Geo-statistical mapping of some soil fertility constraints in sorghum-based cropping system of Sudano-Sahelian zone of Nigeria

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ABSTRACT

This research was aimed at quantifying the extent of spatial variability of some soil fertility constraints under sorghum cropping system along a rainfall gradient to develop appropriate fertilizer recommendation. Sorghum farms were selected through multistage sampling techniques based on rainfall gradients across three States in Sudano-Sahelian Zone of Nigeria. These are Kano, Jigawa and Katsina States. Within the states, twelve communities where sorghum is predominantly grown along Kofa-Zangon Daura transect were selected. From each community, ten sorghum farms were randomly selected using 10 km x 10 km sampling grids. Five quadrants (2m x 2m) were marked diagonally from each farm to collect a composite soil sample. The soil samples were analyzed using standard laboratory procedures and subjected to descriptive statistics and geo-statistical analysis. Results obtained indicated high variability in most soil properties. Potassium presented the highest CV value of 55.3%, while moderate variability was obtained in Available Phosphorous content with a value of 15.4%. The findings also showed that Nugget to Sill ratio of Total Nitrogen, Available Phosphorus was 0% and 14% respectively indicating strong spatial dependency. The trend map also indicated that Soil Organic Carbon, Total Nitrogen, Available Phosphorus and Exchangeable Potassium increased with an increase in rainfall in the study areas. Generally, the soil was poor in major nutrients, we therefore recommend that integrated soil fertility management, and site-specific fertilizer application should be considered for adoption in the study area.

INTRODUCTION

Food insecurity and hunger are the major problems bedeviling humanity in Sub-Saharan African (SSA) countries, where the people living in the region are poor with a population of about 646 million in the dry lands (Woperies et al. 2005; William 2013). The ardent needs and incessant land use by such population creates pressure on agricultural land that may lead to deficits in certain soil nutrients such as Nitrogen, Phosphorous, Potassium and other nutrients (Bationo et al. 2003). However, several works of literature reviewed that sorghum yield in SSA countries is generally low with less than a tonne per hectare compared with other developed countries where obtainable yield could reach up to 4.8 tons per hectare (FAOSTAT 2015). The low yield could be as a result of poor soil fertility, unpredicted weather patterns, poor management practices, and other biotic factors as reported by Adamu et al. (2010). Similarly, the amount and intensity of precipitation has also impact on soil and crop yields. Fatubarin and Olojugba (2014) observed that the peak of rainfall of a season has profound effects on soil properties.

Sorghum is among the most important arable crops in SSA especially Nigeria. Its grains and biomass are used for beverage drinks, baking and confectionery, as well as livestock feed, fencing, thatching (NAERLS 1997; FAOSTAT 2012).

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In Northern Nigeria, sorghum accounts for about 73% of the total caloric intake and 52.3% of the per capita protein. Its production exceeds all other crops in the region where about 4.5 million hectares of sorghum was produced with an annual production of about 6 million tons (FAO 2015). Nigeria is also ranked the third-highest producer after the United States and India (FAOSTAT 2012). Despite the above indices, sorghum yields in Nigeria and most of SSA countries are low and relatively constant. According to FAO 2015, the cultivation of Sorghum in Africa was increasing, but the average yields (800 kg ha⁻¹) has not increased.

MATERIALS AND METHODS

Research Study Area

The research was conducted within the Sudano-Saharan zone of Nigeria, the area located between 11°5.56′N:13°0′.85′N and 008°2.60′E:008°7.23′E with an altitude range 481-500m and transect of about 195km. The area was characterized by tropical wet, dry climate and cold according to Koppen’s classification. The annual mean temperature and rainfall of the study area were 28-32°C and 400-950 mm respectively. The vegetation of the study area was Sudano-Saharan type characterized by short grasses with varieties of scattered trees which are adapted to drought condition and shed their leaves during the dry season (Olofin et al. 2008).

Soil sampling, preparation, and analytical procedures

Twelve (12) communities were selected along Kofa-Zangon Daura transect of the Sudano-Saharan zone of Nigeria. The selection was based on rainfall gradients, the farms were selected using a multistage sampling technique. In each community, ten (10) farms of which sorghum grown were selected using 10 km by 10 km sampling grid. In each farm, two-meter quadrants were placed diagonally (at four cardinal points and center). From each quadrant, one soil sample was collected within the depth of 0-20cm. The soil samples were mixed and re-sampled using the quartering process to obtain a composite soil sample representing each of five (5) quadrants.

Therefore, the one (1) composite soil sample was collected from each farm and given a total of ten (10) composite soil samples from ten identified farms from each community. Thus, one hundred and twenty (120) composite soil samples were collected from the twelve locations/locations. The coordinates of the study were recorded using GPS counter for the purpose of plotting spatial map on soil fertility of the study area. The soil samples collected from the field were air-dried, ground gently with porcelain grinder and then passed through 2 mm sized sieve. Then the fine earth separated was packed in a plastic bottle for laboratory analysis. The soil samples were analyzed using following standard laboratory procedures:

- The total nitrogen was determined using micro-Kjeldahl digestion method as described by Bremma (1996).
- The organic carbon was determined using Walkley black method (Walkley and Black 1934).
- Ascorbic acid molybdate blue calorimetry method was used to determined Available phosphorus (Watanable and Olsen 1965) while the exchangeable K of the soil samples was determined using neutral ammonium acetate method and flame photometric procedure (Anderson and Ingram 1993).

Descriptive statistics

The result of the soil properties data were subjected to descriptive statistics including mean, median, maximum, minimum, coefficient of variation, standard deviation skewness and kurtosis, to estimate the variations between sampling locations and normality of dataset using version 15 GENSTAT and Kolmogorov-Smirnov test at 5% level of significance respectively.

Geo-statistical analysis

The geo-statistical analysis was achieved using kriging interpolation methods in the ArcGIS 10.3 software package to determine the spatial dependency and spatial variability of soil properties. An ordinary, simple and universal kriging was used as interpolation techniques to determine the spatial distribution of the soil properties of the study area. The models of semivariograms such as stable, exponential and Gaussian were used on the basis of goodness of model fit criterion. The data were checked for
normality and transformed as appropriate. Spatial analyses and mapping of the classified, SOC, total N, available P, exchangeable K, were performed in a GIS environment and experimental semivariogram was calculated using:

\[ Y(h) = \frac{1}{2N(\delta)} \sum_{i=1}^{N(\delta)} [(Z(x_i + h) - Z(x_i))^2] \]

Where Y(h) is the semivariance for interval class, N(\( \delta \)) is the number of pairs separation by lag distance (separation distance between sample portions), Z(Xi) is measured variable at spatial location i, and Z(Xi + h) is the measured variable at spatial location i + h.

**RESULTS AND DISCUSSION**

**Descriptive Statistics**

The descriptive analysis of soil properties were presented in Table 1. The variation of soil fertility parameters was interpreted using the coefficient of variability (CV). The criterion was developed by Wilding (1985). He classified the parameters in to high (CV > 35), moderate (15-35) and Low (< 15). Therefore, according to the descriptive result obtained in the study area, all the soil properties measured do not follow a normal distribution, therefore the data set were transformed into a normal distribution.

The result presented in Table 2 shows that there is a high variability of soil organic carbon content (CV = 37.50%) across the locations. The minimum and maximum values of 0.14 and 1.58 were observed (Table 2). The average value of 0.72 indicated low soil organic carbon while the high variation was due to the differences in rainfall, vegetation, soil type, type of organic material added to the soil, bush fallowing and burning of residues between farmers plot, soil moisture and temperature differences (Singh et al., 2004). The nitrogen content across the study ranged from a minimum value of 0.04% to a maximum value of 0.46% with an average of 0.14%, thus nitrogen content was strongly varied between locations (CV = 64.44%). The observed variation could be due to differences in management practices between farms (Tittonell et al. 2005).

However, Available Phosphorous of the study area has moderate variation with a CV of 15.4 (Table 2) with minimum value of 0.15, maximum value of 10.23 and an average of 6.64 indicating moderate variability along the locations which might be due to variations in pH, OM content, zinc content, and application of fertilizers that contain phosphorous between farms (Wade 2017). With regards to exchangeable bases, results showed that there is a strong variation of exchangeable potassium across the locations with a CV of 555.3%. The maximum value recorded was 1.65cmol/kg and a minimum value of 0.005cmol/kg and an average value of 0.03cmol/kg. This variability observed might be due to decreases in organic matter, soil texture, CEC, moisture content of soil, pH, soil drainage, and parent material (Wade 2017).

**Geo-statistical analysis**

The spatial distribution maps and status of some soil properties (Soil Organic Carbon, Total Nitrogen, Available Phosphorous and Potassium) at the Sudano-Saharan zone of Nigeria were designed using kriging interpolation through semivariogram package. A Sempivariogram was used to compute and determine the spatially dependent variance of soil properties. The experimental data were fitted to various semivariogram models ranging from exponential, Stable and Gaussian to select the best model. The model has basic spatial variables such as nugget (Co), partial sill (C), range (A) and sill (C + C0) which can be used to calculate strong spatial dependency ratio. Nugget is the difference at zero distance, the sill is the lag length between measurements at which one value for a variable does not influence adjacent values and range is the distance at which values of one variable become spatially independent of another (Lapez-Granados et al. 2002).

The ratio between the nugget and sill were used to evaluate different spatial dependency classes of the soil variables. However, when the ratio is below 25%, the variable is considered to have a strong spatial dependency, or strongly distributed in patches, when the ratio was between 26% to 75%, the soil variable was said to be

| Soil Fertility parameters | No. | Min. | Max. | Mean | CV | Sk. | Kurt. | Norm. |
|--------------------------|-----|------|------|------|----|-----|-------|-------|
| SOC (%)                  | 120 | 0.14 | 1.58 | 0.72 | 37.50 | 6.35 | 0.23 | No    |
| TN (%)                   | 120 | 0.04 | 0.46 | 0.14 | 64.44 | 1.20 | 0.80 | No    |
| AVP (ppm)                | 120 | 0.15 | 10.23 | 6.64 | 15.4 | 7.09 | 63.24 | No    |
| K (cmol)                 | 120 | 0.005 | 1.65 | 0.03 | 555.3 | 10.78 | 114.4 | No    |

SOC (Soil Organic Carbon), TN (Total Nitrogen), AP (Available Phosphorous) K (Exch. Potassium), NO. (Number of Samples), Min. (Minimum), Max. (Maximum), CV (Coefficient of Variability), Skew. (Skewness), Kurt. (Kurtosis), Norm. (Normality).
moderately spatial dependent, while if the ratio is above 75%, the variable is considered as weak spatially dependent variable, or if the slope of the semivariogram was close to zero, the variable was considered non-spatially correlated (pure nugget) (Cambardella et al. 1994). ArcGIS was used to delineate filled contour maps for some soil fertility parameters.

Therefore, several interpolations techniques and models were fitted into semivariogram to select the best model that will bring positive nugget to minimize estimation error. Based on the models selected, the soil organic carbon (SOC), total nitrogen (TN) and available phosphorus (AVP) in the study area have a value of zero while exchangeable potassium (SDR) has values of 14 as presented in Table 3. This implies strong spatial dependent, hence the variation was due to pedogenic factors. In addition, the coefficient of determination (R²) between observed and predicted soil parameters was found to be good because all the soil properties have values around one.

**Correlation analysis between soil fertility parameters and rainfall gradients**

The correlation analysis results in the study area shown that the SOC, TN, AVP and exchangeable K contents were positively correlated with rainfall (r = 0.059, 0.704**, 0.130 and 0.136 respectively). This implies that the variables were increasing with increases in rainfall.

**Interpretations**

Soil fertility rating of Esu (1991), Landon (1991) and Malgwi (2013) were used for interpretation of the results obtained in the study area.

A strong spatial dependency ratio of soil organic carbon (SOC) was obtained along the transect ranging from low to medium (Figure 2). Low organic carbon was observed in Kofa, Chiromawa, Rimi, Tukwi, Gada and some part of Zango, while medium organic carbon was obtained in Imawa, Langel, Fiji, and Sandamu. In addition, some small portion of medium SOC was found in Imawa and Langel. The moderate organic carbon content obtained might be due to the application of organic materials and its subsequent decomposition, while the low SOC could be as a result of low organic matter content in the soil. A positive correlation (r = 0.059) of soil organic carbon was observed, thus indicating increased with an increase in rainfall as indicated in Figure 2. The results was similar with reported of Singh et al. (2004), (Mandavgade et al. 2015) and Shehu et al. (2015). Moreover, the TN was low in all the areas of the study The TN content was increased with the increase in rainfall (Figure 2). The low content of TN might be as a result of low organic matter, parent material nature, slow of weatherable mineral reserve as well as reserve required for recharging nutrient. The results was found to be same with the findings of Singh et al. (2007) and Wade (2017) who reported that the low TN content was probably due to high temperature resulting in rapid organic matter decomposition, leaching and in combination with low inputs of organic material, microbial activities, moisture content and inherent nature of parent material.

The spatial dependency ratio of AVP content was strong as presented in Table 2 in which medium AVP content was obtained in Kofa, Chiromawa, Imawa, and Langel, while the low AVP content was observed in Dandalama, Rimi, Tukwi, Ajumawa, Gada, Fiji, and Sandamu. This implies that the AVP content in the research area increases with the increase of rainfall (Table 3 as well as Figure 1 and 2). The trend map shows that the AVP concentration was low to medium. This low AVP concentration might be due to widespread

| Soil Fertility Parameters | Statistical Model | Nugget (Co) | Partial Sill (C) | Sill Co + C | Range (A km⁻¹) | SDR (N:S Ratio %) | SDC | R² | Interpolation Techniques |
|--------------------------|------------------|-------------|----------------|-------------|----------------|------------------|-----|----|------------------------|
| SOC (%)                  | Stable           | 1.02        | 0.02           | 1.02        | 0.21           | 0                | Strong | 1.00 | Simple                |
| TN (%)                   | Stable           | 0.79        | 0.01           | 0.79        | 0.18           | 0                | Strong | 0.99 | Simple                |
| AVP (mg kg⁻¹)            | Stable           | 0.07        | 0.47           | 0.55        | 0.19           | 14               | Strong | 0.99 | Ordinary              |
| K (cmol kg⁻¹)            | Exponential      |             | 0.07           | 0.47        | 0.55           | 0.19             | 14    | Strong | 0.99                  |

SOC (Soil Organic Carbon), TN (Total Nitrogen), AP (Available Phosphorous) K (Exch. Potassium), Co. (Nugget), C, (Partial Sill), CO + C (Sill), SDR (Spatial Dependency Ratio), SDC (Spatial Dependency Ratio), R² (Coefficient of Determination).

**Table 2. Semi-variogram of Soil Fertility Parameters of the Study Area**

Table 3. Pearson Correlation (r) Between Soil Fertility Parameters and Rainfall Gradients

| Soil Fertility Parameters | Correlation Coefficient (r) values |
|--------------------------|-----------------------------------|
| SOC                      | 0.059                             |
| TN                       | 0.704**                           |
| AVP                      | 0.130                             |
| K                        | 0.136                             |

*Significance at 5% Level of Probability, **Significance at 1% Level of Probability.

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deficiency of P in tropical soils due to low organic matter content, Zinc, pH, (Ismail et al. 2010 and Wade 2017) and this was in line with the result of Shehu et al. (2015) who reported low AVP concentration in soils of Sudan Savanna of Nigeria. However, the strong dependency variable observed in AVP implies that the variation was from the pedogenic processes.

The strong spatial dependency ratio of exchangeable K and Na (Table 2) could be due to pedogenic factors. The trend map of exchangeable K content in the indicated high concentration K in most sites of Kofa, Chiromawa, Imawa, Lengel, Rimi, Tukwi, Ajumawa, Gada and Firji, with some patches of low to medium concentrations around Dandalama and some parts of Zango (Figure 2). This shows that potassium content increased with increase in rainfall as presented in Table 3 and figure 1. The high content of potassium may be due to release of minerals K by weathering and organic matter decomposition, while the low to medium content might be due to low organic matter decomposition and leaching of bases particularly K (Sharma and Anil 2003; Rao et al. 2008). However, the high content of Exchangeable K of this research contradicted the findings of Shehu et al. (2015) who reported low content of K in Nigerian Sudan Savanna soils.

CONCLUSIONS

Monitoring of soil fertility constraints through geostatistical mapping is one of the pre-requisite to address the issues of low yield in sorghum production and also beneficial in detecting soil fertility problems. Since these geostatistical maps measured the rate of spatial variation of soil fertility constraints and provide the basis for monitoring it, it also imperative to employ site-specific fertility management techniques that are useful for smallholder farmers to improve soil fertility, as well as providing a baseline for research institutes and policymakers for proper land use management and decision-making on land use planning and management strategies. However, due to low concentration of primary soil nutrients (Nitrogen, Phosphorous and Potassium) in the study area, integrated soil fertility management should be adopted to increase sorghum yield in the area.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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