Hindawi
Applied and Environmental Soil Science
Volume 2022, Article ID 5111635, 14 pages
https://doi.org/10.1155/2022/5111635

Research Article

Assessing the Spatial Variability of Soil Properties to Delineate Nutrient Management Zones in Smallholder Maize-Based System of Nigeria

Helen Peter-Jerome,[1] **Julius B. Adewopo**,[1] **Alpha Y. Kamara**,[1] **Kamaluddin T. Aliyu**,[1] **and Mansur U. Dawaki**[2]

[1]*International Institute of Tropical Agriculture, PMB 5320, Ibadan 700001, Oyo, Nigeria*
[2]*Department of Soil Science, Bayero University Kano (BUK), Kano, Nigeria*

Correspondence should be addressed to Helen Peter-Jerome; h.peter@cgiar.org

Received 16 July 2021; Revised 18 February 2022; Accepted 28 March 2022; Published 20 May 2022

Academic Editor: Durgesh Kumar Jaiswal

Spatially explicit information on soil variability is relevant for agronomic decisions; however, such information is limited in the northern Guinea savanna (NGS) agroecological zone of Nigeria. This study was conducted to delineate soil nutrient management zones (MZs), based on spatial variability of soils in the smallholder maize-based farming system within the NGS. Two hundred and eighty-nine soil samples were analyzed for some physical and chemical properties. Principal component analysis (PCA) was used to aggregate the soil properties into four principal components, which accounted for about 60% of the variation in the data, and spatial variability was assessed with a semivariogram. The ordinary kriging technique was used to predict soil properties at unsampled locations, while weighted overlay analysis was conducted to delineate nutrient management zones. Results showed that total nitrogen (0.06%), available phosphorus ($5.6\,\mathrm{mg\,kg^{-1}}$), organic carbon (0.66%), and effective cation exchange capacity ($5.6\,\mathrm{cmol_{(+)}\,kg^{-1}}$) are below optimal requirement for maize production. Four MZs were identifiable in the region with the highest fertility (MZ3 and MZ4) associated with the northern area but covering a relatively small part (9.1%). The differences observed in soil properties among the MZs suggest that each zone requires different agronomic management, especially in relation to fertilizer application.

1. Introduction

The northern Guinea savanna agroecological zone (NGS) of Nigeria is considered the most suitable zone for cereal crop production especially maize [1, 2]. Maize is the most popularly cultivated crop in this region [3] and mostly cultivated by smallholder farmers [4]. Soil properties of this area vary spatially due to the consolidated effect of biological, physical, and chemical processes over time [5]. Farming practices such as irrigation and fertilization together with soil-forming factors such as parent materials, climate, topography, and time also affect the spatial variability of soils [6].

Understanding the variation in soil properties within the maize belt region is important in determining production constraints associated with soil nutrients. The heterogeneous nature of the soil has an impact on ecosystem processes that controls nutrient cycling [7]. Hence, preventing soil degradation and enhancing soil health and fertility status could be achieved by incorporating sustainable soil management practices using the knowledge of soil properties spatial variation [8].

The development of several improved technologies (disease and drought resistance varieties, improved cropping, and fertilization practices) to enhance maize productivity in the NGS area proved promising; unfortunately, these have yielded different results [9–12] due to the underlying large soils spatial variation [13–15]. In addition, yields measured from farmers' fields are variably low; ranging from 1.1 to 2 $t{\cdot}ha^{-1}$ and representing <21% of the yield potential [16].

Over the years, geostatistics is one of the most effective tools used to study the variation and spatial distribution of soil nutrients [8,17]. Geostatistics is a tool for estimating soil property values in nonsampled areas or areas with scanty sampling. It provides a set of statistical tools for the description of spatial patterns, quantitative modeling of spatial continuity, spatial prediction, and uncertainty assessment [18]. Scientists have also used this tool to develop spatial variability maps of soil properties [19–21].

Furthermore, information obtained from spatial variability maps have been used in delineating relatively homogeneous nutrient management zones (MZs) [8, 15, 22, 23]. Nutrient management zones are the most general approach used to manage field spatial variability [24] because MZs are symmetric subregions with similar characteristics affecting yield or with the same yield productivity [25, 26]. Nutrient management zones can help address economic and environmental concerns resulting from improper soil and nutrient management.

Management of soil fertility is one of the challenging problem in the maize belt region of Nigeria because the soils are generally characterized by low nutrient status caused by the sandy nature of the soils [27], low use of organic and inorganic fertilizers [28], the impact of soil erosion caused by water [29], and absence of site-specific nutrient management guide [30]. These factors have led to a decrease and high variability of yield, especially among fields of smallholder farmers, who do not have access to relevant information on inherent variation in soil fertility levels and typically assume that national (blanket) nutrient recommendations are universally applicable to address farm-level soil nutrient deficiencies [30].

The same fertilizer recommendation is used across the study area even though researchers [1, 3, 15] have shown the need for more/less in some areas. In addition, extension systems and policymakers require reliable information on soil variability to guide agronomic intervention and address the yield gap. In this study, we hypothesize that geostatistical techniques can be used to assess the spatial variability of soil properties and delineate the maize cropping system into nutrient management zones. The information is expected to guide the recommendation of best-fit nutrient management strategies for smallholder farmers. In view of that, we utilized georeferenced multilocational data from a regional agronomy project (http://www.cimmyt.tamasa.org) to address the following research questions: are the soils of the NGS zone of Nigeria spatially variable, and if so, can the study area be delineated into nutrient management zones using geostatistical techniques?

The above research questions were responded to using the stated objectives:

(1) Assess the spatial variability of soil nutrients in the NGS agroecological zone of Nigeria and develop soil nutrient maps of the study area

(2) Delineate the study area into nutrient management zones that can guide the appropriate application of agronomic inputs in the maize-based cropping system

2. Materials and Methods

2.1. Study Area. The study was conducted in the northern Guinea savanna zone (NGS) of Nigeria in 2018 and 2019. Seventeen local government areas (LGAs) across three northern Nigeria states were selected based on the high production of maize. Six (Faskari, Kankara, Malumfashi, Bakori, Kafur, and Funtua), eight (Giwa, Sabon Gari, Igabi, Makarfi, Lere, Kauru, Ikara, and Soba), and three (Doguwa, Rogo, and Tudun-wada) LGAs were selected in Katsina, Kaduna, and Kano states, respectively (Figure 1).

The area has a growing period of 150–160 days with mean daily minimum temperature ranges between 10°C and 12°C, while the mean daily maximum temperature is about 30°C–32°C. Rainfall (800–1250 mm per annum) is unimodal and lasts from June to October and well distributed through the growing season, while the dry season starts from late October to May [31].

The soils are leached tropical ferruginous soils classified as Typic Haplustalf according to USDA soil taxonomy [32]. Soils of this area have developed on deeply weathered pre-Cambrian basement complex overlaid by the aeolian drift of varying thickness [32]. The soils are porous, well drained, mostly have a higher proportion of sand (46%), and are considered to be fragile [33]. The vegetation of the NGS is covered by shrubs and grasses; the grasses usually wither off as the dry season sets in. Farmers here mostly cultivate maize in a rain-fed condition that they usually intercrop with legumes such as soybeans, groundnut, and cowpea [4].

2.2. Field Selection and Soil Sampling. Multistage sampling design was used for the soil sample collections. Within the three maize-producing states (Kaduna, Katsina, and Kano), 22 sampling grids of 10×10 km were randomly generated using geographical information system (GIS) techniques, and 99 villages were selected within the grids based on accessibility. In each of the villages, at least three maize farms were randomly selected from a village listing of maize producing households, which resulted in a total soil samples of 297.

Five soil samples were collected at a depth of 0–20 cm from each of the 297 farmers' fields based on a W-shape layout, and the samples were composited for each farm. The coordinate at the center of each farm was taken using a smartphone-based application (Open data kit, http://www.opendatakit.org). A total of 297 soil samples were collected using an auger.

2.3. Soil Analysis. The composite soil samples were prepared and analyzed according to laboratory analytical procedures of [34]. A total of 289 soil samples were analyzed out of the 297 samples collected. Seventeen physical and chemical properties of soil (sand, silt, clay, soil organic carbon (OC), potential hydrogen (pH), total nitrogen (TN), available phosphorus (Av.P), exchangeable potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), extractable zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), effective cation exchange capacity (ECEC), and exchangeable acidity (EA)) were analyzed. Soils particles size distribution was

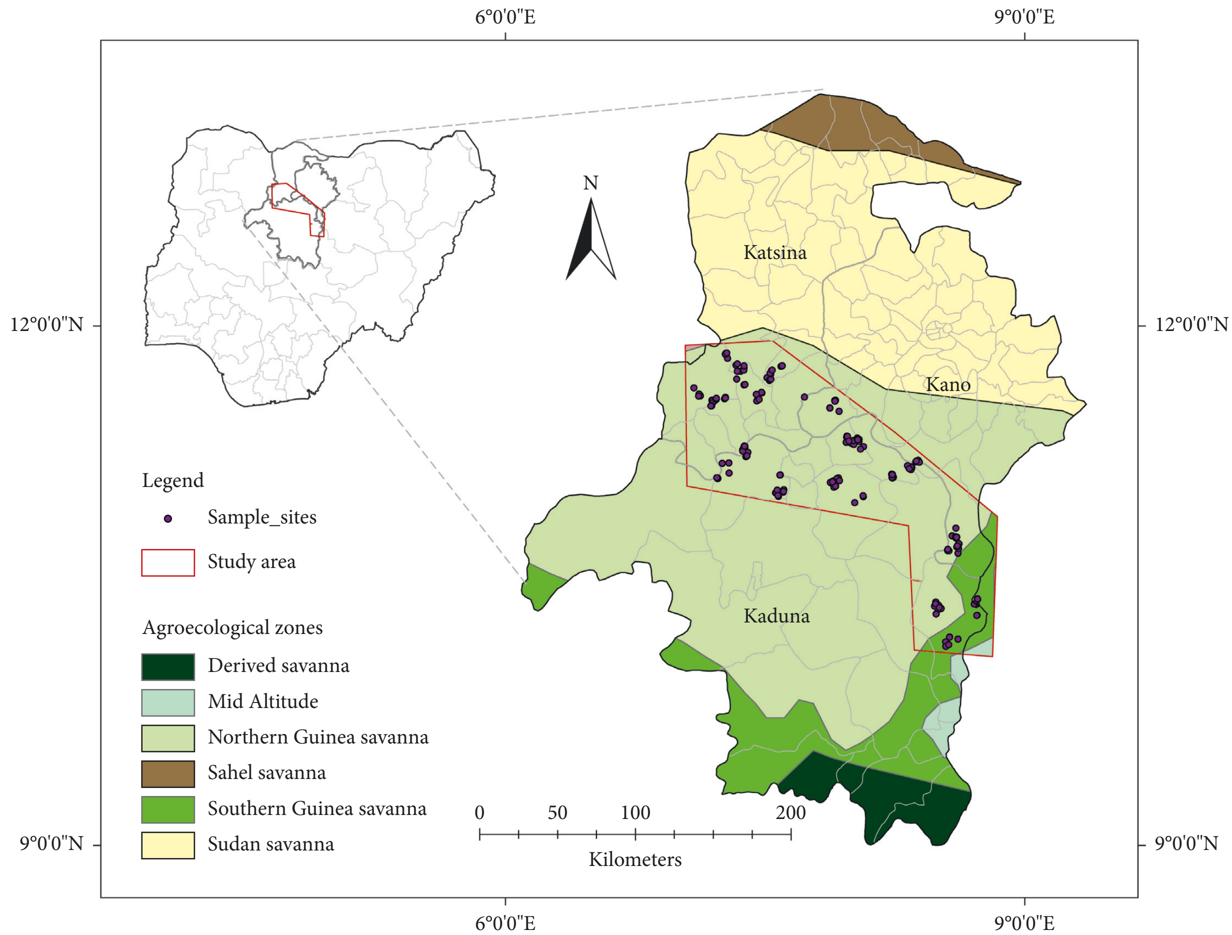

Figure 1: Map showing study location and sampling sites of soils.

determined using the hydrometer method after pre-treatment with H_2O_2 to remove organic matter [35]. Total organic carbon (OC) was measured using a modified Walkley–Black chromic wet chemical oxidation and spectrophotometric method [36]. Total nitrogen (TN) was determined using the micro-Kjeldahl digestion method [37]. Soil pH in water (1:1) was measured using the glass electrode pH meter [38]. Available phosphorus (Av.P), exchangeable cations (K, Ca, Mg, and Na), and micronutrients (Zn, Fe, Cu, and Mn) were analyzed based on the Mehlich 3 extraction procedure [39] and reading with inductively coupled plasma optical emission spectroscopy (ICP-OES). Exchangeable acidity ($H^+ + Al^{3+}$) was determined by extracting the soil with 1 N KCl and titration with 0.5 N NaOH [40]. Effective cation exchange capacity (ECEC) was calculated as the summation of exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, and Na^+) and exchangeable acidity ($H^+ + Al^{3+}$).

2.4. Statistical Analyses

2.4.1. Descriptive Statistics. For each analyzed soil variable, the mean, median, coefficient of variation (CV), standard deviation (SD), and maximum and minimum values were determined using JMP software version 13. Prior to geostatistical analysis, Shapiro–Wilk test of normality was conducted for each soil variable. Log-transformation of some soil parameters values was performed, where necessary, before further analysis. Pearson's correlation coefficient was used to evaluate the relationship among the 17 variables.

2.4.2. Semivariogram Analysis. Geostatistics assumes spatial data analysis with the most common spatial tool variogram as follows:

$$2\gamma(h) = \frac{1}{N(h)} \times \sum_{n=1}^{N(h)} \left[z(u_n) - z(u_n + h)\right]^2, \quad (1)$$

where $N(h)$ = number of data pairs at distance "h," $z(u_n)$ = value at location u_n, and $z(u_n + h)$ = value at location $u_n + h$.

Several models were tested, and the most suitable were selected based on the prediction errors [40]. The predicted values were compared to the measured values using regression analysis. The experimental semivariograms were obtained using the nugget, partial sill, and range. Nugget is defined as the variability at a scale smaller than the sampling interval and or sampling and analytical error; the range is the distance at which the semivariogram stabilizes around a limiting value, while partial sill reflects the amount of spatial structural variance [20].

Mean prediction error (MPE) close to 0 indicates that predictions are unbiased using the following equation:

$$\begin{aligned} \mathrm{MPE} &= \frac{1}{i}\cdot\sum_{j=1}^{1}\left[\hat{Z}(sj) - z^{*}(sj)\right],\\ E\{ME\} &= 0, \end{aligned} \tag{2}$$

where $\hat{z}(sj)$ represents the predicted values, $z^{*}(sj)$ represents actual observations at validation points, and ĭ represents the number of validation sites.

Root-mean-square standardized prediction error (RMSSE) close to 1 indicates that the standard errors are accurate and a low RMSE value, which indicates that the predictions do not deviate much from the measured values [40].

$$\mathrm{RMSSE} = \sqrt{\frac{1}{1}\sum_{i=1}^{1}\left[= z1\left(x_i\right) - z2\left(x_i\right)\right]^2}, \tag{3}$$

where $z1(xi)$ = standardized true value, $z2(xi)$ = standardized prediction value, and

$$\mathrm{RMSE} = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}\left(Z^{*} - Z\right)^2}, \tag{4}$$

where Z^{*} = estimated values, Z = observed values, and n = number of occurrence.

Spatial dependency of soil properties was calculated based on the nugget-to-sill ratio (NSR) as proposed by [20], whereby a nugget-to-sill ratio of ≤0.25 is considered strong, ≥0.25 < 0.75 NSR is considered moderate while ≥0.75 is considered a weak spatial dependence. The ordinary kriging technique [41] was used to generate a continuous surface for each variable. These analyses and calculations were conducted using the geostatistical tool in the ARCGIS 10.4.1 software.

2.5. Delineation of Management Zones (MZs). Principal component analysis and weighted overlay analysis were used to delineate the MZs. Principal component analysis (PCA) was used to summarize the data by aggregating the total variation in the data into principal components (PCs) using JMP software version 13. Principal components were selected based on eigenvalues greater than 1 [42]. The percentage contribution of each PC to the spatial variation in the data set produced from the PCA was used as inputs in the weighted overlay tool of ARCMAP 10.4.1 for the delineation of management zones. Weighted overlay analysis is often applied in multicriteria analysis, especially those related to site selection or suitability modeling [43]. Each selected PC was kriged, converted to a raster, and reclassified into a common preference scale of 1 to 6 before assigning a weight according to its component loading percentage. Since the total weight assigned in weighted overlay analysis must be equal to 100, each PC loading percentage was rescaled prior to the overlay analysis.

3. Results

3.1. Spatial Variability of Soil Properties. Soil particle size fractions indicate a high sand content (47%) relative to clay (27.8%) and silt (25.4%), with a moderate variation among farms (31.8% CV; Table 1). Shapiro–Wilk test shows that most data were skewed, excluding soil pH that exhibited very low variability (8.24%) and a slightly acidic status (6.1–6.5). The total OC of the area was considered low ranging from 0.14% to 1.90% with a CV of 34.34%. The average values of TN (0.06%) and Av.P (5.3 mg kg−1) were low with TN indicating lower variability (37.9%) compared to Av.P (79.6%).

Measured exchangeable cations varied moderately across the fields, with the exception of exchangeable K, which showed greater variability (83.6%), ranging from 0.09 to 2.24 $\mathrm{cmol_+\,kg^{-1}}$. The ECEC and EA values were low [44], that is, <6.0 and <0.1, respectively. High CVs were observed for Zn (160%) and Cu (133%). The average Zn content in the area is rated high (>5 $\mathrm{mg\,kg^{-1}}$), while Cu is rated low (1.0–2.0 $\mathrm{mg\,kg^{-1}}$). The relatively high CVs associated with Cu and Zn are clearly visible in the developed nutrient maps (Figures 2(a)–2(k)) and can also be observed in the legend values.

3.2. Correlation among Soil Properties. A significant correlation exists among the soil properties (Table 2) and is also evident in the spatial variability maps (Figures 2(a)–2(k)).

Soil properties that showed the highest positive significant correlations were between OC and TN ($r = 0.86$), ECEC and Ca ($r = 0.97$), Mg and Ca ($r = 0.66$), and ECEC and Mg ($r = 0.79$). Other important positive correlations between the nutrients were observed with silt and TN ($r = 0.38$), silt and OC ($r = 0.47$), and TN and K ($r = 0.36$). Clay showed a positive significant correlation with OC ($r = 0.38$), TN ($r = 0.40$), and ECEC ($r = 0.22$), while sand was negatively correlated with TN ($r = -0.63$), OC ($r = -0.68$), silt ($r = -0.82$), and clay ($r = -0.54$).

3.3. Semivariogram Analysis. Results of the semivariogram analysis (Table 3) showed that the best-fit theoretical models for most of the soil properties were exponential and stable models except for clay and Cu for which the circular model was best-fitted. The spatial dependency of these properties is measured using the nugget-to-sill ratio (36, 18). Generally, pH, TN, Av.P, exchangeable K, ECEC, EA, Ca, Zn, Mn, Fe, sand, and silt have a strong spatial dependence with a nugget-to-sill ratio of less than 0.25%, while clay, pH, OC, Mg, Na, and Cu showed a moderate spatial dependence with NSR greater than 25% but less than 75%.

Validation metrics for the semivariogram show that the modeled spatial structure for the soil properties is reliable with R^2 values ranging from 0.54 to 0.99 (Figure 3) and approximate values of MPE close to 0, RMSSE close to 1, and low RMSE values for most of the soil properties (Table 3).

The calculated MPE, RMSSE, and RMSE serve as evidence of the reliability of the selected models used for

Table 1: Descriptive statistics of soil properties.

Soil properties	Mean	SD	CV	Kurtosis	Skewness	Minimum	Maximum	Shapiro–Wilk test
Sand (%)	47.35	15.05	31.78	−1.57	0.18	21.00	69.20	<0.0001
Silt (%)	25.38	11.25	44.33	−1.01	−0.34	7.60	49.00	<0.0001
Clay (%)	27.75	8.14	29.35	0.07	−0.56	2.00	44.72	<0.0001
pH (1:1)	6.27	0.52	8.24	0.11	−0.02	4.92	8.10	0.133
OC (%)	0.66	0.23	34.34	3.49	1.19	0.14	1.90	<0.0001
TN (%)	0.06	0.02	37.90	6.66	1.90	0.02	0.19	<0.0001
Av.P (mg kg^{-1})	5.26	4.19	79.59	13.07	3.03	0.08	34.08	<0.0001
Ca ($cmol_+$ kg^{-1})	3.88	1.72	44.20	0.60	0.81	0.80	9.53	<0.0001
Mg ($cmol_+$ kg^{-1})	1.21	0.55	45.93	4.86	1.58	0.20	4.57	<0.0001
K ($cmol_+$ kg^{-1})	0.29	0.25	83.62	15.20	3.06	0.09	2.24	<0.0001
Na ($cmol_+$ kg^{-1})	0.14	0.05	37.29	7.39	2.47	0.01	0.40	<0.0001
ECEC ($cmol_+$ kg^{-1})	5.59	2.21	39.56	0.80	0.87	1.45	13.72	<0.0001
Zn (mg kg^{-1})	13.60	21.81	160.35	8.88	2.82	0.54	128.48	<0.0001
Cu (mg kg^{-1})	1.99	2.65	133.01	63.22	7.15	0.23	30.57	<0.0001
Mn (mg kg^{-1})	83.09	60.27	72.54	11.73	2.69	0.04	482.33	<0.0001
Fe (mg kg^{-1})	134.31	47.51	35.37	4.23	1.25	50.12	420.76	<0.0001

Note. SD: standard deviation, CV: coefficient of variation, OC: organic carbon, TN: total nitrogen, Av.P: available phosphorus, Ca: calcium, Mg: magnesium, Na: sodium, K: exchangeable potassium, ECEC: effective cation exchange capacity, Zn: zinc, Cu: copper, Mn: manganese, Fe: iron, and EA: exchangeable acidity.

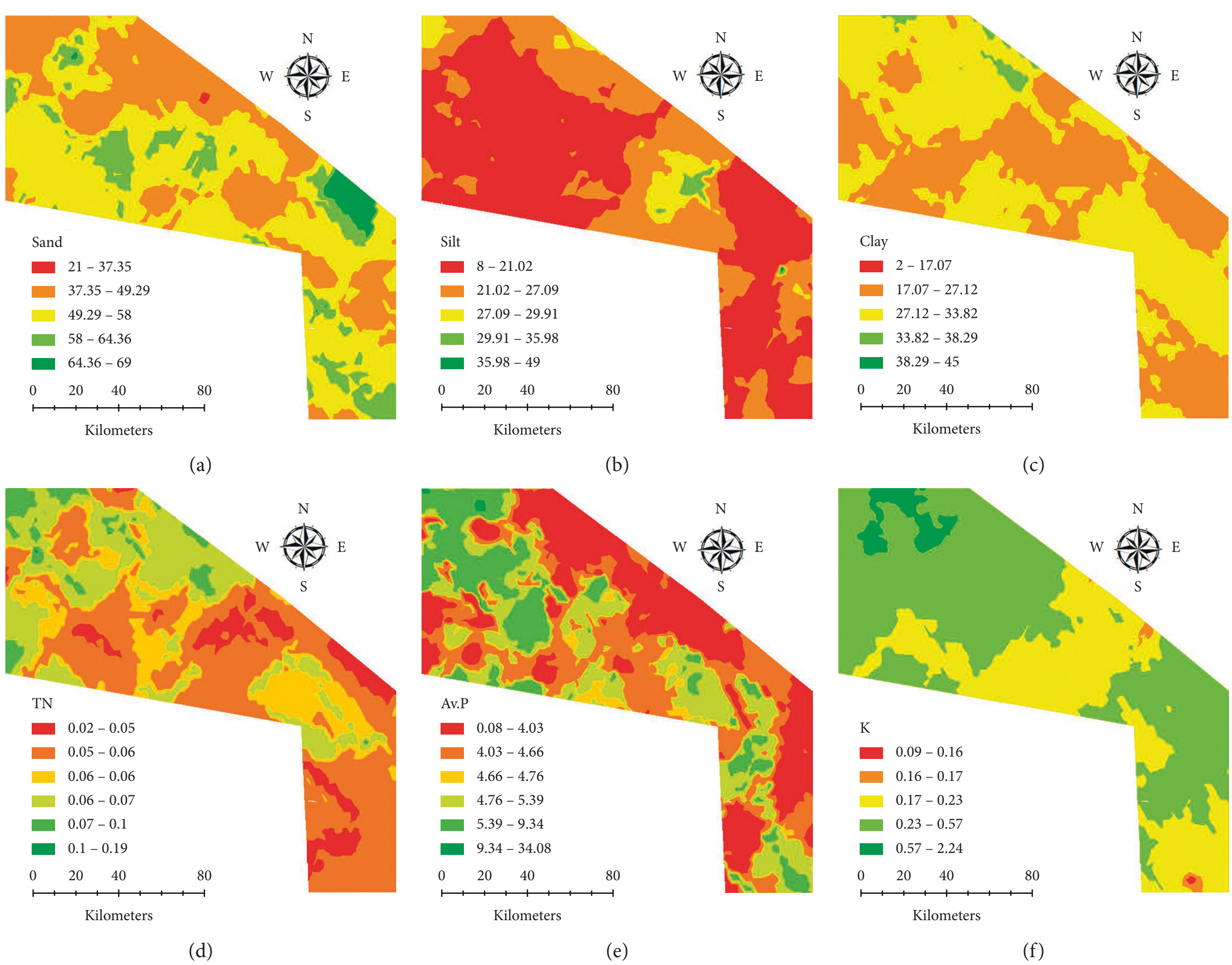

Figure 2: Continued.

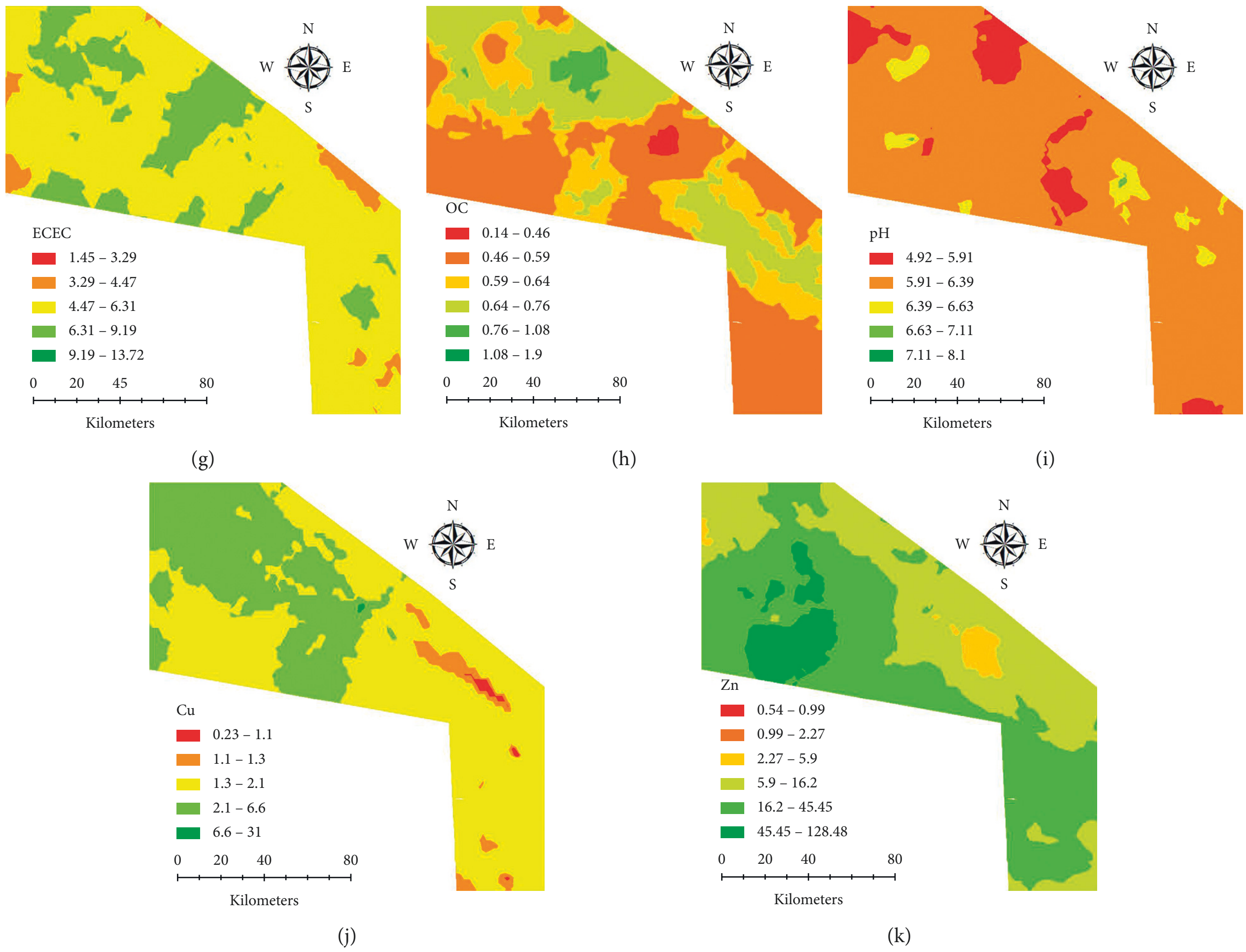

Figure 2: Spatial variability maps of soil properties: (a) sand (%), (b) silt (%), (c) clay (%), (d) total nitrogen (TN%), (e) available phosphorus (Av.P mg kg^{-1}), (f) exchangeable potassium (K cmol(+) kg^{-1}), (g) effective cation exchange capacity (ECEC cmol(+) kg^{-1}), (h) soil organic carbon (OC %), (i) potential hydrogen (pH), (j) copper (Cu), and (k) zinc (Zn).

developing the spatial variability maps (Figures 2(a)–2(k)). From the spatial maps, it was observed that TN (Figure 2(d)) increased in the northward direction (0.2%). Similarly, organic carbon increased from 0.46% to 2.0% towards the north. Available P content was very low in the eastern part of the study area (0.08–4.03 mg kg^{-1}) as shown in the legend (Figure 2(e)), while pH and ECEC values were relatively uniform with few patches where high or low values were predicted. Soil exchangeable K map indicates medium concentration (Figure 2(f)) though higher values were observed around the northern part. The silt spatial map (Figure 2(c)) was slightly uniform for most parts of the study area but higher silt content was observed in the central region. The soil reaction map (pH) for the study area shows that the soils were slightly acid with few patches showing strongly acidic conditions (Figure 2(i)).

3.4. Principal Component Analysis (PCA). Principal component analysis that is a mathematical technique for reducing the dimensionality of data by minimizing a large data set into a smaller one and still maintaining information of the large data set [38] was used to quantify and aggregate the 17 studied soil properties variability into principal components (PCs). Hence, four PCs were selected based on their eigenvalues (>1; Table 4). The four PCs accounted for 60.35% of the total variability in the data set. Maps for the PCs are presented in Figure 4 with PC1, PC2, PC3, and PC4 explaining 23.5%, 19.4%, 10.7%, and 6.72% of the total variance, respectively. From the PCA loading matrix (Table 4), it is observed that PC1 was dominated by sand, OC, TN, and Ca; PC2 accounted for silt, Mg, K, Na, EA, and ECEC and PC3 was dominated by pH, while Av.P dominated PC4.

3.5. Weighted Overlay Analysis for Delineating MZs. Based on the rescaled loading values, PC1, PC2, PC3, and PC4 were assigned values of 39%, 32%, 18%, and 11%, respectively (Table 4), in the weighted overlay analysis to generate the nutrient MZs. Based on the management zone map (Figure 5), MZ1 covered 40.9% of the study area; MZ2 covered 49.9%; MZ3 covered 8.9%, while MZ4 covered a very small portion (0.3%). In general, the concentrations of most major nutrients (TN, AV.P, and OC) were low in the MZs, although a comparison between nutrient management zones MZ3 and MZ4 showed higher nutrient concentrations in MZ4.

Table 2: Pearson's correlation matrix of soil properties in the study area.

Soil properties	pH	Sand (%)	Silt (%)	Clay (%)	OC (%)	TN (%)	Av.P ($mg\ kg^{-1}$)	Ca^{2+} ($cmol_+\ kg^{-1}$)	Mg^{2+} ($cmol_+\ kg^{-1}$)	K^+ ($cmol_+\ kg^{-1}$)	Na^+ ($cmol_+\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)	Cu ($mg\ kg^{-1}$)	Mn ($mg\ kg^{-1}$)	Fe ($mg\ kg^{-1}$)	EA	ECEC ($cmol_+\ kg^{-1}$)
pH	1.00																
Sand (%)	−0.13*	1.00															
Silt (%)	0.18**	−0.82**	1.00														
Clay (%)	−0.06	−0.54**	0.07	1.00													
OC (%)	0.00	−0.68**	0.47**	0.38**	1.00												
TN (%)	−0.01	−0.62**	0.38**	0.40**	0.86**	1.00											
Av.P ($mg\ kg^{-1}$)	0.13*	0.00	0.02	−0.02	0.01	−0.02	1.00										
Ca ($cmol_+\ kg^{-1}$)	0.05	−0.16**	0.00	0.23**	0.26**	0.37**	0.01	1.00									
Mg ($cmol_+\ kg^{-1}$)	−0.04	−0.04	−0.06	0.07	0.15**	0.24**	−0.12*	0.66**	1.00								
K ($cmol_+\ kg^{-1}$)	−0.05	−0.04	−0.16**	0.18**	0.27**	0.36**	0.07	0.23**	0.20**	1.00							
Na ($cmol_+\ kg^{-1}$)	0.28**	−0.34**	0.44**	−0.02	0.14*	0.11	−0.04	0.14*	−0.03	−0.20**	1.00						
Zn ($mg\ kg^{-1}$)	−0.19**	0.23**	−0.33**	0.03	−0.07	−0.04	−0.02	0.02	0.02	0.11	−0.22**	1.00					
Cu ($mg\ kg^{-1}$)	−0.12*	0.06	−0.15	0.10	0.10	0.17**	−0.03	0.19**	0.15**	0.23**	−0.12*	0.05	1.00				
Mn ($mg\ kg^{-1}$)	−0.21**	0.03	−0.14*	0.12*	0.01	0.08	−0.08	0.16**	0.17**	0.22**	−0.22**	0.13*	0.12*	1.00			
Fe ($mg\ kg^{-1}$)	0.01	−0.36**	0.27**	0.19**	0.40**	0.35**	−0.05	0.01	−0.10	0.08	0.16**	−0.07	0.00	−0.05	1.00		
EA	−0.30**	0.37**	−0.56**	0.13*	−0.13*	−0.11	−0.12*	0.10	0.21**	0.31**	−0.53**	0.32**	0.18**	0.28**	−0.16**	1.00	
ECEC ($cmol_+\ kg^{-1}$)	0.02	−0.14*	−0.04	0.22**	0.27**	0.39**	−0.02	0.97**	0.79**	0.35**	0.08	0.04	0.21**	0.20**	−0.01	0.18**	1.00

Note. OC: organic carbon, TN: total nitrogen, Av.P: available phosphorus, Ca: calcium, Mg: magnesium, Na: sodium, K: exchangeable potassium, ECEC: effective cation exchange capacity, Zn: zinc, Cu: copper, Mn: manganese, Fe: iron, and EA: exchangeable acidity. **Correlation is significant at 1% probability level. *Correlation is significant at a 5% level of probability.

Table 3: Best-fitted semivariogram model parameters of soil variables of the study location.

Soil properties	Nugget	Sill	NSR	SDC	Range (km)	Model	RMSE	RMSSE	MPE
pH	0.003	0.010	0.31	Moderate	31.07	Exponential	0.50	1.2	0.01
Sand (%)	0.032	0.145	0.22	Strong	6.09	Exponential	14.90	1.2	0.12
Silt (%)	0.000	0.404	0.00	Strong	68.14	Stable	9.79	1.8	−0.47
Clay (%)	0.134	0.200	0.67	Moderate	2.14	Circular	8.05	0.9	−0.14
OC (%)	0.028	0.054	0.52	Moderate	34.87	Stable	0.23	1.1	0
TN (%)	0.027	0.846	0.03	Strong	8.26	Stable	0.02	1.4	0
Av.P (mg kg^{-1})	0.146	0.941	0.16	Strong	17.51	Exponential	4.45	1.93	−0.04
K ($cmol_+$ kg^{-1})	0.058	0.241	0.24	Strong	12.92	Exponential	0.21	1.8	−0.01
ECEC ($cmol_+$ kg^{-1})	0.000	0.018	0.00	Strong	2.00	Stable	2.13	1.15	−0.07
EA	0.000	0.004	0.00	Strong	22.53	Stable	0.04	2.5	0
Ca ($cmol_+$ kg^{-1})	0.000	0.193	0.00	Strong	2.99	Stable	1.64	0.97	0.01
Mg ($cmol_+$ kg^{-1})	0.086	0.203	0.42	Moderate	11.01	Exponential	0.60	1.4	−0.03
Na ($cmol_+$ kg^{-1})	0.084	0.168	0.50	Moderate	28.30	Exponential	0.04	0.8	0
Cu (mg kg^{-1})	0.133	0.404	0.33	Moderate	6.73	Circular	2.55	2.1	−0.14
Zn (mg kg^{-1})	0.051	2.319	0.02	Strong	21.65	Stable	23.00	4.5	−0.92
Mn (mg kg^{-1})	0.215	0.670	0.32	Strong	10.16	Exponential	63.40	3.2	2.05
Fe (mg kg^{-1})	0.000	0.078	0.00	Strong	0.07	Stable	47.70	1.2	−0.61

OC: organic carbon, TN: total nitrogen, Av.P: available phosphorus, Ca: calcium, Mg: magnesium, Na: sodium, K: exchangeable potassium, ECEC: effective cation exchange capacity, Zn: zinc, Cu: copper, Mn: manganese, Fe: iron, EA: exchangeable acidity, NSR: nugget-to-sill ratio, SDC: spatial dependency class (strong <25%, moderate 25–75%, weak >75%), RMSE: root mean square error, RMSSE: root mean square standardised error, and MPE: mean prediction error.

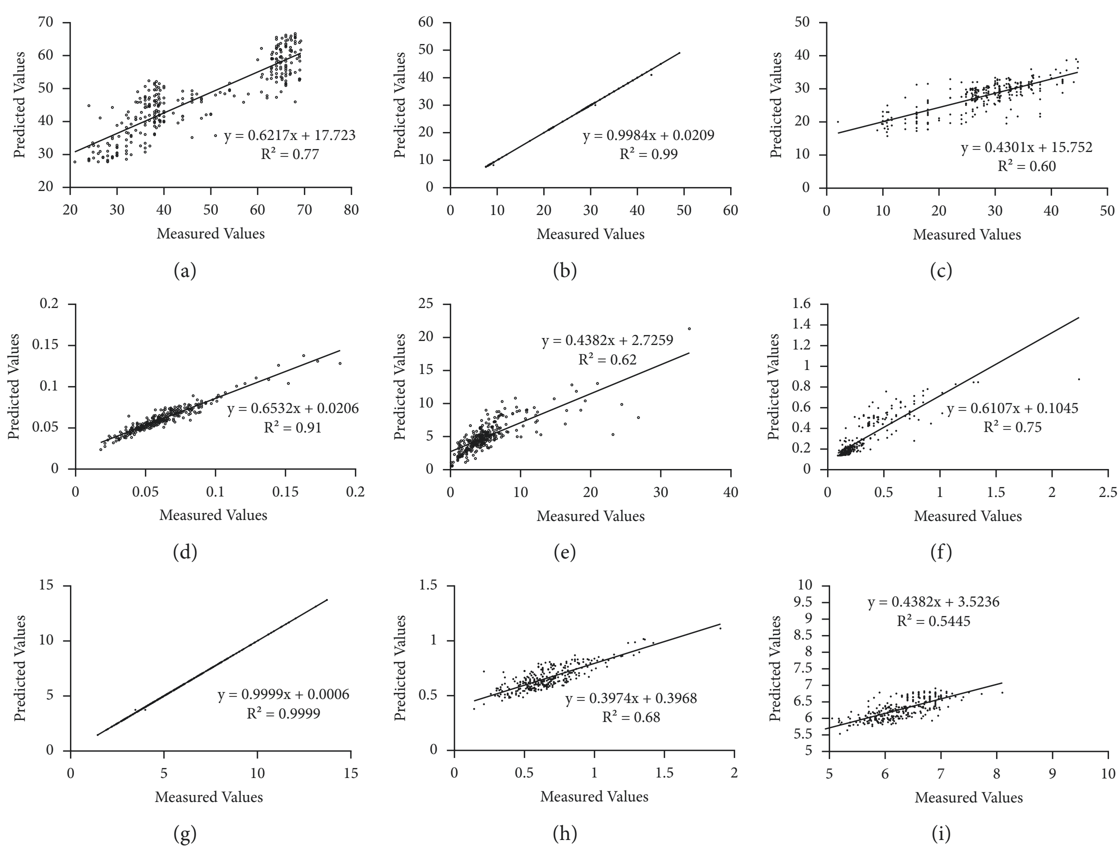

Figure 3: Relationship between measured and predicted values of the soil properties. ECEC = effective cation exchange capacity and pH = potential hydrogen.

4. Discussion

The higher sand fraction (47%) observed from the particle size distribution compared to silt and clay fractions can be attributed to the parent materials that form soils of NGS, as the soils were predominantly developed on deeply pre-Cambrian basement complex rocks such as granite [45]. Furthermore, the dominance of sand may be linked to the sorting of materials by clay eluviation and surface wind erosion [28]. The spatial variability of soil pH in the area is

Table 4: Principal component analysis and loading coefficient of selected principal components of soil properties.

Principal component	Eigenvalues	Component loading (%)	Cumulative percent (%)	Weight assigned (%)
1	3.9982	23.519	23.519	39
2	3.3029	19.429	42.947	32
3	1.8157	10.681	53.628	18
4	1.1416	6.715	60.343	11
5	0.9428	5.546	65.889	
6	0.9016	5.304	71.192	
7	0.817	4.806	75.999	
8	0.8053	4.737	80.736	
9	0.7575	4.456	85.191	
10	0.7069	4.158	89.35	
11	0.5698	3.352	92.702	
12	0.4153	2.443	95.145	
13	0.3713	2.184	97.328	
14	0.288	1.694	99.023	
15	0.1253	0.737	99.76	
16	0.0408	0.24	100	
17	0	0	100	

	Principal component loadings for each soil property																
	pH	Sand	Silt	Clay	OC	TN	Av.P	Ca^{+2}	Mg^{+2}	K^+	Na^+	Zn	Cu	Mn	Fe	EA	ECEC
PC1	0.118	−0.819	0.592	0.506	0.825	0.841	−0.009	0.576	0.392	0.292	0.348	−0.190	0.131	0.054	0.421	−0.246	0.579
PC2	−0.334	0.379	−0.619	0.147	−0.053	0.081	−0.093	0.548	0.594	0.494	−0.491	0.389	0.382	0.448	−0.231	0.727	0.638
PC3	0.426	0.192	0.030	−0.380	−0.320	−0.269	0.058	0.496	0.473	−0.255	0.432	−0.259	−0.112	−0.203	−0.347	−0.288	0.477
PC4	0.402	0.076	−0.133	−0.009	0.070	0.074	0.827	−0.003	−0.169	0.396	−0.138	0.008	0.110	−0.207	−0.048	−0.030	−0.005

Note. OC: organic carbon, TN: total nitrogen, Av.P: available phosphorus, Ca: calcium, Mg: magnesium, Na: sodium, K: exchangeable potassium, ECEC: effective cation exchange capacity, Zn: zinc, Cu: copper, Mn: manganese, Fe: iron, EA: exchangeable acidity, and PC: principal component.

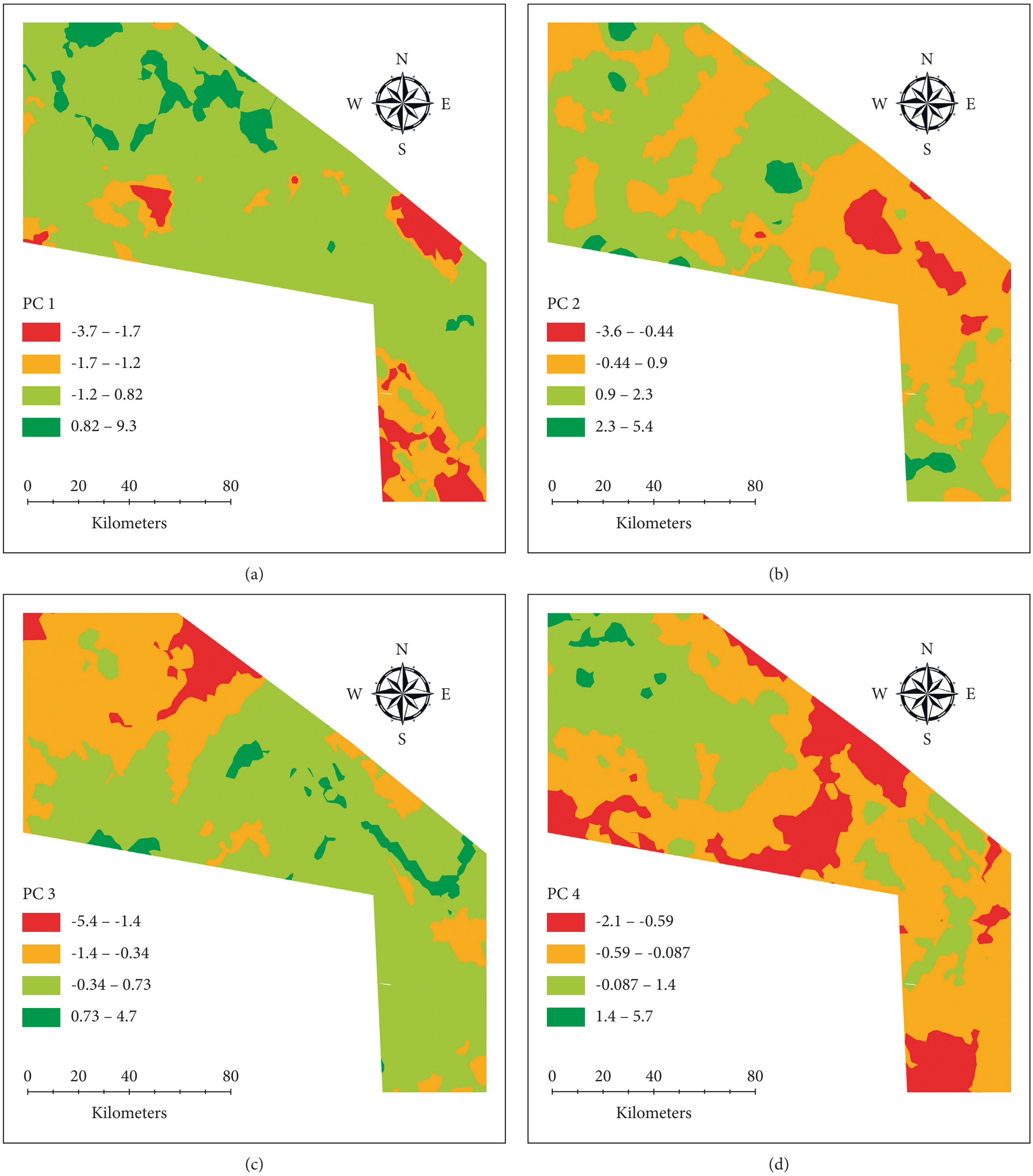

Figure 4: Maps of selected four principal components (PCs).

small, and the soils are slightly acidic that makes the soils of the study area suitable for maize cultivation [46]. Garba [3] and Aliyu [15] obtained similar pH values. The slightly acidic soils of the NGS are associated with the inefficient and continuous use of nitrogenous fertilizers in the area [14]. Nevertheless, there is no concern for extreme soil acidity issues in this maize-based system because the average exchangeable acidity $(Al + H)$ is less than 1 $cmol_+ \ kg^{-1}$.

Total nitrogen, OC, and Av.P content are considerably low when compared to the soil fertility ratings proposed by [44]. While the variability of TN and OC was moderate, it was high for Av.P. Reports of [3,47] indicated that Av.P is usually more variable than most other macronutrients. The low contents of TN, OC, and Av.P might be attributed to the sparse vegetation of the area accompanied by continuous cultivation, bush burning, high rate of mineralization, and removal of crop residues from the field [14,48]. The observed

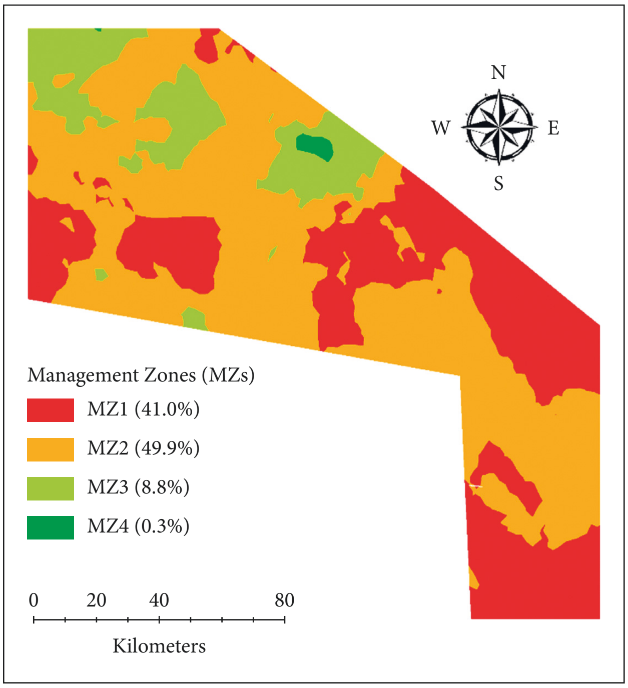

Figure 5: Management zones map for the study area.

low nutrient contents suggest that major interventions and agronomic recommendations should focus on optimizing the availability of major nutrients, with careful focus on maintaining pH balance.

High exchangeable K content of the area was similarly obtained by [3,14] who reported an average content of 0.3 $cmol_+ kg^{-1}$. The high exchangeable K has been attributed to the high level of K-bearing Feldspar minerals in the sand and silt fractions of the study area and the residual effect of the continuous K application from NPK fertilizer in the fields every season [14]. Calcium dominated the exchange site of the studied soils though; according to ratings by [44], the obtained Ca content is rated moderate (2–5 $cmol_+ kg^{-1}$), while Mg content is rated high (>1 $cmol_+ kg^{-1}$). In addition, the ECEC content of the soil is rated low (<6.0 $cmol_+ kg^{-1}$). Similar ECEC content has been reported in most studies conducted in the area [3,6,14]. The obtained low ECEC could be due to the predominance of sesquioxides and kaolinite clays [49] over 2:1 clay minerals in the soil.

Micronutrient contents of the soils were sufficient for most cultivated crops in the area. The micronutrient levels observed are associated with the pH status of the studied soils. At soil pH levels >7, the availability of micronutrients in soil is minimized, but at pH levels of 5.0–6.5, micronutrients are available in the soils for plant use [50,51]. The high Fe content (134 $mg\,kg^{-1}$) observed can be linked to soils of the basement complex rocks that are considered to contain adequate available Fe compounds like haematite and goethite. Similarly, redox reactions resulting in the replacement of exchangeable cations with Al and Fe leading to an increase in the degree of leaching may be responsible for the high Fe content [52]. The high CVs observed for most micronutrients in the area relate to findings by [1,3,15] and have been linked to the spatial variability of other soil nutrients and the heterogeneous management practices, especially the use of fertilizers by smallholder farmers in the area over time, thus stressing the urgent need for site-specific nutrient management.

The positive correlation that exists among OC, N, P, and K reveals the importance of organic manure application in the study area. Since N and P are the major limiting nutrients in maize cultivation of the studied soils [1,3], cultural practices such as cereal-legume crop rotation, preservation of crop residue, and application of well-managed manure could be necessary for OC improvement in the study area [53–55]. The significant negative correlation between sand and TN, OC, and ECEC also explains the low fertility status of this area. Sand-dominated soils promote easy leaching of soil nutrients [55]. Thus, the addition of organic manure will help in improving the nutrient status of these soils.

Exponential, stable, and circular models were the best-fit models for the semivariograms. Findings by [8,56] showed that properties of soils were best described using these models. The spatial dependency class of the soils differed among the various soil properties. Soil properties that exhibited strong spatial dependence might be due to the soil-forming factors such as climate, parent materials, topography, and other natural factors significantly playing a role in the spatial variability of the soils, while soil properties with a moderate spatial dependence might be as a result of the interaction between the inherent soil characteristics and the land use management [8,20,22,23]. The range values of the semivariogram models were large, which is another indication that the estimated properties of soils are influenced by natural factors over large distances [23].

Furthermore, the validation metrics ($R^2 \geq 0.9$, MPE < 0.1, RMSSE near 1, and low RMSE) for most of the soil properties (silt, TN, ECEC, EA, Ca, Zn, and Fe) indicate that the semivariogram models are reliable for prediction of the soil properties at unsampled locations. For this reason, the spatial variability maps produced can be used for decision-making on site-specific inputs management. The increase in TN, K, and OC in the kriged maps (Figures 2(a)–2(i)) towards the north can be linked to the abundance of livestock in the area [57]. The northern part also received less rainfall compared to the southern part of the study area, which may have resulted in N leaching, as noted by [58]. The northern part of the study area had relatively lower sand and higher clay contents compared to the southern part. This may be a major factor favoring the maximal accumulation of soil nutrients in the northern part of the study area (Figures 2(a)–2(k)).

Fertility status of the study area can be rated MZ4 > MZ3 > MZ2 > MZ1 with MZ4 and MZ1 having the highest and lowest fertility status, respectively. The higher fertility level of MZ3 and MZ4 (located in the northern part) conforms to the soil properties map (Figures 2(a)–2(k)), which shows considerably higher TN, OC, clay, Av.P, K, and ECEC contents. This may be attributed to the high rate of manure application practiced by most farmers in those areas through livestock grazing activities [59]. Considering that a large portion (40.8%) of the study area is located in the least fertile zone (MZ4), site-specific nutrient management needs to be encouraged as blanket fertilizer recommendations may be incompatible with the need for efficient nutrient management in this smallholder farming system. Consequently, fertilizer recommendations cannot be generalized to the study area. Maize production might be more challenging in MZ1 and MZ2 compared to other zones due to the poor soil fertility levels observed in those regions.

5. Conclusion

Spatial variability of 17 soil chemical properties within the Nigeria Guinea savanna was assessed to develop nutrient management zones for the maize belt zones. The most limiting nutrients (TN and P) required for maize production were discovered to be insufficient in the soils of the area, and most of the nutrients contents were highly variable. The nugget-to-sill ratio of less than 0.25 for most of the soil properties (sand, silt, TN, exchangeable K, Av.P, ECEC, Ca, Mg, Zn, MN, and Fe) from the geostatistical analysis indicates that internal (soil-forming processes) factors were responsible for the spatial dependency of the soil properties. The contrast among the developed management zones based on their soil nutrients was clearly visible in the soil properties maps with the northern part exhibiting higher nutrient contents compared to the southern part of the studied area. Based on these findings, a multiyear assessment of maize yields in these management zones may be relevant to understanding the agronomic significance of the delineated management zones and their implications for the reduced yield gap in the maize cropping system.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no potential conflicts of interest.

Acknowledgments

The authors thank IITA under the auspices of the project "Taking Maize Agronomy to Scale in Africa (TAMASA)" for all the support given, especially with field operations and soil analysis. This research was carried out with funding support from the Bill and Melinda Gates Foundation (Contract no. OPP1113374, Grant no.: PJ-002113).

References

[1] B. M. Shehu, B. A. Lawan, J. M. Jibrin et al., "Balanced nutrient requirements for maize in the Northern Nigerian Savanna: parameterization and validation of QUEFTS model," *Field Crops Research*, vol. 241, Article ID 107585, 2019.

[2] A. I. Tofa, U. F. Chiezey, B. A. Babaji et al., "Modeling planting-date effects on intermediate-maturing maize in contrasting environments in the Nigerian savanna: an application of DSSAT model," *Agronomy*, vol. 10, no. 6, 871 pages, 2020.

[3] I. Ibrahim Ga, J. Mohammed J, A. Yaya Kamar, A. Aminu Adna, and B. Lawan Abdu, "Response of maize to secondary nutrients and micronutrients in the Guinea savanna of Nigeria," *Journal of Agronomy*, vol. 19, no. 2, pp. 120–130, 2020.

[4] J. B. Adewopo, "Smallholder maize-based systems multifunctional land uses in Africa: sustainable food security solutions," in *Earthscan Food and Agriculture Series*, S. Elisabeth and O. Madelene, Eds., pp. 114–129, Routledge, London, UK, 2019.

[5] M. Z. Khan, M. R. Islam, A. B. Salam, and T. Ray, "Spatial variability and geostatistical analysis of soil properties in the diversified cropping regions of Bangladesh using geographic information system techniques," *Applied and Environmental Soil Science*, vol. 2021, Article ID 6639180, 19 pages, 2021.

[6] A. Mouazen, K. Dumont, K. Maertens, and H. Ramon, "Two dimensional prediction of spatial variation in topsoil compaction of a sandy loam field-based on measured horizontal force of compaction sensor, cutting depth and moisture content," *Soil and Tillage Research*, vol. 74, no. 1, pp. 91–102, 2003.

[7] A. Fitter, C. Gilligan, K. Hollingworth, A. Kleczkowski, R. Twyman, and J. Pitchford, "Biodiversity and ecosystem function in soil," *Functional Ecology*, vol. 19, pp. 369–377, 2005.

[8] M. S. Metwally, S. M. Shaddad, M. Liu et al., "Soil properties spatial variability and delineation of site-specific management zones based on soil fertility using fuzzy clustering in a hilly field in Jianyang, Sichuan, China," *Sustainability*, vol. 11, no. 24, p. 7084, 2019.

[9] A. Y. Kamara, S. U. Ewansiha, and A. Menkir, "Assessment of nitrogen uptake and utilization in drought tolerant and Striga resistant tropical maize varieties," *Archives of Agronomy and Soil Science*, vol. 60, no. 2, pp. 195–207, 2013.

[10] A. Y. Kamara, S. U. Ewansiha, and A. I. Tofa, "Yield, N uptake N utilization of early maturing, drought and striga-tolerant maize varieties under low N conditions," *Communications in Soil Science and Plant Analysis*, vol. 50, no. 3, pp. 1–15, 2019.

[11] A. Y. Kamara, A. Menkir, D. Chikoye, R. Solomon, A. I. Tofa, and L. O. Omoigui, "Seed dressing maize with Imazapyr to control striga hermonthica in farmers' fields in the Savannas of Nigeria," *Agriculture*, vol. 10, no. 3, 83 pages, 2020b.

[12] A. A. Adnan, J. M. Jibrin, A. Y. Kamara, B. L. Abdulrahman, A. S. Shaibu, and I. I. Garba, "CERES–maize model for determining the optimum planting dates of early maturing maize varieties in northern Nigeria," *Frontiers of Plant Science*, vol. 8, p. 1118, 2017.

[13] J. Kihara, G. Nziguheba, S. Zingore et al., "Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa," *Agriculture, Ecosystems & Environment*, vol. 229, pp. 1–12, 2016.

[14] B. Shehu, R. Merckx, J. Jibrin, A. Kamara, and J. Rurinda, "Quantifying variability in maize yield response to nutrient applications in the northern Nigerian savanna," *Agronomy*, vol. 8, no. 2, p. 18, 2018.

[15] K. T. Aliyu, A. Y. Kamara, J. M. Jibrin et al., "Delineation of soil fertility management zones for site-specific nutrient management in the maize belt region of Nigeria," *Sustainability*, vol. 12, no. 21, p. 9010, 2020.

[16] O. Oyinbo, J. Chamberlin, B. Vanlauwe et al., "Farmers' preferences for high-input agriculture supported by site-

specific extension services: evidence from a choice experiment in Nigeria," *Agricultural Systems*, vol. 173, pp. 12–26, 2019.

[17] Y. Li, Z. Shi, and J. M. Xu, "Utilization and perspective of geostatistics in soil sciences," *Journal of Soil Water Conservation*, vol. 17, no. 1, pp. 178–182, 2003.

[18] X. L. Sun, H. L. Wang, F. Dermot, W. Fu, H. Tunney, and C. Zhang, "Limited spatial transferability of the relationships between kriging variance and soil sampling spacing in some grasslands of Ireland: implications for sampling design," *Pedosphere*, vol. 29, no. 5, pp. 577–589, 2019.

[19] T. M. Burgess and R. Webster, "Optimal interpolation and imapping of soil properties," *Journal of Soil Science*, vol. 31, no. 2, pp. 315–331, 1980.

[20] C. A. Cambardella, T. B. Moorman, J. M. Novak et al., "Field-scale variability of soil properties in central Iowa soils," *Soil Science Society of America Journal*, vol. 58, no. 5, pp. 1501–1511, 1994.

[21] S. K. Reza, D. C. Nayak, T. Chattopadhyay, S. Mukhopadhyay, S. K. Singh, and R. Srinivasan, "Spatial distribution of soil physical properties of alluvial soils: a geostatistical approach," *Archives of Agronomy and Soil Science*, vol. 62, no. 7, pp. 972–981, 2015.

[22] T. Rahul, N. A. Kumar, D. Biswaranjan et al., "Assessing soil spatial variability and delineating site-specific management zones for a coastal saline land in eastern India," *Archives of Agronomy and Soil Science*, vol. 65, no. 13, pp. 1775–1787, 2019.

[23] M. Zeraatpisheh, E. Bakhshandeh, M. Emadi, T. Li, and M. Xu, "Integration of PCA and Fuzzy clustering for delineation of soil management zones and cost-efficiency analysis in a citrus plantation," *Sustainability*, vol. 12, no. 14, p. 5809, 2020.

[24] R. Khosla and T. Shaver, "Zoning in on nitrogen needs," *Colo. State Univ. Agronomy Newsletter*, vol. 21, pp. 24–26, 2001.

[25] R. Khosla and M. Alley, "Soil-specific nitrogen management on mid-Atlantic coastal plain soils," *Better Crops*, vol. 83, pp. 6-7, 1999.

[26] A. R. Schepers, J. F. Shanahan, J. S. Scheppers, J. S. Schepers, S. H. Johnson, and A. Luchiari, "Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years," *Agronomy Journal*, vol. 96, no. 1, p. 195, 2004.

[27] B. Vanlauwe, J. Diels, O. Lyasse et al., "Fertility status of soils of the derived savanna and northern Guinea savanna and response to major plant nutrients, as influenced by soil type and land use management," *Nutrient Cycling in Agroecosystems*, vol. 62, no. 2, pp. 139–150, 2002.

[28] L. S. O. Liverpool-Tasie, B. T. Omonona, A. Sanou, and W. O. Ogunleye, "Is increasing inorganic fertilizer use for maize production in SSA a profitable proposition? Evidence from Nigeria," *Food Policy*, vol. 67, pp. 41–51, 2017.

[29] A. C. Odunze, S. Azubuike, N. Tarawali et al., "Grain legumes for soil productivity improvement in the northern Guinea savanna of Nigeria," *Journal of Food Agriculture and Environment*, vol. 4, pp. 222–224, 2014.

[30] J. Rurinda, S. Zingore, J. M. Jibrin et al., "Science-based decision support for formulating crop fertilizer recommendations in sub-Saharan Africa," *Agricultural Systems*, vol. 180, Article ID 102790, 2020.

[31] S. Jagtap, "Changes in annual, seasonal and monthly rainfall in Nigeria during 1961-1990 and consequences to agriculture," *Discovery and innovation, Africa Journals Online*, vol. 7, no. 4, pp. 337–348, 1995.

[32] Soil Survey Staff, *New Soil Survey Manual:USDA Handbook*, No.18 US Government Printing Office, Washington, DC, USA, 1981.

[33] B. M. Shehu, J. O. Ogunwole, and J. M. Jibrin, "Physical quality of northern Nigeria savanna Alfisol: influence of *Jatrophacurcas L.* and other land use systems," *Cogent Food and Agriculture*, vol. 2, no. 1, 2016.

[34] IITA (International Institute of Tropical Agriculture), *Procedures for Soil Analysis*, IITA, Nigeria, 1981.

[35] ISRIC/FAO (International Soil Reference and Atomic Centre/ Food and Agricultural Organisation), *Procedures for Soil Analysis*, L. P. Van Reeuwijk, Ed., ISRIC, Wageningen, Netherlands, 2002.

[36] D. Heanes, "Determination of total organic-C in soils by an improved chromic acid digestion and spectrophotometric procedure," *Communications inCommunications in Soil Science and Plant AnalysisSoil Science and Plant Analysis*, vol. 15, pp. 1191–1213, 1984.

[37] J. M. Bremner, "Nitrogen-total," in *Methods of Soil Analysis: Chemical Methods*, D. L Sparks, Ed., pp. 1085–1121, Soil Science Society of America Journal, Madison, WI, USA, 1996.

[38] W. G. Gee and D. Or, "Particle-size analysis," in *Methods of Soil Analysis: Part 4. Physical Methods*, J. H. Dane and G. C. Topp), Eds., vol. 5, pp. 255–293, Soil Science Society of America Book Series, Madison, WI, USA, 2002.

[39] A. Mehlich, "Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant," *Communications in Soil Science and Plant Analysis*, vol. 15, no. 12, pp. 1409–1416, 1984.

[40] A. Z. Njandjock Nouck P, N. P. Nouck, R. Nouayou, J. L. Méli'I, and F. E. Kemgang, "Influence of the variogram model on an interpolative survey using kriging technique," *Journal of Earth Science & Climatic Change*, vol. 06, no. 10, p. 316, 2015.

[41] D. G. Krige, *Lognormal-de Wijsian Geostatistics for Ore Evaluation: Monograph Series No. 1*, SAIMM, Johannesburg, South Africa, 2nd edition, 1981.

[42] R. Sendhil, K. Anuj, S. Singh, A. Vema, K. Venkatesh, and V. Gupta, *Data Analysis Tools and Approaches (DATA) in Agricultural Sciences*, ICAR-Indian Institute of wheat and Barley Research, Karnal, Haryana, 2017.

[43] R. Chaudhari and D. Lal Weighted, "Overlay analysis for delineation of ground water potential zone: a case study of pirangut river basin," *International Journal of Remote Sensing*, vol. 7, no. 1, pp. 2319–3484, 2018.

[44] I. E Esu, *Detailed Soil Survey of NIHORT Farm at Bunkure Kano State, Nigeria*, Ahmadu Bello University Zaria: Kaduna, Nigeria, 1991.

[45] N. Voncir, S. Mustapha, V. A. Tenebe, A. L. Kumo, and S. Kushwaha, "Content and profile distribution of extractable zinc (Zn) and some physicochemical properties of soil along a toposequence at Bauchi, northern Guinea savanna of Nigeria," *International Journal of Soil Science*, vol. 3, no. 2, pp. 62–68, 2008.

[46] I. G. Harun, E. M. Benson, and O. D. Benjamin, "Effect of lime and goat manure on soil acidity and maize (Zea mays) growth parameters at Kavutiri, Embu County- Central Kenya," *Journal of Soil Science and Environmental Management*, vol. 6, no. 10, pp. 275–283, 2015.

[47] M. Karaman, S. Ersahin, and A. Durak, "Spatial variability of available phosphorus and site- specific P fertilizer recommendations in a wheat field," in *Plant Nutrition: Developments Plant and Soil Sciences*, W. J. Horst, Ed., vol. 92, Dordrecht, Netherlands, Springer, 2001.

[48] A. C. Odunze, "Soil properties and management strategies for some sub –humid savanna zone Alfisols in Kaduna state, Nigeria," *Journal of Agricultural Research*, vol. 22, pp. 1–3, 2006.

[49] A. S. Fasina, A. Raji, G. Oluwatosin, O. J. Omoju, and D. Oluwadare, "Properties, genesis, classification, capability and sustainable management of soils from south-western Nigeria," *International Journal of Soil Science*, vol. 10, no. 3, pp. 142–152, 2015.

[50] K. Jackson, T. T. Meetei, and T. Thomas, "Influence of pH on nutrient availability: a review," *Journal of Emerging Technologies and Innovative Research*, vol. 5, no. 2, pp. 707-708, 2018.

[51] M. Sillanpää, "Micronutrients and the nutrient status of soils," in *A Global Study: FAO Soil Bulletin 48*Werner Söderström Osakeyhtiö, Helsinki, Finland), 1982.

[52] L. Maniyunda and M. G. Gwari, "Soils development on a toposequence on loessial deposit in northern Guinea savanna, Nigeria," *Research Journal of Agriculture and Biological Sciences*, vol. 9, pp. 110–116, 2014.

[53] S. Zingore, R. J. Delve, J. Nyamangara, and K. E. Giller, "Multiple benefits of manure: the key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms," *Nutrient Cycling and Agroecosystem*, vol. 80, pp. 267–282, 2008.

[54] B. Vanlauwe, J. Kihara, P. Chivenge, P. Pypers, and R. Coe, "Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management," *Plant and Soil*, vol. 339, no. 1-2, pp. 35–50, 2011.

[55] F. K. Salako, G. Tian, and B. T. Kang, "Indices of root and canopy growth of leguminous cover crops in the savanna zone of Nigeria," *Tropical Grasslands-Forrajes*, vol. 36, pp. 33–46, 2002.

[56] "Spatial analysis of soil properties using GIS based geostatistics models," *Modeling Earth Systems and Environment*, vol. 2, p. 107, 2016.

[57] A. Yusuf, A. Aruwayo, and I. R. Muhammad, "Characterisation of small ruminant production systems in semi-Arid Urban areas of northern Nigeria," *Journal of Applied Sciences & Environmental Management*, vol. 22, no. 5, pp. 725–729, 2018.

[58] Y. Yao, Q. Dai, R. Gao, Y. Gan, and X. Yi, "Effects of rainfall intensity on runoff and nutrient loss of gently sloping farmland in a karst area of SW China," *Plus One*, vol. 16, no. 3, Article ID e0246505, 2021.

[59] A. S. Abdullahi, A. H. Kwaru, K. U. Adamu, and I. D. Sule, "Usage and effectiveness of fertility enhancement techniques among small-holder farmers in the Kano close settled zone, kano state," *Fudma Journal of Sciences*, vol. 4, no. 1, 2020.