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DEVELOPMENT OF SOIL FERTILITY MAP BY GIS TECHNOLOGY FOR WUKARI LOCAL GOVERNMENT AREA OF TARABA STATE

Waizah Yakub

Department of Soil Science and Land Resources Management, Faculty of Agriculture Federal University Wukari, Taraba State, Nigeria

Corresponding authors’ email: waizahyakub@gmail.com   Phone: +2348038223360

ABSTRACT

Soil fertility mapping is critical for site-specific nutrient management as it gives information about soil nutrient content, which is vital for land use, site-specific management, fertilizer recommendations, and sustainable management of soil resources. Semi-detailed soil survey was carried out in Wukari Local Government Area to establish a soil fertility map. A coordinated data collection was designed using GIS in such a way that the entire LGA was divided into grids of 155 blocks, out of which a total of 98 augured samples were collected at the depth of 0-25 cm. All samples collected were analyzed following standard analytical procedures. ArcGIS was used in the creation of the models. The ordinary Kriging interpolation was adopted for soil mapping. Semivariogram analysis fitted into the Gaussian model was used to test the spatial dependence of the soil parameters. Spatial distribution maps were developed with sub-models of 10 classes of raster values; the values of this element were then regrouped based on the documented standards to produce soil nutrient maps showing areas of low, medium, and high concentration. A general soil fertility map was developed using fertility expert judgement based on the contribution of some key fertility elements (pH, N, P, K, S, OC, ECEC, Mn, Zn, and Fe), and the nutrient maps earlier reclassified were combined based on the weighted overlay model in ArcGIS 10.5 to produce one single fertility map with four classes: fertile (F1) 11.88% (51,149.37), moderately fertile (F2) 24.79% (106,703.76), slightly fertile (F3) 55.79% (240,174.70), and low fertility (F4) 7.54% (32,476.78).

Keywords: Kriging, Spatial Distribution, Mapping, Fertility

INTRODUCTION

Wukari Local Government is an agrarian community that engages in farming diverse crops, cereals; Maize, Millet, Sorghum, and Rice, roots, and tubers; Yam, Cassava and Sweet potatoes, Legumes; Sesame, Groundnut, Soybean and cowpea, Vegetables; Tomatoes, Pepper, etc at both subsistence and commercial scale. However, despite the intense and continued cultivation with the eminent consequence of declined soil productivity, there has not been any detailed assessment of the status of the soils of the local government.

Important also is the fact that despite the diversity of crops cultivated in the area, only primary nutrient fertilizers have been in use in the area, with the high possibility of creating nutrient imbalances. Soil fertility mapping is an essential practice in modern agriculture that can enhance fertilizer recommendations, promote sustainable farming practices, and ultimately increase crop production. Investing in soil fertility mapping, farmers can optimize their yields and contribute to a more sustainable and productive agricultural industry. Using soil fertility mapping for site-specific fertilizer recommendations, farmers can make informed decisions about the type and amount of fertilizer needed for each field. This precision agriculture approach allows for targeted fertilization, where fertilizers are applied only where and when they are needed, based on the soil's nutrient levels and crop requirements. This study aims to map the soils of Wukari local government for present and future agricultural development.

MATERIALS AND METHODS

Description of The Study Area

Wukari Local Government is located in the southern part of Taraba State (Figure 1). It is about two hundred kilometers away from Jalingo, the state capital. The local government is bounded by Plateau State in the north, Benue State in the south, Nasarawa State to the west and Bali LGA to the east; it is in the Guinea Savannah of the middle belt region of Nigeria. Geographically it is located between longitude 9° 08′ and 10° 23′ East (392487.77E, 81642288.39N) of the Greenwich Meridian and latitude 7° 35′ and 8° 15′ North (500000.00E, 90539916.70N) of the Equator, with an elevation of 200 m above sea level. (Waizah *et al.*, 2022)

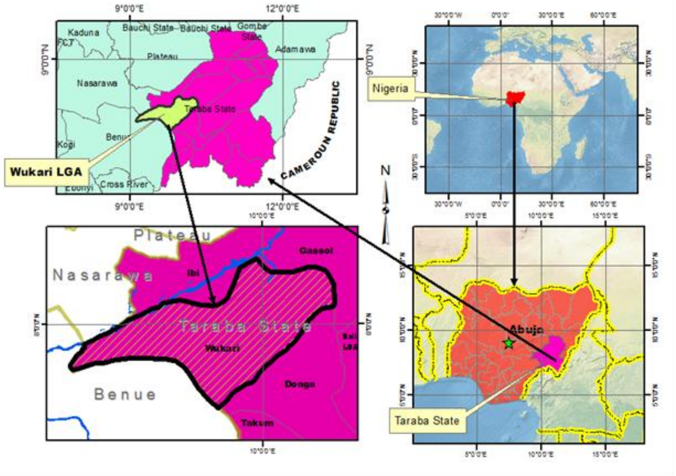

Figure 1: Location of the Study Area

Production of Base Map

Prior to the main survey and fieldwork, a base map of the study area was produced using ArcGIS 10.5. The grid map was used to identify boundaries to fix tentative sampling sites; a general field visual observation and survey by the help of the map of the area was carried out to consolidate and determine sampling points. The exact field location was determined and properly marked with a global positioning system (GPS). The whole study area was divided into a 5,000 by 5,000 m grid (Figure 2). The location of each auger sampling point was geo-referenced before the actual fieldwork.

Soil Sampling

Prior to soil sampling, a coordinated data collection scheme was designed in such a way that the entire LGA was divided into blocks of grids at about 5,000 m^2 using GIS tools; coordinates at the intersection lines of the blocks were extracted. The extraction was done carefully such that all special features of the LGA were added on the georeferenced map environment to avoid taking coordinates from rivers, mountains, built-up areas, and other difficult terrain. The coordinates collected were thereafter loaded into Garmin GPS waypoints. Sample locations were visited using GPS waypoint navigation. Auger samples were collected at the depth of 0-20, after which coordinates of each sample were written and tagged on each sample's container.

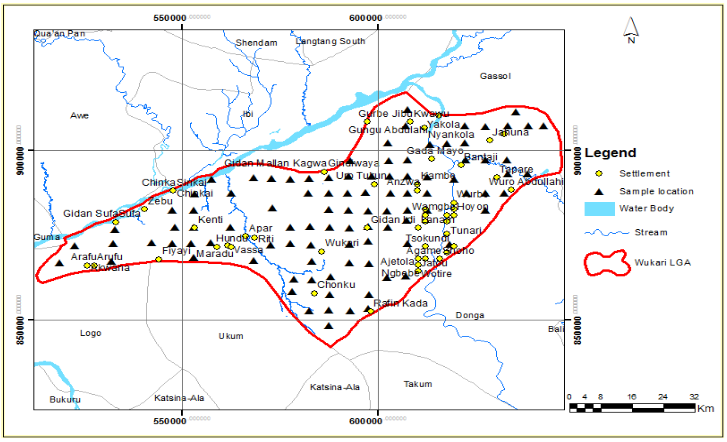

Figure 2: Base Map of the Study Area showing Sampling Coordinates

Soil Sample Preparation and Laboratory Analysis

Soil samples collected were transported to the laboratory for analysis. The soil samples were air-dried at room temperature, ground, and made to pass through a 2 mm sieve in the laboratory for the analysis of the soil parameters except for soil organic carbon (OC) and total N. For the analysis of OC and total N, the soil samples were further passed through a 0.5 mm sieve. The samples were processed and analyzed for major soil chemical properties, which include soil pH, organic carbon (OC), total N, available phosphorus, potassium, sulphur, ECEC, manganese, zinc and iron. The soil pH was determined potentiometrically using a pH meter in the supernatant suspensions of a 1:2.5 soil-to-water ratio as described by Jaiswal (2003). The organic carbon was determined using the Walkley and Black wet oxidation method (Nelson and Sommers, 1982). Total nitrogen was determined by micro Kjeldahl digestion, distillation and titration procedure as described by Jaiswal (2003). The available phosphorus was determined using the Bray I method as described by Bray and Kurtz (1995). The exchangeable potassium was determined by extraction with the neutral 1 N ammonium acetate (NH_4O AC) method (Jaiswal 2003); the potassium in the extract was determined by the flame photometer; and the micronutrients (Mn, Zn, and Fe) were determined using the DTPA extraction method. (Lindsay and Norwell, 1978).

Geostatistical Analysis

Geostatistics is a classical statistic used to analyze and predict the values associated with spatial or spatiotemporal phenomena; statistical and geostatistical analyses of soil fertility were carried out using surface soil. Ordinary kriging (OK) and semivariogram were used for estimation and analysis of spatially dependent variables. The ordinary kriging method is based on the weighted average of adjacent observed points within a given area. OK can predict an unobserved location of variable *z*. Kriging interpolation is given a random process under the condition of the measured value and obtains the unbiased estimation at point Z(xi) data to estimate the sample Z (*xi* + *h*) value according to the formula

$$Z\,(xi + h) = \sum_{i=1}^{N} \lambda_i\, Z\,(x_i,)$$

Where λ = weight of the measured sample points, which is determined by the analysis of variance function. The OK interpolation has the advantage of using semi-variogram information. OK allows prediction of values of non-sampled locations and production of maps exhibiting the spatial distribution of variables.

Building the Geostatistical Model

The geostatistical model here entails the normalized spatial distribution map of major nutrient elements under study. The model showcases unit spatial variations in the distribution of micro- and macronutrients across Wukari LGA. ArcGIS Desktop 10.5's Geostatistical wizard was used in the creation of the models. The ordinary kriging (OK) interpolation method was adopted. The output surface type was set as 'prediction surface' since the model will predict values for un-sampled locations. A semivariogram function was implemented to fit curves to the dataset so as to achieve the best fit; the Gaussian semivariogram model was used. The data was optimized and later used in the predictions. Sill, nuggets and range were all set to generate data for sensitivity analysis.

Mapping Nutrient Concentration

The developed spatial distribution maps and unit class distributions of the elements were reclassified into sub-modals. For example, with 10 classes of raster values grouped during kriging interpolation. The values of this element were then regrouped based on the documented standards to portray where this nutrient concentration is low, medium, and high. This regrouping was implemented through reclassification of pixel values in ArcGIS' spatial analytical tool. All mapped elements passed through this process to show the concentration level of each nutrient under study.

Mapping Soil Fertility

Mapping soil fertility is the decision stage in this study; the decision first involved expert judgement and secondly, a multivariate decision model. The GIS weighted overlay model was implemented using averaged decisions taken by experts in soil nutrients study. The idea was to deploy geospatial techniques in figuring out visibly the portions of Wukari LGA that are highly fertile, fertile, moderately fertile, and not fertile. It is worth noting that nutrient concentration levels affect soil fertility either positively or negatively; in addition, some elements have more positive influential factors than others. These factors were taken into consideration by the soil experts, the researcher, and the weighted overlay model in GIS. Ten elements were selected (pH, N, P, K, OC, S, ECEC, Mn, Zn, and Fe) and ranked by an expert on a scale of 1-100% as they influence soil fertility, and the total marks were summed, after which the mean values were computed.

The mean values now portray the level of influence of each element and its sub-modals when combined to form a fertility map. The overall idea here is to combine all the nutrient concentration maps of these elements earlier reclassified to produce one single map based on the weighted overlay model. Nutrient concentration maps of ten selected elements were inputted in the overlay wizard. The average percentage influence of each element was indicated in the wizard, while the scale values of the elements were populated respectively. The result of the analysis gave birth to only one fertility class map with four classes that were later symbolized into: low fertility, slightly fertile, moderately fertile, and fertile.

RESULTS AND DISCUSSION

Fitted Semivariogram Models for Major Soil Nutrients

The result of geospatial analysis that explains the spatial dependence and variability of the soil parameters, showing their spatial dependence fitted to a Gaussian model, is presented in Table 1. The spatial correlation (range) of the soil parameters varied widely between 8933.49 m for Zn and 41829.84 m for pH. In general, nugget is found to be high in most of the soil properties studied, implying moderate to weak spatial dependence. The nugget-to-sill ratio is used to define the spatial dependence of soil properties; nugget-to-sill ratios of less than 0.25 are considered to have strong spatial dependence within them; the spatial dependence is considered moderate if the ratio is between 0.25 and 0.75 and weak if it is more than 0.75 (Cambardella *et al., 1994*; Antwi ***et al.,*** 2016). The higher ratio indicates that the spatial variability is caused by extrinsic factors, such as fertilization farming practices, cropping systems and other human activities. The lower nugget/sill ratio suggests that the structural or intrinsic factors, such as climate, parent material, topography, soil properties, soil texture and other natural factors, play a significant role in spatial variability.

The semivariogram model nugget-to-sill ratio obtained from the study area indicated strong spatial dependence < 0.25 for organic carbon (0). The strong spatial dependence of OC may be controlled by intrinsic variation in soil properties such as parent material, topography, texture mineralogy and other natural factors (Khallah *et al.*, 2025); this is in conformity with the works of Hedge *et al.* (2018). The nugget-to-sill ratios obtained for manganese (Mn), pH and Zn were 0.59, 0.51 and 0.47, indicating moderate spatial dependence which is controlled by extrinsic variation such as fertilizer application, tillage, soil and water conservation and other management practices. The moderate spatial dependence of these soil parameters implies that the degree of association between the parameters at different locations may increase as the distance becomes closer; this suggests that the soil parameters may exhibit some degree of similarity at a shorter distance in the study area. Therefore, farmers located within a shorter distance are likely to adopt similar fertilizer management strategies regardless of their variation in soil nutrients.

The nugget-to-sill ratios obtained for effective cation exchange capacity (ECEC), iron (Fe), phosphorus (P), potassium (K), and sulphur (S) were 0.93, 0.85, 0.86, 0.96, 0.77, and 0.92, respectively, an indication of weak spatial dependence. As the distance increases, fertilizer management strategies may differ, and their dependence could become weaker or stronger depending on the impact of the management (Johnson and Moen, 1998).

Table 1: Geostatistical Parameters of The Fitted Semivariogramme Models for Soil Properties

Soil Parameter	Model	Spatial Dependence	Nugget	Part/Sill	Range	Sill	Nugget /sill
pH	Guassian	Moderate	0.125375	0.086965	41829.84	0.259381	0.51175
OC	Guassian	Strong	0	6.487022	20743.69	5.778053	0
TN	Guassian	Moderate	0.876339	1.012646	9642.81	1.888979	0.463919
P	Guassian	Weak	13.93511	0.634714	23027.61	14.50777	0.961582
S	Guassian	Weak	0.876823	0.053007	39245.53	0.954428	0.920086
K	Guassian	Weak	0.102412	0.047232	10676.35	0.135592	0.779037
ECEC	Guassian	Weak	0.091174	0.006546	20616.06	0.097991	0.931145
Fe	Guassian	Weak	0.487135	0.11223	16349.81	0.572951	0.853432
Mn	Guassian	Moderate	0.862406	1.38554	13782.10	1.737404	0.593977
Zn	Guassian	Moderate	0.883679	2.002367	8933.49	2.100456	0.473973

KEY: OC=Organic carbon, TN= Total nitrogen, AvP= Available phosphorous, S=Sulphur, K = Potassium, ECEC =Effective cation exchange capacity, Fe= Iron, Mn=Manganese, Zn=Zinc.

Spatial Distribution Map of Major Soil Properties

The spatial distribution maps obtained are useful in understanding spatial variability of soil properties, which can be influenced by natural factors (particle size composition and topography) and anthropogenic factors (land cover and management practices). The ordinary kriging technique was used to switch point samples into continuous fields of soil properties. The spatial variability map of soil properties (pH, N, P, K, OC, ECEC, S, Fe, Mn and Zn) was produced using ArcGIS 10.5.

The spatial distribution of soil pH (Fig. 3) was moderately acidic in most parts of the study area, though slightly acidic to neutral was observed in the western part of the study area around Arufu and Akwana, while total nitrogen (Fig. 4) indicated higher concentrations in the central part of the study area, which includes Wukari municipality, Chunku, Rafin Kada and Gindin Waya, whereas low to moderate concentrations were observed in most parts of the study area. The available P (Fig. 5) was higher in the central part, and low concentrations were observed at the extreme west and eastern corners of the study area, while potassium (Fig. 6) showed some pockets of low to high agglomeration.

The spatial distribution map of organic carbon (Fig. 7) was higher at the central and northeastern parts of the study area, whereas low agglomeration was observed at the extreme east and extreme west of the study area; a similar result was reported by Gouri *et al.* (2018). The higher agglomeration of ECEC (Fig. 8) was found around the Southern part (Rafin Kada and Chunku) and the Eastern part of the study area.

The distribution of sulphur (Fig. 9) showed a low concentration around the central part, while a higher concentration is seen at the western part of the study area. The spatial distribution of iron (Fig. 10) showed a high concentration at the central, western and southern parts, whereas the areas of Chinkai, Kenti, Gidan Idi, Vassa, Wotire, etc. had a low assemblage of Fe. Manganese distribution (Fig. 11) showed high concentration at the southern part covering the areas of Arufu and Akwana and the eastern part; low concentration was observed at Chinkai, Kenti, and Maradu, while zinc (Fig. 12) had medium to high agglomeration at the central to western part of the study area, while low concentration was observed at the eastern part. The spatial relationship of soil properties evidenced the different amount of heterogeneity of field intrinsic factors such as relief, drainage, erosion and soil texture and extrinsic factors such as management practices, irrigation, fertilization etc. (Liu *et al.*, 2006).

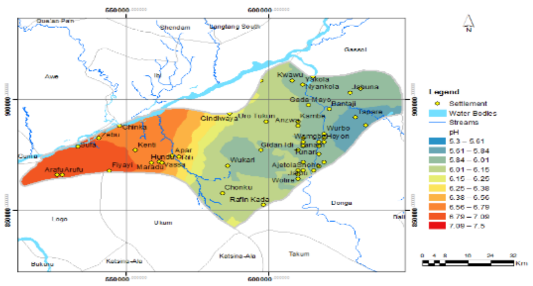

Figure.3: Spatial Distribution Map of pH

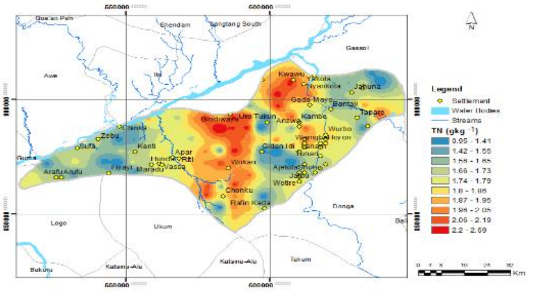

Figure.4: Spatial Distribution Map N

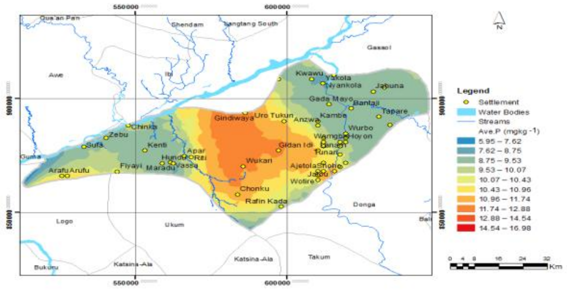

Figure.5: Spatial Distribution Map P

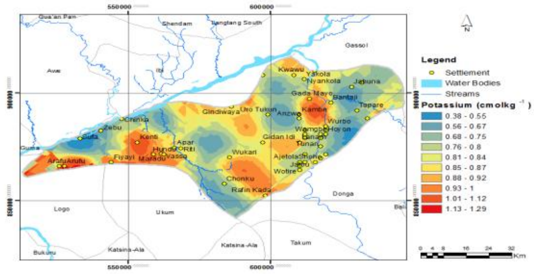

Figure. 6: Spatial Distribution Map K

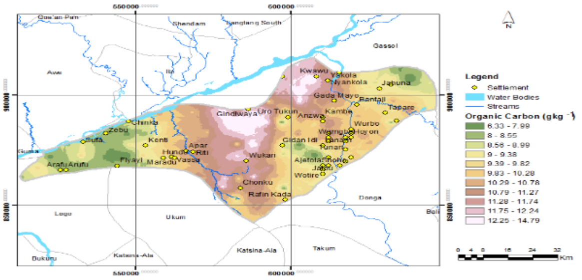

Figure 7: Spatial Distribution Map OC

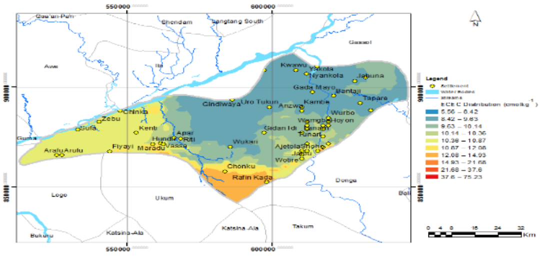

Figure 8: Spatial Distribution Map ECEC

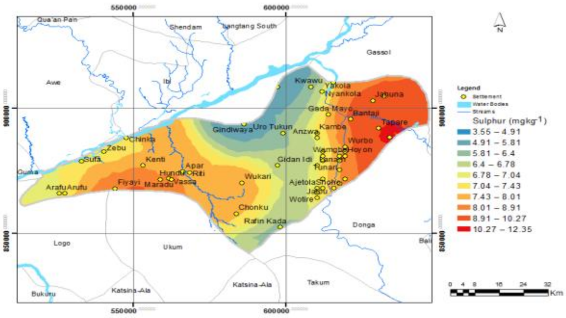

Figure 9: Spatial Distribution Map S

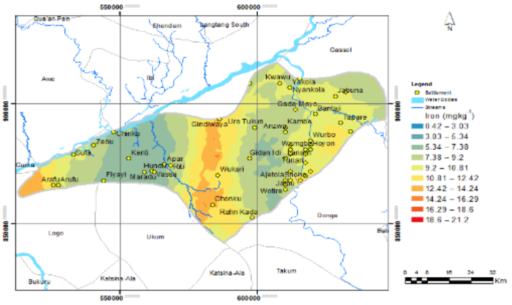

Figure 10: Spatial Distribution Map Fe

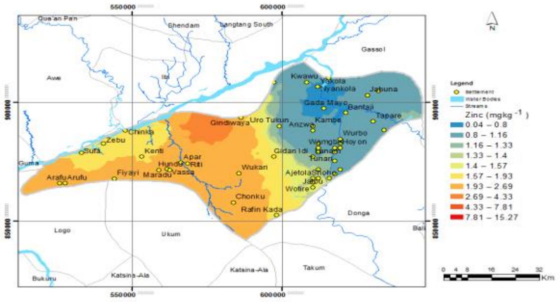

Figure 11: Spatial Distribution Map Mn

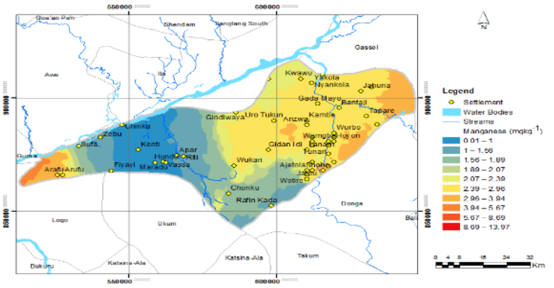

Figure 12. Spatial Distribution Map Zn

Nutrient Maps of Major Soil Properties

Nutrient maps of the soil properties were produced from the developed spatial maps to show areas where the nutrient element is low, medium and high. The soil pH controls the mobility and the availability of soil nutrients (Amacher *et al.*, 2007). Soil pH is one of the most important characteristics of soil fertility because it has a direct impact on nutrient availability and plant growth (Brady and Weil, 2002).

The distribution of soil pH varied from moderately acidic to slightly alkaline; the majority of the study area had a pH ranging between 5.6 and 6.6 (Fig. 13). Most of the soils of the study area are acidic in nature; this may be due to natural systems like mineralogy (soil containing Fe, Al, etc.), climate (excessive rainfall) and weathering, use of acid-forming nitrogenous fertilizers or removal of bases (K, Ca and Mg) (Rawal *et al.*, 2018). The pH of the study area falls within the range for optimal mineral element availability for most crops; a similar result was also reported by Khadka *et al.* (2018).

The total nitrogen content of the soils of the study area is generally medium, with some areas having pockets of low concentration (Fig. 14). The low nitrogen content may be due to low organic carbon content of the soil, crop removal and high temperature, which facilitate faster degradation and removal of organic matter, which may result in nitrogen deficiency. (Khadka *et al.*, 2018; Khadka *et al.*, 2019), this low to medium N requires the application of the full recommended dose of nitrogen for optimum production of crops (Rawal *et al.*, 2018).

The distribution of available phosphorus in the study area showed low to medium, with the central parts having medium-range available P and the western and eastern parts having low available P (Fig. 15). Potassium is an essential macronutrient for plants. It is involved in many physiological processes, which include the activation of a large number of enzymes. It plays an important role in the synthesis of amino acids and proteins from ammonium ions, which are observed from the soil (Rawul *et al.*, 2018). The potassium content of the study area is generally high with pockets of low to medium agglomeration (Fig. 16).

The distribution of OC in the study area is low to medium, with the medium range occupying the central part of the area and low agglomeration at the western, eastern and southeastern parts (Fig. 17). The low organic carbon is mainly due to low organic matter content in the soil of the study area, which is accounted for through the general sparse vegetation and common use of crop residue as animal feed, which constrains its return to the soil (Panday *et al.*, 2018);

The ECEC of the soils of the study area was generally at the medium range with pockets of high ECEC at the southern part around Rafin Kada and some pockets of low around Wukari, Uro Tokun, Jibu Nyankola and the Gurbe area (Fig. 18). The ECEC is an important indicator of soil fertility because it shows the soil's ability to supply three important soil nutrients: Ca, Mg and K. ECEC can be improved by the addition of lime in weathered soil to raise the pH; otherwise, adding organic matter is the most effective way of improving the ECEC of a soil. The distribution of sulphur was low to medium (Fig. 19). Low organic matter content and removal of sulphur by crops without application of sulphur-containing fertilizer might be the cause of the low amount of sulphur in the soil (Balanagoudar, 1989).

Iron is an essential micronutrient for almost all living organisms. It plays a critical role in metabolic processes such as DNA synthesis, respiration, and photosynthesis. (Rout and Sahoo, 2015). The distribution of Fe ranged from low to high, although medium Fe content was more prevalent (Fig. 20). A similar result was reported by Khadka *et al.* (2017) during their studies in different sites of Nepal. The high Fe availability reduces the uptake of different nutrients such as P, K, Mn, and Zn, thus resulting in plants with deficiency stress of these elements (Fageria *et al.*, 2005). The distribution of manganese ranged from low to high but was predominantly medium (Fig. 21). Zn distribution ranged from low to high, with the major part of the study area having medium Zn content (Fig. 22). The map suggests that deficiency of zinc is only noticed in a small portion of the study area; this result is in conformity with the work of Khadka *et al.* (2018).

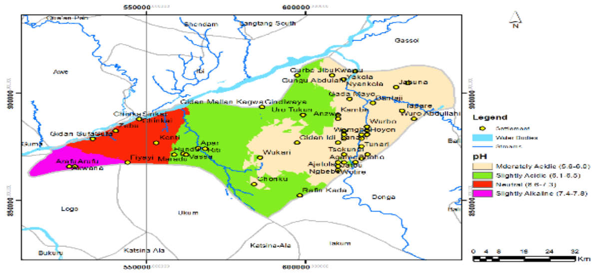

Figure 13: Spatial Distribution Map pH

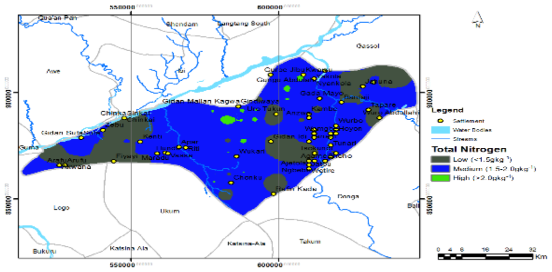

Figure 14: Spatial Distribution Map TN

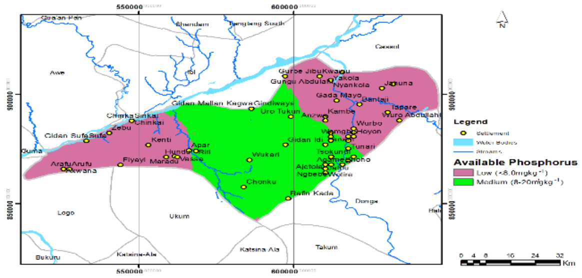

Figure 15: Spatial Distribution Map Av.P

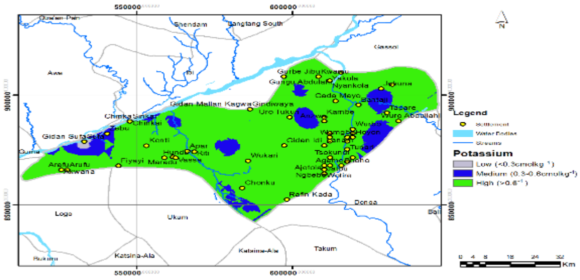

Figure 16: Spatial Distribution Map K

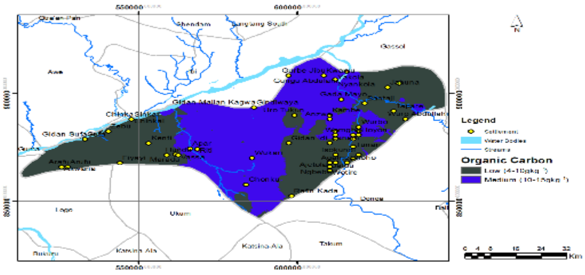

Figure 17: Spatial Distribution Map OC

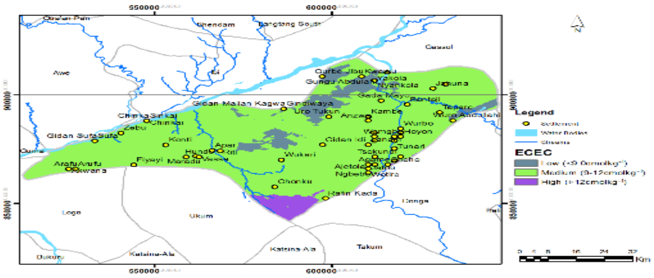

Figure 18: Spatial Distribution Map ECEC

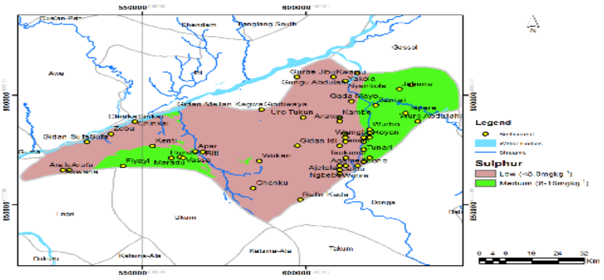

Figure 19: Spatial Distribution map S

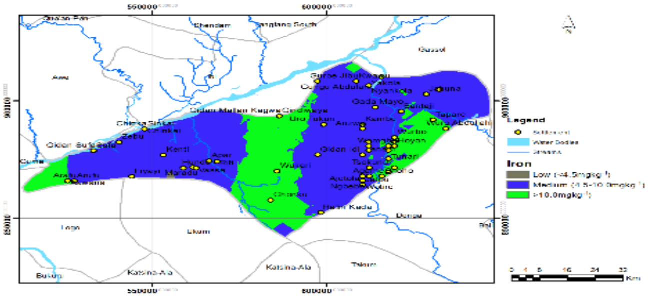

Figure 20: Spatial Distribution map Fe

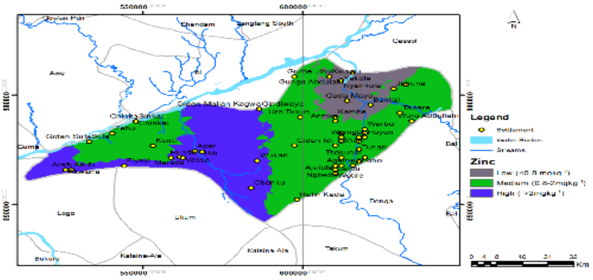

Figure 21: Spatial Distribution Map Zn

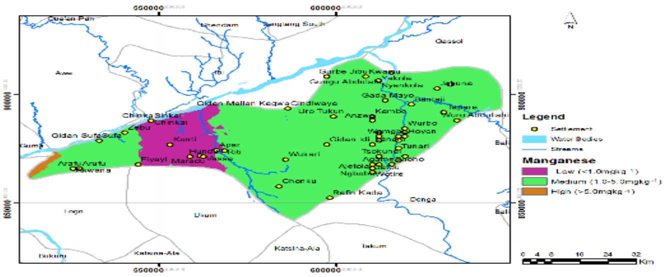

Figure 22: Spatial Distribution Map Mn

Soil Fertility Class Map and Area Evaluation

The result of the soil fertility class map of the study area (Fig. 23) indicates four fertility assessment classes. Fertile (F1), moderately fertile (F2), slightly fertile (F3) and low or non-fertile (F4). The F1 occupies 11.88%, equivalent to 51,149.37 hectares of the total study area, and the F2 occupies 24.79%, equivalent to 106,730.76 hectares, while most of the study area was the slightly fertile F3, which occupies a total of 55.79%, equivalent to 240,174.70 hectares, and the fertile area, or area of low fertility, occupies 7.54%, equivalent to 32,476.78 hectares.

The F1 assessment class of the study area is slightly acidic pH to slightly alkaline pH at the extreme. It has moderate organic carbon, phosphorus, nitrogen, manganese and effective cation exchange capacity, while the zinc and potassium content are high but available sulphur is low. These values place this fertility class within the fertile soils, which will be good for most crop production with minimal fertilization. The F2 class has the second largest coverage of the study area (24.79%). The soil is characterized by low to moderate nitrogen, moderate phosphorous, organic carbon, effective cation exchange capacity and manganese. The soil is slightly acidic with high iron and zinc but low available sulphur; this characteristic place the area within the moderate fertility class and requires fertilization for optimum crop production.

The F3 fertility class includes most of the study area. The soil of this fertility class is characterized by low to moderate effective cation exchange capacity, moderate manganese, nitrogen, iron and zinc, low organic carbon and phosphorous, high potassium content and moderately acidic to neutral pH. These values place this area within the slightly fertile fertility class. In the F4 fertility class, low soil fertility is a common problem in many regions of the world, especially the tropical soils (FAO, 2011). This fertility class includes a small portion (7.54%). It is located in the northeastern part of the study area. The F4 class is characterized by low nitrogen, phosphorous and organic carbon with moderate micronutrients (Zn, Fe and Mn); the potassium content of this class is high, and the soil is moderately acidic. For optimum crop production proper management and fertilization should be employed to improve and enhance its capacity.

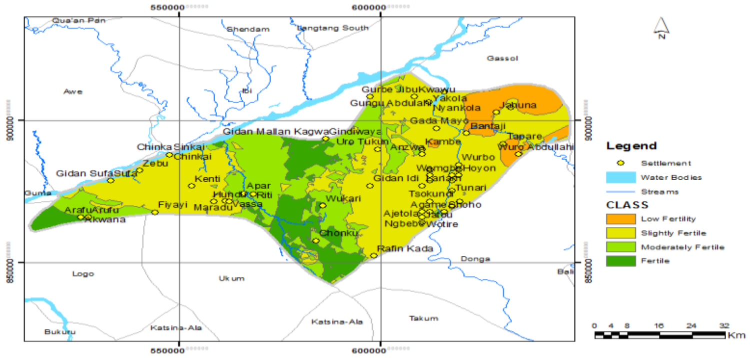

Fig. 23 Soil Fertility Class Map

CONCLUSION

The maps of soil chemical properties were found effective in explaining the distribution of soil properties in non-sampled locations based on sampled data. Understanding the spatial distribution and accurate mapping of soil characteristics are essential for precision farming, environmental monitoring and modelling.

The soil fertility map of the study area was generated using GIS with four fertility assessment classes. The fertile soil class was 11.8% of the total area and has slightly acidic to slightly alkaline soil pH, moderate OC, P, N, Mn and ECEC, and high Zn and K content, the moderately fertile class covers 24.79% of the total study area with low to moderate N, moderate P, OC, and slightly acidic pH with high Fe and Zn, the slightly fertile class was 55.79% of the total area characterized by low to moderate ECEC, moderate Mn, N, Fe and Zn, low OC and P, high content of K and moderate to neutral pH, and the low-fertile class covers 7.54% of the total area, characterized by low N, P and OC with moderate micronutrients (Zn, Fe and Mn) and moderate pH. The development of a fertility class map of the study area will help in precision agriculture, site-specific soil management and sustainable use of soil resources, it will also help stakeholders in making efficient and sustainable management decisions.

This study recommends the use of soil map for periodic soil fertility monitoring to see the trends of soil fertility change and the use of organic manure, organic mulch and chemical fertilizer to improve soil productivity and sustainable use of soil resources.

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