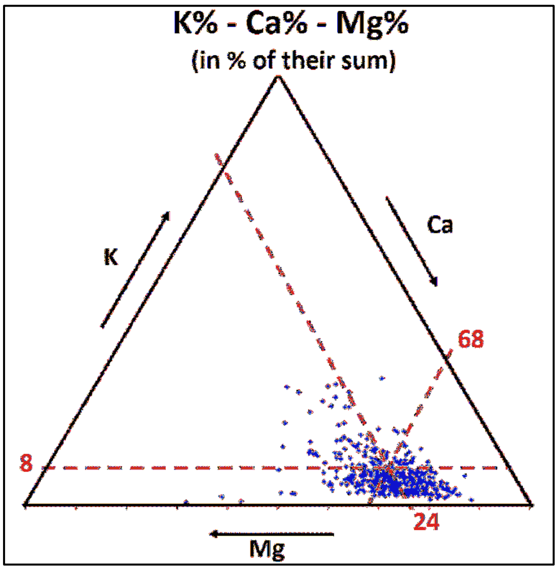

Figure 5: Soil K, Ca and Mg points showing their position relative to the optimum balance

The results show that 88%, 81% and 83% of soils will respond positively to K, Ca and Mg inputs, respectively. Furthermore, even though most of the soils were poor, 69% of them were rather balanced in cations. This indicates that the corresponding formulae will be similar regarding the proportions of K, Ca and Mg.

For base saturation, the results showed that 11% of the soils are highly desaturated (BS < 40%) and will require higher amounts of cations to reach the required minimum of 60%.

Micronutrients

The analysis of the soil samples showed that 12% of soils are below threshold for boron, 5% are below threshold for zinc, 3% are below threshold for copper, 1% of soils are below threshold for manganese, 0% are deficient in iron.

3-4 Nutrients recommended for each LU

Major nutrients

The nutrient requirements were calculated for all soil samples and then grouped into five classes. The amount of each of the five nutrients recommended in each class (0 to 4) is the weighted average of the amounts in the class (Table 3).

Table 3: Amounts of recommended doses of each major nutrient and % of cacao growing areas requiring the corresponding dose

Class	N		P		K		Ca		Mg	
	(g tree^{-1})	(%)	(g tree^{-1})	(%)	(g tree^{-1})	(%)	(g tree^{-1})	(%)	(g tree^{-1})	(%)
4	290	0.3	380	0.7	1,080	0.3	2,360	0.3	410	0.3
3	220	0.7	210	6.4	710	1.4	1,650	1.0	290	1.0
2	160	0.7	180	9.5	420	1.7	820	1.0	160	4.4
1	90	40.0	60	71.9	110	11.2	200	7.5	30	21.0
0	0	58.3	0	4.1	0	12.2	0	19.0	0	17.3

Note : Each dose is the weighted average of the class

Even though the theoretical number of formulae that are possible is big (i.e. 3,125 = 5×5×5×5×5), the actual possibilities gave only 43 formulae. The formulae found to be similar were grouped again, particularly those accounting for less than 1% of cultivated areas. Then, when the ratios between nutrients are identical and only the doses are higher, the dose was divided by two; which has eliminated classes 3 and 4. The final number of formulae to be recommended is 23 (Figure 6 and Table 4), of which 15 are without N and 8 are with N.

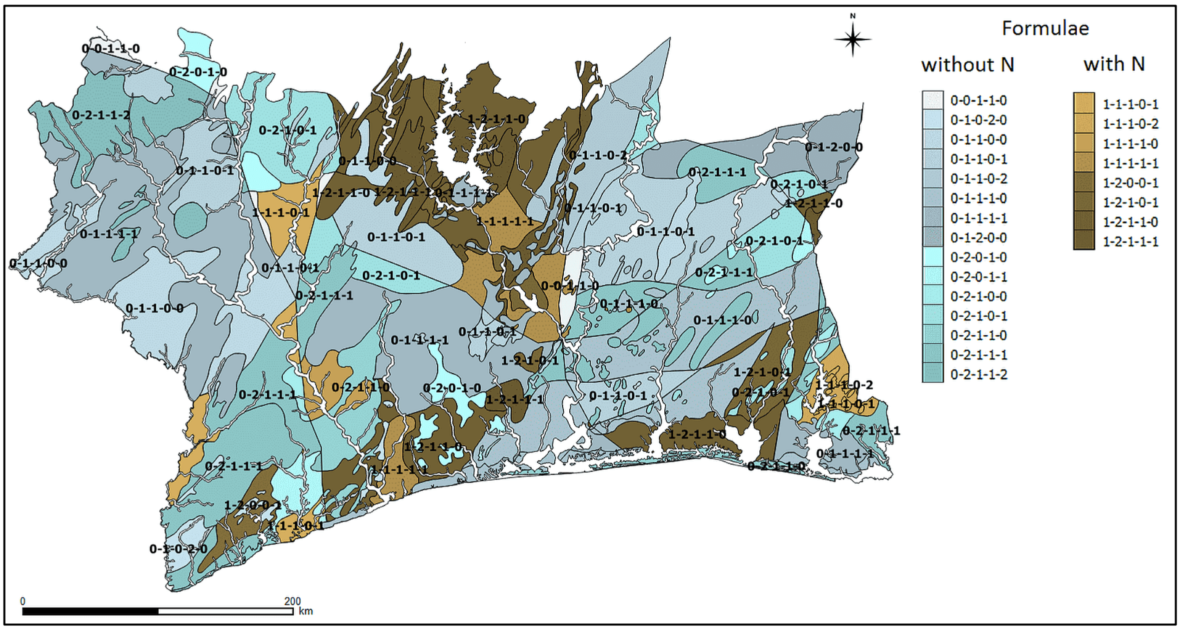

Figure 6: Map showing the areas covered by each of the 23 recommended fertiliser formulae (based on N, P, K, Ca and Mg nutrients)

Table 4: Surface area covered by fertiliser formula based on N, P, K, Ca, Mg balances

N-P-K-Ca-Mg	**Area (km²)**	***Freq. (%)***	**N-P-K-Ca-Mg**	**Area (km²)**	***Freq. (%)***
0-0-1-1-0	1,255	*0.9*			
0-1-0-2-0	1,091	*0.8*			
0-1-1-0-0	8,596	*5.9*			
0-1-1-0-1	16,604	*11.4*	1-1-1-0-1	3,402	*2.3*
0-1-1-0-2	4,347	*3.0*	1-1-1-0-2	976	*0.7*
0-1-1-1-0	9,881	*6.8*	1-1-1-1-0	1,240	*0.9*
0-1-1-1-1 *	23,921	*16.5*	1-1-1-1-1	4,370	*3.0*
0-1-2-0-0	5,866	*4.0*			
0-2-0-1-0	2,633	*1.8*			
0-2-0-1-1	1,969	*1.4*	1-2-0-0-1	1,221	*0.8*
0-2-1-0-0	1,086	*0.7*			
0-2-1-0-1	9,405	*6.5*	1-2-1-0-1	3,504	*2.4*
0-2-1-1-0	3,035	*2.1*	1-2-1-1-0	12,357	*8.5*
0-2-1-1-1	16,474	*11.4*	1-2-1-1-1	6,247	*4.3*
0-2-1-1-2	5,545	*3.8*			
Total without N	111,708	*77.0*	Total with N	33,317	*23.0*

** indicates the current 0-23-19 "engrais cacao" formula.*

Six of the 23 formulae are sufficient to cover 61% of the surface area of the cacao growing zone. Five of them contain no nitrogen (52.5% of areas) and only one contains nitrogen (8.5% of areas). With reference to the total surface area, 77% plantations do not need fertiliser containing N, while the other 23% will require N-based fertilisers. The 0-1-1-1-1 formula corresponds to the current blanket fertiliser "*Engrais Cacao*" and is suitable for 16.5% of the cacao growing areas in Côte d'Ivoire.

The spatial distribution analysis of nutrients availabilities showed that: For N: 82% of the soils are low based on the N threshold, but only 37% of soils will respond positively to a N input when considering the balances with cations. On Figure 6, the extent of the LUs containing soil data which will respond positively to N are represented by the dark LU. The zones with higher N requirement are particularly found on schist, while those on tertiary granite and sands do not require N. Superposition of the N requirement map onto the soil pH map shows that low N areas are most frequent in the upper centre regions or along the coast in the south. For C: 57% of the soils are low in organic C. Low C areas are mainly found in the Centre and the West. The superposition of N and C maps shows that the zones responding to N fertilisation are those where both C and N are low. For P: 81% of the soils are low in P, with the poorest being located in South-West and West regions. For K:

34% of the soils are low in K, and K is also low compared to Ca and Mg, thus K is required almost everywhere. For Ca: 61% of the soils are low in Ca. Low Ca areas are mainly in the South, South-West and West and Centre. For Mg: 37% of the soils are low in Mg. Low Mg areas are the same than for Ca. For soil acidity: 23% of sampled soil are too acidic for cacao (pH < 5.5). Low pH areas are mainly found in the South-West and South-East.
Highly significant correlations were found between the cations, and particularly between K and the other two (Ca and Mg). The linear regression analysis gave the following formulae: Ca = 7.524×K + 1.219 (r^2 = 0.23; $p < 0.001$), Mg = 2.315×K + 0.397 (r^2 = 0.26; $p < 0.001$) and Mg = 0.242×Ca + 0.256 (r^2 = 0.70; $p < 0.001$).

Micronutrients
The decision to apply micronutrients is only based on the thresholds. In particular for boron, the recommendation is to add 0.8 kg·ha^{-1} in soils where B < 0.30 ppm (Loué & Drouineau 1993; Spector 1964).

4 DISCUSSION

This work is based on the principle that the chemical status of a soil at a given time depends on its geological and pedological origin [13], its environment (particularly the climate) and how it is cultivated. By applying this principle, there are as many different soils as cultivated plots. However, the real situation appeared less complicated for two reasons: 1) The number of different soils by their type of origin is 7 according to the FAO classification; 2) Most farmers within a region use the same farming practices, thus reducing the extent of the variation of soil conditions between plantations [27]. This study confirms both points. On the one hand, our results show that the current recommendation of a single formula should be transformed into a recommendation of several formulae which account for the diversity of environments and soils, even though the number of formulae will not be so many. On the other hand, 69% of soils had their cations balance rather close to the optimum, thus decreasing the number de formulae that came out of our calculations. However, the results also showed that the soil nutrients levels are low and justify that there is high need to apply fertilisers. Moreover, the choice of nutrients used in the fertiliser composition must take into account the balance between nutrients and not just their individual levels.
The N requirements are highly dependent on the cations levels in the soil. In particular, N use in cacao plantations should be moderate and N should only be recommended when there is no doubt that it is a limiting factor in the soil [17], [8] because N contributes more to vegetative growth than to fruit growth. Hence, adding N when not required is often to the detriment of the pods production [28], [29]. Another drawback was demonstrated by [30] who observed an increase in branch lodging when an excess of N fertiliser was supplied to vigorous cacao. Based on the observation that N is already provided by other natural sources, such as rainfall and litter decomposition in amounts that are sufficient for shaded cacao trees [31], we suggest favouring organic mulch as a source of N rather than mineral fertiliser. In addition, as cacao is native to the forest understory, its photosynthetic efficiency is low, and consequently, its nitrogen needs are also low ([32], [33].
The centre of gravity of the K-Ca-Mg balance was found to be 6-70-24 on average for the whole cacao growing zone. This means that the soils are globally low in K, and hence that this cation is important and has to be present in all fertiliser formulae.
Among the micronutrients, boron was found to be the most important to take into consideration when planning fertilisation. Our results show that soil B deficiency is prevalent in 12% of the cacao growing areas. The need for B has already been demonstrated in Côte d'Ivoire [34], [30 and in Ghana [35].
The map (Figure 6) represents the formulae obtained after having grouped similar formulae by a fuzzy classification, by simplification of small areas and without considering the dose rates. This explains that the recommended number of complete formulae (Table 4) and displayed on map (Figure 6) is of 23. However, some fertiliser dealers still consider that this number is too high for the manufacture and sale of fertilisers to farmers remain profitable. To comply with this point, an alternative option is to consider only N, P and K nutrients to build the fertiliser formulae and add Ca and Mg as a percentage of K. Our results showed that this option makes sense as both the Ca:K and Mg:K ratios are very highly significantly correlated ($p < 0.001$) in all types of soils independent of the soil origin. Based on this, the complete fertiliser formulae can be built by computing both the Ca and Mg amounts as a function of their ratio with K and the formulae will be expressed as N-P-K (the three first columns in Table 3).
The study on the calculation of fertiliser recommendation follows a previous study on the same subject conducted 40 years ago by [24] who also drew a map of nutrient recommendations using the same soil diagnosis method. The comparison of both maps shows that the soil chemical fertility has changed between the two periods, particularly for N. For example, Jadin's results showed that, in 1975, no soil samples needed any N, while in 2015 (this study), our results showed that about 23% of soil samples will respond positively to N. Our

results also show that the number of soils depleted in N will continue to increase as demonstrated by the number of points close to the line in Figure 4. One possible explanation is that the absence of fertilisation is leading to N depletion, as demonstrated by our results showing that more than 86% of the soils deficient in N are also deficient in organic matter. The correlation between the increase in N requirements and the loss of organic matter is consistent with the results of [36] who showed that 90% of N measured in the topsoil horizon of a cacao plantation come from organic matter. The N deficient zones mainly correspond to the highly anthropized areas located in the upper centre of the cacao growing zones and the highly-leached areas located along the coast in the south. In addition, it is consistent with the overall soil nutrient depletion as demonstrated below. P requirements were found to be high in both 1975 and 2015. In practice, almost all P levels measured in 2015 are below the critical threshold, as they were in 1975 indicating that the needs for this nutrient was already significant in the past, and still remains important today. K, Ca and Mg requirements were higher in 2015 than in 1975. This result is consistent with global soil impoverishment because the soils were not fertilised in the last 30 years. This depressive effect has also been reported in Ghana [37, [2].

Future continuation of the study will be to validate our findings in a multilocal trial comparing the proposed optimised formulae with no fertiliser as control and the current blanket formula as competitive treatment.

5 CONCLUSION

Our results showed that 77% of cacao plantations in Côte d’Ivoire do not need N. More specifically, complete N-P-K-Ca-Mg based fertilisers are mainly required in highly depleted zones, particularly areas with a strong anthropic effect or where the soils are heavily leached. This is consistent with our observation on the general leaching of soils, which have been continuously cultivated with no fertiliser applied. The current blanket fertiliser “Engrais Cacao” is suitable for only 16.5% of the cacao growing areas in Côte d’Ivoire. In the South-West, both P and K are required, while in the South-East, K will be more required. At a more local level, a more detailed map enabling to address more specific and detailed needs should be used. Our results highlighted a change in nutrient requirements over time, mainly linked to soil leaching and insufficient use of adequate fertilisation. This indicates the urgent need for better soil and fertiliser management.

REFERENCES

[1] Hanak Freud E, Petithuguenin P, Richard J. 2000. Les champs du cacao : un défi de compétitivité Afrique-Asie. [Cocoa fields: an Africa-Asia Challenge competitiveness]. Montpellier, France. ISRIC. A framework of international classification, correlation and communication. World Resource Report No. 103.

[2] Afrifa AA, Ofori-Frimpong K, Appiah MR, Acquaye S, Snoeck D. 2006. Nitrogen, phosphorus and potassium budget under the cocoa ecosystem: Produce harvesting phase. In: 15th International Conference on Cocoa Research. San José, Costa Rica.

[3] Koko L, Kassin EK, Assiri AA, Yoro G, Ngoran, K. Snoeck D. 2011. Fertilisation minérale du cacaoyer (*Theobroma cacao* L.) en Côte d'Ivoire : Acquis vulgarisables et perspectives de recherche. [Mineral fertilization of the cacao (Theobroma cacao L.) in Côte d'Ivoire: available results and research perspectives]. Agron. Afr. 23 (3): 217 – 225.

[4] Abdoellah S, Nur’Aini F. 2012. Effects of macro- and micronutrients on resistance of cocoa to vascular streak dieback disease. In: 17th International Cocoa Research Conference, Yaoundé, Cameroon.

[5] Nakayama LHI. 1995. Influência da nutrição mineral na manifestação dos sintomas da vassoura-de-bruxa (*Crinipellis perniciosa* Stahel.) em cacaueiro. [Influence of mineral nutrition on the onset of symptoms of the witch's broom (*Crinipellis pernicious* Stahel.) in cacao]. Piracicaba.

[6] Lachenaud P. 1995. Variations in the number of beans per pod in *Theobroma cacao* L. in the Ivory Coast. III. Nutritional factors, cropping effects and the role of boron. J. Hortic. Sci. 70 (1): 7-13.

[7] Verlière G. 1981. Étude par la méthode du diagnostic foliaire de la fertilisation et de la nutrition minérale du cacaoyer *Theobroma cacao* L. en Côte d’Ivoire. [Study of the foliar diagnosis method of fertilization and mineral nutrition of the cacao *Theobroma cacao* L. in Côte d'Ivoire]. Thesis report: 256 p.

[8] Lockard RG, Asomaning EJA. 1965. Mineral nutrition of Cacao *Theobroma cacao* L.: II. Effects of swollen-shoot virus on the growth and nutrient content of plants

grown under nutrient deficiency, excess and control conditions in sand culture. Trop. Agric. 42 (1): 39-53.

[9] Kébé I, N'Goran K, Konan A, N'Guessan F, Kofi N'Goran J, Irié Bi Z. 2005. Bien cultiver le cacaoyer en Côte d'Ivoire. [To cultivate well cacao in Côte d'Ivoire]. Technical document of CNRA. 4 p.

[10] Appiah MR, Ofori-Frimpong K, Afrifa AA. 2000. Evaluation of fertiliser application on some peasant cocoa farms in Ghana. Ghana J. Agri. Sci. 33: 183–190.

[11] Sanial E. 2015. Fertilizer and shade in Ivorian cocoa farming: crossed exploratory analyse. Student report: 21 p.

[12] Snoeck D, Abekoe MK, Appiah MR, Afrifa AA. 2006. Soil diagnostic method for formulating fertiliser requirements on cocoa plantations. In: 15th International Conference on Cocoa Research. San José, Costa Rica.

[13] Ponge JF. 1994. Pedology, Soil, vegetation, environment, 3rd Ed. By Ph. Duchaufour. In: Vegetatio / Vegetatio Acta Geobot; Plant Ecol. Vegetation 1122: 189 p.

[14] Malavolta E. 1997. Nutrição e adubação do cacaueiro. [Nutrition and fertilization of cacao]. In: ABEAS ed.. Curso de nutrição mineral de plantas: nutrição mineral do cacaueiro e do cafeeiro. módulo 06, Piracicaba.

[15] Araujo QR, Gaha L, Santana SO, Baligar VC. 2013. Soil Classification and Carbon Storage in Cacao Agroforestry Farming Systems of Bahia, Brazil. J. Sustainable For. 326: 625-647.

[16] Kassin KE. 2009. Études des conditions pédoclimatiques pour la replantation cacaoyère au Centre-Ouest de la Côte d'Ivoire : cas des départements de Divo et Gagnoa. [Studies of soil and climatic conditions for cacao replanting in Centre West of Côte d'Ivoire: case of the departments of Divo and Gagnoa]. PhD thesis, UFR STRM, Université de Cocody, Abidjan, Côte d'Ivoire: 112 p.

[17] Wessel M. 1985. Shade and nutrition. In: Wood GAR, Lass RA eds. Cocoa. Blackwell Science Ltd: 166-194.

[18] IRD. 2016. Internet mapping service. Available from: http://sphaera.cartographie.ird.fr/

[19] QGIS. 2016. *QGIS,* a user friendly Open Source Geographic Information System GIS. In: OSGeo ed. GNU General Public License. Available from: http://qgis.osgeo.org

[20] Blakemore IC, Searle PL, Daly BK. 1972. Methods of Chemical Analysis of Soils. New Zealand Soil Bureau Report. New Zealand Soil Bureau Wellington.

[21] Liebig V J. 1847. Chemistry in Its Application to Agriculture and Physiology. Lyon Playfair Baron Playfair. T. B. Peterson: 131 p.

[22] Jadin P, Snoeck J. 1985. La méthode du diagnostic sol pour calculer les besoins en engrais des cacaoyers. [The soil diagnosis method to calculate fertilizer needs of cacao]. Café Cacao Thé. 29 (4): 255–272.

[23] Snoeck D, Koko L, Joffre J, Bastide P, Jagoret P. 2016. Chapter 4: Cacao Nutrition and Fertilisation. In: Sustainable Agric. Rev. 19: 155-202.

[24] Jadin P. 1975. L'utilisation du diagnostic sol pour l'estimation des besoins en engrais des cacaoyers ivoiriens. [Use of soil diagnosis for the estimation of Ivorian cacao fertilizer requirements]. Café Cacao Thé. 19 (3): 203-220.

[25] Kollias VJ, Kalivas DP, Yassoglou NJ. 1999. Mapping the soil resources of a recent alluvial plain in Greece using fuzzy sets in a GIS Environment. Eur. J. Soil Sci. 1999: 261 –273.

[26] FAO. 2015. World reference base for soil resources. International soil classification system for naming soils and creating legends for soil maps. Publisher: FAO, Editor: P. Schad, C. van Huysteen, E. Michéli: 203 p.

[27] Snoeck D, Abolo D, Jagoret P. 2010. Temporal changes in VAM fungi in the cocoa agroforestry systems of central Cameroon. Agrofor. Syst. 78 (3): 323-328.

[28] Loué A. 1961. Étude des carences et des déficiences minérales sur le cacaoyer. [Study of deficiencies and mineral imbalances on cacao]. Technical document. Bingerville, Côte d'Ivoire. IRCC: 52 p.

[29] Chepote RE, Sodré GA, Reis EL, Pacheco RG, Marrocos PC, Valle RR. 2013. Recomendações de corretivos e fertilizantes na cultura do cacaueiro no sul da Bahia. [Recommendations for lime and fertilizer in cacao cultivation in southern Bahia] Ministério da Agricultura, Pecuária e Abastecimento**:** 41 p.

[30] Stemler C. 2012. Analyse de la variation dans les réponses à l'engrais, et dynamiques d'intensification dans le secteur cacaoyer en Côte d'Ivoire. [Analysis of changes in

responses to fertilizer and dynamic intensification in the cocoa sector in Côte d'Ivoire]. Studentship report: 42 p.

[31] Ojeniyi SO, Egbe NE, Omotoso TI. 1982. Effects of nitrogen and phosphorus fertilisers on unshaded Amazon cocoa in Nigeria. Fertil. Res. 3: 13-16.

[32] Alvim PdT. 1977. « Cacao ». In: Ecophysiology of tropical crops. Alvim PT, Koslowski TT. Eds. NewYork, USA, Academic Press: 279-313.

[33] Bastide P, Cilas C, Jimmy I. 2003. Variability of leaf parameters in the foliage of cocoa trees in Vanuatu. In: 14th International Cocoa Research Conference, Lagos, Ghana.

[34] Loué A, Drouineau G. 1993. Les oligoéléments en agriculture. [Micronutrients in agriculture]. 2nd Edition. Paris: 577 p.

[35] Ojeniyi SO, Egbe NE, Omotosho TI. 1981. Boron nutrition of amazon cocoa in Nigeria: I. Early results of fertiliser trials. Exp. Agric. 17: 399-402.

[36] Hartemink AE. 2005. Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: A review. In: Adv. Agron. 86: 227-253.

[37] Appiah MR, Sackey ST, Ofori-Frimpong K, Afrifa AA. 1997. The consequences of cocoa production on soil fertility in Ghana: a review. Ghana J. Agri. Sci. 30: 183–190.