Comparison of leaf mineral content and soil nutrient status and their combined effect as predictors of cocoa (*Theobroma cacao* L.) bean yield

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Abstract

There is a dearth of research focusing on predicting cocoa bean yield using soil nutrients and/or leaf mineral content, even though such yield predictions exist for other crops. The study examined the relationship between soil nutrients, cocoa leaf mineral content, and yield. A progeny trial field in Bunso with two cocoa varieties and thirty stands was selected from three plots. Sixty pairs of soil samples were taken from the surface and subsurface within a two-meter rhizosphere diameter. Four fully expanded young leaves were sampled from each selected tree three times during the season. Both the soils and leaves were analyzed for nutrient content. The results indicated low correlation coefficients between the soil and the leaf nutrients. The separate multiple regression of the nutrient content of surface soils against pod number, the subsurface soil nutrients against the pod number, and the leaf nutrient against the pod number all recorded low significance ($p < 0.05$) R^2 (0.32, 0.36, and 0.20, respectively). However, when soil nutrients at each depth were combined separately with leaf nutrients and regressed against the pod number, relatively greater R^2 values were recorded (0.61 and 0.57, respectively). The combined soil and leaf nutrient content at each depth was a better predictor of yield than using them separately. Soil nutrients were found to have a better relationship with yield than their leaf counterparts. It was also found that the ideal time for soil and/or leaf sampling is at the onset of the rainfall.

Keywords: Cocoa pod number, leaf nutrient content, soil nutrient status, subsurface soil, surface soil

Introduction

Soil quality is the blended effect of the chemical, physical, and biological characteristics of the soil (Brady and Weil, 2002). For soil to be considered quality or suitable for the cultivation of cocoa, it must be able to supply plants with sufficient nutrients in a favourable soil environment. Healthy cocoa development and maximum output are substantially influenced by fertile soil and efficient farm management, among others.

Cocoa plantations are mostly cultivated on marginally to moderately fertile soils and are therefore less suitable to support optimum cocoa growth and bean yield (Aikpokpodion, 2010). These soils are extensively leached, well-drained and intensively weathered. Smith (1975) concluded that because cocoa has such strict soil requirements, it will not grow well if these requirements are not met. For example, Ahenkora et al. (1987) reported a decrease in cocoa yield in Ghana due to soil nutrient depletion and long-term cocoa cultivation without soil nutrient replenishment.

Cocoa requires soils with an average pH between 5.60 and 8.00, organic carbon content of 35.00 g kg^{-1}, available P greater than 20.00 mg kg^{-1}, total N of 0.90 g kg^{-1}, cation exchange capacity between 10.00 and 25.00 $cmol_c$ kg^{-1}, exchangeable K not less than 0.25 $cmol_c$ kg^{-1}, Ca greater than 7.50 $cmol_c$ kg^{-1}, and Mg greater than 1.33 $cmol_c$ kg-1 (Snoeck et al., 2016). Furthermore, to produce its highest output, the macronutrient content of the leaf should not be less than the critical values for calcium, magnesium, nitrogen, phosphorus, and potassium (0.60, 0.50, 0.90, 0.20, and 2.00% respectively) (Aikpokpodion, 2010).

To improve yield and create effective nutrient management strategies, modern cocoa production places a strong emphasis on providing plants with appropriate nutrition (Sousa et al., 2018). Soil and/or leaf diagnosis is crucial to ensure effective and sustainable nutrient management. Various soil chemical, biological and physical factors affect soil fertility and crop yield, making quantitative analysis of yield-dependent soil-related factors essential for managing farm resources and predicting cocoa bean yield (Whetton et al., 2021).

Many works have shown the effect and possibility of using soil and leaf mineral content to predict crop yield. For instance, Aikpokpodion (2010) reported low cocoa yields in response to the lower (< critical values) K and P contents of the cocoa leaf in different tropical soils. Battaglia et al. (2001) also reported a positive relationship between increased crop yield and increased leaf and soil nutrient contents. An assessment by Ajami et al. (2020) showed that field topography can significantly affect variation in wheat yield due to its effect on soil properties. Furthermore, Whetton et al. (2021) used soil properties in the random forest model to predict the yield of wheat and rape oil in two growing seasons (2013 and 2014) and found that 55.62 and 45.81% of the yield were attributable to the soil properties measured in the two seasons, respectively.

Several works have demonstrated the possibility of predicting the yield of various crops (wheat, rape, maize) using soil and/or leaf nutrient content or properties. However, there is a dearth of research focusing on predicting cocoa bean yield using soil nutrients and/or leaf mineral content. Most cocoa farmers rarely conduct soil and/or leaf nutrient diagnosis, particularly on already established farms, largely due to the scarcity of information on the importance of these practices in modern cocoa production. Earlier works that focused on the analysis of soil and cocoa leaf nutrients only reported soil or leaf nutrient levels without establishing any relationship and using the relationship to predict cocoa bean yield (Afrifa et al., 2017; Mohammed et al., 2020). This study aims to determine the nutrient content of cocoa plantation soils, analyze the leaf mineral content of the cocoa crop, establish the relationship between the two, and use this relationship to predict cocoa bean yield.

Materials and Methods

Study site

The study was conducted on an established progeny trial field at the Cocoa Research Institute of Ghana (CRIG) substation, Bunso. The area is characterized by a bimodal rainfall pattern with the major season between March and July and the minor season between September and November. The mean annual rainfall ranges from 1250.00 to 1750.00 mm, with a mean temperature of 29.10 ^{o}C, relative humidity of 85% and 2336.20 hours of annual sunshine. The trial was established in 2017. The experiment was laid out in a single-tree randomization design. The soil at the site was classified as Ferric Lixisol (WRB, 2015). Three plots classified as P1, P2 and P3 (06°16'N and 0°27' W) were selected and used as study plots. Each plot was blocked into three subplots for soil and leaf sampling. Ten trees from each of the two cocoa varieties (A and B) were selected in each plot. The chosen trees were tagged for soil and leaf sampling.

Soil sampling

Four soil samples were taken within a rhizosphere radius of 100 cm, at depths of 0-15 and 15-30 cm for each selected cocoa tree across the three plots. The four soil samples from each depth for each cocoa tree were combined, and representative samples were extracted. Soil samples collected from the field were air-dried, homogenised, sieved (2 mm), and characterised by chemical analysis. The textural class of the soil used ranged from sandy clay loam to clay loam. The soils were sampled in April 2021. Some weather data from the study area is presented in Table 1, Figures 1 and 2.

TABLE 1
Some weather data of the study area in the year 2021

Month	Wet days	Relative humidity (%) at 1500 GMT	Sunshine duration (hours)
January	3.00	60.00	237.40
February	6.00	58.90	210.30
March	7.00	60.50	191.30
April	6.00	61.90	211.80
May	7.00	62.40	219.60
June	16.00	98.60	161.80
July	5.00	71.30	161.80
August	11.00	68.10	140.50
September	11.00	70.77	126.90
October	14.00	72.45	202.60
November	5.00	66.63	219.50
December	0.00	49.81	252.70

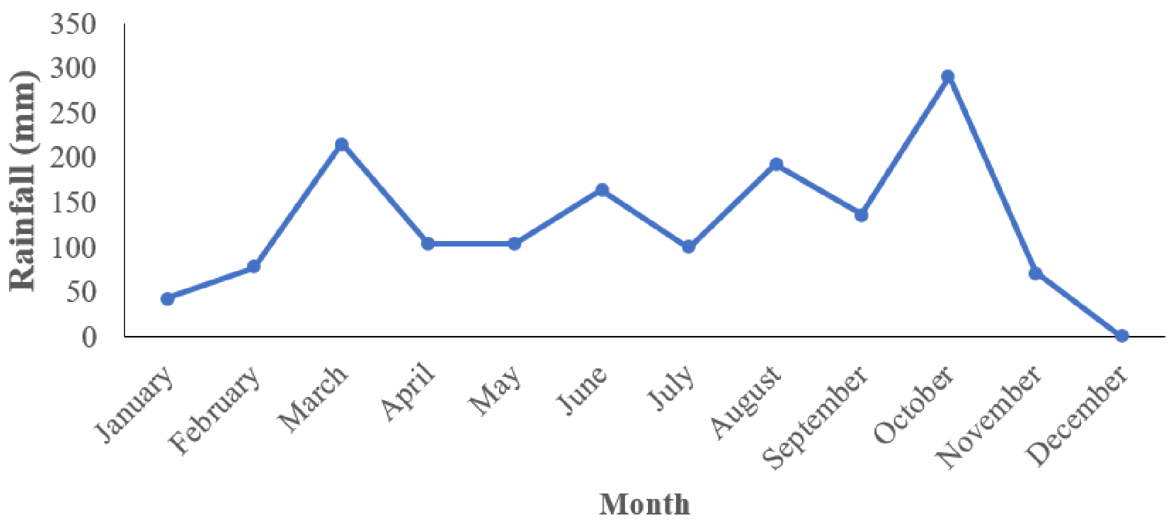

Figure 1 Rainfall pattern of the study area in the year 2021

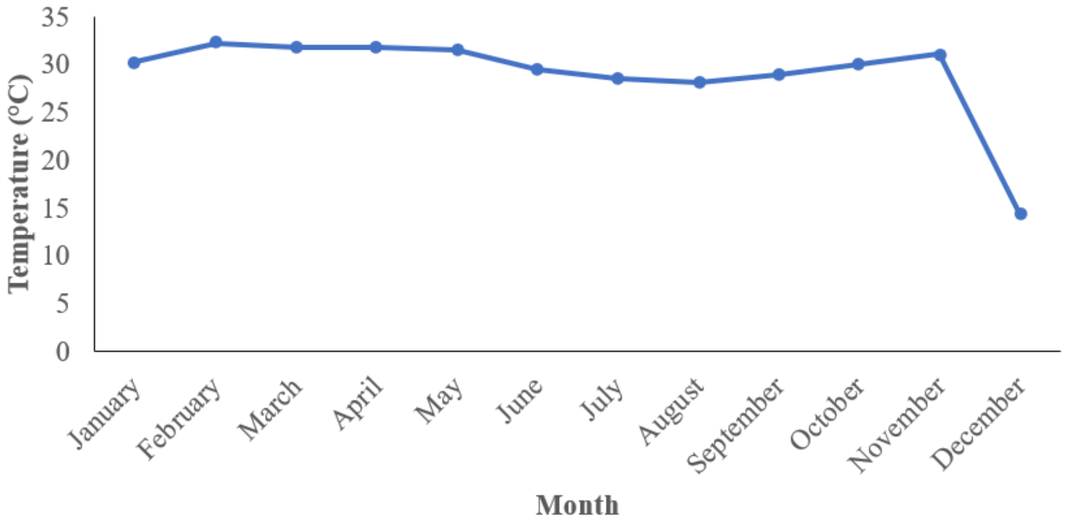

Figure 2 Temperature of the study area in the year 2021

Leaf sampling

A modified method outlined by Aikpokpodion (2010) was used to sample the cocoa leaves. The selected trees were divided into four sections along the trunk for leaf sampling. Leaves were sampled in the upper part of the third section in a north-south direction and early in the morning before 10:00 am to minimize the intensity of sunlight on the leaves. Four young fully expanded leaves were sampled from each selected cocoa tree. The fourth leaves below the apex leaf on the branches were sampled. The cocoa leaves were sampled at three different times within the season, thus at the beginning of the rainfall (S1), at the start of the flowering (S2) and the maturity of the pod (S3).

Soil analysis

Soil pH was determined in water (1:2.5). The organic carbon content of the soils was determined using the Walkley and Black (1934) wet oxidation method, the total nitrogen content of the soils was determined using the Kjeldahl (1883) method. Available phosphorus was determined using the method of Mehlich (1984). Exchangeable bases were extracted by the ammonium acetate method (Black, 1965) and the filtrates were analyzed on an atomic absorption spectrometer version iCE 3300 (Thermo Scientific, Waltham, Massachusetts, USA).

Leaf analysis

The sampled leaves were washed with deionized water and oven-dried to a constant weight at 75.00 °C. Part of the oven-dried leaves was milled for analysis of the nutrient content. The dried milled leaf samples were digested with perchloric and sulpheric (1:3) acid and then analyzed for total N, and with perchloric and nitric acid (1:3) and then analyzed for total P, total K, total Ca and total Mg using the Walkley and Black (1934) wet oxidation method. Mature pods removed from each selected tree were counted and recorded at each harvest time (bi-weekly).

Statistical analysis

Analysis of variance (ANOVA) was done using the Genstat statistical package (12th edition) and the standard error of difference (SED) was used to compare means at a probability level of 5%. Correlation was done using the Pearson correlation method and multiple regression was used for regression analysis.

Results

Chemical properties of the soils sampled from the three experimental plots

Some selected soil chemical properties of the three plots used for the study are presented in Table 2. All the measured parameters had values greater than their respective critical minimum values (Snoeck et al., 2016) required for optimum cocoa yield, except organic carbon, available phosphorus and exchangeable calcium. The soil nutrient content decreased as the soil depth increased. The organic carbon was lowest (11.60 g kg^{-1}) on the subsurface of plot 2 (depth 15-30 cm), while the greatest organic carbon (30.00 g kg^{-1}) was recorded on the surface of plot 3 (depth 0-15 cm). The pH of the soil was less than 7 (Table 2) and ranged from strongly acidic to neutral according to the descriptive classification of soil pH (USDA, 1999). Except for plot 1, subsurface soil, all depths measured in the three plots had pH values greater than the critical minimum (5.60) (Snoeck et al., 2016) needed for cocoa production. Total nitrogen was greatest in plot 3, surface soil (0.33%), while in plot 2, subsurface soil had the lowest TN (0.13%). The available phosphorus values ranged from 2.25 mg kg^{-1} in plot 1, subsurface soil, to 5.77 mg kg^{-1} in plot 3, surface soil. The exchangeable K was between 1.70 and 0.57 cmol$_c$ kg^{-1} (Table 2), with the surface soil of plot 3 recording the greatest exchangeable K. The exchangeable Mg ranged from 1.47 to 2.51 cmol$_c$ kg^{-1} in the three plots and at the two depths. The Ca content was between 3.94 and 2.52 cmol$_c$ kg^{-1}.

Effect of sampling time on the nutrient content of the leaf samples

The nutrient content of the leaves is presented in Figures 3 to 8. Generally, there was no

TABLE 2
Some chemical properties of the soils used in the study

Plot	Depth	pH	OC	TN	Av. P	Ex. K	Ex. Mg	Ex. Ca
	cm		-------%----		mg kg^{-1}	-------------cmolc kg-1------------------		
P1	0-15	5.77 ± 0.15b	2.82 ± 0.07d	0.30 ± 0.02d	3.44 ± 0.30b	0.38 ± 0.02b	2.51 ± 0.13c	3.53 ± 0.06b
	15-30	5.44 ± 0.11a	1.63 ± 0.15b	0.16 ± 0.01b	2.25 ± 0.1a	0.21 ± 0.02a	1.58 ± 0.13a	2.65 ± 0.13a
P2	0-15	6.49 ± 0.14c	2.38 ± 0.21c	0.26 ± 0.01d	3.31 ± 0.32b	0.36 ± 0.04b	2.22 ± 0.18b	3.27 ± 0.04b
	15-30	6.42 ± 0.14c	1.16 ± 0.08a	0.13 ± 0.01a	2.75 ± 0.30ab	0.17 ± 0.03a	1.47. ± 0.09a	2.28 ± 0.08a
P3	0-15	5.96 ± 0.14b	3.00 ± 0.14d	0.33 ± 0.02e	5.77 ± 0.42d	0.57 ± 0.03c	2.34 ± 0.12bc	3.94 ± 0.12c
	15-30	5.77 ± 0.13b	1.80 ± 0.12b	0.21 ± 0.01c	4.41 ± 0.51c	0.35 ± 0.03b	1.50 ± 0.10a	2.52 ± 0.11a
	CM	5.60	3.50	0.09	20.00	0.25	1.33	7.50

NB: OC = organic carbon, TN = total nitrogen, Av. P = available phosphorus, Ex. K = exchangeable potassium, Ex. Mg = exchangeable magnesium, Ex. Ca = exchangeable calcium, CM = critical minim

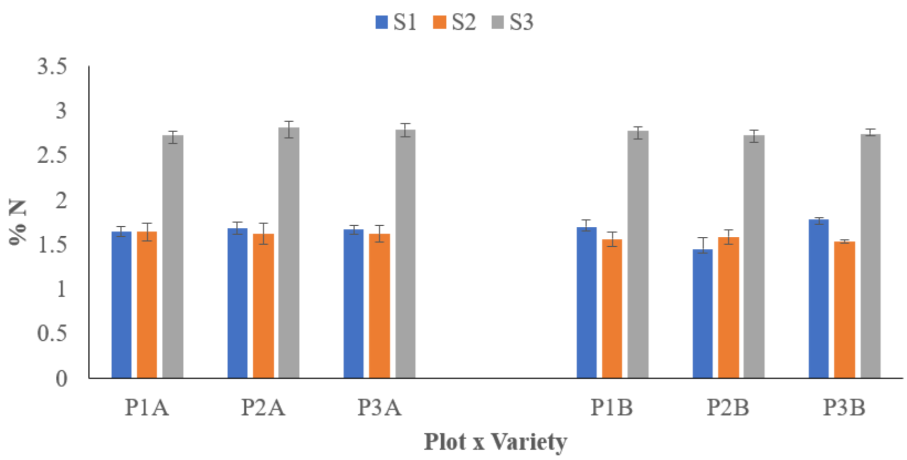

Figure 3 Effect of sampling time on leaf N content
NB: S1 = sampling time one, S2= sampling time two and S3 = sampling time three, P1, P2 and P3 = plot1, plot 2 and plot 3 respectively. A and B are two cocoa varieties

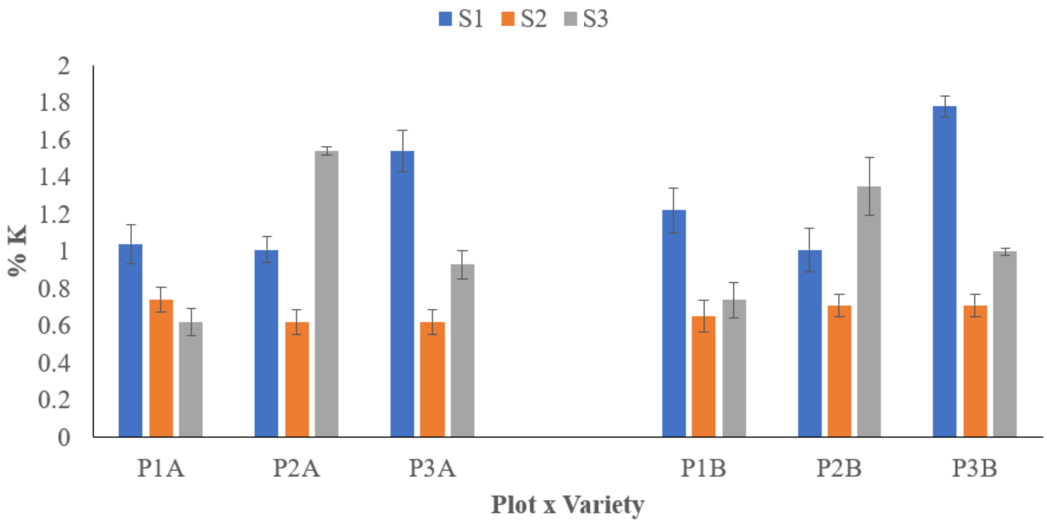

Figure 4 Effect of sampling time on leaf K content

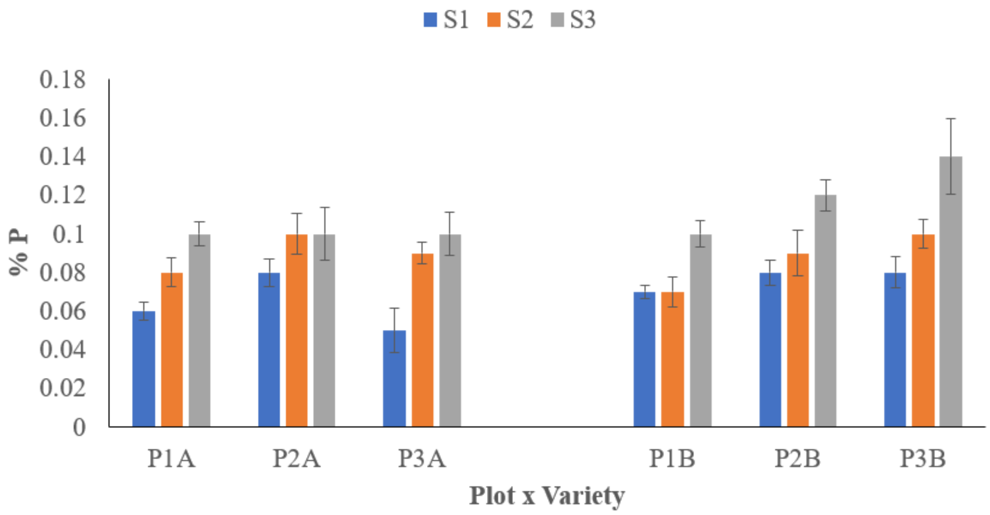

Figure 5 Effect of sampling time on leaf P content

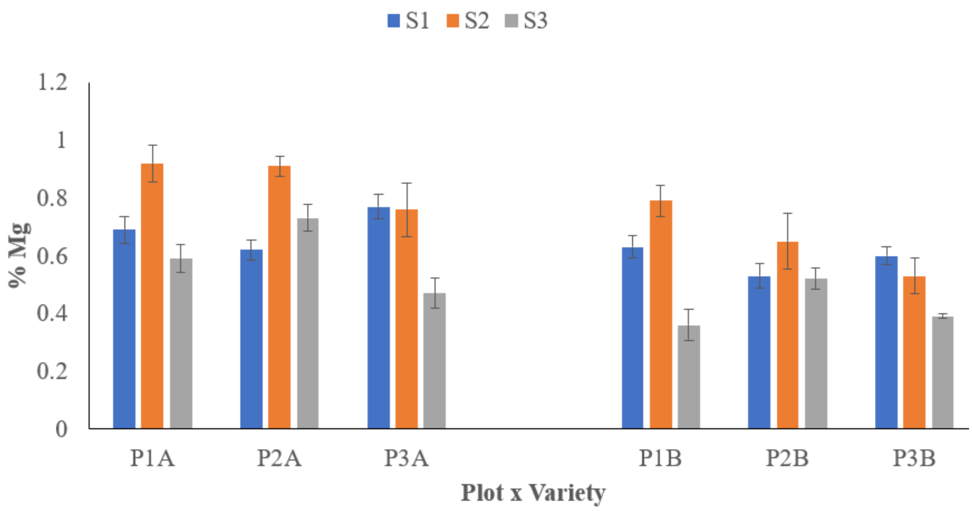

Figure 6 Effect of sampling time on leaf Mg content

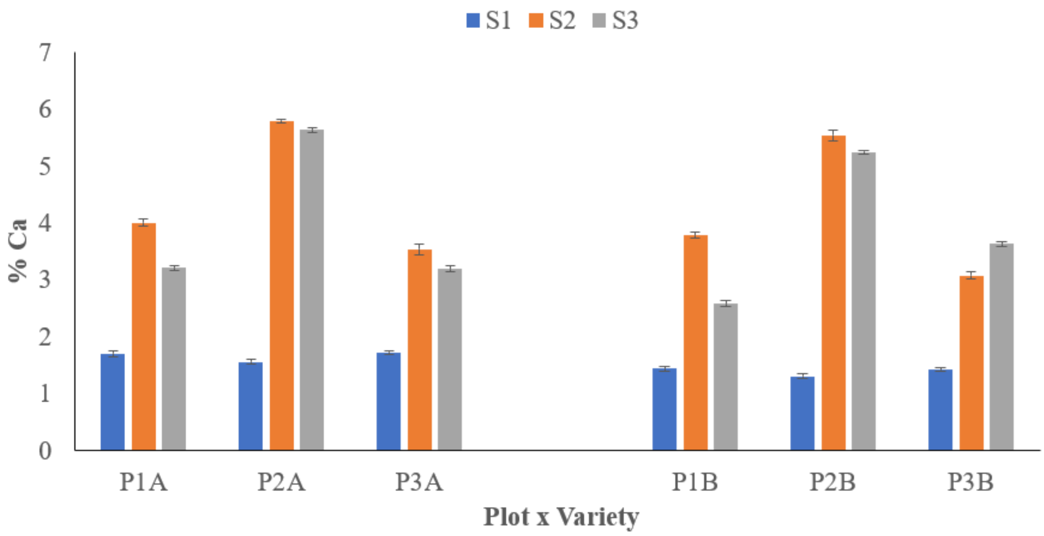

Figure 7 Effect of sampling time on leaf Ca content

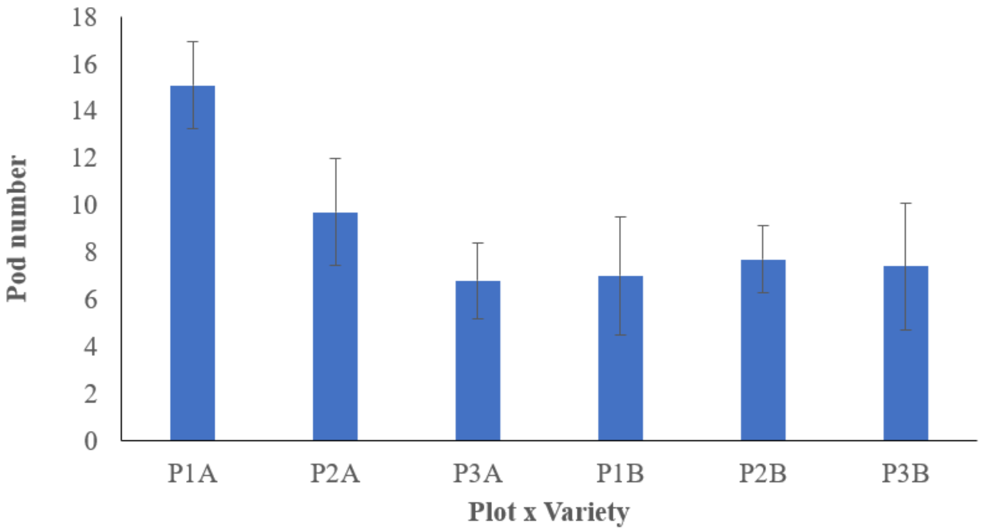

Figure 8 Number of pods of the two varieties of cocoa from the three plots

consistency in the effect of sampling time on leaf mineral content. The nitrogen content of the leaves was higher ($p < 0.05$) in S3 (sampling at pod maturity) in all the plots, while S1 (sampling at the beginning of rain) and S2 (sampling at the start of flowering) showed a similar N content. Plot 1 (P1A and P1B) recorded the greatest K content in S1 as compared to the K content of the same varieties on the same plot in S2 and S3. However, plot 2 (P2) with the two varieties (A and B) had the greatest K content at S3, followed by S1, with S2 recording the least leaf K content in the two varieties. The leaf K content of the two varieties at different sampling times in plot 2 was in the order of S2 < S1 < S3. While that of plot 3 at the different sampling times was in the order of S2 < S3 < S1. It is worth noting that, at all the sampling times in the different plots, S2 recorded the lowest K content except on plot 1. The total P contents of the leaves in all the plots at different sampling times were lower than the critical minimum needed for optimal cocoa yield. The leaf P content of variety B was greatest in S3. Sampling time 2 (S2) recorded the highest leaf Mg contents in P1A, P2A and P1B, which were significantly different from the remaining sampling times from the same plots. The Ca content of the leaves of all the plots was lowest at sampling time 1 (S1). Plot two (P2) recorded Ca concentrations in the order of S1 < S3 < S2.

Pearson correlation (r) between soil nutrient content and leaf mineral content

The correlation between soil nutrient content at the two depths and leaf mineral content at the various sampling times is presented in Table 3-8. There were significant ($p < 0.05$) positive and negative correlations between the nutrients in the leaves at different sampling times (S1, S2, and S3) and the soils at both depths (0-15 and 15-30 cm).

At the first leaf sampling time, the leaf nitrogen content (LN) had a positive correlation coefficient with the N and K content of the surface soil (Table 3). The surface soil Mg content also significantly correlated ($p < 0.001$) with leaf Ca and Mg. The soil K and P at the surface and the leaf K at the first sampling had a significant correlation coefficient ($p < 0.05$). The leaf K content at the first leaf sampling time had a significant ($p < 0.05$) positive correlation with the total N, OC, available P and exchangeable K of the subsurface soil (Table 4). The N content of the leaves and the N content of the subsurface soil recorded a significant correlation coefficient ($p < 0.05$) of 0.38. Again, the leaf N content recorded a significant ($p < 0.05$) correlation coefficient of 0.30 with the subsurface soil K content.

However, in the second leaf sampling, the K content of the surface and subsurface soils recorded a significant negative correlation

TABLE 3

Correlation between surface soil and leaf mineral content at the first sampling

Soil nutrient	Leaf mineral content				
	LN	LP	LK	L Mg	L Ca
pH	-0.11	0.15	-0.23	-0.10	-0.13
OC	0.16	0.01	0.18	-0.11	-0.03
TN	0.26*	0.06	0.14	0.13	-0.07
Av. P	0.04	-0.12	0.31**	0.04	-0.02
Ex. K	0.36***	0.11	0.57***	0.07	-0.01
Ex. Mg	0.05	-0.25	-0.14	0.35***	0.33***
Ex. Ca	0.11	-0.01	0.02	0.01	-0.08

NB: L N = leaf nitrogen content, L P = leaf phosphorus content, L K = leaf potassium content, L Mg = leaf magnesium content, L Ca = leaf calcium content, significant at ($p < 0.05$) = *, ($p < 0.01$) = ** and ($p < 0.001$) = ***

TABLE 4

Correlation between soil nutrients in the subsurface and leaf mineral content in the first sampling

Soil nutrient	Leaf mineral content				
	LN	LP	L K	L Mg	L Ca
pH	-0.07	0.22	-0.21	-0.12	-0.26**
OC	0.22	0.01	0.41***	-0.15	-0.13
TN	0.38***	-0.06	0.44***	0.17	0.04
Av. P	0.07	-0.01	0.35***	-0.03	-0.06
Ex. K	0.30**	0.14	0.61***	-0.10	-0.07
Ex. Mg	0.06	0.05	-0.02	0.02	-0.21
Ex. Ca	-0.09	-0.18	-0.01	0.07	-0.17

($p < 0.05$) with the leaf Ca and Mg content (Table 5). Soil Mg and the leaf counterpart recorded a significant positive correlation coefficient ($p < 0.05$) of 0.42. The Ca content of leaves also recorded significant ($p < 0.05$) positive correlation coefficients of 0.33 and 0.43 with OC and pH, respectively. The leaf Ca content had a significant ($p < 0.05$) positive correlation coefficient with pH, OC and TN of the subsurface soil (0.47, 0.50 and 0.45, respectively) (Table 6). The P content of the leaves also had significant ($p < 0.05$) negative correlation coefficients with the Mg and Ca content of the subsurface soils.

The leaf Ca content in the third leaf sampling recorded a significant ($p < 0.05$) positive correlation coefficient of 0.39 with the pH of the surface soil, while the soil K and the leaf Mg had a significant ($p < 0.05$) negative correlation of 0.26 (Table 7). The K content of the leaves had a significant positive correlation with OC and a significant negative correlation with the Ca content of the surface soil. Additionally, the Mg content of the surface soil recorded a significant ($p < 0.05$) positive correlation with the leaf Mg content and a significant ($p < 0.05$) negative correlation with the leaf P content at the third sampling time. The Ca content of the leaves at the third sampling time had a significant ($p < 0.05$) positive correlation with pH and OC, while it recorded a significant negative correlation with the N content of the subsurface soil. The Mg content of the leaves also had a significant ($p < 0.05$) negative correlation with the OC and N content of the subsurface soils. The K content of the leaves also had a significant ($p < 0.05$) positive correlation coefficient with pH and a significant ($p < 0.05$) negative correlation coefficient with the N content of the subsurface soil (Table 8). The organic carbon (OC) content of the subsurface soil had

TABLE 5

Correlation between soil nutrients on the surface and leaf mineral content in the second sampling

Soil nutrient	Leaf mineral content				
	LN	LP	L K	L Mg	L Ca
pH	-0.023	0.09	-0.02	0.04	0.43***
OC	0.07	0.10	0.25	-0.20	0.33**
TN	0.05	-0.01	0.13	-0.17	-0.25
Av. P	-0.03	0.09	0.24	-0.19	-0.18
Ex. K	-0.03	0.05	0.18	-0.38***	-0.41***
Ex. Mg	0.19	-0.07	0.03	0.42***	0.09
Ex. Ca	-0.03	-0.17	0.04	0.07	-0.01

TABLE 6

Correlation between soil nutrients in the subsurface and leaf mineral content in the second leaf sampling

Soil nutrient	Leaf mineral content				
	LN	LP	L K	L Mg	L Ca
pH	0.03	0.06	-0.13	-0.06	0.45***
OC	-0.12	-0.06	-0.02	-0.16	0.50***
TN	-0.03	-0.13	0.11	-0.25	0.47***
Av. P	0.06	0.13	0.21	-0.10	-0.05
Ex. K	-0.08	-0.02	0.19	-0.34***	-0.35***
Ex. Mg	-0.09	-0.32*	-0.12	0.11	0.13
Ex. Ca	-0.22	-0.31**	-0.22	0.13	-0.03

TABLE 7
Correlation between soil nutrients on the surface and leaf mineral content in the third sampling

Soil nutrient	Leaf mineral content				
	LN	**LP**	**L K**	**L Mg**	**L Ca**
pH	-0.02	-0.12	0.22	-0.01	0.39***
OC	0.06	-0.01	0.43***	-0.26	-0.10
TN	0.01	-0.06	-0.36	-0.14	-0.19
Av. P	-0.03	-0.07	-0.08	-0.08	-0.11
Ex. K	0.13	0.05	-0.12	-0.26*	-0.19
Ex. Mg	0.05	-0.32**	-0.03	0.40***	-0.02
Ex. Ca	0.09	-0.19	-0.32**	-0.12	-0.21

TABLE 8
Correlation between soil nutrients in the subsurface and leaf mineral content in the third sampling

Soil nutrient	Leaf mineral content				
	LN	**LP**	**LK**	**L Mg**	**L Ca**
pH	0.01	-0.07	0.34***	0.02	0.45***
OC	0.05	0.40***	-0.19	-0.40***	0.37***
TN	-0.13	0.04	-0.37***	-0.27**	-0.34***
Av. P	-0.10	-0.09	-0.12	-0.07	0.01
Ex. K	0.06	0.11	-0.08	-0.22	-0.21
Ex. Mg	0.07	0.01	-0.04	0.19	-0.05
Ex. Ca	-0.10	0.10	-0.04	0.01	-0.21

NB: L N = leaf nitrogen, L P = leaf phosphorus, LK = leaf potassium, L Mg = leaf magnesium

a significant ($p < 0.05$) positive correlation coefficient with the P content of the leaves at the third sampling time.

Number of pods of the two varieties in the three plots

The number of pods of the two cocoa varieties from the three plots is presented in Figure 8. Variety B did not show significant differences in pod numbers across the three plots. However, variety A recorded the greatest (15) pod number, which was significantly ($p < 0.05$) different from the same variety on the remaining plots.

Regression of soil and leaf nutrient content at different sampling times against pod number

Regression of the chemical properties of the surface soil (0-15 cm) and the subsurface soil (15-30 cm) versus the number of pods is presented in Table 9. Multiple regression of surface soil chemical properties against pod number gave an R^2 value of 0.32, while subsurface soil chemical properties against pod number had an R^2 value of 0.36. Organic carbon, exchangeable K and pH significantly ($p < 0.05$) contributed to the pod number.

Multiple regressions of the mineral content of the leaves at the three different sampling times

TABLE 9
Multiple regression of the soil surface and subsurface nutrient content against the number of pods

	Surface	**subsurface**
R^2	0.32	0.36

TABLE 10
Multiple regression of leaf mineral content at different sampling times against pod number

	S1	S2	S3
R^2	0.20	0.13	0.20

TABLE 11
Multiple regression of combined surface soil nutrients and leaf mineral content at different sampling times against pod number

	Surface +S1	Surface + S2	Surface + S3
R^2	0.61	0.42	0.46

TABLE 12
Multiple regression of combined subsurface soil nutrients and leaf mineral content at different sampling times against pod number

	Subsurface +S1	Subsurface + S2	Subsurface + S3
R^2	0.57	0.46	0.32

against the number of pods are presented in Table 10. Multiple regression of each leaf mineral content at a sampling time against the number of recorded lower R^2 values. The soil nutrient content at the two different depths was separately bulked with the leaf mineral content at each leaf sampling time and each was regressed against the pod number. The resulting multiple regression coefficients are shown in Tables 11 and 12. Bulking separately the soil nutrient content at two different depths, each with leaf nutrient content at the first sampling time against pod number, gave a relatively greater R^2 of 0.61 and 0.56 in surface soil/leaf mineral content and subsurface soil/ leaf mineral content, respectively. Bulking of the same soil nutrient content at both depths separately, with leaf mineral content at the second leaf sampling time against pod number, recorded multiple regression coefficients of 0.42 and 0.45 for the surface soil/leaf minerals and the subsurface soil/leaf minerals, respectively. At the third sampling time, the bulking of soil nutrients with leaf nutrients against the number of pods recorded similar R^2 values (Tables 11 and 12). Soil chemical properties such as pH, organic carbon, and leaf total NPK contributed significantly ($p < 0.05$) to the multiple regression coefficients of the combined leaf nutrient content with soil nutrient content at each depth versus the number of pods.

Discussion

Chemical properties of the soil

The soils had low organic carbon content, which is typical of most tropical soils used for cocoa production in Ghana. Organic matter must be added to the soils to increase the organic carbon content and productivity. Additionally, P availability is anticipated to be very low given the low levels of organic matter and the low pH of these soils. This agrees with the findings of Nartey et al. (1997) and Abekoe et al. (2001). As a result, improving the capacity of these soils to produce cocoa requires amendments that will increase the availability of P.

The surface soil (0-15 cm), being the top layer, receives litter from the vegetation cover. These organic materials undergo decomposition and release nutrients into the topsoil. Additionally, nutrients are applied to the top layer of the soil. Consequently, it has more nutrients than subsurface soil (15-30 cm). This result is consistent with the findings of Adugna and Abegaz (2015), who showed comparable trends in nutrient concentration at various soil depths. The fact that all other nutrients examined decreased as the organic matter content decreased highlights the importance of organic matter as a reservoir of nutrients and a key sign of soil health, particularly in the tropics. Plots 1 and 3 had higher soil nutrient levels than plot 2, which could be attributed to either of those plots' inherent high fertility levels or management practices such as fertilizer application.

Leaf mineral content

The low P content of the leaves may be attributed to the low P in the soils and the potential low P supply to the plants. Potassium, on the other hand, was higher than the critical minimum in the soil but lower than the critical minimum in the leaves, suggesting that the element may have been channelled to other plant parts (such as the roots, stem, and branches) and functions such as pod development. The absence of signs of P deficiency in the plants raises the possibility that they are experiencing hidden hunger for P and this could negatively affect plant growth and development.

The continuous erratic rainfall as the season progressed and the consequential increase in soil water and available nutrients might be the reason for the higher leaf N at the third sampling. This might also explain the relatively higher leaf P and Ca content in the second and third leaf samples than in the first leaf samples. This is in contrast with the finding of Olff et al. (2002), who reported an inverse relationship between available soil water and grass leaf mineral levels and attributed it to the dilution effect of plant growth. The higher leaf K contents of the first and third leaf samples from most of the plots could be attributed to the sampling times. The first and third leaf samples were taken when the intensity of the sunshine was nearing its peak and the rainfall had typically stopped or had just begun. The plant may channel more K into its leaves as a way of retaining moisture in response to these changes in rainfall intensities and weather patterns. Aidoo et al. (2017) stated that one of the functions of K in plant leaves is to regulate stomatal opening to limit water loss through transpiration.

The higher amount of Mg in the leaves may have resulted in the greenish colour of the leaves, indicating a high chlorophyll content, during the second sampling. Prajapati and Modi (2012) reported that magnesium is a significant component of chlorophyll. The fact that K is said to have an inverse relationship with Mg during uptake may also explain the increase in Mg content of the leaf during the second sampling when the K content decreased. This is corroborated by the substantial negative association between the Mg content of the leaves and the K content of the surface and subsurface soils during the second and third leaf samplings. Laekermarian et al. (2018) reported an antagonistic interaction between K and Mg nutrients and stated that it is a prevalent problem in tropical and subtropical regions with high rainfall and low pH.

Relationship between soil nutrients and leaf mineral content

The relatively low levels of nutrients in the leaves acquired from the soil or the possibility that the leaves obtain nutrients from other sources could explain the poor correlation coefficients between the minerals in the leaves and the nutrients in the soils. Laekermarian et al. (2018) also reported that the availability of nutrients from the soil is not the sole factor that affects the mineral concentrations in leaves. The roots, stems, and branches of the plant may also receive nutrients that the plants acquire from the soil.

Although soil nutrients analyzed are important for high yields, they may not be the sole factors that determine the yield, as evidenced by the fact that plot 3 had a higher nutrient content than plot 1, but plot 1 recorded a greater yield than plot 3. Micronutrients such as Zn, B and other soil properties that were not measured might have also helped in improving the bean yield. This is supported by the findings of Whetton et al. (2018), who stated that all soil properties as well as farm management practices, function together to boost crop production. This is supported by the low multiple regression coefficients, which were obtained when the yield was separately regressed with soil chemical properties at the different depths and leaf nutrient content. The heterogeneity of the soil might have contributed to the high yield of variety A on plot 1 than the other plots and its B counterpart.

The fact that soil nutrient content at the different sampling depths, with each combined separately with leaf nutrient content at the three sampling times and each regressed against yield had a greater regression coefficient value suggests that the combination of soil nutrient content and leaf mineral content is a better predictor of yield compared to using them individually. It is therefore deemed prudent to analyse both soil and leaf samples to ensure effective nutrient management of perennial crops such as cocoa, as reported in the work of Pushparajah (2022). Additionally, the greatest regression coefficient was found when the mineral content of the leaves at the initial sampling was paired with the nutrient content of the surface soil. This may also be the reason why cocoa fertilizers, particularly granular and organic fertilizers, are applied at the beginning of rainfall to give the cocoa trees a good start and increase production. Although Zinc and boron were not investigated in this study, they function to enhance flowering and pod set (Kouadio et al., 2017). However, plant uptake of these nutrients is hindered by K uptake in the soil. This might explain the negative relationship between soil K and the pod number. Also, organic matter and pH influence the phyto-availability of Zn and B (Brady and Weil 2002) and consequently, pod number. This might explain the negative relationship between the latter and the former.

Conclusions

The findings of this work indicated that the soils in the study area were quite fertile; however, some nutrients fell below the critical minimum required for cocoa production. Nevertheless, the leaf mineral contents were generally above the critical minimum, except for phosphorus and potassium. Both the leaf mineral content and the soil chemical properties significantly contributed to bean yield. Combining distinct leaf nutrient content with soil minerals provides a more accurate prediction of cocoa bean yield. It is essential to conduct simultaneous diagnostics of leaf and soil nutrient levels to ensure effective nutrient management of cocoa plantations. Soil nutrients demonstrated a stronger relationship with yield than leaf nutrients.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

Abekoe, M. K. & Sahrawat, K. L. (2001). Phosphate retention and extractability in soils of the humid zone in West Africa. *Geoderma* **102(1)**: 175-187.

Adugna, A. & Abegaz, A. (2015). Effects of soil depth on the dynamics of selected soil properties among the highlands resources of Northeast Wollega, Ethiopia: are these signs of degradation? Solid Earth Discussions **7(3)**: 2011-2035.

Afrifa, A. A., Dogbatse, J. A. & Arthur, A. (2017). Integrated plant nutrient management strategy for sustainable and competitive cocoa production in Ghana. Proceedings of International Symposium on Cocoa Research (ISCR), Lima, Peru, 13-17 November.

Ahenkorah, Y., Halm, B. J., Appiah, M. R., Akrofi, G. S. & Yirenkyi, J. E. K. (1987). Twenty years' results from a shade and fertilizer trial on Amazon cocoa (Theobroma cacao) in Ghana. *Experimental Agriculture* **23(1)**: 31-39.

Aidoo, M. K., Sherman, T., Lazarovitch, N., Fait, A. & Rachmilevitch, S. (2017). A bell pepper cultivar is tolerant to chilling enhanced nitrogen allocation and stress-related metabolite accumulation in the roots in response to low root-zone temperature. *Physiologia Plantarum*. **161**: 196-210.

Aikpokpodion P. E. (2010). Nutrient dynamics in cocoa soils, leaf and beans in Ondo State, Nigeria. *Journal of Agricultural Sciences* **1**: 1-9.

Ajami, M., Heidari, A., Khormali, F., Zeraatpisheh, M., Gorji, M., & Ayoubi, S. (2020). Spatial variability of rainfed wheat production under the influence of topography and soil properties in loess-derived soils, northern Iran. *International Journal of Plant Production* **14**: 597-608.

Bataglia, O. C., Santos, W. R. & Quaggio, J. A. (2001). Reference populations for evaluation of the nutritional status of coffee by DRIS. In: Horst, W.J., et al. Plant Nutrition. Developments in Plant and Soil Sciences, Springer, Dordrecht **92**: 728-729.

Brady, N. C. & Weil, R. R. (2002). Prospects for soil health in the Anthropocene: In The Nature and Properties of Soils (15th Edition). Prentice Hall, New Jersey 1001-1014.

Kjeldahl, J. (1883). A new method for the determination of nitrogen in organic matter. *Analytical Chemistry* **22**: 366-382.

Kouadio, S. G., Tienebo, E-O., Kouadio, K. T., Kouame, K. B-J., Koko, L. & Abo, K. (2017). Foliar application of boron during flowering promotes tolerance to cocoa (*Theobroma cacao* L.) swollen shoot viral disease. *European Scientific Journal* **13**: 38-

406.

Laekemariam, F., Kibret, K. & Shiferaw, H. (2018). Potassium (K)-to-magnesium (Mg) ratio, its spatial variability and implications to potential Mg-induced K deficiency in Nitisols of Southern Ethiopia. *Agriculture and Food Security* **7(1)**: 1-10.

Mehlich, A. (1984). Mehlich 3 Soil Test Extractant: A modification of Mehlich 2 Extractant. *Communication in Soil Science and Plant Analysis* **15**:1409-1416.

Mohammed, A. M., Robinson, J. S., Verhoef, A. & Midmore, D. J. (2020). Nutrient stocks and distribution in Ghanaian cocoa ecosystems. *International Journal of Agronomy* **2020**: 1- 9.

Nartey, E., Dowuona, G. N., Ahenkora, Y., Memut, A. R. & Tiessen, H. (1997). Amount of distribution of some forms of phosphorus in ferruginous soils of the interior savanna zone of Ghana. *Ghana Journal of Agricultural Science* **30**: 135-143.

Olff, H., Ritchie, M. E. & Prins, H. H. T. (2002). Global environmental controls of diversity in large herbivores. *Nature* **415**: 901-904.

Prajapati, K. & Modi, H. A. (2012). The importance of potassium in plant growth–a review. *Indian Journal of Plant Sciences* **1**: 177-186. www.cibtech.org/jps.htm accessed on 02/11/2022

Pushparajah, E. (2014). Penn State Extension. Interpreting soil and leaf analysis. www.citeseerx. Ist. psu. Edu. Accessed on 15/10/2022.

Smith, D. (1975). Effects of potassium topdressing a low fertility silt loam soil on alfalfa herbage yields and composition on soil values. *Agronomy Journal* **67**: 60-64.

Snoeck, D., Louis, K., Joël, J., Philippe, B. & Patrick, J. (2016). Cacao nutrition and fertilization. *Sustainable Agriculture Reviews* **19**: 155-202.

Sousa, L. J. R., de Moraes, S. W., de Medeiros, E. V., Duda, G. P., Corrêa, M. M., Martins, F. A. P. & Hammecker, C. (2018). Effect of biochar on physicochemical properties of sandy soil and maize growth in a greenhouse experiment. *Geoderma* **319**: 14-23.

U.S.D.A. (Soil Survey Division Staff). (1999). Soil survey manual. U.S.D.A Handbook 18, U. S. Government Printing Office. Washington D.C.

Walkley, A. & Black, L. A. (1934). An examination of the method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* **37**: 29-38. Accessed on 15/03/2022.

Whetton, R. L., Zhao, Y., Nawar, S. & Mouazen, A. M. (2021). Modeling the influence of soil properties on crop yields using a non-linear NFIR model and laboratory data. *Soil System* **5**: 12-14.

World reference base for soil resources (WRB) IWG. (2015): International soil classification system for naming soils and creating legends for soil maps, Food and Agriculture Organization of the United Nations, Rome. 2014.