



SOIL ORGANIC CARBON AND pH VARIABILITY ACROSS COCOA-PRODUCING AGROECOLOGICAL ZONES: IMPLICATIONS FOR SITE-SPECIFIC SOIL FERTILITY MANAGEMENT

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Abstract

The soil organic carbon (SOC) and soil pH are both important characteristics of soil fertility and play important roles in soil nutrient availability, biological activity, and long-term cocoa production. The study quantified the SOC and pH variation for the different cocoa-producing agroecological zones of Ghana and determined the implications for site-specific fertility management. Seven hundred and thirty-nine observations from cocoa-farm soils across the six agroecological zones were used for the analysis of a secondary dataset through descriptive statistics, variability measures, correlation analysis, multivariable regression, and spatial assessment. Mean SOC was 0.393 ± 0.235 , while mean soil pH was 5.345 ± 0.744 . The highest mean for SOC and pH was recorded for MSNW, while the lowest was recorded for DSIZ for SOC and WE for pH. The relative variability of SOC was significantly larger than that of pH. There was a weak, but significant, positive correlation between SOC and pH. SOC was related to agroecological zone, pH and clay content and among the parameters of pH variation were associated with agroecological zone, clay content, exchangeable iron and aluminium. The results indicate that there are different fertility limitations in the cocoa soils depending on the zones. Incorporating SOC and pH can in turn, help to manage for targeted restoration of organic matter, acidity correction and better management of site-specific soil fertility for sustainable cocoa production, in a heterogeneous cocoa-growing landscape in the face of changing environmental conditions.

Keywords: Cocoa; Soil organic carbon; Soil pH; Agroecological zones; Site-specific soil fertility management



1. Introduction

Cocoa is a key element of tropical agriculture and plays a vital role in rural livelihoods, export earnings, and landscape-based agriculture systems in West Africa. Cocoa in Ghana is often grown on very weathered tropical soils, and there is considerable variation in the nutrient status, acidity, organic matter and history of the management of these soils, which are a major constraints on sustainable cocoa productivity. Productivity may be limited when soil conditions are not accurately diagnosed and managed because of the effects of soil degradation and low nutrient reserves. Therefore, enhancing soil health is an important way of reducing cocoa yield gaps and maintaining sustainable cocoa production in a changing environment (Amponsah-Doku et al., 2022). Cocoa systems in Cameroon also indicate that soil fertility is influenced by biophysical factors and farm management strategies, highlighting the need for localized approaches to soil fertility (Tsufac et al., 2020).

Soil organic carbon (SOC) is one of the key soil quality indicators as it affects soil water holding capacity, soil resilience, aggregate stability, biological activity and nutrients retention. SOC also connects the productivity of the crops with climate smart land use. Organic amendments, residue retention, reduced disturbance, and vegetation cover can lead to increased SOC and soil functions (Crystal-Ornelas et al., 2021). Tree-based production can have an impact on the litter input, nutrient cycling and below ground carbon sequestration, which makes agroforestry systems particularly significant for cocoa, while reducing microclimate stress. Generally, agroforestry has positive impacts on soil health as evidenced across humid and sub-humid tropics, compared with less diversified land-use systems (Muchane et al., 2020). There are also ecoregional variability in land use, vegetation structure and management intensity that means that the soil responses cannot be considered as uniform production landscapes, such as the cacao-based systems (Gama-Rodrigues et al., 2021).

The soil pH is also critical as it influences nutrient availability, microbial activity, metal solubility and root development. Highly-acidic soils can decrease the availability of nutrients and increase the solubility of potentially toxic elements like aluminium. Acid-soil constraints are common in tropical agroecosystems and generally need tailored soil management procedures, such as liming, addition of organic materials, nutrient balancing and better soil monitoring (Agegnehu et al., 2021). A recent study of cacao under acid-soil conditions also shows that fertility status and carbon storage can significantly differ between soil chemical environment and soil management context (Góngora-Duarte et al., 2026). The interactions of these make the dual evaluation of SOC and pH helpful in the assessment of fertility restriction that is not apparent from either indicator individually.

The cocoa growing areas are also highly agroecologically heterogeneous in terms of their rainfall, temperature, parent material, topography, vegetation and land-use history. These affect organic matter inputs, decomposition, leaching, nutrient cycling and soil acidity. The geovisualization has revealed that cocoa districts in Ghana are not all of the same soil conditions and capability, highlighting the need for spatially explicit soil assessment (Doe et al., 2022). Ecoscape factors are also associated with the variability of soil health and cocoa productivity within contrasting soil ecotypes (Doe et al., 2023). However, direct geospatial assessment of cocoa zones has shown that there is significant spatial variation in SOC concentrations and soil pH, suggesting that an action plan for managing soil in cocoa zones should be considered by zone, instead of making general recommendations (Quaye et al., 2021b).



The use of site-specific management is also dependent on the farmers' responses to soil constraints. The availability of knowledge, resources and management options for integrated soil fertility management in cocoa systems suggest recommendations need to be locally applicable (Quaye et al., 2021a). Farmers' perception can play an important role in determining soil fertility management in cocoa agroforestry systems, and in the uptake of recommended practices (Kenfack Essougong et al., 2020). Similarly, socio-economic factors also play a role in the agroforestry and soil carbon management choices across West Africa (Kumah et al., 2024). The results here provide support for the approach of relating measured soil variability to the spatially targeted and practically relevant management options.

There has been an increased focus on the health of cocoa soils, there is still need to quantify the variations in SOC and pH along agroecological areas and to understand the implications of these variations in terms of soil fertility management. Comparative assessment can be used to detect areas where SOC and/or high acidity is a major constraint and can help allocate inputs of organic amendments, liming materials and nutrients more efficiently.

Objectives:

- Assess and compare SOC and soil pH among the cocoa-producing agroecological zones
- Investigate the interaction of SOC, pH and certain soil properties; and
- Determine fertility patterns in a zone that are relevant to targeted soil management.

2. Materials and Methods

2.1 Research Design and Data Source

The study was of a quantitative nature, with a secondary data analysis design that seeks to investigate the level of variability in soil parameters such as soil organic carbon (SOC) and soil pH, within the cocoa-producing agroecological zones of Ghana. The publicly available dataset, “Multi-scale data for delineating cocoa zones for site-specific soil fertility and productivity management in Ghana” (Version 2), developed by Quaye and Doe (2021) and deposited in Mendeley Data, was used for the analysis. A total of 739 soil observations were taken in the analytical dataset from cocoa farms in six agroecological zones. The present study was based on the file `mydata_SOC_pH_Paper_Data.csv` (Quaye & Doe, 2021).

2.2 Study Area and Agroecological Classification

The dataset comprised cocoa-producing locations in Ghana with the observations categorized into six agroecological zones, namely DSFZ, DSIZ, ME, MSNW, MSSE and WE. The main grouping variable used to evaluate the difference in SOC and soil pH was agroecological zone (Ecology). Geographical coordinates for region, district, and farm were also kept to characterize the geographic distribution of cocoa growing locations.

2.3 Study Variables and Data Preparation

Soil organic carbon (SOC) and soil pH (pH) were the main variables, and agroecological zone was considered the main categorical explanatory variable. Other soil properties such as clay content



(Clay), exchangeable iron (Fe_{meq100g}) and exchangeable aluminium (Al_{meq100g}) were also kept for further analysis. The data set was checked for missing values, duplicate data records, improper codes, numbers out of order, and possible outlier data. Histograms, boxplots, and descriptive statistics were used to assess the distributions of SOC and soil pH.

2.4 Descriptive and Variability Analysis

The data were analysed using descriptive statistics, which were applied to the entire data set, as well as to each agroecological zone separately. These were the mean, standard deviation, median, interquartile range, minimum, maximum and coefficient of variation. The coefficient of variation was calculated as:

$$CV(\%) = \frac{SD}{\bar{X}} \times 100$$

where SD is the standard deviation and X is the arithmetic mean. The relative variability in the respective soil property was reflected in higher CV values.

2.5 Comparison of SOC and Soil pH across Agroecological Zones

The SOC and soil pH differences between the six soil zones were evaluated separately. The normality and homogeneity of variances were checked prior to group comparison.

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{ij}$$

where Y_{ij} represents the SOC or pH value for observation j in agroecological zone i , μ is the overall mean, α_i is the effect of agroecological zone i and ε_{ij} is the random error term. .

2.6 Relationship between Soil Organic Carbon and Soil pH

Correlation analysis was used to explore the relationship between SOC and soil pH. For approximately linear relationships that met the assumptions, the Pearson's correlation coefficient was calculated, whereas the Spearman's rank correlation was calculated for those with strong non-normality or influential outliers. The Pearson's correlation coefficient was represented as:

$$r = \frac{\sum_{i=1}^n (SOC_i - \overline{SOC})(pH_i - \overline{pH})}{\sqrt{\sum_{i=1}^n (SOC_i - \overline{SOC})^2 \sum_{i=1}^n (pH_i - \overline{pH})^2}}$$

where SOC_i and pH_i are the observed values for farm i , while $\overline{SOC}$ and $\overline{pH}$ are the corresponding sample means.

2.7 Multivariable Regression Analysis

Agroecological zone and the selected soil properties were subjected to multiple linear regression analysis to explore their independent relationship with SOC and soil pH. In the case of SOC, the explanatory variables were agroecological zone, pH and clay content. The agroecological zone, SOC, clay, exchangeable iron and exchangeable aluminium were used as explanatory variables for soil pH. The general regression model was set to be:



$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_k X_{ki} + \varepsilon_i$$

where Y_i represents the dependent variable, β_0 is the intercept, β_1 to β_k are regression coefficients, X_{1i} to X_{ki} are explanatory variables, and ε_i is the residual error term.

For SOC, the model was:

$$SOC_i = \beta_0 + \beta_1 pH_i + \beta_2 Clay_i + \sum_{j=1}^5 \gamma_j Zone_{ji} + \varepsilon_i$$

For soil pH, the model was:

$$pH_i = \beta_0 + \beta_1 SOC_i + \beta_2 Clay_i + \beta_3 Fe_i + \beta_4 Al_i + \sum_{j=1}^5 \gamma_j Zone_{ji} + \varepsilon_i$$

Residual diagnostics and multicollinearity checks were used to assess model assumptions. The regression coefficients were presented with standard errors, 95% confidence interval, and P-values.

2.8 Site-Specific Soil Fertility Assessment

The second objective is to carry out a site-specific soil fertility assessment. The SOC and soil pH patterns were combined at the agroecological-zone level to distinguish the zones of soil fertility conditions. The spatial patterns were illustrated using farm geographical coordinates, while comparisons at the zone level were conducted to highlight those zones where a relatively low SOC level, acidic soil conditions, or both, occurred. Patterns were discussed with reference to the possible management approaches including organic matter restoration, liming, residue management and specific nutrient application. The research findings have been analyzed statistically and presented in tabular and graphical format.

2.9 Statistical Analysis and Data Presentation

The data from the results were presented in tabular and graphical form. Box plots were employed to display SOC and soil pH variability with agroecological zones; scatter plots were employed to display spatial plots of the SOC-pH relationship, and geographical plots were employed to show the geographical variability. All statistical tests were two-sided and statistical significance was defined as:

$$p < 0.05$$

Effect estimates and 95% confidence intervals were provided along with p-values, if applicable.

2.10 Ethical Considerations

This is a secondary analysis of openly available agricultural soil data and no interaction with human subjects or experimental animals was involved. Multi-scale data for delineating cocoa zones for site-specific soil fertility and productivity management in Ghana was sourced from Mendeley Data and access to the data is granted under the open access conditions set by Mendeley Data. No new field



samples were collected, farmers weren't sought out, nor was personally identifiable information collected. All analyses were done transparently, and the original data source was appropriately acknowledged to preserve integrity and research repeatability of the data.

3. Results

3.1 Distribution and General Characteristics of Soil Observations

The analysis included a total of 739 observations of soil under cocoa farms in 6 cocoa production agroecological zones. MSSE had the highest number of observations (298 samples or 40.32% of the data), followed by ME (182 observations or 24.63%). MSNW made 103 observations, DSIZ 75, WE 56 and DSFZ 25. The frequency distribution of the observations by agroecological zones is given in Table 1.

Table 1. Distribution of soil observations across cocoa-producing agroecological zones

Agroecological zone	Number of observations	Percentage (%)
DSFZ	25	3.38
DSIZ	75	10.15
ME	182	24.63
MSNW	103	13.94
MSSE	298	40.32
WE	56	7.58
Total	739	100.00

Mean soil organic carbon was 0.393 ± 0.235 with range of 0.000 to 2.586 across the whole dataset. Mean soil pH was 5.345 ± 0.744 , with a minimum of 3.450 and a maximum of 7.430. The coefficient of variation was much higher for soil organic carbon than for pH at 59.70% and 13.92%, respectively. Other soil properties are tabulated in Table 2.

Table 2. Overall descriptive characteristics of the principal soil variables

Variable	n	Mean	SD	Median	Minimum	Maximum	CV (%)
Soil organic carbon	739	0.393	0.235	0.339	0.000	2.586	59.70



Soil pH	739	5.345	0.744	5.400	3.450	7.430	13.92
Clay	739	21.395	8.738	20.760	2.760	54.760	40.84
Exchangeable Fe	739	0.087	0.036	0.081	0.023	0.200	41.68
Exchangeable Al	739	7.661	4.880	6.790	0.190	37.370	63.70

3.2 Variability of Soil Organic Carbon across Agroecological Zones

There was a wide range of SOC across the six agroecological zones. As shown in Table 3, MSNW recorded the highest mean SOC at 0.579 ± 0.253 , followed by DSFZ at 0.465 ± 0.167 and ME at 0.401 ± 0.278 . DSIZ had the lowest mean SOC (0.268 ± 0.130). The intermediate values of MSSE and WE were 0.357 and 0.354, respectively.

There was also a considerable amount of variation within areas. The SOC variability was highest in the relative sense in the case of ME (CV 69.36%) and MSSE (CV 56.41%). WE had the lowest difference in SOC (34.37%). The distribution, as shown in Figure 1, reveals that there is a clear difference in the SOC distribution for each zone and the central tendency of the distribution, with MSNW having the highest range overall and DSIZ having the lowest range in the centre of the distribution.

Table 3. Soil organic carbon and soil pH characteristics by agroecological zone

Zone	n	SOC Mean $\pm$ SD	SOC Median	SOC CV (%)	pH Mean $\pm$ SD	pH Median	pH CV (%)
DSFZ	25	0.465 ± 0.167	0.456	35.83	5.662 ± 0.686	5.700	12.12
DSIZ	75	0.268 ± 0.130	0.251	48.60	5.750 ± 0.544	5.820	9.47
ME	182	0.401 ± 0.278	0.333	69.36	5.080 ± 0.694	5.055	13.67
MSNW	103	0.579 ± 0.253	0.553	43.70	5.907 ± 0.543	5.910	9.19
MSSE	298	0.357 ± 0.201	0.307	56.41	5.319 ± 0.719	5.360	13.53



WE	56	0.354 ± 0.122	0.334	34.37	4.630 ± 0.531	4.600	11.46
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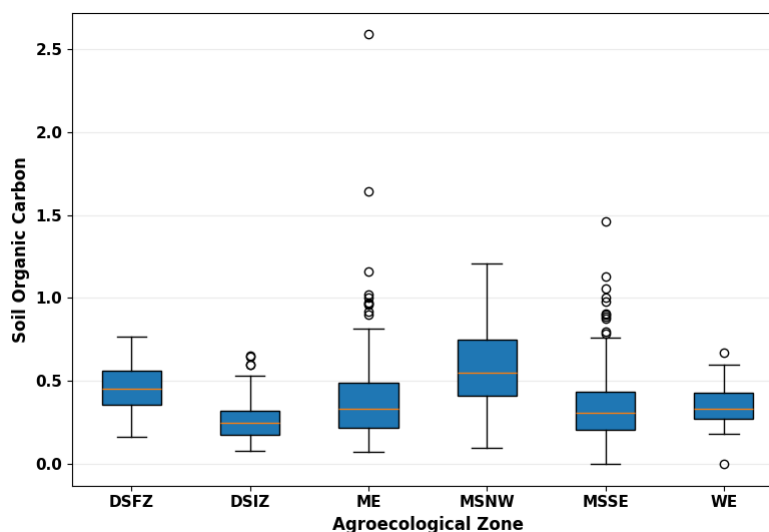


Figure 1. Distribution of soil organic carbon across cocoa-producing agroecological zones

3.3 Variation in Soil pH across Agroecological Zones

There were also significant differences in soil pH. MSNW recorded the highest mean soil pH at 5.907 ± 0.543 , followed by DSIZ at 5.750 ± 0.544 and DSFZ at 5.662 ± 0.686 . WE had the least mean soil pH of 4.630 ± 0.531 which means the soil had the most acidic conditions of the other zones. The mean pH values for ME and MSSE are in the intermediate range with values 5.080 and 5.319, respectively, as reported in Table 3.

The soil acidity variations between the agroecological zones are well reflected in Figure 2. WE observations were focused at the lower range of pH while MSNW and DSIZ observations were focused at the relatively higher range of pH. There was some variation within zones, but the pH had less relative dispersion than the SOC.

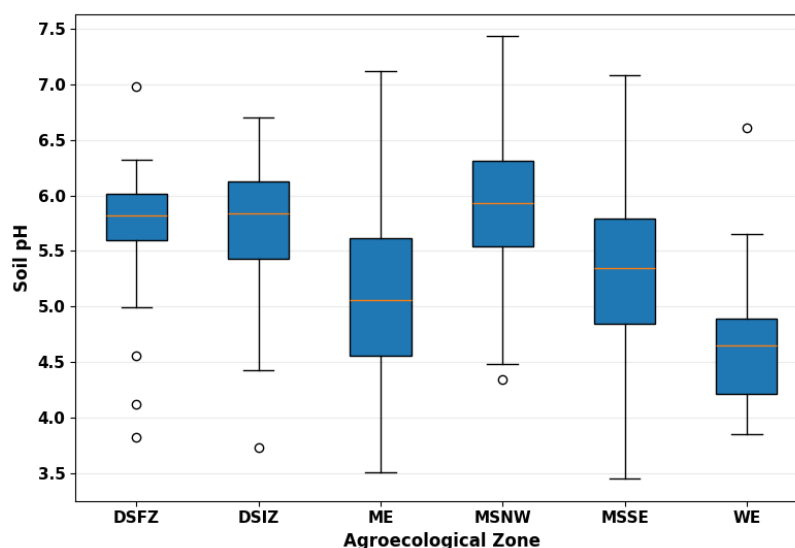


Figure 2. Distribution of soil pH across cocoa-producing agroecological zones

3.4 Comparative Differences among Agroecological Zones

Both SOC and soil pH were significantly different among the six agroecological zones as revealed in the comparative analysis with $p < 0.001$ in both cases. The highest SOC contrast was found between MSNW and DSIZ with mean SOC 0.579 and 0.268, respectively. The soil pH had the greatest difference between the two different soil moisture types, MSNW and WE, where the means of the soil pH were 5.907 and 4.630, respectively.

The lowest-SOC agroecological zone was the DSIZ while the most acidic zone was the WE zone, as summarized in Table 4. The most extreme of all the mean values was MSNW which showed the highest mean SOC as well as the highest mean pH which separated MSNW from several other cocoa growing environments. The distributions shown in Figures 1 and 2 were consistent with these differences.

Table 4. Comparative differences in SOC and soil pH among agroecological zones

Soil property	Lowest mean zone	Lowest mean	Highest mean zone	Highest mean	Overall difference
Soil organic carbon	DSIZ	0.268	MSNW	0.579	$p < 0.001$
Soil pH	WE	4.630	MSNW	5.907	$p < 0.001$



3.5 Relationship between Soil Organic Carbon and Soil pH

There was a weak positive relationship between SOC and soil pH in the 739 observations from cocoa farms. The correlation coefficient was $r = 0.097$, $p = 0.008$, which shows that there was a slight positive correlation between soil pH and SOC. But the coefficient value was small, indicating a weak relationship.

In the pattern in Figure 3, the trend line has a small positive slope but the data points are quite scattered. This dispersion suggests that soil pH is not the only factor that strongly influenced the variation in SOC levels, but other agroecological and soil properties could also have influenced variability in carbon status.

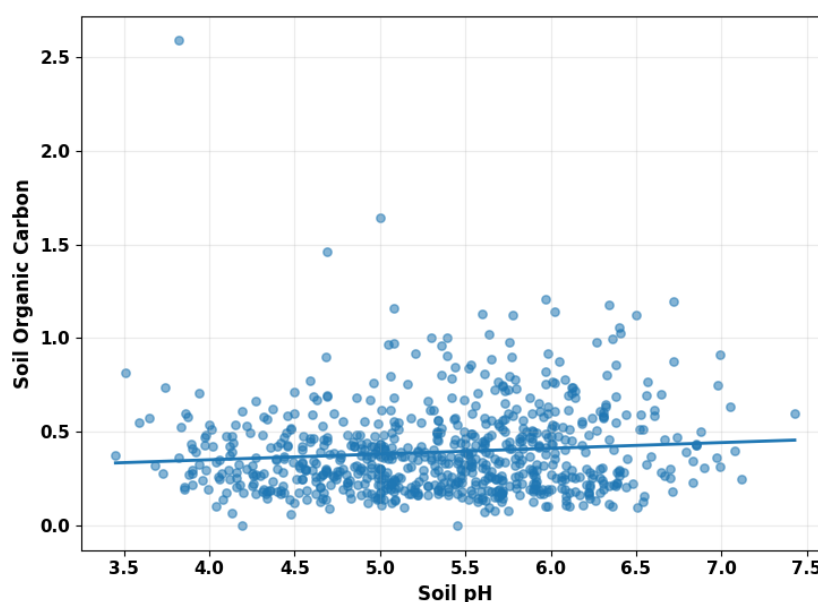


Figure 3. Relationship between soil organic carbon and soil pH across cocoa-farm observations

3.6 Factors Associated with Soil Organic Carbon

About 21.6% of the observed variation of SOC was explained by the multivariable model, and had an adjusted (R^2) of 0.208. DSIZ had significantly lower SOC than DSFZ ($B = -0.153$) and $p < 0.001$ and MSNW had significantly higher SOC than DSFZ ($B = 0.104$) and $p = 0.015$.

The adjusted SOC values of MSSE and WE were also lower than DSFZ. The soil pH was significantly and positively related to SOC ($B = 0.036$, $p = 0.012$) and clay content ($B = 0.008$, $p < 0.001$). Details of the full estimates are given in Table 5.

Table 5. Factors associated with soil organic carbon

Predictor	B	SE	95% CI	p-value
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DSIZ vs DSFZ	-0.153	0.039	-0.231 to -0.076	<0.001
ME vs DSFZ	-0.049	0.039	-0.125 to 0.027	0.208
MSNW vs DSFZ	0.104	0.043	0.020 to 0.189	0.015
MSSE vs DSFZ	-0.078	0.037	-0.151 to -0.006	0.035
WE vs DSFZ	-0.096	0.041	-0.176 to -0.017	0.018
Soil pH	0.036	0.015	0.008 to 0.065	0.012
Clay content	0.008	0.001	0.006 to 0.010	<0.001

The adjusted differences confirm that agroecological location remained associated with SOC even after accounting for soil pH and clay content.

3.7 Factors Associated with Soil pH

The soil pH model accounted for about 33.8% of the observed variability with an adjusted R^2 (R^2) of 0.330. ME had the least negative difference in soil pH ($B=-0.268$ and $p = 0.047$) and WE had the greatest negative difference ($B=-0.485$ and $p = 0.002$) compared to DSFZ.

Soil pH was negatively related to clay content ($B=-0.018$) and $p < 0.001$. A negative association was also seen for Exchangeable Fe ($B=-5.853$, $p < 0.001$) and exchangeable Al ($B=-0.014$, $p = 0.015$) with pH. SOC is not significantly correlated with pH ($p = 0.164$) when the other soil properties are removed from the correlation.

Spatial distribution, as depicted in Figure 4, also reflected that soil pH was geographically different at the different locations where the cocoa beans were grown with the concentration of more acidic soil and less acidic soil being different from one locality to another.

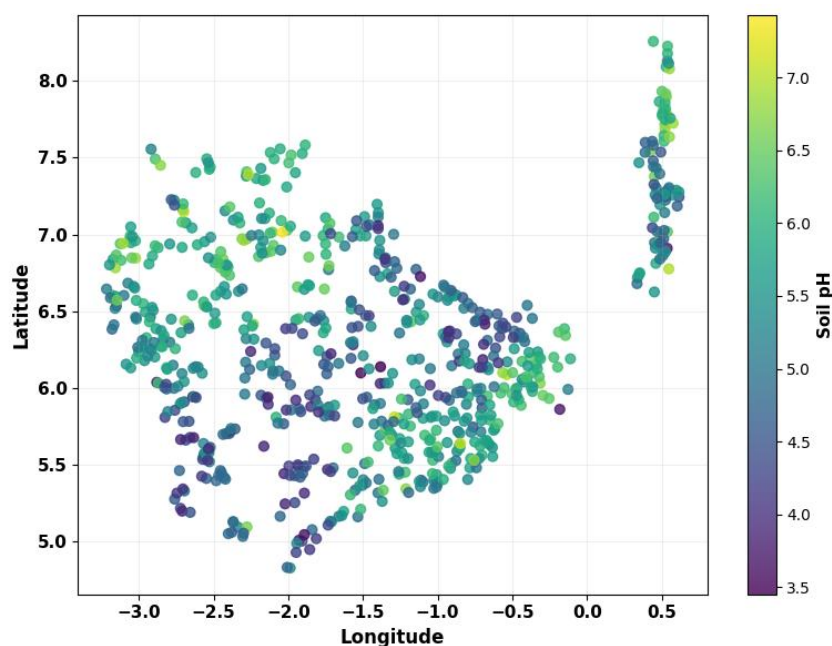


Figure 4. Spatial distribution of soil pH across sampled cocoa-farm locations

3.8 Integrated SOC–pH Patterns across Agroecological Zones

The overall evaluation of the soil mineralization and soil pH indicated different agroecological soil fertility patterns. The highest mean SOC (0.579) was combined with the highest mean pH (5.907) by MSNW, while the lowest SOC was combined with a relatively high mean pH (5.750) by DSIZ. In contrast, the mean soil pH of 4.630 was the lowest, and intermediate SOC indicated that soil acidity was a more prominent constriction in this zone.

The soils of MSSE and ME were described as having moderate SOC and fairly acidic conditions. When considering mean SOC and mean pH simultaneously, the six agroecological zones were clearly distributed as in Figure 5.

These compound patterns suggest that soil fertility constraints were not homogeneous on the cocoa growing regions. Organic matter enhancement would need to be emphasized in relatively low SOC areas, while acidity management and nutrient availability would need to be emphasized in strongly acidic areas.

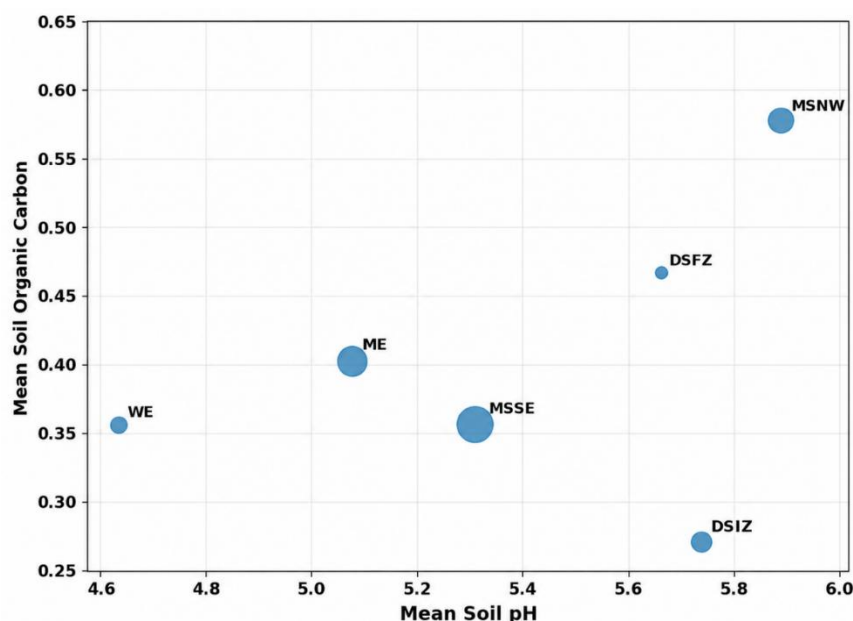


Figure 5. Integrated pattern of mean soil organic carbon and soil pH across cocoa-producing agroecological zones

3.9 Summary of Results

The 739 soil observations from the cocoa farm demonstrated good agroecological variability in soil organic carbon and soil pH overall. The highest SOC and lowest soil pH values were obtained in MSNW and WE, respectively. The relative variability of pH was much more variable in SOC than in the other parameters across the study area. There was a weak but statistically significant positive relationship between SOC and pH, suggesting that there was only a slight increase in pH with the increase in SOC. In conclusion, the results showed that soil fertility conditions differed significantly between the various agroecological zones and between various soil parameters, and that a one-size-fits-all approach to soil fertility recommendations is not suitable for all areas where cocoa is grown.

4. Discussion

In the present study, the authors found that there is agroecological variation in soil organic carbon and soil pH across cocoa-producing zones; meaning that the soil fertility conditions are spatially heterogeneous. The mean SOC level was the highest in MSNW, while the lowest level was observed in DSIZ, and a soil pH level was the highest in MSNW and the lowest in WE. This means that the carbon status and acidity can be different and do not always go together. The same spatial variations in cocoa soils have been documented in Ghana where management history, ecological conditions and land use (as trees) affect the accumulation of carbon and soil properties (Adiyah et al., 2023). The variability allows for site-specific fertility management while offering no general guidelines.

The high SOC in MSNW may be attributable to interactions between the organic inputs, vegetation cover, soil texture and microclimatic conditions. Crops grown on AFS can increase carbon inputs via litterfall, root turnover, pruning residues and biomass of shade trees, and lead to C storage in the soil (Akinbode et al., 2022). Management intensity and organic matter return also affect carbon and nutrient cycling, and diversified systems have shown to have better soil conditions than simplified systems (Agbotui et al., 2024a). Between-zone contrasts may arise due to stand development, because



of plantations age effects on carbon stocks and nutrient accumulation (Arthur et al., 2022). Tree diversity also has the potential to affect organic matter supply and belowground processes, affecting carbon retention in degraded cocoa landscapes (Atangana et al., 2025).

Low SOC in DSIZ indicates a risk of decrease in nutrient retention and aggregation and moisture holding capacity. Soil quality and microbial diversity in cocoa systems can be improved by adopting organic management practices, highlighting the need for sustained Carbon inputs to maintain soil functioning (Lori et al., 2022). Additionally, the strategy of fertilization is relevant because of different effects of organic and chemical fertilization on SOC pools, stability and soil quality (Eduah et al., 2025). Residue retention, compost or manure incorporation, mulching, cover vegetation, more integration of shade trees may be appropriate in low-SOC zones, depending on local conditions.

The distribution of soil pH was different with WE being the most acidic. This is agronomically significant as it can lead to decreased nutrient availability and increased solubility of potentially toxic elements, due to strong acidity. The association of soil pH with clay, exchangeable iron and aluminium produce a negative relationship which suggests that the mineralogical and chemical properties of the soil are also responsible for soil acidity. In Ghana, similarly, various soil properties influence soil condition, as indicated by the fertility indices for cocoa agroforests (Agbotui et al., 2024b). Climate-smart fertility practices and shade management can also have an effect on nutrient cycling and soil processes under different ecological conditions in cocoa landscapes (Anokye et al., 2024).

SOC and pH were weakly correlated suggesting that when the carbon status was higher, the pH increased only slightly. Therefore, SOC and acidity can't be essentially substituted for each other when assessing fertility. Organic matter inputs and nutrient recycling can benefit fertility of agroforestry systems but this depends on environmental context and management (Suárez et al., 2021). Shade-tree species can also be found to have varying effects on the microclimate, decomposition, and growth of cocoa plants, each with indirect impact on variations in soil carbon and nutrient dynamics (Kohl et al., 2024). The agroecological context is also important when interpreting soil measurements, as carbon stocks and cocoa yields can also differ along climatic gradients (Manu et al., 2026).

The results have implications for site-specific fertility management. Organic matter restoration is a strategy for zones of low SOC, while acidity correction may be a needed strategy for strongly acidic zones that also have unbalanced nutrient inputs. Economic and institutional feasibility should be taken into consideration, as adoption is dependent on the farmers' ability to implement recommended interventions. Profitability of alternative cocoa agroforestry (AF) and carbon-based-management depends on the type of management and farm situation (Agbotui et al., 2023). Technically suitable soil recommendations must also consider the farmer access, tenure and resource constraints in land-use decision making (Kumeh, 2024). Cacao trees and soils are also carbon stores, further highlighting the need to consider aboveground and belowground systems as a whole (Leiva-Rojas & Ramírez-Pisco, 2021).

The soil fertility of cocoa was organized by different mixtures of SOC and pH instead of a unique dominant gradient. There are therefore three areas which should be differentiated: carbon-limited, acidity-limited and comparatively favorable. This differentiation can help to more precisely target organic amendments, liming and nutrient management, and assist in sustainable cocoa farming in agroecologically diverse environments and longer term stability of cocoa soils in the region.

5. Conclusion



The objective of this study was to identify the variability of soil organic carbon and soil pH between the cocoa producing agroecological zones, and to understand how this variation can be considered for site specific soil fertility management. The results indicated a significant variation in both indicators and confirmed the non-spatially uniform nature of cocoa soils. MSNW had the highest mean soil organic carbon, meanwhile soils in DSIZ had the lowest soil organic carbon while the most acid soil was in WE. The relative variance of SOC was higher than for pH, demonstrating a higher degree of carbon status heterogeneity in the study area. The weak positive correlation between soil organic carbon and pH also indicated that these properties do not necessarily represent similar information and cannot be viewed as synonyms. The results of the multivariable indicated association of agroecological zone, soil pH and clay content with soil organic carbon, and association of soil pH variation with agroecological zone, clay, exchangeable iron, and aluminium. The data highlight the importance of implementing differentiated management strategies. The remediation of organic matter may be more extensive in low carbon zones and acidity correction and balanced nutrient management may be needed in strongly acidic zones. Overall, the integration of soil organic carbon and pH offers a realistic alternative to target interventions, enhance soil health and more sustainable cocoa production across a wide range of cocoa landscapes globally.

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