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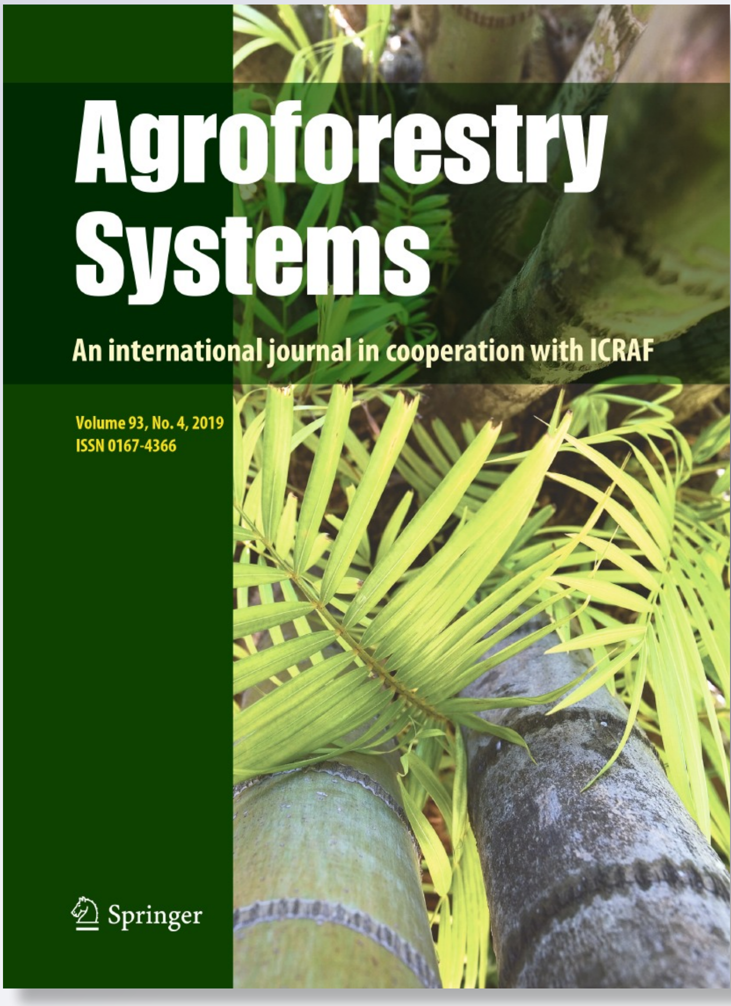

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Abstract Inadequate or lack of prudent soil fertility management by cocoa farmers leads to nutrient depletion in cocoa production fields. The objective of this study was to assess current soil fertility status of cocoa farms from six cocoa growing regions in Ghana and to derive an integrated soil quality index (SQI). Composite soil samples from 0 to 30 cm depth were collected from 100 selected farms covering the six cocoa regions. Soil pH, %C, %N, total and available P, cation exchange capacity (CEC), and exchangeable cations (Ca, Mg, K) were measured. These parameters were analyzed using principal component analysis, normalized, and integrated into a weighted-additive SQI. Soil pH of majority (59.0%) of the farms was within 5.6–7.2, suitable for cocoa production. Available soil-P in most (82%) of the farms was < 20 mg kg^{-1}. Soil quality in most farms was generally low, with an average SQI of 0.41 ± 0.14. Soil quality in Western region farms was relatively high, followed by farms in Brong Ahafo and Volta regions. Farms in Eastern, Central and Ashanti regions had the least soil quality. Soil pH, CEC and available P showed great influence on SQI. Given the latter observation, diagnostic yield response experiments should be conducted, which include: application of locally generated liming materials, organic residues and agro-mineral base fertilizers such as phosphate rock and dolomite.

Keywords Cocoa · Soil fertility · Ghana · Sustainable intensification · Soil quality index

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Introduction

Cocoa is a cash crop of global importance especially, to the economies of producing countries, confectionery industries and the millions of smallholder farmers who depend on cocoa for their livelihoods. After Côte d'Ivoire, Ghana is the world's second largest cocoa producer, contributing about 20% of the total global production (International Cocoa Organization [ICCO] 2017). However, cocoa production and productivity in Ghana has been fluctuating annually over the last decade (Okoffo et al. 2016). Current cocoa yields are poor with an average of 10 fruits per cocoa tree, which is very low for a crop that has potential yield of more than 100 fruits per tree (Aneani and Ofori-Frimpong 2013). With increasing global demand for sustainable cocoa, there is the need to close the yield gap by addressing the causes of low yield on small holder farms in a sustainable way.

Several reasons have been reported to account for the low cocoa productivity on smallholder farms in Ghana. These include poor farm management practices, planting low-yielding varieties, pests and diseases, aging cocoa trees and loss of soil fertility (Kongor et al. 2017). Among the aforementioned reasons, studies by the Cocoa Research Institute of Ghana (CRIG) identified low soil fertility as the major cause of yield decline (Baah et al. 2011). Cocoa trees prefer light textured soils with optimum nutrient content to a depth of about 1.5 m for better root and canopy development (ICCO 2013). Optimum soil pH ranging from 5.6 to 7.2 has been reported to favour cocoa production (Ahenkorah 1981). Wood and Lass (2001) reported that for each hectare of cocoa farm, about 200 kg N, 25 kg P, 300 kg K and 140 kg Ca are needed for the trees to grow prior to pod production.

Cocoa cultivation in Ghana is carried out in two main agro-ecological zones: deciduous forest and rain forest (Ministry of Food and Agriculture [MOFA] 2013). Soil types found in these areas are predominantly Acrisols, Lixisols, Luvisols, Nitisols and Ferralsols (Snoeck et al. 2010), and are usually characterized by greater accumulation of organic matter with adequate nutrients that are tied-up with the organic layers in their top soils (Obeng 2000). However, most of the soils are exhausted of their nutrient reserves as a result of several years of cultivation with inadequate or no prudent management systems to sustain soil fertility (Afrifa et al. 2009).

Loss of soil fertility is usually triggered by the removal of nutrients from the soil through plant uptake, coupled with low or no application of fertilizer (Hartemink 2006). Removal of essential plant nutrients from the soil through harvesting over long periods without replenishment has been reported as one of the major causes of soil fertility loss and the declining in productivity on cocoa farms (Appiah et al. 1997). Aside the high nutrient requirements of the cocoa tree, Hartemink (2005) reported that for each 1000 kg of dry beans harvested, about 20 kg N, 4 kg P and 10 kg K are removed; if the pod husks are also removed from the field, the amount is increased to about 35 kg N, 6 kg P, and 60 kg per 1000 kg beans, indicating that K removal by the husks is high. Ahenkorah et al. (1974) already reported the depletion of N, Ca, Mg and K in cocoa farms in Ghana after several years of cultivation. Soil also becomes more acidic with continuous cultivation, which causes interference to the availability and the uptake of some nutrients, such as P (Koko 2014). This underscores the need for efficient soil fertility restoration scheme that is cost effective and addresses targeted soil fertility issues in cocoa producing areas.

Several fertilizer trials have been conducted in Ghana (Ahenkorah et al. 1974, 1987; Appiah et al. 2000; Afrifa et al. 2009), Nigeria (Wessel 1971) and Côte d'Ivoire (Jadin and Snoeck 1985). Differences in yield response to nutrient application between regions, farms and plants are poorly understood, in part because of unclear reporting of the original data (van Vliet and Giller 2017). Surprisingly, few cocoa yield response trials have been carried out and as a consequence, the relation between cocoa yield and nutrient type, application rates and the conditions under which particular nutrients should be applied, remains unclear. According to van Vliet and Giller (2017), without this fundamental knowledge, farm level recommendations have a weak scientific base. More basic research is therefore needed to complement current knowledge.

The response of cocoa to nutrient application depends on the initial soil fertility, nutrient requirements of the cocoa tree and other factors such as climate and shade management (van Vliet and Giller 2017). Cocoa production systems vary greatly among producing countries and regions, with varying management practices, soils and diverse resource status of cocoa farmers (Dumont et al. 2014; Asare et al. 2017; van Vliet and Giller 2017). Thus, on-farm measurement of soil fertility is needed to capture the wide diversity in soil nutrient availability and allow for further trials to assess the impact of different management practices on the response of cocoa yields to nutrient applications under different conditions. This will allow appropriate soil fertility management

Table 1 Climatic data, vegetation and soil type of cocoa growing regions in Ghana. *Source*: Ministry of Food and Agriculture (2011) and Snoeck et al. (2010)

Region	Precipitation (mm)	Temperature (°C)	Humidity (%)	Natural vegetation	Soil type
Brong Ahafo	1000–1400	23.9	75	Deciduous forest	Acrisols, Lixisols, Nitisols
Western	1600–2200	26.0–30.0	70–80	Rain forest	Acrisols, Lixisols, Luvisols, Ferralsols
Eastern	1500–2000	22.0–33.0	65–95	Deciduous forest	Acrisols, Lixisols, Luvisols
Ashanti	1100–1800	25.5–32.0	65–85	Deciduous forest	Acrisols, Lixisols, Luvisols, Nitisols
Central	1000–2000	24.0–30.0	50–85	Deciduous forest	Acrisols, Lixisols
Volta	1168–2103	21.0–32.0	60	Deciduous forest	Acrisols, Luvisols

recommendations to be developed and tailored to different soil conditions and management practices. The objective of this study was to assess current soil fertility status of cocoa farms and to derive an integrated soil quality index for six cocoa growing regions in Ghana.

Methodology

Sampling

The study was conducted in the six cocoa producing regions in Ghana (Table 1) from November 2015 till January 2016, i.e. 2015–2016 main season. It was preceded with a socio-economic survey of 731 cocoa farmers from 26 selected districts (Fig. 1) in the same six cocoa growing regions (Kongor et al. 2017). Results from the survey showed low cocoa productivity, small farm sizes and variable farm management practices (Table 2) (Kongor et al. 2017). Farm management practices such as weed control, pruning, use of cocoa pod husks, fertilizer application, type and number of multi-purpose trees (agroforestry) are reported to influence soil fertility (Owolabi et al. 2003; Asare et al. 2017; Dumont et al. 2014; van Vliet and Giller 2017); which in turn influence cocoa productivity. Also, the effectiveness of fertilizer application in improving cocoa productivity has been found to be dependent on farm management practices such as effective control of black pod disease, capsids, judicious pruning and shade management (Baah et al. 2011). These practices vary from one farm to the other even within the same cocoa growing region. Thus, farm management practices of each farmer (weed control, pruning, fertilizer application, capsids and black pod disease control) were converted into a farm management score by scoring (scale 0–4) each farm management practice according to CRIG's recommended good farm management practices, and summing the individual scores into a percent score. Farm management score and productivity of the farmers were then used to group the 731 farmers into 4 different clusters (or groups) using k-means clustering (SPSS version 22.0). Cluster 1 included farmers with high productivity (846 ± 146 kg ha^{-1}) and high farm management score (78 ± 17%), while cluster 4 included farmers with low productivity (85 ± 50 kg ha^{-1}) and low farm management score (59 ± 19%) (Table 3). Cluster 2 and 3 represent all farmers with average productivity and farm management score in between cluster 1 and cluster 4 (Table 3). A total of 100 cocoa farmers were selected from the four clusters (25 farmers from each cluster). This was done to allow for the selection of a wide range of farms (i.e. farms with high productivity, well-managed and well maintained and vice versa and all those in between). Selection of farmers in each cluster was done to include farmers from all the six regions. Soil samples from 0 to 30 cm depth were taken on each of the 100 selected farms from the six regions. Ten different plots (30 m × 30 m) were established on each farm. A soil sample was taken at 0–30 cm depth per plot (n = 10) and mixed to form composite sample for each farm; i.e. farms per region served as true farm replicates. Each composite sample was air dried, sieved (< 2 mm sieve) to remove coarse debris and stones.

Soil analyses

All analyses were performed on the air-dried soil fractions (< 2 mm). Acidity (pH) was measured potentiometrically (WTW Inolab Level 1) in a 1/5

Table 2 Cocoa productivity, farm size and farm management practices of cocoa farmers in Ghana. All data are adapted from Kongor et al. (2017)

Parameters	Brong Ahafo n = 158	Western n = 110	Eastern n = 126	Ashanti n = 115	Central n = 112	Volta n = 110	Total n = 731
	Mean ± standard deviation						
Cocoa productivity (kg ha^{-1})	214 ± 208	380 ± 214	221 ± 194	180 ± 148	222 ± 144	197 ± 193	234 ± 197
Farm size (ha)	4.8 ± 3.7	5.5 ± 5.0	3.8 ± 2.8	5.6 ± 4.2	4.4 ± 3.3	2.2 ± 1.5	4.4 ± 3.7
Frequency of weed control (per season)	2.7 ± 0.7	3.2 ± 0.6	2.8 ± 0.8	3.0 ± 0.7	3.1 ± 0.6	2.8 ± 0.9	2.9 ± 0.7
Frequency of pruning (per season)	2.3 ± 1.3	2.3 ± 1.1	2.0 ± 1.1	2.2 ± 1.1	2.2 ± 1.0	1.5 ± 1.0	2.1 ± 1.2
Frequency of capsids control (per season)	2.9 ± 1.2	3.0 ± 0.9	3.0 ± 1.1	3.1 ± 1.0	3.0 ± 0.9	2.1 ± 1.3	2.9 ± 1.1
Frequency of black pod disease control (per season)	2.8 ± 1.7	3.1 ± 1.7	2.6 ± 2.2	3.1 ± 2.0	1.9 ± 1.9	3.2 ± 2.2	2.8 ± 2.0
Fertilizer application (per season)[a]	65.2	59.1	45.3	65.2	82.1	51.8	61.4

[a]Fertilizer application is expressed as percentage of farmers who applied fertilizer

soil to water suspension (ISO 10390:2005). Total C and N were determined according to the Dumas-principle using a CN-analyzer (Elementar, Vario Max). One gram of soil was catalytically combusted at 900 °C in an oxygen rich atmosphere. Combustion gasses were quantified using a thermal conductivity detector. Total P was measured using inductive coupled plasma optical emission spectroscopy (Thermo IRIS Intrepid II XSP). One gram of soil was extracted with 12 ml aqua regia solution for 12 h at ambient temperature, followed by a 2 h heated extraction using reflux cooling. The extract was filtered using a whatman 5 filter before ICP analysis. Available P was measured according to the Bray II method (Bray and Kurtz 1945). Exchangeable Ca^{2+}, Mg^{2+}, and K^{+} were quantified by saturating cation exchange sites with ammonium acetate buffered at pH 7.0 followed by measuring the cation concentrations in the filtrated extracts with inductively coupled plasma optical emission spectroscopy (Thermo IRIS Intrepid II XSP). The cation exchange capacity (CEC) was determined by quantifying NH_4^{+} using steam distillation. NH_4^{+} was exchanged with 1 M KCl after saturating cation exchange sites with ammonium acetate buffered at pH 7.0 (Van Ranst et al. 1999).

Soil quality assessment

The quality of the soil from each selected farms was estimated using soil quality index (SQI) described by Vasu et al. (2016). The method involves three steps: (1) selection of a minimum data set (MDS) of parameters which includes the most significant variables that best represent soil fertility, (2) transformation and weighting of parameters and (3) combination of the scores into an index.

Selection of minimum data set (MDS)

The selection of parameters was done using principal component analysis (PCA). The objective of PCA was to reduce the dimension of data while minimizing loss of information (Armenise et al. 2013). The reduction of the number of components was obtained using the eigenvalue-one criterion. According to this criterion, principal components (PC) with high eigenvalues were considered best representatives explaining the variability (Armenise et al. 2013). PCs with eigenvalues ≥ 1 were selected since PC with eigenvalue < 1

Table 3 Grouping of cocoa farmers in Ghana based on their productivity and farm management practices (mean plus minus standard deviation)

Parameters	Clusters			
	1 (n = 61)	2 (n = 109)	3 (n = 240)	4 (n = 321)
Farm management score (%)	78 ± 17	69 ± 15	65 ± 18	59 ± 19
Productivity (kg ha^{-1})	846 ± 146	471 ± 76	257 ± 55	85 ± 50

accounts for less variation than generated by a single variable.

Under each selected PC, only the parameters with high factor loadings were retained for indexing. High factor loadings were defined as absolute values within 10% of the highest factor loading (Armenise et al. 2013). If more than one parameters were retained under a single PC, a multivariate correlation analysis was used to determine if the parameters could be considered redundant and eliminated from the MDS. Among well-correlated parameters ($r > 0.70$), the parameter(s) with the highest factor loading was chosen for the MDS. If parameters were not correlated, then each of them was considered important and was retained in the MDS.

Transformation and weighting of parameters into scores

Selected parameters in MDS were transformed into dimensionless values ranging from 0.0 to 1.0 using the linear scoring method as described by Liebig et al. (2001). Soil parameters were divided into groups based on three mathematical algorithm functions: (a) 'more is better' (b) 'less is better' and (c) 'optimum'. 'More is better' refers to those soil parameters whose increment has a positive impact on soil quality. Conversely, the 'less is better' suits those parameters whose increment negatively affects soil quality. 'Optimum' parameters are those, which have a positive influence up to a certain level beyond which the influence could be considered detrimental. For 'more is better' parameters, each data value was divided by the highest value such that the highest value received a score of 1.0. For 'less is better' parameters, each data value was divided by the lowest value such that the lowest value received a score of 1.0. For "optimum" parameters, they were scored as 'higher is better' up to a threshold value and then scored as 'less is better' above the threshold.

Weights were assigned to the MDS parameters using the PCA outcomes, and were equal to the percentage of variance explained by the PC standardized to unity. Each PC explained a certain amount (%) of the variation in the total dataset. The total percentage of variance from each PC was divided by the percentage of cumulative variance to derive the weighting factor.

Combining scores into an index

After transforming soil parameters, the scores were integrated into an additive SQI using the following formula:

$$SQI = \sum_{i=1}^{n} Wi * Si$$

where Wi is the PCA weighting factor of the parameter and Si the corresponding score.

Statistical analyses

Data were analyzed using the SPSS version 22.0. Each soil parameter measured for all farm replicates in each region was averaged and reported with the standard deviation for the region. One-way analysis of variance was used to compare mean of the studied parameters in the six regions. PCA and correlation analysis were done using XLSTAT. Significance was accepted at 5% level ($p < 0.05$). Descriptive statistics was done using cross tab to determine the percentage of farms in the studied regions with soil nutrients below or above reported optimum values. Optimum values reported by Ahenkorah (1981) was used for the comparison. Linear discriminant analysis (LDA) was done using the MASS package in R, version 3.3.2, to separate the

Table 4 Soil physicochemical properties and SQI of farms in cocoa growing regions of Ghana. [a]*Source*: Ahenkorah (1981); [b]*Source*: Wood and Lass (2001)

Parameters	Brong Ahafo n = 23	Western n = 23	Eastern n = 17	Ashanti n = 11	Central n = 10	Volta n = 16	Total n = 100	Optimum nutrient values in Ghana[a]
	Mean ± standard deviation							
pH	5.6 ± 0.6^{ad}	6.0 ± 0.7^{a}	5.5 ± 1.0^{ab}	6.0 ± 0.8^{a}	5.7 ± 0.7^{abc}	5.7 ± 0.5^{a}	6.0 ± 0.8	5.6–7.2
%C	1.94 ± 0.98^{b}	2.53 ± 0.83^{c}	1.41 ± 0.36^{b}	1.59 ± 0.62^{b}	1.28 ± 0.41^{b}	1.63 ± 0.53^{b}	1.83 ± 0.82	na
%N	0.20 ± 0.09^{a}	0.24 ± 0.08^{ac}	0.14 ± 0.03^{ab}	0.17 ± 0.07^{ab}	0.12 ± 0.04^{b}	0.17 ± 0.06^{ab}	0.18 ± 0.08	0.09
Total P (mg kg^{-1})	243 ± 115^{a}	305 ± 130^{a}	179 ± 61^{a}	175 ± 90^{a}	150 ± 75^{a}	397 ± 556^{a}	254 ± 249	na
Available P (mg kg^{-1})	11.4 ± 14.9^{a}	17.1 ± 16.2^{ab}	8.9 ± 5.6^{a}	8.4 ± 8.5^{ab}	12.0 ± 8.4^{a}	39.4 ± 67.7^{b}	16.5 ± 30.5	20
CEC ($cmol_c$ kg^{-1})	12.8 ± 6.0^{b}	17.0 ± 6.7^{c}	10.2 ± 3.1^{b}	9.7 ± 4.2^{b}	7.7 ± 3.0^{b}	12.0 ± 4.8^{b}	12.3 ± 5.9	12[b]
Ca (cmol kg^{-1})	9.09 ± 5.66^{a}	9.00 ± 5.31^{a}	4.00 ± 3.27^{b}	6.07 ± 5.06^{ab}	3.91 ± 3.63^{ab}	6.23 ± 3.69^{ab}	6.89 ± 5.06	7.50
Mg (cmol kg^{-1})	1.79 ± 0.98^{a}	2.53 ± 1.35^{ab}	1.22 ± 0.73^{ac}	1.63 ± 1.34^{a}	0.92 ± 0.68^{ac}	1.85 ± 0.97^{a}	1.77 ± 1.16	1.33
K (cmol kg^{-1})	0.25 ± 0.17^{a}	0.37 ± 0.30^{a}	0.24 ± 0.26^{a}	0.30 ± 0.19^{a}	0.17 ± 0.07^{a}	0.21 ± 0.13^{a}	0.27 ± 0.22	0.25
SQI	0.41 ± 0.15^{a}	0.51 ± 0.15^{ab}	0.35 ± 0.07^{ac}	0.34 ± 0.10^{ac}	0.31 ± 0.07^{ac}	0.43 ± 0.14^{a}	0.43 ± 0.14	na

na: Optimum values not available; Values with different letters (a–d) in each row represent significant difference ($p < 0.05$) according to Tukeys HSD test

cocoa growing regions based on the studied soil parameters.

Results

Soil fertility status of cocoa farms in Ghana

Soil pH of the sampled farms ranged from 4.7 to 7.7 with an average of 6.0 ± 0.8 (Table 4). There was significant difference ($df = 5$; F value = 4.943; $p < 0.05$) in soil pH between farms from the six regions. Further analysis of the data revealed that 59.0% of the studied farms had soil pH within the 5.6–7.2 optimum value (Table 5). Majority of the farms in Brong Ahafo (87.0%), Volta (75.0%), Ashanti (63.6%) and Western (60.9%) regions had soil pH within 5.6–7.2, whereas only 5.9% of the farms in Eastern region had pH within 5.6–7.2. Most of the farms in Eastern region (76.5%) had pH < 5.6, followed by farms in the Central region (50.0%).

Total C and N content of the soils ranged from 0.55–4.73% to 0.07–0.43%, respectively. There was significant difference in total C ($df = 5$; F value = 7.329; $p < 0.05$) and N ($df = 5$; F value = 6.710; $p < 0.05$) content between farms from the six regions (Table 4). Soils from farms in the Western region recorded the highest C and N content of 2.53 ± 0.83% and 0.24 ± 0.08%, respectively. Farms in Brong Ahafo and Volta regions also had relatively high %C content than farms in Ashanti, Eastern and Central regions (Table 4). Majority (97.0%) of the studied farms in the six regions recorded N content above the reported optimum value of 0.09% (Table 5).

Total P content in the sampled farms ranged from 60 to 2010 mg kg^{-1} with a mean value of 254 ± 249 mg kg^{-1} (Table 4). Total P varied markedly among the sampled farms within each region. Farms in the Volta region had the highest variability in total P content with values ranging from 77 to 2010 mg kg^{-1}. Most of the P in the soil was however, not readily available for plant utilization (Table 4). Available P in the farms in Brong Ahafo, Eastern and Ashanti regions was only about 5% of their respective total P, 6% in Western region, 8% in Central region and 10% in the Volta region farms. Results also showed that majority (82.0%) of the farms in the six regions had available P content below reported optimum value of 20 mg kg^{-1}, with only 18.0% of

Table 5 Distribution of cocoa farms (%) into different soil fertility parameter categories

Soil fertility parameters	Region							
	Category	Brong Ahafo (n = 23)	Western (n = 23)	Eastern (n = 17)	Ashanti (n = 11)	Central (n = 10)	Volta (n = 16)	Total (n = 100)
pH	<5.6	4.3	34.8	76.5	27.3	50.0	25.0	34.0
	5.6–7.2	87.0	60.9	5.9	63.6	50.0	75.0	59.0
	>7.2	8.7	4.3	17.6	9.1	0.0	0.0	7.0
%N	<0.09	4.3	0.0	0.0	0.0	20.0	0.0	3.0
	≥0.09	95.7	100.0	100.0	100.0	80.0	100.0	97.0
P-avail (mg kg^{-1})	<20	87.0	78.3	94.1	90.9	90.0	56.3	82.0
	≥20	13.0	21.7	5.9	9.1	10.0	43.8	18.0
CEC ($cmol_c$ kg^{-1})	<12	47.8	21.7	76.5	72.7	80.0	56.3	54.0
	≥12	52.2	78.3	23.5	27.3	20.0	43.8	46.0
Ca (cmol kg^{-1})	<7.5	47.8	43.5	88.2	72.7	80.0	75.0	64.0
	≥7.5	52.2	56.5	11.8	27.3	20.0	25.0	36.0
Mg (cmol kg^{-1})	<1.33	39.1	13.0	64.7	54.5	70.0	37.5	42.0
	≥1.33	60.9	87.0	35.3	45.5	30.0	62.5	58.0
K (cmol kg^{-1})	<0.25	52.2	43.5	76.5	36.4	80.0	75.0	59.0
	≥0.25	47.8	56.5	23.5	63.6	20.0	25.0	41.0

NB: Bold values represents optimum categories for cocoa production

farms recording $\geq$ 20 mg kg^{-1} (Table 5). Most of the farms in Eastern (94.1%), Ashanti (90.9%), Central (90.0%) and Brong Ahafo (87.0%) regions had available $p < 20$ mg kg^{-1}. Available P content $\geq$ 20 mg kg^{-1} was recorded in relatively more farms in the Volta (43.8%) and Western (21.7%) regions.

The cation exchange capacity of the selected farms ranged from 4.1 to 33.4 $cmol_c$ kg^{-1} with an average of 12.3 $\pm$ 5.9 $cmol_c$ kg^{-1} (Table 4). There was a significant (df = 5; F value = 6.506; $p < 0.05$) difference in CEC of the selected farms in the six cocoa growing regions. Farms in Western region had the highest CEC of 17.0 $\pm$ 6.7 $cmol_c$ kg^{-1}, while farms in Eastern, Ashanti and Central regions had the lowest CEC of 10.2 $\pm$ 3.1, 9.7 $\pm$ 4.2 and 7.7 $\pm$ 3.0 $cmol_c$ kg^{-1} respectively. Farms in Brong Ahafo and Volta regions also recorded relatively high CEC of 12.8 $\pm$ 6.0 and 12.0 $\pm$ 4.8 $cmol_c$ kg^{-1}, respectively. Further analysis of the data revealed that only 46.0% of the farms in all six regions had CEC $\geq$ 12 $cmol_c$ kg^{-1}, with the majority of farms (54.0%) recording CEC $<$ 12 $cmol_c$ kg^{-1} (Table 5). With the exception of farms in Western (78.3%) and Brong Ahafo (52.2%) regions which had CEC $\geq$ 12 $cmol_c$ kg^{-1}, most farms in Eastern (76.5%), Ashanti (72.7%), Central (80.0%) and Volta (56.3%) regions had CEC $<$ 12 $cmol_c$ kg^{-1} (Fig. 1).

The amount of exchangeable cations varied among the selected farms in the six regions (Table 4). Exchangeable Ca ranged from 0.63 to 27.08 cmol kg^{-1}, while Mg and K ranged from 0.19–6.75 to 0.00–1.09 cmol kg^{-1}, respectively. Ca was the dominant cation in all farms with an average of 6.89 $\pm$ 5.06 cmol kg^{-1}. This was followed by Mg and K with average concentrations of 1.77 $\pm$ 1.16 and 0.27 $\pm$ 0.22 cmol kg^{-1}, respectively. The Ca content in majority (64.0%) of the farms was $<$ 7.5 cmol kg^{-1}, while 59.0% of farms had K content $<$ 0.25 cmol kg^{-1}. Majority (58.0%) of the farms however, had Mg content $\geq$ 1.33 cmol kg^{-1}. Results showed that most farms in Eastern (82.2%), Central (80.0%), Volta (75.0%) and Ashanti (72.7%) regions had Ca content $<$ 7.5 cmol kg^{-1}. Again, farms in Eastern (64.7%), Central (70.0%) and Ashanti (54.5%) regions recorded Mg content $<$ 1.33 cmol kg^{-1}. There was high variability in the studied cations from one farm to the other within each region (Table 4).

Table 6 Principal component analysis summary for measured soil parameters

Principal component	PC1	PC2	PC3
Eigenvalue	**5.627**[a]	**1.556**	**1.175**
Variability (%)	56.28	15.56	11.75
Cumulative (%)	56.28	71.83	83.58
Weighting factor	0.67	0.19	0.14
Factor loading			
pH	0.523	− 0.141	− **<u>0.792</u>**
%N	**0.923**[b]	− 0.174	0.169
%C	**0.911**	− 0.201	0.206
Total P	0.621	**0.755**	0.078
Available P	0.432	**<u>0.880</u>**	0.042
CEC	**<u>0.940</u>**[c]	− 0.048	0.092
Ca	**0.876**	− 0.063	− 0.400
K	0.539	− 0.162	0.252
Mg	**0.885**	− 0.078	− 0.167

[a]Bold eigenvalues correspond to the PCs examined for the soil quality index

[b]Bold factor-loadings are considered highly weighted

[c]Bold and underlined factor loadings correspond to indicators included in the minimum data set

The LDA plot (Fig. 2) showed how the sampled farms in the cocoa growing regions are clustered on the basis of the studied parameters. Both LD1 (43.1%) and LD2 (25.7%) explained a total of 68.8% of the variance in the data. Farms in Western, Brong Ahafo, Volta and Ashanti regions clustered separately and showed distinction from each other. Farms in Central region shared similarities with farms in the Volta, Ashanti and Eastern regions. Farms in Eastern region completely shared similarities with farms in Ashanti and Central regions.

Soil quality assessment

All nine soil parameters measured, namely pH, %N, %C, total P, available P, CEC, Ca, Mg, and K, were included in the PCA analysis. Nine PCs were generated. The first three PCs were selected since their eigenvalues were > 1 (Table 6). Of each of the three selected PCs, only the parameters with high factor loadings were retained for indexing. Under PC1, %N, %C, CEC, Ca, and Mg were selected; total P and available P were selected under PC2, while pH was the only parameter selected under PC3 (Table 6). The selected soil parameters under PC1 were all significantly correlated ($r > 0.70$) (Table 7). Thus, only CEC was retained in PC1 since it had the highest factor loading (0.940) (Table 6). Total P and available P in PC2 were highly correlated ($r = 0.91$) (Table 7), and available P was retained since it had the highest factor loading (0.880) (Table 6). Available P and CEC were considered 'more is better' while pH was considered 'optimum'.

The soil quality index of the sampled farms in the cocoa growing regions of Ghana was generally very low (Table 4). SQI of the selected farms in the six regions ranged from 0.20 to 0.85 with an average of 0.41 ± 0.14. Farms in the Western region had SQI ranging from 0.31 to 0.81 and the highest average SQI of 0.51 ± 0.15, followed by farms in the Volta and Brong Ahafo regions with an average SQI of 0.43 ± 0.14 and 0.41 ± 0.15, respectively. Farms in the Eastern, Central and Ashanti regions had the lowest SQI between 0.24–0.49, 0.20–0.43 and 0.24–0.57, respectively.

Discussions

Soil fertility status of cocoa farms in Ghana

Excessive acidity has been found to impede the availability of nutrients in soil (e.g. P) and can lead to toxicity of other nutrients such as Al (Snoeck et al. 2016). Findings from this study suggest that most farms in Eastern and Central regions are slightly acidic. Excessive acidity could either be native to the soil or due to the use of acidifying fertilizer (Snoeck et al. 2016). Farms in these regions will thus, require a soil fertility program that includes the application of liming materials such as cocoa pod husk ash and wood ash to the soil to increase the pH to optimum values (5.6–7.2). The use of cocoa pod husk ash and wood ash as liming materials has been reported to increase soil pH, P, K, Ca and Mg content of soil (Owolabi et al. 2003). These materials are low cost, internally generated and could serve as both liming materials and organic fertilizers.

Soil N is needed to support vegetative growth and it greatly influences cocoa yields by increasing the number of flowers and pods (Snoeck et al. 2016). Majority of farms in the six regions had N content ≥ 0.09%, indicating high soil N content. The high N content in the soils of the studied farms might be due

Table 7 Correlation matrix for the highly weighted variables under the first three PCs

Variables	pH	N	C	Total P	Available P	CEC	Mg
pH	1						
N	0.346**	1					
C	0.306**	0.978**	1				
Total P	0.176	0.459**	0.424**	1			
Available P	0.088	0.232*	0.208*	0.910**	1		
CEC	0.367**	0.912**	0.925**	0.542**	0.341**	1	
Mg	0.569**	0.754**	0.746**	0.471**	0.297**	0.822**	1

**Correlation is significant at the 0.01 level

*Correlation is significant at the 0.05 level

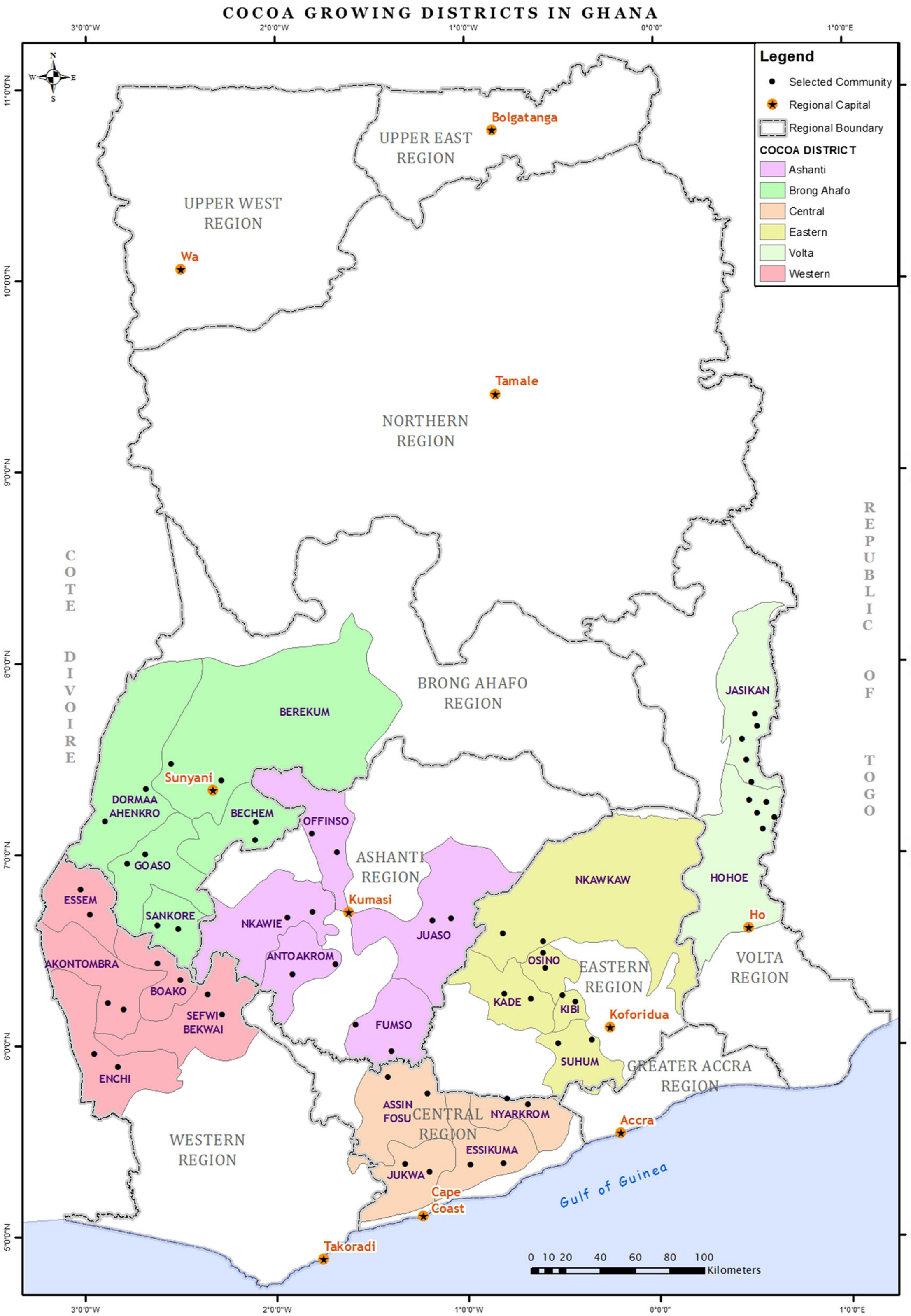
to the provision of N from natural sources such as litter decomposition, in amounts that are sufficient for cocoa trees. However, further studies should be carried on the bio-availability of the N for plant utilization.

Although findings of this work showed high amount of total P in the studied farms in all six regions, majority of the P was not available for plant utilization. Other authors have also reported low levels of available P in cocoa farms in Ghana and other West African countries (Hartemink 2005; Aikpokpodion 2010; Agyemang et al. 2011; Asare et al. 2017). Availability of soil P is greatly influenced by the soil acidity, with available P decreasing when soil pH drops below 5.5 (Ziadi et al. 2013). The low available P (< 20 mg kg^{-1}) recorded in most farms (82.0%) might be due to the relatively high number of farms (34.0%) with soil pH < 5.6 (Table 3). Improving soil pH through the addition of cocoa pod husk ash and wood ash as liming materials will in turn improve the availability of P in the soil. In addition to the use of liming materials, P availability in soil can be increased by the addition of organic residues to increase the organic matter content of soil, and the use of phosphate rock. Phosphate rock is a cheap source of high content phosphate mineral and can be utilized as direct application fertilizer in acid soils to increase soil pH and improve P availability (van Straaten 2002). Large deposits of phosphate rock exist in West Africa (McClellan and Notholt 1986) such as the Togo phosphate rock in Togo, which is close to Ghana. The use of phosphate rock will eliminate or reduce the reliance on water-soluble commercial P fertilizers, which are expensive.

Soils with high CEC have the ability to hold more exchangeable cations such as Ca, Mg, and K, while soils with low CEC are easily deficient in these cations (Sharma et al. 2015). The high Ca, K and Mg content in majority of the farms in Western and Brong Ahafo regions can be attributed to a high CEC, while the low Ca, K and Mg content in most farms in Eastern, Ashanti and Central regions can be attributed to the low CEC. This suggest that increasing the CEC content of farms in Eastern, Ashanti and Central regions would have significant impact on the Ca, K and Mg content.

The CEC content of the farms can be improved by increasing the organic matter content of the soils. Organic matter has negatively charged sites which attract and hold on to cations (Sharma et al. 2015). Organic waste such as household wastes and agricultural residues could be used to increase the organic content of soil (Issaka et al. 2012). Agro-minerals such as dolomites have been found to contain high quantities of Mg and Ca (Issaka et al. 2012). Large deposits of dolomites have been reported in several parts of Ghana (van Straaten 2002; Issaka et al. 2012) and could be exploited for use in cocoa farms with low Mg and Ca content. Dolomites are also used as liming materials due to the abilities of the Ca and Mg to neutralize soil acidity, thus are used to raise the pH of acid soils, provide Ca and Mg ions, decrease Al-toxicity and increase CEC (van Straaten 2002). The use of agro-minerals and organic residues will contribute to reducing the cost associated with the use of imported chemical fertilizers as well as the adverse environmental impacts caused by the excessive application of chemical fertilizers.

The observed high variability in the total and available P, Ca, Mg and K contents in the studied farms within each region indicates great differences in


COCOA GROWING DISTRICTS IN GHANA
Legend
Selected Community
Regional Capital
Regional Boundary
COCOA DISTRICT
Ashanti
Brong Ahafo
Central
Eastern
Volta
Western
UPPER WEST REGION
UPPER EAST REGION
NORTHERN REGION
BRONG AHAFO REGION
ASHANTI REGION
EASTERN REGION
VOLTA REGION
GREATER ACCRA REGION
CENTRAL REGION
WESTERN REGION
COTE DIVOIRE
REPUBLIC OF TOGO
Gulf of Guinea
Bolgatanga
Wa
Tamale
Sunyani
Kumasi
Ho
Koforidua
Accra
Cape Coast
Takoradi
BEREKUM
DORMAA AHENKRO
BECHEM
GOASO
SANKORE
OFFINSO
NKAWIE
ANTOAKROM
JUASO
FUMSO
JASIKAN
HOHOE
NKAWKAW
OSINO
KADE
KIBI
SUHUM
ESSEM
AKONTOMBRA
BOAKO
SEFWI BEKWAI
ENCHI
ASSIN FOSU
NYARKROM
ESSIKUMA
JUKWA
0 10 20 40 60 80 100
Kilometers
3°0'0"W
2°0'0"W
1°0'0"W
0°0'0"
1°0'0"E
11°0'0"N
10°0'0"N
9°0'0"N
8°0'0"N
7°0'0"N
6°0'0"N
5°0'0"N

◀**Fig. 1** Map of cocoa growing areas within districts in Ghana where a baseline field survey (location of the selected communities is indicated with a black circle) was conducted. Adapted from: Kongor et al. (2017)

the concentration of these nutrients from one farm to the other even in the same region. Indigenous soil fertility knowledge widely used by cocoa farmers in Ghana includes, slashing weeds without burning, spreading of cocoa pod husks and retention of selected trees on farmlands (Dawoe et al. 2012; van Vliet and Giller 2017). These practices have been found to influence the level of soil nutrients (Owolabi et al. 2003; Asare et al. 2017; Dumont et al. 2014; van Vliet and Giller 2017), and varies from one farm to the other even within the same cocoa growing region. The high variability in most of the studied nutrients observed in this current study might be due to the variations in the application of these indigenous soil fertility knowledge.

The formation of separate clusters of the farms in Western, Brong Ahafo, Volta and Ashanti regions (Fig. 2) suggests that farms in these regions are distinct from each other in terms of studied parameters. Farms in these regions will thus, require different management programs to address specific soil fertility constraints in the regions. Farms in the Eastern region however, shared similarities with farms in the Ashanti and Central regions. This also indicates that farms in these regions might require similar soil fertility program. Farms in these regions also showed the least content in most of the nutrients studied.

Soil quality assessment

Retaining CEC, available P and pH as MDS for the estimation of SQI suggests that these soil parameters play key roles in maintaining soil fertility. Thus, soil fertility management program for all farms in the six regions should focus on improving these parameters to address the challenges of soil fertility. The average SQI of the selected farms in this study was low compared to SQI values of 0.60 reported by Hussain et al. (1999) for Albic Luvisol soil under soybean cultivation and 0.78 reported by Glover et al. (2000) for soil under apple orchards. Average SQI in this study was however, similar to the SQI value of 0.49 reported in cocoa agroforestry system in the Orinoco Region, Colombia (Parra-González and Rodriguez-

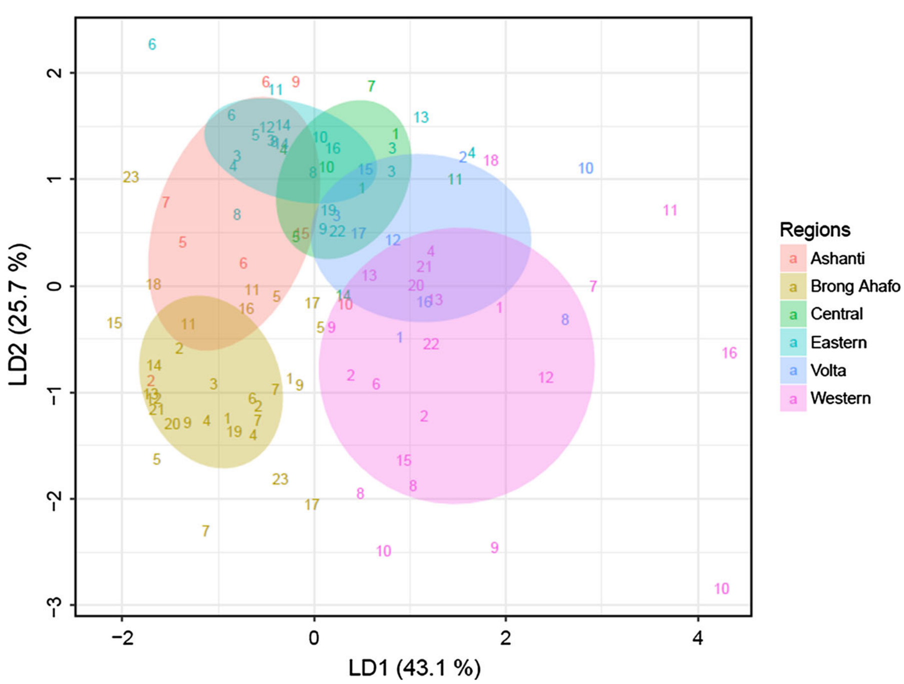


Fig. 2 Linear discriminant analyses (LDA) separation of cocoa farms from six cocoa growing regions in Ghana based on soil nutrient content

Valenzuela 2017). The relatively high SQI of farms in Western region can be attributed to the high percent of farms in the region which recorded high CEC, available P content and pH within optimum value. Also, the low SQI in Eastern, Ashanti and Central regions might be due to the low CEC and available P content as well as soil pH below the optimum recorded in most of the farms in these regions. Again, soils in Western region were recently converted to cocoa production compared with farms in Eastern and Ashanti regions where cocoa cultivation in Ghana started. Thus, the level of nutrient depletion in the Western region soils is relatively lower compared with those in the Eastern and Ashanti regions.

Conclusion

Soil fertility in the cocoa farmlands varied greatly in the six cocoa growing regions. Most farms had low levels for most of the studied soil nutrients. Farms in Western region however, had relatively high SQI and showed relatively higher concentration in most of the studied parameters, followed by farms in Volta and Brong Ahafo regions. Farms in Eastern, Ashanti and Central regions had lowest levels of most of the studied nutrients and the lowest SQI. Soil pH, CEC and available P showed significant impact on the quality of soil in cocoa farms. Hence, farms in Ashanti, Eastern and Central regions require most urgent attention addressing soil fertility. Soil fertility programs in the cocoa growing areas in Ghana should focus on improving these soil parameters with locally generated resources such as organic resources, dolomites and phosphate rock to increase fertility of the soil at reduced cost. Diagnostic yield response experiments should be conducted using these inputs.

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Compliance with ethical standards

Conflict interest The authors declare that they have no conflict of interest.

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