Assessment of spatial variability and mapping of soil properties for sustainable agricultural production using geographic information system techniques (GIS)

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Abstract: Mapping of soil properties is an important operation as it plays an important role in the knowledge about soil properties and how it can be used sustainably. The study was carried out in a local government area in Oyo state in order to map out some soil characteristics and assess their variability within the area. Soil sampling was carried out in three different locations in the local government area using the cluster sampling technique. Ten samples were collected in each location within a 10 by 10 km area, soil was sampled at two depths (0–20 and 20–40 cm) respectively. The soil samples were air-dried, crushed and passed through a 2 mm sieve before analyzing it for Nitrogen, phosphorus, Potassium, Organic carbon, pH and exchangeable bases in the laboratory while the SAR, ESP% and cation exchange capacity (CEC) were calculated. After the normalization of data classical statistics was used to describe the soil properties and geo-statistical analysis was used to illustrate the spatial variability of the soil properties by using kriging interpolation techniques in a GIS environment. Results showed that the soil properties with high variability in terms of coefficient of variation are available phosphorus and...
potassium (C.V = >35%), nitrogen, CEC, OC, SAR and ESP were all moderately variable (C.V = 34–15%) while pH had low variability (C.V = <15%). These variations in chemical properties are mostly related to the different soil management practices carried out in the study area and the parent material on which the soil is formed.

Subjects: Environment & Agriculture; Soil Science; Geography; GIS, Remote Sensing & Cartography

Keywords: spatial variability; soil properties; soil mapping; interpolation and geographic information system (GIS)

1. Introduction

Soil is a dynamic natural body which develops as a result of pedogenic natural processes during and after weathering of rocks. It consists of mineral and organic constituents, processing definite chemical, physical, mineralogical and biological properties having a variable depth over the surface of the earth and providing a medium for plant growth (Biswas & Mukherjee, 1994). Soil is a heterogeneous, diverse and dynamic system and its properties change in time and space continuously (Rogerio, Ana, & de Quirijn, 2006). Heterogeneity may occur at a large scale (region) or at small scale (community), even in the same type of soil or in the same community (Du Feng, XuXuexuan, & Shan, 2008). Soil which is a natural resource has variability inherent to how the soil formation factors interact within the landscape. However, variability can occur also as a result of cultivation, land use and erosion. Salviano (1996) reported spatial variability in soil attributes as a result of land degradation due to erosion. Spatial variability of soil properties has been long known to exist and has to be taken into account every time field sampling is performed and investigation of its temporal and spatial changes is essential.

Soil properties vary spatially from a field to a larger regional scale and it is affected by soil forming factors which can be termed as intensive factors and extrinsic factors such as soil management practices, fertility status, crop rotation etc. (Cambardella & Karlen, 1999). The variation can also be as a result of a gradual change in soil properties caused by landforms, geomorphic elements, soil forming factors and soil management practices (Buol, Hole, McCracken, & Southard, 1997). The variation of soil properties should be monitored and quantified to understand the effects of land use and management systems on soils.

Soil survey provides an accurate and scientific inventory of different soils, their kind, nature and extent of distribution so that one can make prediction about their characters and potentialities. It also provides adequate information in terms of land form, terraces and vegetation (Brown, Newman, Rayner, & Weir, 1978). The importance of reliable and timely information on soils cannot be overlooked in other to acquire spatial information of the soil properties, such information are necessary in the implementation of effective management strategies for sustainable agricultural production. Geographical information system (GIS) technologies has great potentials in the field of soil and has opened newer possibilities of improving soil statistic system as it offers accelerated, repetitive, spatial and temporal synoptic view. It also provides a cost effective and accurate alternative to understanding landscape dynamics. GIS is a potential tool for handling voluminous data and has the capability to support spatial statistical analysis, thus there is a great scope to improve the accuracy of soil survey through the application of GIS technologies.

Therefore, assessing spatial variability distribution on nutrients in relation to site characteristics including climate, land use, landscape position and other variables is critical for predicting rates of ecosystem processes (Schimel, Kittel, & Parton, 1991), understanding how ecosystem work (Townsend, Vitousek, & Trumbare, 1995) and assessing the effects of future land use change on nutrients (Kosmas, Gerontidis, & Marathianou, 2000).
2. Materials and method

2.1. Study area
The study was carried out in Irepo local government area of Oyo state, Nigeria. It has its headquarters in the town of Kishi and has an area of 948 km². According to the national population census of 2006 it has a population of about 122,553. Kishi is currently located at the northern part of Oyo state and it is about two hundred and fifty kilometers from Ibadan, the capital city of Oyo state.

2.2. Climate
The climate is equatorial, with distinct wet and dry seasons and high relative humidity. The dry season lasts from November to March while the wet season starts from March and ends in October. Average daily temperature ranges between 25°C (77°F) and 35°C (95°F) almost throughout the year. The mean temperatures are highest at the end of the harmattan (averaging 28°C), that is from the middle of January to the onset of the rains in the middle of March. It falls within the derived savannah agro-ecological zone.

2.3. Rainfall
Rainfall figures over the state vary from an average of 1,200 mm at the onset of heavy rains to 1,800 mm at its peak in the southern part of the state to an average of between 800 mm and 1,500 mm at the northern parts of the state.

It is located in the southern guinea ecology. The people of the area are predominantly farmers and the climate of the area is suitable for the production of large varieties of agricultural products such as maize, rice, melon, cowpea, soya beans and other cereals, tubers like yam and cassava.

2.4. Sampling procedure
For the purpose of this study three locations or intervention sites were chosen within Irepo local government area. This was based on the level of farming activities and soil types, the farming communities sampled are Eedu, Gegese and Agbagba.
Soil sampling was carried out using the Integrated Soil Fertility Management (ISFM) protocol, the soil samples were taken randomly within 10 × 10 km in each intervention site (Figure 1). Samples were collected at two depths 0–20 cm and 20–40 cm using the cluster technique so as to be representative, ten clusters was located in each intervention site. A total of 60 samples were collected in the local government area.

2.5. Laboratory analysis
The soil samples were air-dried, crushed and passed through a 2 mm sieve. Soil samples were analyzed for soil pH in both water and 0.01 M potassium chloride solution (1:1) using glass electrode pH meter (McLean, 1982). Total nitrogen was determined by the macro-Kjeldahl digestion method of Jackson (1958), available phosphorous (Av. P) was determined using Olsen’s extraction method (UV/visible Spectrometer, Lambda EZ 201) (Olsen, 1965). Available K is part of the exchangeable bases the exchangeable bases (Ca²⁺, Mg²⁺, K⁺ and Na⁺) were measured by atomic absorption spectrophotometry after extraction with ammonium acetate at pH 7 (Black, 1965). The cation exchange capacity (CEC) was determined by extraction with ammonium acetate (Chapman, 1965); Percent base saturation was calculated by dividing the sum of the charge equivalents of the base cations (Ca²⁺, Mg²⁺, K⁺, and Na⁺) by the CEC of the soil and multiplying by 100. All these analysis were carried out using standard procedures and protocols to ensure accuracy of the results.

2.6. Descriptive statistics and geo-statistical analysis
Statistical analysis for the work was done in three stages. First, the means were calculated and separated using the GenStat software, it was also used in determining the LSD values for each parameter to test their level of significance. Secondly, the distribution of data was described using conventional statistics such as mean, median, minimum, maximum, standard deviation (SD), skewness and kurtosis in order to recognize how data is distributed and each soil characteristics were investigated using descriptive statistics. Thirdly, geo-statistical analysis was performed using the kriging interpolation technique within the spatial analyst extension module in ArcGis 10.2 software package to determine the spatial dependency and spatial variability of soil properties. Kriging method is a statistical estimator that gives statistical weight to each observation so their linear structure’s has been unbiased and has minimum estimation variance (Kumke, Schoonderwaldt, & Kienel, 2005). This estimator has high application due to minimizing of error variance with unbiased estimation (Pohlmann, 1993). The experimental variogram model was constructed using the Kriging method, with data obtained from the research area. The spatial transformation was performed to determine the most appropriate model to use with the parameters of the generated maps.

Isotropic semi-variograms for the soil parameters were computed to determine any spatially dependent variance within the field. Experimental semi-variograms were fitted to two models (i.e. exponential and Gaussian) separately and the best model was selected based on the fit. Using the model semi-variogram, basic spatial parameters such as nugget (C₀), partial sill (C), range (A) and sill (C + C₀) was calculated. Nugget is the variance at zero distance, sill is the lag distance between measurements at which one value for a variable does not influence neighboring values and range is the distance at which values of one variable become spatially independent of another (López-Granados et al., 2002). Different classes of spatial dependence for the soil variables were evaluated by the ratio between the nugget and the sill. For the ratio lower than 25%, the variable was considered to be strongly spatially dependent, or strongly distributed in patches; For the ratio between 26 and 75%, the soil variable was considered to be moderately spatially dependent, For the ratio greater than 75%, the soil variable was considered weakly spatially dependent; and for the ratio of 100%, or if the slope of the semi-variogram was close to zero, the soil variable was considered non-spatially correlated (pure nugget) (Cambardella et al., 1994).

The ordinary Kriging formula is as follows: (Isaaks & Srivastava, 1989; ESRI, 2003).
where $Z(S_i)$ is the measured value at the location (ith), $\lambda_i$ is the unknown weight for the measured value at the location (ith) and $S_0$ is the estimation location.

The unknown weight ($\lambda_i$) depends on the distance to the location of the prediction and the spatial relationships among the measured values.

The statistical model estimates the unmeasured values using known values. A small difference occurs between the true value $Z(S_0)$ and the predicted value, $\sum \lambda_i Z(S_i)$. Therefore, the statistical prediction is minimized using the following formula:

$$[Z(S_0) - \sum \lambda_i Z(S_i)]^2$$

The Kriging interpolation technique is made possible by transferring data into the GIS environment. In this way, analysis in areas that have no data can be conducted. The following criteria were used to evaluate the model: the average error (ME) must be close to 0 and the square root of the estimated error of the mean standardized (RMSS) must be close to 1 (Johnston, Hoef, Krivoruchko, & Lucas, 2001). While implementing the models, the anisotropy effect was surveyed.

3. Results and discussion

Soil mapping and survey is an important activity because it plays a key role in the assessment of soil properties and its use in agriculture, irrigation and other land uses. This study was carried out to assess the spatial variability of some physical and chemical soil properties so as to determine their current situations in the study area, therefore the results can be presented as follows:

3.1. Descriptive statistics

The summary of the descriptive statistics of soil parameters as shown in Table 1 suggest that they were all normally distributed. The coefficient of variation for all the variables observed was very different ranging from 9.83–40.91% at 0–20 cm depth and 9.83–73.14%. The lowest coefficient of variation was observed in pH with a value of 9.83%, which could be as a result of the uniform conditions in the area such as little changes in slope and its direction leading to a uniformity of soil in the area (Afshar, Salehi, Mohammadi, & Mehnatkesh, 2009; Cambardella et al., 1994; Kamare, 2010) while available phosphorus had the highest variation at both depths. The soil properties with high variability in terms of coefficient of variation are available phosphorus and potassium (C.V. = >35%), nitrogen, CEC, OC, SAR and ESP were all moderately variable (C.V. = 34–15%) while pH had low variability (C.V. = <15%) according to the guidelines provided by Warrick, 1998 for the variability of soil properties. Most of the soil properties were highly positively skew at both depths i.e. Nitrogen, phosphorus, potassium, CEC and OC while SAR and ESP were both symmetrical (−1.626 and −0.727 at 0–20 cm) and (−1.226 and −0.403 at 20–40 cm). These variations in chemical properties are mostly related to the different soil management practices carried out in the study area, parent material on which the soil is formed, role of the depth of ground water and irrigation water quality (Abel, Kutywayo, Chagwesha, & Chidoko, 2014; Al-Atab, 2008; Al-Juboory, Alaqid, & Al-Issawi, 1990).

3.2. Chemical properties of the soil

The soil analysis showed that pH has no significant difference ($p < 0.05$) at both depths i.e. 0–20 cm and 20–40 cm with the pH ranging between 5.685 and 5.715 in the three locations and 5.677–5.730 between depths (Table 2). The soils in the three locations can be said to be moderately acidic (Federal Fertilizer Department, 2012). The pH values for the soil samples in the different depths were then plotted and interpolated using kriging interpolation algorithm method to show the spatial distribution of the pH at depths 0–20 cm and 20–40 cm respectively as shown in Figure 2(a) and (b). From Figure 2 it can be observed that majority of the soils in the 0–20 cm layer of the area are moderately acidic. The spatial distribution of the pH in the sub soil layer (20–40 cm) is also moderately acidic.
Table 1. Descriptive statistics for variables within the field grid to a depth of 20 and 40 cm

| Variables | Mean | Median | Min  | Max  | C.V.% | SD   | Skewness | Kurtosis |
|-----------|------|--------|------|------|-------|------|----------|----------|
| pH (−log [H+]) | 5.73 | 5.70 | 4.60 | 7.80 | 9.83  | 0.563 | 1.474    | 7.901    |
| N (%)     | 0.273 | 0.266 | 0.150 | 0.496 | 29.30 | 0.080 | 0.884    | 3.513    |
| Av. P (ppm) | 3.96 | 3.62 | 1.85 | 8.20 | 40.19 | 1.62  | 0.641    | 2.763    |
| K (Cmol/kg) | 0.145 | 0.143 | 0.048 | 0.289 | 37.93 | 0.055 | 0.708    | 3.394    |
| CEC (Cmol/kg) | 6.56 | 6.29 | 4.06 | 11.09 | 21.19 | 1.39  | 1.166    | 5.361    |
| OC (%)    | 7.812 | 7.250 | 5.200 | 15.00 | 28.35 | 2.215 | 1.688    | 5.612    |
| SAR       | 0.046 | 0.049 | 0.013 | 0.064 | 23.91 | 0.011 | −1.626   | 6.001    |
| ESP (%)   | 1.29  | 1.35  | 0.19  | 2.23  | 33.02 | 0.426 | −0.727   | 4.249    |

| Variables | Mean | Median | Min  | Max  | C.V.% | SD   | Skewness | Kurtosis |
|-----------|------|--------|------|------|-------|------|----------|----------|
| pH (−log [H+]) | 5.73 | 5.70 | 4.60 | 7.80 | 9.83  | 0.563 | 1.474    | 7.901    |
| N (%)     | 0.273 | 0.270 | 0.150 | 0.50  | 29.30 | 0.080 | 0.879    | 3.575    |
| Av. P (ppm) | 3.086 | 2.47 | 1.44 | 11.79 | 73.14 | 2.257 | 2.871    | 10.833   |
| K (Cmol/kg) | 0.114 | 0.100 | 0.07  | 0.21  | 32.46 | 0.037 | 1.233    | 3.765    |
| CEC (Cmol/kg) | 5.509 | 5.395 | 2.99  | 8.02  | 21.17 | 1.166 | 0.092    | 2.698    |
| OC (%)    | 5.613 | 5.60  | 2.75  | 11.26 | 28.29 | 1.588 | 1.570    | 7.109    |
| SAR       | 0.051 | 0.053 | 0.019 | 0.067 | 19.61 | 0.010 | −1.226   | 4.743    |
| ESP (%)   | 1.548 | 1.590 | 0.23  | 2.59  | 31.33 | 0.485 | −0.403   | 3.995    |

Table 2. Means of chemical properties of the soil at the three locations and at depth

| Locations | pH (H2O) | N (%) | Av. P (ppm) | K (Cmol/kg) | CEC | OC (g/kg) | SAR | ESP% |
|-----------|----------|-------|-------------|-------------|-----|----------|-----|------|
| Eedu      | 5.715    | 0.390 | 3.73        | 0.122       | 5.21| 6.53     | 0.054| 1.72 |
| Gegese    | 5.685    | 0.326 | 2.88        | 0.145       | 6.91| 6.14     | 0.046| 1.56 |
| Agbagba   | 5.710    | 0.300 | 3.96        | 0.122       | 7.67| 7.48     | 0.046| 1.38 |
| LSD       | 0.331    | 0.066*| 1.213       | 0.028       | 2.303|1.190    | 0.006*|0.378|

| Depth     | pH (H2O) | N (%) | Av. P (ppm) | K (Cmol/kg) | CEC | OC (g/kg) | SAR | ESP% |
|-----------|----------|-------|-------------|-------------|-----|----------|-----|------|
| 0–20 cm   | 5.677    | 0.405 | 3.96        | 0.145       | 6.56| 7.82     | 0.047| 1.293|
| 20–40 cm  | 5.730    | 0.273 | 3.09        | 0.114       | 6.63| 5.61     | 0.051| 1.811|
| LSD       | 0.271    | 0.018***|0.991     | 0.023*       | 1.880|0.972***|0.005|0.309|

*Significant at 5% probability.  
***Significant at 0.01% probability.

Figure 2. (a) pH at 0–20 cm and (b) pH at 20–40 cm.
For the nitrogen content of the soil, the analysis showed significant differences between the three locations (\( p < 0.05 \)) and at depth. However Eedu had the highest nitrogen content of 0.390% followed by Gegese with 0.326% and then Agbagba with 0.300% (Table 1). This indicates that all the soils in the three locations have very low nitrogen content (FDLAR, 2012). The nitrogen values for the two depths were then interpolated to assess the spatial variability and spread across the study area (Figure 3(a) and (b)).

Available phosphorus levels in the area showed from analysis that there were variations between the three locations but no significant differences were recorded. Agbagba and Eedu had the highest values at 3.96 and 3.73 ppm respectively which can be classified as low while Gegese had the lowest value of 2.88 ppm can be classified as very low (FDLAR, 2012). The available phosphorus values for the two depths were then interpolated to assess the spatial variability and spread across the study area although there was no significant difference between the depths (Figure 4(a) and (b)).

Potassium values in the study area showed no significant difference between the three locations but was significantly different at depth (\( p < 0.05 \)) all the potassium values for the three location are very low ranging between 0.122 and 0.145 Cmol/kg (Table 1). Gegese had the highest value while Eedu and Agbagba both had the same value of potassium. The potassium values for the two depths were then interpolated to assess the spatial variability and spread across the study area (Figure 5(a) and (b)).

Organic carbon values for the area were generally low according to the FDLAR (2012) classification. It ranged between 6.14 and 7.48 g/kg with Agbagba having the highest value of 7.48 g/kg. There were no significant differences observed between the three locations but at depth it was significantly different at (\( p < 0.05 \)). The organic carbon values for the two depths were then interpolated to assess the spatial variability and spread across the study area (Figure 6(a) and (b)).
The results from soil samples analysis for sodium adsorption ratio (SAR) showed significant differences between locations at \( p < 0.01 \) while it was not significant at depth. From these figures, it can be observed that the majority of soils in the locations have low SAR values and also at depths. The SAR values from the soil samples were plotted and spatially analyzed to show the distribution of SAR in the study area (Figure 7(a) and (b)).

The CEC values in all the locations were generally low with values ranging from 5.21–7.82 Cmol/kg, this is as a result of the exchangeable bases being low. For CEC to be considered adequate it has to have a value greater than 10 Cmol/kg of soil. There were also no significant difference between the three locations and depths as all the values were below the adequate amount (Figure 8(a) and (b)).
The ESP% of all the soils in the locations were low which implies that the soils are non-sodic, all the values were lower than 2%, while for a soil to be considered sodic it has to have an ESP% greater than 15% (Figures 9(a) and (b)).

3.3. Geostatistical analysis

The possible spatial structure of the different soil properties were identified by calculating the semi-variograms and the best model that describes these spatial structures was identified. These results are shown in Tables 3 and 4 for the two depths. The model with the best fit was applied to each parameter, the Gaussian model was the best fit for all d parameters at the first depth except SAR that was exponential model while the lower depth parameters were fitted to the spherical, Gaussian and exponential models. The nugget effect (Co), the sill (Co + C) and the range of influence for each of the parameters were noted. The spatial dependencies (Nugget/Sill ratio) were found to be related to the degree of autocorrelation between the sampling points and expressed in percentages. The spatial dependent variables was classified as strongly spatially dependent if the ratio was <25, moderately spatially dependent if the ratio is between 25 and 75% while it is classified as weak spatial dependent if it >75% (Cambardella et al., 1994; Clark, 1979; Erşahin, 1999; Robertson, 1987; Trangmar, Yost, & Uehara, 1985).

For the 0–20 cm depth, nitrogen had a strong spatial dependence with a ratio of 9.28% (Table 3) while the other nutrients; pH, N, Av. P, K, CEC, OC%, SAR and ESP were classified as moderately spatially dependent with a ratio of 42.12, 53.11, 32.55, 32.76, 42.76, 54.93, 39.70 and 42.95% respectively. At the lower depth i.e. 20–40 cm pH, nitrogen and Organic carbon had a strong spatial dependence (22.56, 9.86, and 18.37%), Available phosphorus, potassium, CEC and ESP% had a moderate spatial dependence (44.95, 36.84, 33.46, and 42.95%) while only SAR had a weak spatial dependence of 99.99% (Table 4). The value of nugget effect for pH and K were the lowest at both depths which suggest that the random variance of variables is low in the study area. this implies that near and away samples have similar and different values respectively. Therefore, nugget effects that
is small and close to zero indicates a spatial continuity between the neighboring points, this can be backed with the results of Vieira and Paz Gonzalez (2003) and Mohammad Zamani, Auubi, and Khormali (2007) which showed that variogram of nitrogen had very small nugget effect.

4. Conclusion
Assessing spatial variability and mapping of soil properties is an important pre-requisite for soil and crop management and also useful in identifying land degradation spots. The production of soil nutrient maps is the first step in precision agriculture because these maps will measure spatial variability and provide the basis for controlling it. It would also help in reducing the amount of inputs been added to the soil in form of supplements so as not to over burden the soil which can lead to pollution thereby degrading the land. The results shows that the spatial distribution and spatial dependence level of soil properties can be different even within the same local government area. It also demonstrates the effectiveness of GIS techniques in the interpretation of data. These results can be used to make recommendations of best management practices within the locality and also to improve the livelihood of smallholder farmers.
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