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Accounts of Soil Health at Varying Altitudes in Selected Agroecologies of Northwest Nigeria

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ACCOUNTS OF SOIL HEALTH AT VARYING ALTITUDES IN SELECTED AGROECOLOGIES OF NORTHWEST NIGERIA

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ABSTRACT

Soil organic carbon (OC) is a critical indicator of soil health, influenced by environmental factors, including altitude, temperature, agroecology and soil texture. This study assessed the distribution of OC and related soil properties across agroecological zones in Kano, Katsina and Jigawa States, Northwest Nigeria. A total of 180 agricultural fields were sampled across selected local government areas and villages. Composite soil samples were analysed in situ using dry chemistry method (Agrocares soil scanner), while elevation data were obtained using handheld GPS devices. Statistical analyses, including analysis of variance, effect-size estimation and correlation analysis, were performed using R software (version 4.1.2) to evaluate the effects of altitude, agroecology, soil texture and village on OC, pH, total nitrogen (TN), total phosphorus (TP), potassium (K) and cation exchange capacity (CEC). Altitude significantly influenced OC distribution ($F = 25.40$, $p = 1.38 \times 10^{-15}$). Transect, agroecology, soil texture and village contributed 34%, 18%, 18% and 48%, respectively, to OC variation. Significant differences occurred between the Sahel and Guinea savannas (adjusted $p = 1.49 \times 10^{-6}$) and between the Sudan and Guinea savannas (adjusted $p = 7.78 \times 10^{-8}$), whereas the Sudan and Sahel savannas did not differ significantly. Altitude was positively correlated with OC across four transects ($r = 0.35–0.58$) but negatively correlated in one ($r = -0.10$). These findings demonstrate that altitude influences soil OC distribution, although its effects vary with agroecological and other site-specific factors.

Key words: Agroecology, altitude, organic carbon, soil health, transect

INTRODUCTION

The Earth's non-submerged surface is delicately covered by a thin yet crucial layer known as soil. This unassuming layer plays a pivotal role in driving essential cycles such as carbon, nitrogen and water, which sustain life on our planet. Within this unassuming realm thrives a vast array of species, each contributing invaluable services that support society's well-being [14, 15]. The significance of soil health has gradually gained recognition in global and

national discussions, with efforts shifting from theoretical understanding to practical soil management to enhance its well-being [15].

Soil health, as defined by [9], pertains to the soil's robust physical, chemical and biological condition, enabling it to support the growth and development of terrestrial plants. The intricate interplay of soil functions influenced by human practices forms the crux of soil health, as articulated by The Cornell Framework Manual [32]. Central to soil health, soil organic carbon (SOC), a vital component of soil organic matter (SOM), is often referred to as natural soil capital due to its pivotal role in critical soil functions. SOC significantly contributes to essential facets like food production, climate change mitigation and adaptation and the attainment of Sustainable Development Goals (SDGs) [4, 15]. Elevated levels of soil organic matter bolster plant nutrition and enhance water availability, thereby augmenting soil fertility and ultimately boosting food productivity. Nevertheless, the agricultural lands of the Nigerian savanna face inherent fertility challenges, characterized by low to very low SOC content, limited total nitrogen, medium to high acidity and constrained cation exchange capacity and base saturation. These soils are further compromised by continuous utilization [11, 14, 20, 21, 25, 27].

Soil organic carbon and its associated nutrients emerge as key contributors to soil resilience, as highlighted by [25], underscoring the significance of preserving the soil organic carbon reservoir to combat degradation. Altitude, a critical environmental factor, influences soil properties, with certain attributes showing positive correlation with increasing altitude, while others display an inverse relationship. This intricate dance between soil characteristics and altitude has been well-studied [5, 16, 19, 29, 30, 31, 35, 36]. Alterations in altitude wield substantial influence over the abiotic environment, reshaping climatic factors and topography [3, 5, 28]. Both altitude and vegetation wield sway over soil organic matter content and microbial biomass activity, yet the combined impact of these factors on soil chemical and biochemical attributes remains a complex puzzle [18, 29, 38]. The dynamic relationship between altitude, vegetation and soil properties holds pivotal implications for understanding global carbon dynamics [5, 10, 16].

Climate and vegetation are key determinants of an environment's agroecology, influencing soil characteristics in intricate ways [18, 26, 29, 30, 38]. The interaction between soil attributes, altitude and agroecologies has been well-explored, illustrating the profound

influence of altitude on observed soil property variations [5, 7, 10, 22, 36, 37]. The ecological zones of Nigeria are defined based on climate and vegetation, ranging from South to North [8]. This study focuses on the semiarid regions of Nigeria, spanning three Northern States; Kano, Katsina and Jigawa. Within these states, selected local government areas lie within the savanna agroecological zone.

The investigation encompasses the guinea, sudan and sahelian savannas, each distinct in vegetation and rainfall patterns. Guinea savanna features a mix of trees and grasses, with annual rainfall between 1000 – 1500 mm. Sudan savanna experiences a shorter rainy season and features shorter grasses and stunted trees. Sahel savanna, the northernmost zone, receives minimal rainfall and is characterized by grasses, sporadic shrubs and scattered trees [8, 21].

Given the substantial variation in soil organic carbon across altitudes in the semi-arid smallholder farming systems of Nigeria, impacting crop productivity and fertilizer response, this study aims to assess how altitude influences the distribution of soil organic carbon, a key determinant of soil health in the guinea, sudan and sahelian agroecologies of northwest Nigeria, alongside a comparative analysis of other soil properties.

MATERIALS AND METHODS

Study Area Description and Site Selection

The study encompassed a geographical range of 10.5° to 14.0°N latitude and 7.0° to 10.5°E longitude, situated in the northwestern region of Nigeria (Fig. 1). This area spans across the northern guinea, sudan and partially the sahel savanna agroecologies within Nigeria. The choice of the northwest geopolitical zone of Nigeria was deliberate and it consists of seven states, from which three were selected for this study: Jigawa, Kano and Katsina. Within each selected state, three local government areas (LGAs) were chosen. Specifically, for Jigawa State, the chosen LGAs were Gumel, Malam Madori and Gwaram; for Kano State, the selected LGAs were Bebeji, Bichi and Minjibir; and for Katsina State, the designated LGAs were Dutsin-Ma, Kafur and Zango. Within each LGA, two villages were purposefully selected. As a final step, a total of 180 farm fields were meticulously chosen for inclusion in the study, with ten fields selected from each of the villages.

The selection of the northwest geopolitical zone was based on careful consideration, while the choice of states was guided by the intention to cover the three distinct agro-ecology types

present in the region: northern guinea, sudan and sahel savannas. The selection of local government areas, villages and farm fields was executed using random sampling techniques, ensuring the representation of at least two agro-ecology types within each state.

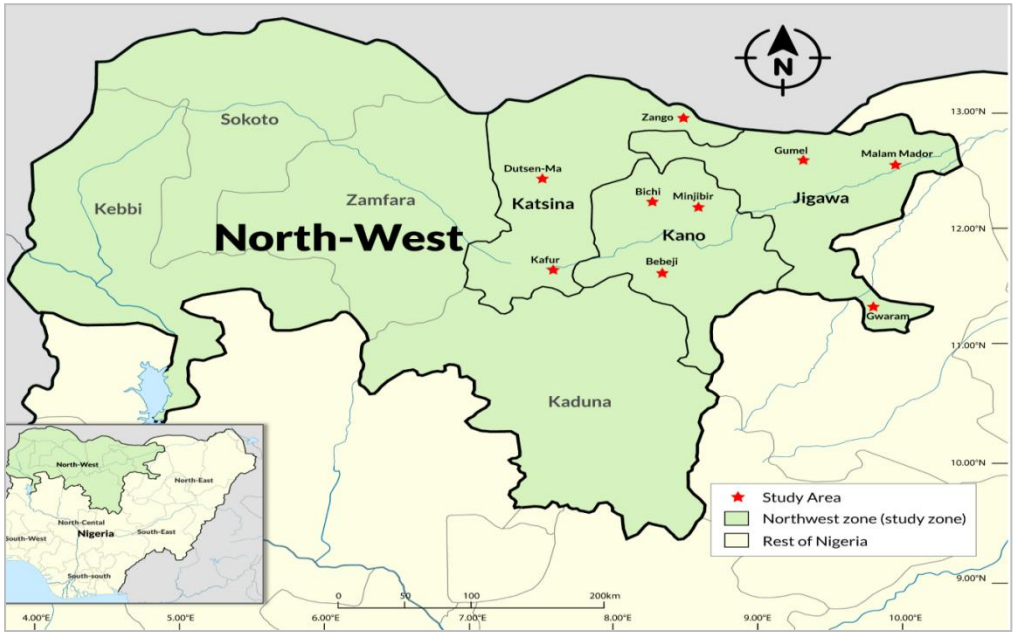


Fig. 1 Map of North-west Nigeria showing the study areas

The study areas exhibit an average annual rainfall ranging from 600 to 875 mm. Rainfall follows a unimodal pattern, occurring exclusively between June and September each year. The growing period spans 105 to 140 days. Generally, the southern and southwestern regions of the States experience more prolonged and abundant rainfall compared to the northern and northeastern parts. The annual mean temperature fluctuates between 25.2 and 26.6 ℃. Notably, areas with higher rainfall tend to exhibit relatively lower temperatures. The chosen farmlands are cultivated with either sorghum or millet to ensure a consistent land use type. The topography across all study areas remains predominantly flat, situated within an altitude range of 349 to 528 meters (Table 1).

Regarding site sampling and soil analysis, this study employed five elevation transects. These transects were generated by initially arranging elevation values from a total of 180 fields in ascending order (349 to 528 meters) using the 'sort' command. Subsequently, elevation values were automatically distributed into five transects: Transect1 (349 - 384 m), Transect2 (385 - 420 m), Transect3 (421 - 456 m), Transect4 (457 - 492 m) and Transect5 (493 - 528 m). This distribution was determined based on the trend of values, with segments corresponding to <

20%, >= 20%, >= 40%, >= 60% and >= 80% of the total. Both operations were executed using the WPS spreadsheet software. These five transects represent increments of 36 meters in altitude between each consecutive transect (Fig. 2).

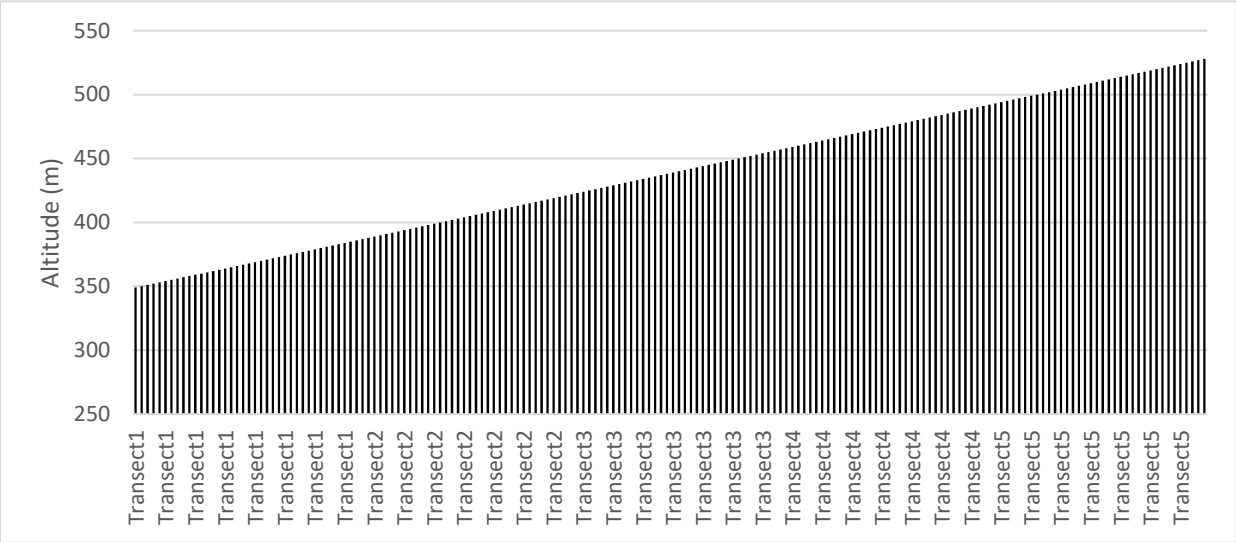


Fig. 2 Transects generated from the sites' altitudes

Surface soil samples were gathered from each 0.2-hectare farm field at a depth of 0 to 30 cm. A total of ten sampling points were strategically selected in a diagonal pattern across each field. These individual samples were combined to create a composite sample, from which a 500 g sub-sample was set aside for subsequent soil analysis for each field. To determine specific soil characteristics, an in-situ analysis was conducted using a dry chemistry method known as spectroscopy, utilizing the Agrocares Scanner. This scanning process was facilitated through the AgroCares Scanner, which operates in conjunction with its corresponding mobile application. The scanning and data synchronization occurred on-site, taking advantage of available mobile data networks. Upon synchronization, immediate results including geo-location, soil texture, pH, organic carbon (OC), total nitrogen (N), total phosphorus (P), exchangeable potassium (K) and cation exchange capacity (CEC) were generated and reported.

Data analysis

The collected data underwent thorough analysis using the R 4.1.2 statistical software [39] and the WPS spreadsheet for graphical representation. Analysis of variance (ANOVA) was employed to assess the impact of factors such as altitude (transects), agroecology and soil texture type on the measured variables, with particular focus on organic carbon (OC). The

generalized eta squared (ges) effect size metric was utilized to quantify the proportion of variability in the OC variable that could be attributed to the transect factor.

When significant effects were identified, a pairwise comparison test was carried out using estimated marginal means (emmeans) in conjunction with the Bonferroni-adjusted method to discern distinct group differences. Additionally, a correlation analysis was performed to uncover relationships between the various measured variables. Statistical significance was established at threshold levels of $P \leq 0.05$, 0.01 and 0.001 for all conducted analyses.

RESULTS AND DISCUSSION

The data presented in Table 1 underwent a series of statistical assessments to ensure its adherence to statistical assumptions. This process was crucial to affirm its suitability for the subsequent ANOVA analysis, which aimed to examine the impact of altitude (transect) – our primary variable of interest – as well as other factors like agroecology, soil texture and villages, on soil organic carbon (OC) content, the designated outcome variable. This was evaluated in relation to several other measured soil parameters including pH, total nitrogen (TN), total phosphorus (TP), exchangeable potassium (K) and cation exchange capacity (CEC).

Given that both soil sampling and analysis were conducted on-site across 180 different locations (farm fields), some of which shared similar altitudes, a system of five transects (illustrated in Fig. 2 and detailed in Table 1) was established to create distinct levels for robust analysis of variance. To gauge the reliability of the data, means and standard deviations (SD) of soil OC content within each transect (corresponding to site altitudes) were computed. Comparison between the observed SD values and the corresponding mean values provided insight into the data's consistency and reliability (Fig. 3a).

Furthermore, a concise numerical summary of the data was compiled, offering a straightforward visualization of the distribution of OC content across the various transects (Fig. 3b). To provide a comprehensive perspective on the distribution patterns relative to study locations, OC content and the other examined variables (pH, TN, TP, K and CEC) were graphically depicted in relation to transect (site altitude). This graphical representation (Fig. 4) allows for a clearer understanding of how these variables are distributed across the study area.

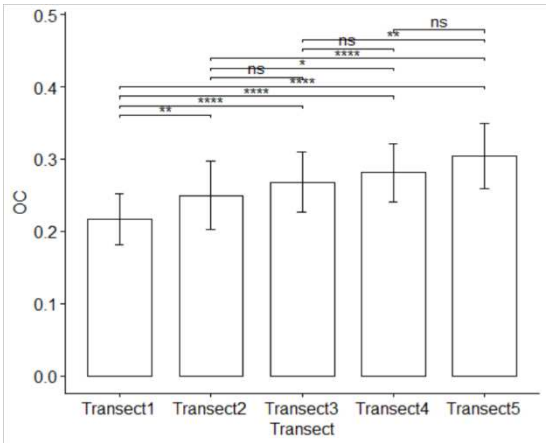


Fig. 3a Barplot showing mean distribution and the SD of OC by transects

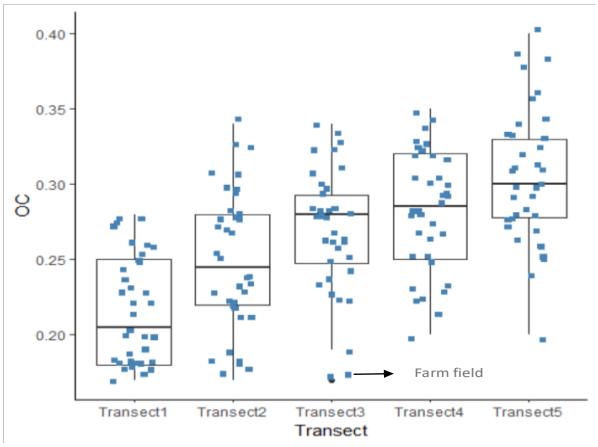


Fig. 3b Boxplot showing distribution of farm fields per transect and the percentile distribution of OC

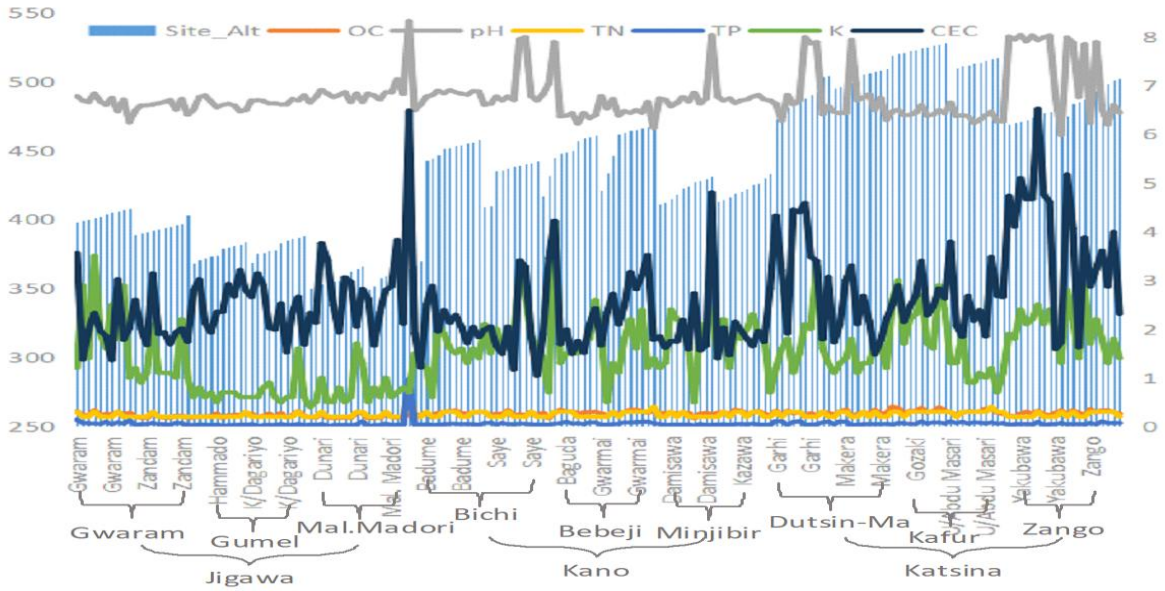


Fig. 4 Distribution of measured parameters by transect villages, LGAs and State

The examination of the outlier assumption in the data revealed that only Transect3, which covers the villages of Baguda and Damisawa, exhibited an outlier (Fig. 3b). However, no extreme outlier was observed in this case. Additionally, an assessment of normality and homogeneity of variance was conducted on the dataset. To assess normality, the model residuals were analyzed using both a QQplot and the Shapiro-Wilk test. The results of the normality check indicated that the majority of data points closely aligned with the reference line (Figs. 5a and 5b), suggesting conformity to a normal distribution. This observation was supported by the Shapiro-Wilk test, which yielded a non-significant p-value ($p = 0.468$).

Similarly, the homogeneity of variance was examined using Levene's test. The outcome of this test revealed a non-significant p-value ($p > 0.05$, $p = 0.552$), indicating that the assumption of homogeneity of variances across different groups (factors) is reasonable. The analysis indicates that while an outlier was present in Transect3, it was not an extreme outlier. Furthermore, the data demonstrated a satisfactory level of normality, as evidenced by the QQplot and Shapiro-Wilk test results. Similarly, the assumption of homogeneity of variances was supported by the non-significant result from Levene's test, allowing for the consideration of consistent variances among the various groups (factors).

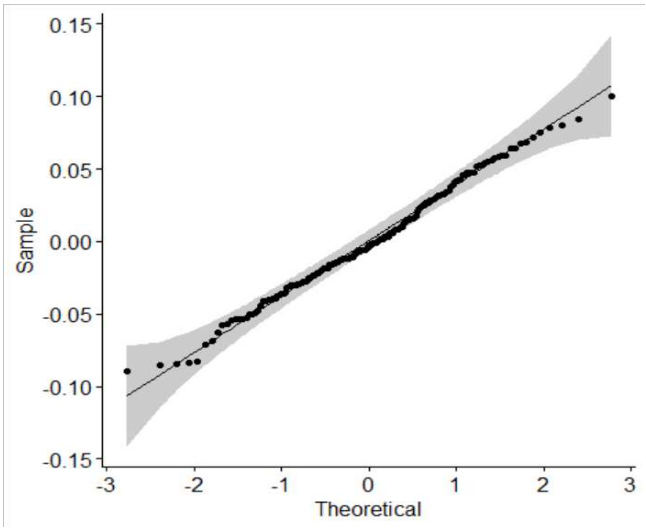


Fig. 5a QQplot showing a normally distributed data of OC

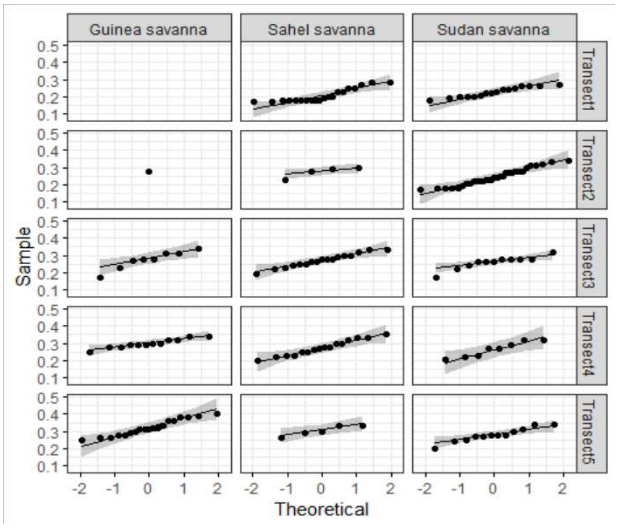


Fig. 5b QQplot showing a normally distributed data of OC by transect and agroecology

The data, which satisfied all the assumptions for ANOVA, underwent ANOVA analysis to ascertain both the interaction effects of the variable factors and their individual impacts on each outcome variable. Results revealed no statistically significant interactions between transect and agroecology, transect and soil texture, transect and village, agroecology and soil texture and soil texture and villages at a 5% level of significance. This suggests that none of the variable factors are dependent on one another, as each factor independently influences organic carbon (OC) synthesis and buildup.

Nonetheless, the effects of the different factors were found to be statistically significant on OC content synthesis and buildup. Specifically, transect ($F = 25.40$, $Pr(>F) = 1.38 \times 10^{-15}$***), agroecology ($F = 5.14$, $Pr(>F) = 0.00709$**), soil texture ($F = 8.00$, $Pr(>F) = 0.00540$**) and

village (F = 2.00, Pr(>F) = 0.01712*) all exhibited significant effects on the process of OC content synthesis and buildup.

Based on the preceding data, it can be deduced that altitude had the most significant influence on organic carbon (OC) formation within the studied regions. The statistically significant correlation between transect (site altitude) and OC (Fig. 2) aligns with the findings of [2], who noted that Nigeria's climate is characterized by relatively high temperatures year-round, with average annual maximum temperatures ranging from 31 to 35 °C (in the South and North, respectively) and this temperature pattern is influenced by altitude. Mujiyo *et al*. [23] associated temperature effects with mineralization, suggesting that higher temperatures lead to lower OC content in soils, a concept supported by Wang *et al*. [33], who emphasized the significant impact of altitude on soil organic matter decomposition rates. More recent evidence likewise shows that elevation is associated with systematic changes in soil temperature, SOC and nutrient dynamics, although the direction and magnitude of these relationships vary with climate, vegetation and ecosystem context [29, 36, 38].

The computed effect size quantifies the proportion of OC variability explained by transect, agroecology, soil texture and village factors. Specifically, transect, agroecology, soil texture and village contributed proportions of 34 (ges = 0.339), 18 (ges = 0.176), 18 (ges = 0.184) and 48 (ges = 0.48), respectively, to OC distribution and buildup. The 48 % contribution from the village signifies a substantial effect size on OC changes. Notably, it should be emphasized that farm management practices, especially in the Sahel region, exert a significant influence on the recorded village percentage. This interpretation is consistent with recent evidence from the Sahel showing that integrated soil fertility management, particularly the use of organic amendments, can substantially alter soil C, N and P dynamics [1], while recent work in northern Nigeria has demonstrated marked spatial differences in OC and other fertility indicators among management zones in the Sudan and Sahel savannas [6]. Since the effects on OC were statistically significant across all cases, a Bonferroni adjustment was employed for pairwise comparisons to discern distinct groups.

Table 1: Selected soil health parameters for the study areas

State	LGA	Village (No. of farm fields)	Transect	Agroecology	SoilTexture	Mean Site_Alt	Mean OC	Mean pH	Mean TN	Mean TP	Mean K	Mean CEC
Jigawa	Mal. Madori	Dunari (10)	Transect1	Sahel savanna	Loamy Sand	356.8	0.21	6.77	0.23	0.04	0.78	2.70
Jigawa	Gwaram	Gwaram (10)	Transect2	Sahel savanna	Loamy Sand	403.0	0.26	6.64	0.23	0.08	2.07	2.12
Jigawa	Gumel	Hammado (10)	Transect1	Sudan savanna	Loamy Sand	376.4	0.22	6.60	0.21	0.03	0.65	2.62
Jigawa	Gumel	K/Dagariyo (6)	Transect1	Sudan savanna	Loamy Sand	376.4	0.23	6.62	0.21	0.03	0.66	2.59
Jigawa	Gumel	K/Dagariyo (4)	Transect2	Sudan savanna	Loamy Sand	386.5	0.24	6.70	0.23	0.04	0.85	2.05
Jigawa	Mal. Madori	Mal. Madori (10)	Transect1	Sahel savanna	Loamy Sand	360.4	0.21	6.94	0.26	0.13	0.85	2.78
Jigawa	Gwaram	Zandam (10)	Transect2	Sudan savanna	Loamy Sand	394.0	0.20	6.59	0.21	0.05	1.28	2.06
Kano	Bichi	Badume (9)	Transect3	Sahel savanna	Sandy Loam	450.6	0.28	6.84	0.26	0.05	1.49	2.22
Kano	Bichi	Badume (1)	Transect4	Sahel savanna	Sandy Loam	458.0	0.30	6.87	0.30	0.03	1.40	1.83
Kano	Bebeji	Baguda (1)	Transect2	Guinea savanna	Sandy Loam	417.0	0.28	6.82	0.20	0.04	1.40	1.90
Kano	Bebeji	Baguda (5)	Transect3	Guinea savanna	Sandy Loam	444.8	0.28	6.82	0.28	0.06	1.84	2.57
Kano	Bebeji	Baguda (4)	Transect4	Guinea savanna	Sandy Loam	459.3	0.29	6.34	0.20	0.07	1.90	1.95
Kano	Minjibir	Damisawa (4)	Transect2	Sudan savanna	Sandy Loam	414.0	0.28	6.66	0.23	0.04	1.78	1.74
Kano	Minjibir	Damisawa (6)	Transect3	Sudan savanna	Sandy Loam	427.0	0.25	6.95	0.22	0.04	1.78	2.42
Kano	Bebeji	Gwarmai (3)	Transect3	Guinea savanna	Sandy Loam	433.7	0.26	6.68	0.23	0.04	1.23	2.24
Kano	Bebeji	Gwarmai (7)	Transect4	Guinea savanna	Sandy Loam	465.0	0.31	6.43	0.30	0.08	1.67	2.71
Kano	Minjibir	Kazawa (5)	Transect2	Sudan savanna	Sandy Loam	401.5	0.27	6.70	0.24	0.04	1.28	1.93
Kano	Minjibir	Kazawa (5)	Transect3	Sudan savanna	Loamy Sand	427.2	0.27	6.74	0.24	0.04	1.76	2.00
Kano	Bichi	Saye (2)	Transect2	Sahel savanna	Loamy Sand	409.5	0.26	6.61	0.25	0.08	1.80	2.02
Kano	Bichi	Saye (8)	Transect3	Sahel savanna	Loamy Sand	438.5	0.26	7.04	0.23	0.05	2.06	1.99
Katsina	Dutsin-Ma	Garhi (8)	Transect4	Sudan savanna	Sandy Loam	484.0	0.27	7.09	0.25	0.07	1.83	3.72
Katsina	Dutsin-Ma	Garhi (2)	Transect5	Sudan savanna	Loamy Sand	503.5	0.29	6.50	0.25	0.09	1.45	2.43
Katsina	Kafur	Gozaki (10)	Transect5	Guinea savanna	Sandy Loam	518.9	0.33	6.46	0.28	0.07	2.11	2.58
Katsina	Dutsin-Ma	Makera (10)	Transect5	Sudan savanna	Sandy Loam	502.2	0.28	6.70	0.24	0.06	1.39	2.25
Katsina	Kafur	U/Abdu Masari (1)	Transect4	Guinea savanna	Sandy Loam	482.0	0.29	6.65	0.30	0.10	1.30	3.79
Katsina	Kafur	U/Abdu Masari (9)	Transect5	Guinea savanna	Sandy Loam	514.0	0.30	6.34	0.30	0.07	1.12	2.42
Katsina	Zango	Yakubawa (10)	Transect4	Sahel savanna	Loamy Sand	475.6	0.27	7.66	0.22	0.05	2.06	4.25
Katsina	Zango	Zango (5)	Transect4	Sahel savanna	Loamy Sand	484.4	0.29	7.34	0.24	0.05	2.20	3.52
Katsina	Zango	Zango (5)	Transect5	Sahel savanna	Loamy Sand	497.6	0.30	6.73	0.28	0.07	1.70	3.20

In terms of agroecology, significant differences were observed in pairwise comparisons. Notably, there was a statistically significant mean difference between Guinea savanna (low plant population) and Sahel savanna (lowest plant population) ($p = 4.96 \times 10^{-7}$, $p.adj = 1.49 \times 10^{-6}$****), as well as between Guinea savanna and Sudan savanna (lower plant population) ($p = 2.59 \times 10^{-8}$, $p.adj = 7.78 \times 10^{-8}$****). However, no significant difference was recorded when comparing Sudan savanna and Sahel savanna ($p = 6.61 \times 10^{-1}$, $p.adj = 1^{ns}$) (Fig. 6). These results underscore the substantial impact of plant abundance on OC formation and buildup. Interestingly, the Sahel savanna exhibited a higher OC buildup compared to the Sudan savanna, which could be attributed to soil management practices involving consistent application of farm manure to enhance soil structure. This practice is commonly observed in the Sahel study sites and serves to explain that plant population was not a significant contributor to OC content in the Sahel savanna study areas. The importance of organic inputs in maintaining or increasing soil C in Sahelian systems is supported by long-term evidence showing that manure addition can increase soil C, N and P and buffer soil acidification [1].

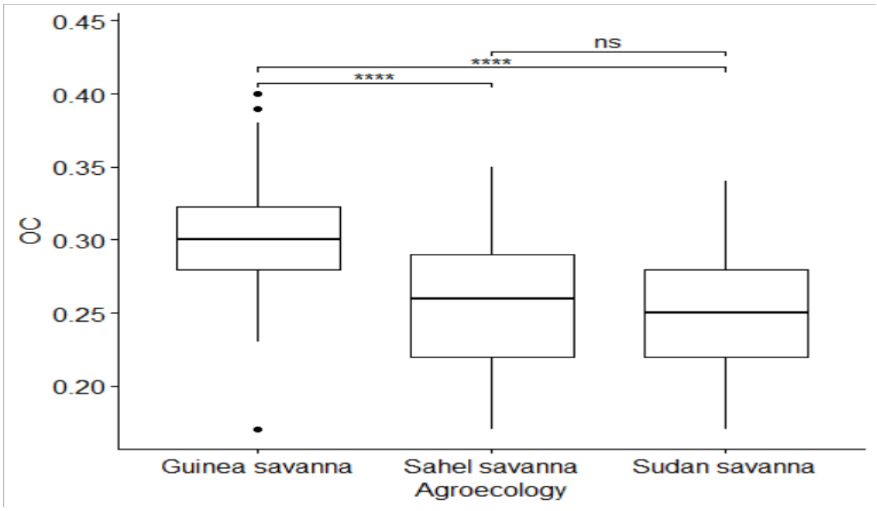


Fig. 6 Boxplot showing statistical significance among agroecological types

A pairwise comparison among the groups comprising the ten potential outcomes, as indicated in Table 2, reveals that the average disparities in organic carbon (OC) are not statistically significant for only three pairs. Specifically, these pairs are Transect2 and Transect3, Transect3 and Transect4 and Transect4 and Transect5. This suggests that these pairs either share the same agroecological characteristics or fall within the transitional zone between Sahel and Sudan savannas.

In terms of soil texture, all the examined soil samples were categorized as either loamy sand or sandy loam, as shown in Table 1 and Fig. 7. The average disparity between these soil

groups exhibited statistical significance (p.adj = 1.81 x 10^{-9}****). Recent research further supports the importance of soil texture in controlling SOC stabilization and nutrient dynamics, because texture affects physical protection, mineral association and the retention and movement of nutrients within the soil profile [17; 21]. Certain soil and land attributes, such as temperature, which is influenced by altitude, may not be amenable to enhancement. When considering land enhancement, it becomes essential to weigh the necessary level of managerial efficiency in terms of both cost and energy, taking into account factors like the findings from Wicaksono *et al*. [34]. Recent studies similarly indicate that elevation-related climatic controls cannot be managed directly at farm scale, whereas soil organic matter, nutrient cycling and soil fertility can be modified through appropriate management interventions [1, 20].

Table 2: Bonferroni-adjusted p-values showing statistic significance between groups

	term	.y.	group1	group2	df	statistic	p	p.adj	p.adj.signif
1	Agroecology	OC	Guinea savanna	Sahel savanna	177	5.220806341	4.96×10^{-7}	1.49×10^{-6}	****
2	Agroecology	OC	Guinea savanna	Sudan savanna	177	5.828410972	2.59×10^{-8}	7.78×10^{-8}	****
3	Agroecology	OC	Sahel savanna	Sudan savanna	177	0.438948371	0.661234301	1	ns
1	SoilTexture	OC	Loamy Sand	Sandy Loam	178	-6.342334425	1.81×10^{-9}	$1.81\ 10^{-9}$	***
1	Transect	OC	Transect1	Transect2	175	-3.36004731	0.000956656	0.009566559	**
2	Transect	OC	Transect1	Transect3	175	-5.20807333	5.32×10^{-7}	5.32×10^{-6}	****
3	Transect	OC	Transect1	Transect4	175	-6.552092254	6.11×10^{-10}	6.11×10^{-9}	****
4	Transect	OC	Transect1	Transect5	175	-8.876124977	8.01×10^{-16}	8.01×10^{-15}	****
5	Transect	OC	Transect2	Transect3	175	-1.84802602	0.066286302	0.662863018	ns
6	Transect	OC	Transect2	Transect4	175	-3.192044944	0.001674998	0.016749979	*
7	Transect	OC	Transect2	Transect5	175	-5.516077667	$1.23\ 10^{-7}$	$1.23\ x10^{-6}$	****
8	Transect	OC	Transect3	Transect4	175	-1.344018924	0.180682104	1	ns
9	Transect	OC	Transect3	Transect5	175	-3.668051647	0.000324101	0.003241013	**
10	Transect	OC	Transect4	Transect5	175	-2.324032723	0.021272638	0.21272638	ns

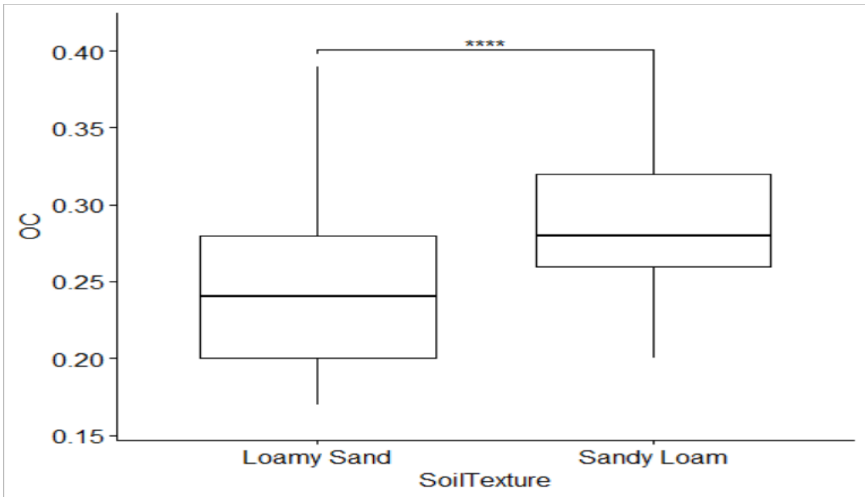


Fig. 7 Boxplot showing mean difference between factor variables

Due to the distinct farming practices observed in certain research areas, particularly within the Sahel savanna regions, we have focused on examining the role of the village as a determining factor. Our aim is to better understand the impact of these practices on the buildup of organic carbon (OC). This management-related interpretation is supported by evidence that long-term organic inputs and improved soil fertility practices can increase soil organic carbon and associated nutrient stocks in savanna and Sahelian agricultural systems [1, 11, 20]. Among the 153 potential comparisons conducted, we have identified statistical significance in 38 instances. Notably, these variations are predominantly noticeable in villages with significant differences in transect width, indicating that altitude plays a pivotal role as the differentiating factor. For a visual representation of these mean distinctions, refer to Figures 8a and 8b.

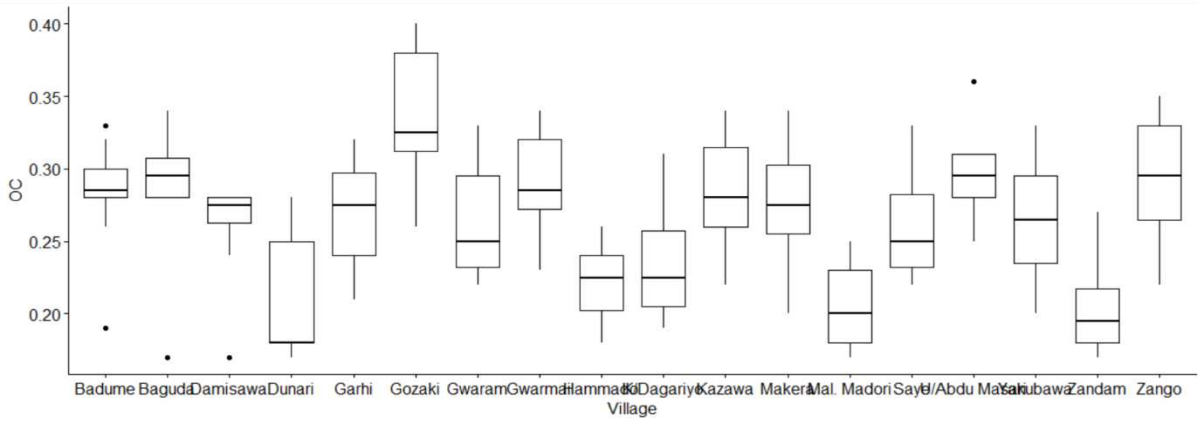


Fig. 8a Boxplot showing the distribution of OC by villages

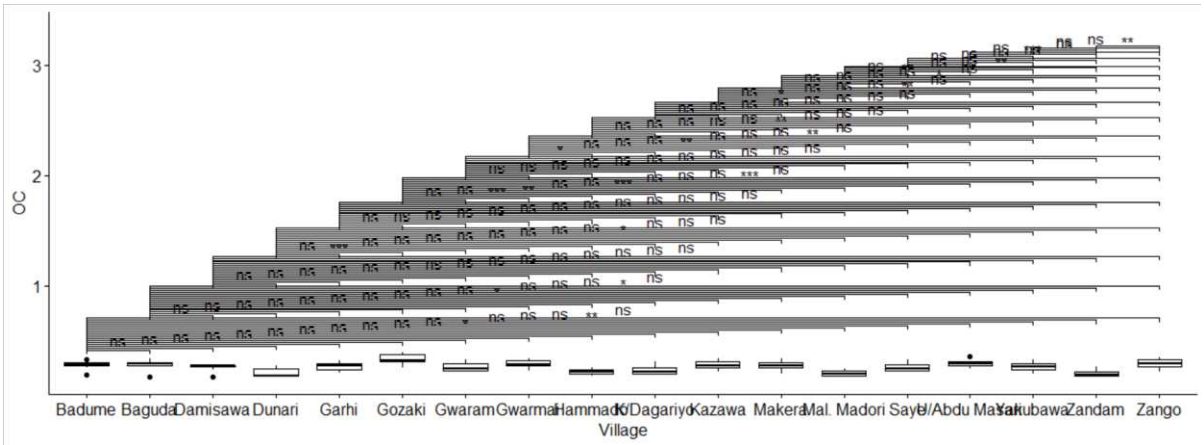


Fig. 8b Boxplot showing significance in the distribution of OC by villages

Moreover, a multivariate analysis of variance was conducted on the dataset to examine the impacts of several variable factors (namely, transect, agroecology, soil texture and village) on various measured soil parameters, including pH, total nitrogen (TN), total phosphorus (TP), potassium (K) and cation exchange capacity (CEC). Notably, the levels of total nitrogen and total phosphorus were found to be unaffected by factors such as site altitude (transect), agroecology type, village and soil texture. Such context-dependent responses are consistent with recent elevation-gradient studies showing that C and N responses to elevation can vary with climatic regime, vegetation and other environmental controls rather than following a single universal pattern [29, 36].

However, a statistically significant variation was observed in village-specific data concerning pH ($F = 1.900$, $p = 3.00 \times 10^{-2}$*) and cation exchange capacity (CEC) ($F = 4.218$, $p = 3.05 \times 10^{-6}$). This suggests that soil amendment practices have an impact on both soil pH and CEC within the village context. This interpretation is consistent with recent evidence that organic amendments and integrated soil fertility management can modify soil chemical properties, including acidity and nutrient retention, in Sahelian farming systems [1, 20]. Exchangeable potassium (K) exhibited significant variations related to agroecology ($F = 4.959$, $p = 2.70\ 10^{-2}$*), soil texture ($F = 4.440$, $p = 3.70 \times 10^{-2}$*) and village ($F = 3.326$, $p = 1.16 \times 10^{-4}$*).

Furthermore, the correlation analysis conducted at different transect levels (Figures 9, 10, 11, 12 and 13) revealed an inverse relationship between pH and transects 1 and 5 (as illustrated in Figures 9 and 13). This suggests that site altitudes ranging from 389 to 518 meters are suitable for cultivating a variety of crops that are less sensitive to pH fluctuations.

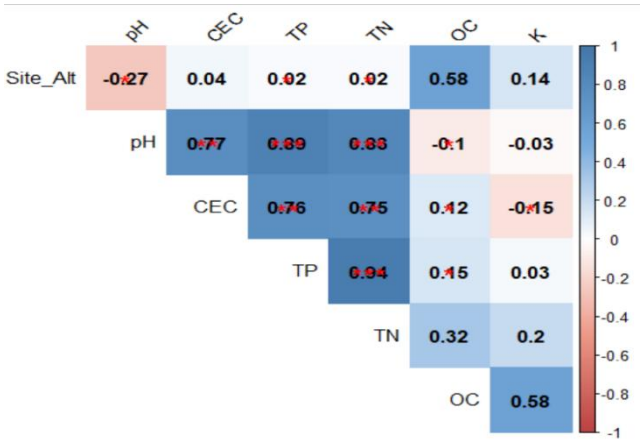


Fig. 9 Corrplot of Transect1

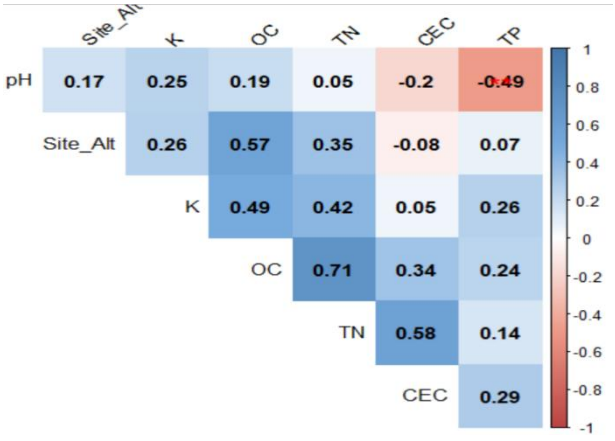


Fig. 10 Corrplot of Transect2

The elevation of the site exhibited a positive correlation with organic carbon (OC) levels across various transects. This relationship was evident in transect 1 (r = 0.58, Fig. 9), transect 2 (r = 0.57, Fig. 10), transect 3 (r = 0.35, Fig. 11) and transect 5 (r = 0.41, Fig. 13). This positive correlation indicated that as altitude increased, the content of organic carbon also increased. However, at transect 4 (r = -0.1, Fig. 12), a negative correlation was observed. This negative correlation could be attributed to the specific agroecology (Sudan savanna) previously mentioned. Recent global and elevational-gradient studies likewise demonstrate that SOC responses to elevation are strongly contingent on climatic conditions, vegetation and local environmental factors, with positive relationships particularly common in lower-latitude systems [29, 36].

Moreover, the association between site altitude and total nitrogen (TN) was consistently proportional across all transects. This relationship indicated that higher altitudes were associated with greater total nitrogen content. Comparable elevation-gradient research has reported coordinated changes in SOC and total N with elevation, while also showing that the strength and direction of these relationships depend on the surrounding environmental conditions [36, 38]. This implies that the synthesis of nitrogen in the soils, coupled with the mineralization process, would progressively increase while keeping agroecology and soil texture constant. This relationship was statistically significant in transect 1 (r = 0.02*, Fig. 9), suggesting an increase in TN with altitude regardless of the influences of agroecology, soil texture and village.

A similar trend was observed for total phosphorus (TP), mirroring the pattern seen with TN, except for transect 4 (Fig. 12), where an inverse relationship with altitude was observed. This suggests that organic matter significantly contributes to the total phosphorus within this transect. Recent national-scale evidence from Nigeria further indicates that SOC, texture, Fe and Al oxide-associated processes jointly regulate available P across contrasting agroecosystems [21]. The negative correlation between site altitude and cation exchange capacity (CEC) was evident in transect 2 (Fig. 10) and transect 5 (Fig. 13). Additionally, a statistically significant negative correlation was found between site altitude and potassium (K) in transect 3 (r = -0.08*). This suggests a limited influence of organic matter on the synthesis of CEC and K as organic carbon content improved in an alternating manner. Such variation is consistent with recent Nigerian evidence showing that soil fertility indicators, including OC, TN, P, K and exchange properties, can vary substantially among management zones and agroecological settings [6, 21].

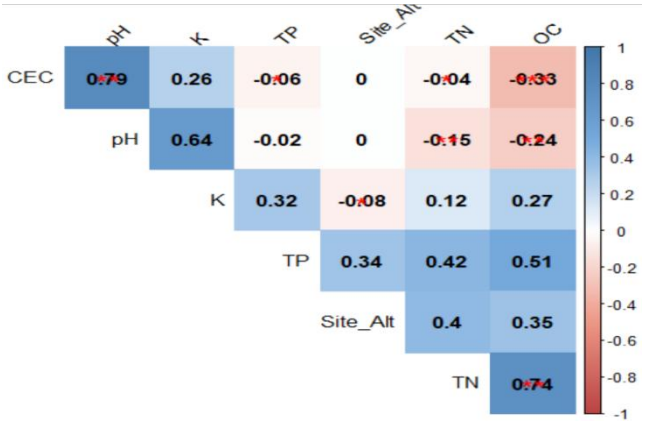


Fig. 11 Corrplot of Transect3

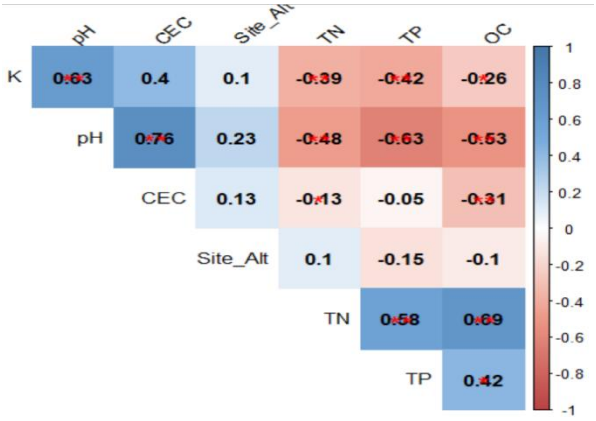


Fig. 12 Corrplot of Transect4

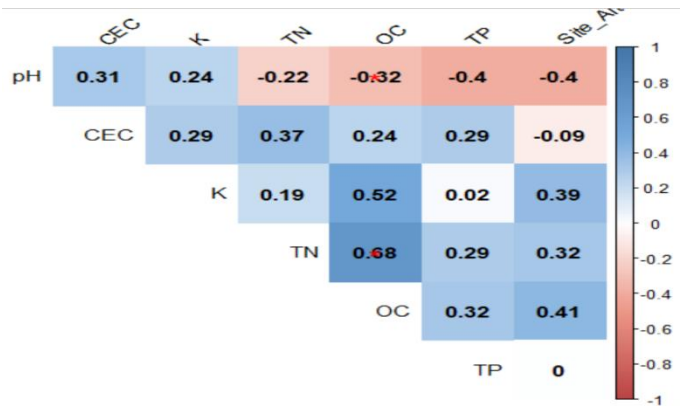


Fig. 13 Corrplot of Transect5

CONCLUSION

The utilized dataset in this study proved to be sufficiently appropriate for drawing dependable conclusions, as it fulfilled all required statistical assumptions necessary for investigating the assessment of soil health within the study locations. The investigation uncovered that the examined variables (transect, agroecology, soil texture and village) exhibited no interdependence in terms of their impact on organic carbon formation and accumulation.

The findings demonstrated that individual variable factors exerted a notable influence on the soil health within the study regions. Notably, it was determined that farmers' management practices at the village level held a predominant influence over the altitude of the majority of study sites. Consequently, altitude, in turn, exhibited a stronger effect on soil health compared to the impact of agroecology. The effect of soil texture was found to be the least influential.

While site altitudes had no significant impact on measured soil parameters such as total nitrogen and total phosphorus, which typically contribute to favorable soil health conditions, they did influence soil pH, potassium (K) and cation exchange capacity (CEC). Generally, a positive correlation was observed between site altitudes and organic carbon content. In conclusion, it can be inferred that altitude indeed plays a substantial role in the formation, accumulation and distribution of organic carbon within the study areas. However, its influence can be superseded by other factors.

DECLARATIONS

Funding Declaration

This research was supported by the Tertiary Education Trust Fund (TETFund), Nigeria, through its research intervention programme at Ahmadu Bello University, Zaria, Nigeria.

Clinical Trial Number

Clinical trial number: not applicable.

Ethics, Consent to Participate, and Consent to Publish

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

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DATA AVAILABILITY

The datasets generated and analysed during the current study are provided as supplementary material accompanying this article. The supplementary dataset contains the soil health measurements and associated information (data) collected during the research work.

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- SupplementaryDataSoilHealthNorthwestNigeria.csv