Original Research Article

Geostatistical Evaluation of Spatial Variability of Selected Soil Physical Properties under Different Landuse Systems in Ado Ekiti, southwest Nigeria

ABSTRACT

The characterization of spatial variability of soil physical and chemical characteristics is very important for precision farming and managing agricultural soils. Therefore, the objectives of this study therefore were to evaluate some selected soil physical properties of a cultivated field in Ado Ekiti, southwest Nigeria and quantify the spatial characteristics of the evaluated properties using classical statistical and geostatistical techniques. The field was planted to cowpea, sole maize and maize/cassava intercrop. A total of one hundred and eighty-four (184) georeferenced surface samples were collected for analysis of texture, bulk density (BD), particle density (Pd), porosity (Pt) and saturated hydraulic conductivity (Ksat). The soil properties showed varying degree of spatial variability, with Ks highly variable. There was weak correlation between Ksat versus BD and Pt but the correlation was significant with sand content. The variability of these properties revealed weak to strong spatial dependence. The BD, Pd, Pt and Ksat could be well described using either Gaussian or spherical models while sand and clay content gave pure nugget effect. The range of spatial dependence values indicated that future sampling could be done within a distance between 214 and 511 m. The kriged maps further showed the spatial distributions of these soil physical properties across the three different land use systems. The documentation of these physical properties in field scale distribution maps will allow derivation of zones of physical and mechanical sensitivity. This can further help define management zones, which can be combined with minimum soil samples to provide a more accurate prediction of spatial variability of soil properties for site-specific soil management under different agricultural land use systems.

Keywords: Spatial variability, classical statistics, geostatistics, soil management, soil physical properties

1.0 INTRODUCTION

Soils are known to vary across landscapes and so do their properties. Significant within – field variability attributable to natural factors of oil formation and crop management practices has also been reported [1]. Under similar management practices, soils in agricultural fields have shown highly variable properties [2]. In view of this within –field variability in soil properties, applying uniform management treatments, such as blanket fertilizer application or excessive tillage, often result in over – application of such inputs in low-yielding areas and over application of inputs in high-yielding areas [3].

Quantifying the spatial variability of soil properties therefore becomes appropriate in farm planning and management for developing a more productive and efficient crop management systems [1]. Traditionally, the spatial variability of soil properties has been evaluated through classical descriptive statistics and geostatistical techniques that verify relationships among several soil samples of a specific area or field, using the study of regionalized variables [4]. While classical statistics uses the measure of central tendency to quantify only the degree of spatial variability of soil properties within the field, geostatistical analysis methods of variography and kriging have been proven to be more useful for characterizing and mapping spatial variation of soil properties and have also received increasing interest by soil scientists and agricultural engineers [5, 6, 7, 8]. In quantitative evaluation of within – field spatial variability, geostatistical technique has been successfully applied by various authors [e.g. 9, 10, 1, 11]. Nigeria agricultural soils are also characterized by the variability of soil properties in space and thus the variability of crop yield within field, however field management has remain uniform such as blanket application of fertilizer. This practice portends danger to the environment as well as increased cost of production. Elsewhere, the study of spatial variability of soil properties has been used to generate information to mitigate these problems through precision farming. Therefore, the objectives of this study therefore were to evaluate some selected soil physical properties of a cultivated field and quantify the spatial characteristics of the evaluated properties using classical statistical and geostatistical techniques.

2.0 MATERIALS AND METHODS

2.1 Description of study site

The study site is a 3-ha field cultivated to arable crops (cowpea, sole maize and maize/cassava intercrop) located on the SIWES Training Farm of the Teaching and Research Farm, Ekiti State University, Ado Ekiti, Ekiti State. The site is located on latitude 70 41´ 57.9″ N, longitude 50 05´ 0″ E and 406 m above the mean sea level. The land has been previously used for the cultivation of yam and cowpea and was left fallow for about 3 years before the SIWES students started cultivating on it for training on crop production.

2.2 Field procedure and soil sampling

Of the 3-ha field, 1 ha planted to cowpea, 1 ha to sole-maize and only about 0.7 ha to maize/cassava inter-crop were used for the study. Grids were set up on the field within the three land use. Ninety-four (94) grids (10 m x 10m) were set up in cowpea plot, fifty (50) grids (20 m x 10 m) in sole maize and forty-four (44) grids (15 m x 10 m) in maize/cassava intercrop, giving a total of one hundred and eighty-four (184) grids (Figure 1). The center of each grid was geo-referenced with the aid of GPS (Garmin model) for soil sampling. Disturbed and undisturbed soil samples were collected from the 0-20 cm surface layer at the center of each grid. Thus, a total of one hundred and eighty-four (184) samples were collected altogether. The samples collected were neatly packed and transferred to the laboratory for analysis.

2.3 Evaluations

Soil texture. The granulometric analysis was determined using the modified hydrometer method following the procedure described in [12] from disturbed air-dried soil samples after passing through 2-mm sieve.

Bulk density. After preparation in the laboratory, the undisturbed core samples were oven-dried at 105°C for 48 h and the weight of dry soil was determined. The bulk density was determined using the equation according to [13]:

$$BD = \frac{M_s}{V_s} \quad (1)$$

where BD is bulk density, g cm^{-3}; M_s is weight of dry soil, g; V_s is volume of soil, cm^3.

Particle density. Particle density was determined using volumetric bottle method following the procedure described in [14] from disturbed air-dried soil samples after passing through 2-mm sieve and then oven-dried for 24 h.

Total porosity. It was determined using the relation:

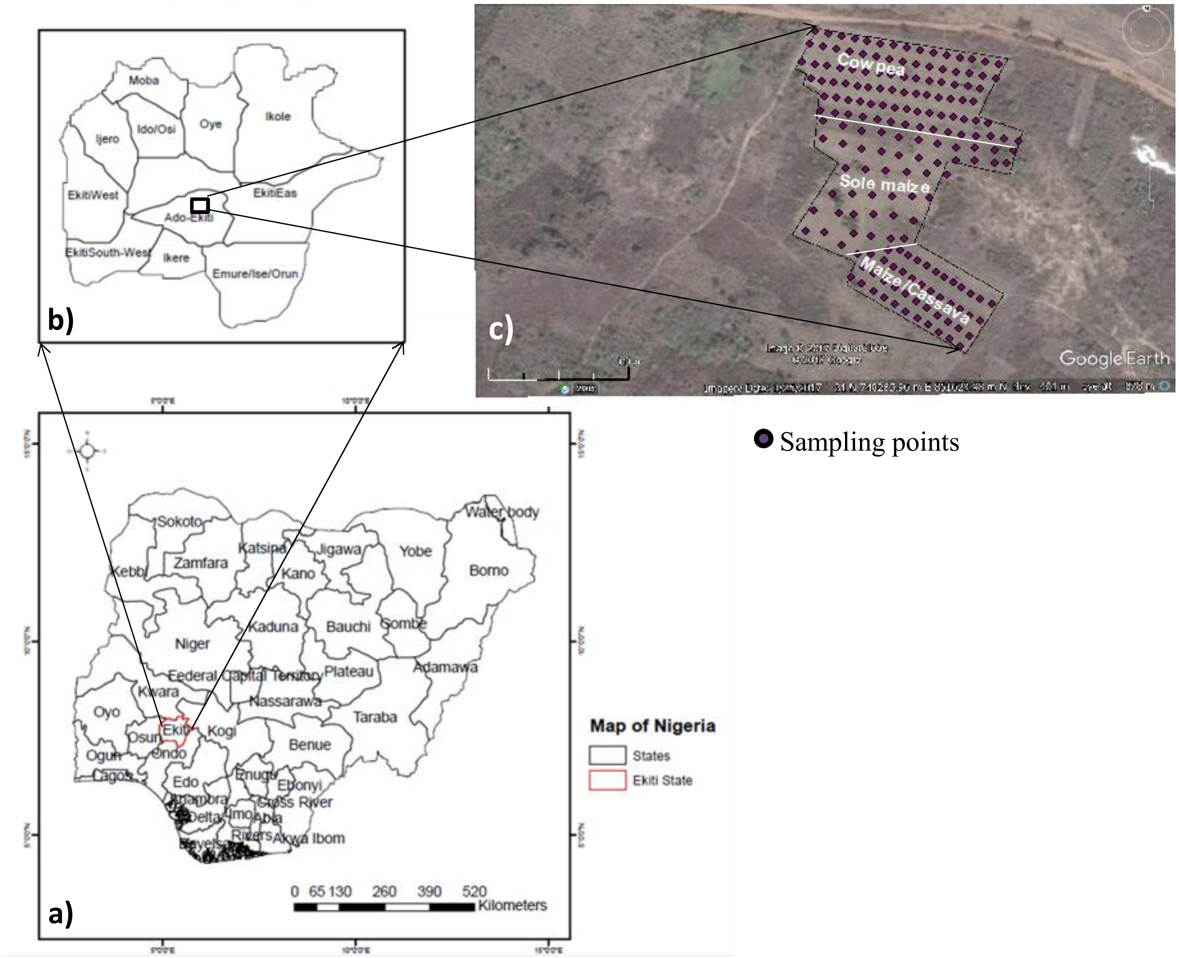

Figure 1. (a) Map of Nigeria showing (b) Ekiti State and (c) the study site

$$Pt = 1 - \frac{BD}{Pd} \tag{2}$$

where Pt is the total porosity, $cm^3\ cm^{-3}$; BD is the bulk density, $g\ cm^{-3}$; Pd is the particle density, $g\ cm^{-3}$.

Soil saturated hydraulic conductivity. Soil saturated hydraulic conductivity (Ksat) was determined by the constant-head permeameter [15] on undisturbed soil samples collected in metal cylinders (of known volume) after saturation by capillarity in a water bath for 48 hours. The determination of Ksat was performed by collecting and measuring the amount of water that percolates through the soil sample under a constant hydraulic head of about 3 cm in the water column, according to the methodology described by [12]. From the data, soil Ksat was calculated according to Equation 3.

$$Ksat = \frac{Q*L}{A*H*t}$$

3

where Ksat is saturated hydraulic conductivity, cm/hr; Q is volume of water that flow through the soil column in a given time, cm^3; L is length of the soil column, cm; H is length of soil column + water head above the soil column, cm; A is area the soil column, cm^2; t is time, h.

2.4 Data analysis

2.4.1 Descriptive statistics of soil properties

Descriptive statistics of minimum, maximum, average, standard deviation (SD), skewness, kurtosis and coefficient of variation (CV) of data on sand, clay, bulk density, saturated hydraulic conductivity, particle density and total porosity. The saturated hydraulic conductivity data that did not follow normal distribution (Shapiro-Wilk test) was log transformed for further analysis. In addition, the frequency distribution graph was plotted for each variable. All classical statistical analyses were carried out using SPSS (IBM version 20).

2.4.2 Geostatistical analysis

Geostatistical analysis was done using the GS+ (Gamma Design Software, Version 5.2, 2005) to determine the spatial dependency and estimation of the soil properties evaluated. Isotropic semivariograms of linear, power, spherical, exponential and Gaussian, were tested from omnidirectional semivariances, $\hat{\gamma}(h)$, of a set of spatial observations, Y_{xi}, expressed as [16]:

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (Y_{x+h} - Y_x)^2$$

4

where $\hat{\gamma}(h)$ is the covariance; h is the spatial separation distance, known as the time lag; $N(h)$ is the number of pairs of observations separated by a distance; Y_x is soil variable observed at point x while Y_{x+h} soil variable observed at point $x + h$.

To characterize the spatial covariance structure of the variables, the best model was selected based on the coefficient of determination, R^2. From the models, basic spatial parameters such as nugget (Co), sill (C+Co) and range (Ao) were determined. The nugget to-sill ratio expressed as the structural variance was calculated for each soil physical property and used to evaluate the degree of spatial dependence associated with each soil property. Structural variance values were categorized into one of three classes of spatial dependence as proposed by [17]. For structural variance less than 0.25, the variable is considered strongly spatially dependent; if the structural variance is greater than 0.25 and less than 0.75, the variable is considered moderately spatially dependent; and if the structural variance is greater than 0.75, the variable was considered weakly spatially dependent [17, 18]. In addition, a structural variance value close to zero indicates continuity in the spatial dependence.

After selecting the best fit semivariogram model for each variable, contour maps were created through ordinary kriging of the Geostatistical Analyst extension in ArcGIS v. 10.1® (Esri, Redland, CA, USA). Cross-validation of the kriged results was made using validation statistics of mean absolute error (MAE) and mean square error (MSE) as:

$$MAE = \frac{\sum_{i=1}^{N} |z^* - \bar{z}|}{N}$$

5

$$MSE = \frac{\sum_{i=1}^{N}(z^{*}-\bar{z})^{2}}{N}$$

6

where z^* is the predicted soil variable; $\bar{z}$ is the mean of measured soil variable; N is the total number of sampling locations. The predicted values for each soil variable were obtained from the cross-validation procedure in the GS^+.

3.0 RESULTS AND DISCUSSION

3.1 Descriptive statistics

The descriptive statistics of soil variables of the SIWES Training Farm is presented in Table 1. The sand content ranged between about 51 and 68% (mean = 64.3%) while clay content was low, ranging between 2 and 11% (mean = 7.04%). The soil had BD ranging from 1.10 to 1.73 g cm^{-3} (mean = 1.43 g cm^{-3}) while the particle density ranged from 2.02 to 2.97 g cm^{-3} (mean = 2.51 g cm^{-3}). For total porosity (Pt), the values were between 0.27 and 0.0.56 cm^3 cm^{-3} (mean = 0.43 cm^3 cm^{-3}). The saturated hydraulic conductivity (Ksat) ranged from 2.35 to 326.20 cm h^{-1}, with an average value of 48.74 cm h^{-1}. For Ksat, the results are in agreement with the findings of [19]and [20] who from different studies reported high variability in Ksat. The relatively low values of BD and clay content obtained from the study could have led to increase in the value of Ksat. Low Ksat also indicated low level of compaction and presence of large number of macrospores which allow water to percolate through the soil. The least varied physical property was found to be particle density. For instance, the spatial distribution of water retention properties closely followed the distribution pattern of sand and clay content. This indicates a differential water retention capacity of different textured soils across the field. The relatively high variability of Ksat may be attributed to differences in soil pore geometry as a result of soil disturbance. Increase in porosity could be as a result of low bulk density i.e. degree of compaction and granulation is very low and also increase in organic matter.

Table 1. Descriptive statistics of soil physical properties of the field.

Property	N	Min.	Max.	Mean	SD	CV	Skewness	Kurtosis
Sand, %	184	51.29	67.65	64.30±0.170	2.35	0.037	-1.85±0.18	6.04±0.36
Clay, %	184	2.32	11.32	7.04±0.110	1.49	0.211	-0.13±0.18	0.27±0.36
BD, g cm^{-3}	184	1.10	1.73	1.43±0.098	0.13	0.093	-0.07±0.18	-0.56±0.36
Pd, g cm^{-3}	184	2.02	2.97	2.51±0.011	0.13	0.050	-2.24±0.18	14.04±0.36
Pt, cm^3 cm^{-3}	184	0.27	0.56	0.43±0.004	0.06	0.137	-0.31±0.18	-0.33±0.36
Ksat, cm h^{-1}	94	2.35	326.20	48.74±5.928	57.50	1.179	2.61±0.25	8.14±0.49

BD: bulk density; Pd: particle density; Pt: total porosity; Ksat: saturated hydraulic conductivity
N: number of samples; Min.: minimum value; Max.: maximum value; SD: standard deviation; CV: coefficient of variation

According to the classification proposed by [21], a parameter is considered to be low in terms of variability if the CV<12%, moderately variable when 12% < CV<60% and highly variable when CV>60%. In this study, the CVs for sand, BD, and Pd were less than 12%, indicating that these variables had low variability within the field. On the other hand, Clay and Pt, had CV between 12 and 60%, indicating moderate variability while Ksat had CV>100%, indicating very high variability. Similar studies have also reported low CV for sand [10] and BD [10, 11]. [10] found moderate CV for clay content. For Ksat, the result agrees with the findings of [19] and [20] who reported high variability of Ksat. In this study, the high variability of Ksat may be attributed to differences in soil pore geometry as a result of variable soil disturbance during land preparation. Certain sampling points may be characterized by biopores created by soil organisms and plant roots, thus increasing the water movement.

The frequency and normal distribution curves for the variables are shown in Figure 2. Only the logarithm transformed Ksat (LnKsat) had positive skewness, showing skewness to the right, while other variables sand, clay, BD, Pd and Pt had negative skewness (Table 1), showing skewness to the left (Figure 2). [22] stated that where a variable shows symmetry to either right

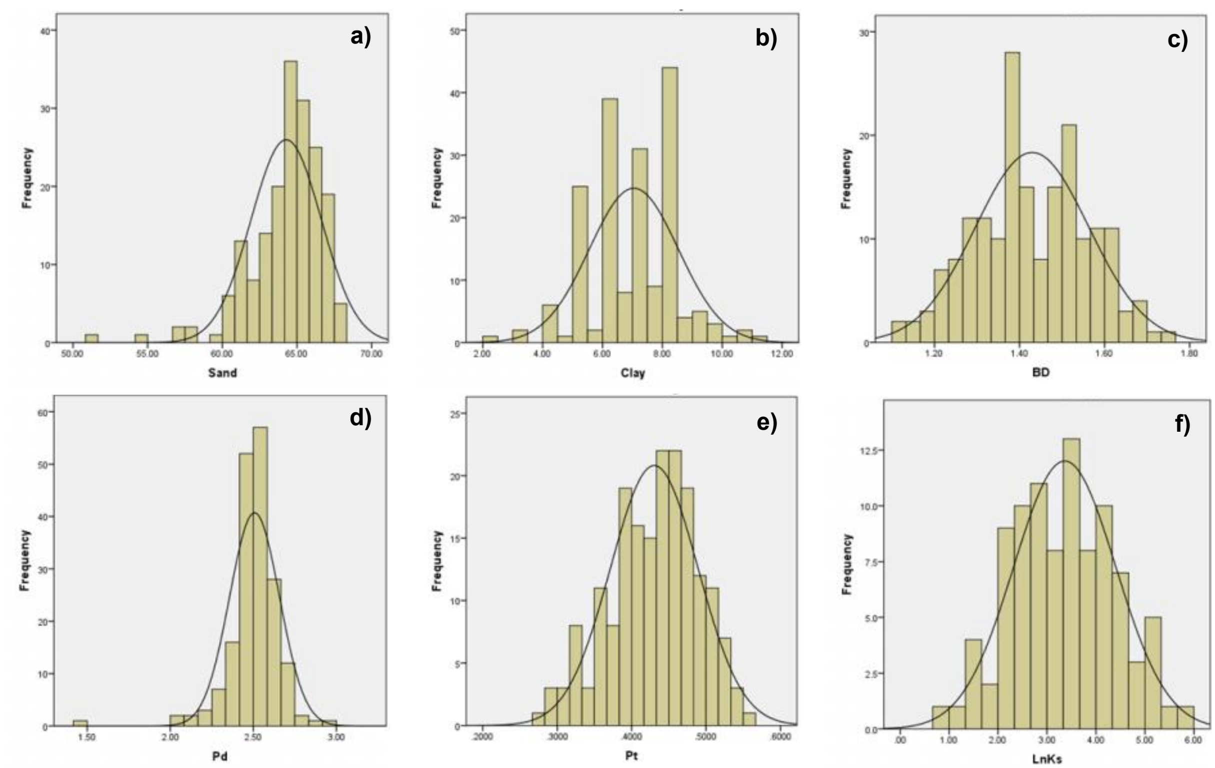

Figure 2. Frequency and normal distribution curve of the selected soil physical properties of the field.

or left, there is the tendency of high frequency of values below or above mean, respectively. In this study, sand, clay, BD, Pd and Pt had high frequency of values above the mean. [11] in a study on spatial variability of physical properties under land use change reported negative and positive skewness for BD and Pt, respectively. According to [23], for a normal distribution, the kurtosis coefficient must be zero, and values between +2 and -2 are accepted. In this study, only the kurtosis values for clay, BD and Pt were within the acceptable limit. In addition, the negative kurtosis for BD and Pt (Table 2) indicates that the curves were platykurtic, showing the distribution was flatter than normal. Whereas the positive kurtosis for clay indicates that the data was leptokurtic, that is, the distribution was narrower than normal (Figure 2). Other researchers [e.g. 24, 11] have also reported this behavior.

3.2 Relationships between soil physical properties

The relationships between sand, clay, BD, Pd, Pt and LnKsat are presented in Table 2. There was significant positive correlation between Ks and sand content. Total porosity (Pt) had negative and significant correlation with BD whereas the correlation was positive with Pd. Sand had negative and significant correlation with clay content. The basis of the positive relationship between soil Ksat and sand content is direct; that is, higher Ksat values are associated with coarser rather than finer textured soil. In addition, high sand content indicates more macropore or transmission pores, hence increased water conductivity. Total porosity has an inverse relationship with bulk density, thus the confirmation obtained here. On the other hand, an increase in particle density indicates more pores, especially micropores and hence contributes to total pores. A soil having a more of sand will definitely have low content of clay which is a function of parent material from which the soil is formed.

3.3 Spatial variability and mapping of soil physical properties

Table 3 and Figure 3 show the results of the geostatistical analysis of the measured soil physical properties. Sand and clay showed pure nugget effect (Figure 3 a and b); BD, Pd, and Pt were fitted to Gaussian model (Figure 3c, d and e) while LnKsat was fitted to spherical model (Figure 3f), with the coefficient of determination (R^2) ranging from 0.104 (sand) to 0.947 (LnKs). Other researchers [e.g. 10, 24, 25, 26, 11] have reported these models for soil physical properties. The nugget effect or the semivariance at separation distance of zero ($h = 0$) ranged between 0.00 $(cm^3\ cm^{-3})^2$ (from Pt) and 5.6 $(\%)^2$ (from sand). According to [27], the range is a function of field and experimental variability, or random variability that is undetectable at the scale of sampling. Except for sand and clay, the close to zero nugget from other variables is an indication of very smooth spatial continuity between neighbouring points. The sand and clay content that had high nugget effect compared to other variables indicates high discontinuity

Table 2. Results of Pearson correlation test between the soil physical properties.

Property	LnKs	BD	Pd	Pt	Sand	Clay
LnKs	1	0.122	-0.054	-0.138	0.215*	-0.100
BD		1	-0.097	-0.879**	0.071	-0.131
Pd			1	0.555**	0.027	0.103
Pt				1	-0.044	0.151
Sand					1	-0.310**
Clay						1

BD: bulk density; Pd: particle density; Pt: total porosity; LnKs: log transformed saturated hydraulic conductivity
**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

among samples. [28] stated that the higher the nugget effect, the greater the discontinuity in samples. As the separation distance (h) increases, the semivariance increases to a more or less constant value, known as the sill or total semivariance. The sill values ranged from 0.02 (cm^3 $cm^{-3})^2$ (Pt) and 5.60 $(\%)^2$ (sand). The ranges of spatial dependencies vary between 214 and 511 m, indicating that the optimum sampling interval varies greatly among the different soil properties [10]. The sand and clay content that showed small range (214 m) of spatial dependence indicates that spatial continuity diminishes rapidly over a short distance. The value of semi-variogram range of the soil physical properties obtained in this study were not in agreement with the range obtained in previous studies [e.g. 25, 26, 29]. Differences in soil, land use type, cropping and management systems in the different regions may account for these contrasting results.

Furthermore, the resulting semivariograms indicate strong spatial dependencies (SSD) for BD, Pd and Pt. The structural variance also showed moderate spatial dependence for Ksat and weak spatial dependence for sand and clay. These results indicate that the distribution of the soil properties in space is not random. Strong spatial dependent in soil properties is an indication that such properties are controlled by variability in intrinsic soil properties such as geology, soil

Table 3. Fitted models and estimated parameters of the experimental semivariograms of soil physical properties of the field.

Var.	Model	C_o	C_o+C	A_o	$C_o/(C_o+C$	Spatial dependence	R^2	MAE	MSE
Sand	Nugget effect	5.600	5.60	214.3	1.00	WSD	0.104	0.620	0.553
Clay	Nugget effect	2.170	2.17	214.3	1.00	WSD	0.596	0.304	0.139
BD	Gaussian	0.020	0.07	510.9	0.23	SSD	0.833	0.046	0.003
Pt	Gaussian	0.003	0.02	510.9	0.13	SSD	0.900	0.020	0.001
Pd	Gaussian	0.013	0.05	510.9	0.25	SSD	0.560	0.021	0.001
LnKs	Spherical	0.768	1.83	410.9	0.42	MSD	0.947	0.498	0.306

BD: bulk density, g cm^{-3}; Pd: particle density, g cm^{-3}; Pt: total porosity, cm^3 cm^{-3}; LnKs: log transformed saturated hydraulic conductivity, cm h^{-1}

C_o: nugget effect; C_o+C: sill; A_o: spatial range, m; SSD: strong spatial dependence; MSD: moderate spatial dependence; WSD: weak spatial dependence

R^2: coefficient of determination; MAE: mean absolute error; MSE: mean square error.

forming factors, texture and so on [30], whereas moderate and weak spatial dependence could be due to management such as land use, tillage, cropping system, irrigation, among others.

By using the kriging algorithm of the geospatial analyst tool in ArcGIS, the contour maps of the individual soil property are shown in Figures 4-8. The visualization of the distribution maps showed that the soil varies in terms of physical properties, that is heterogeneity, indicating that the distribution of the variables are strongly influenced by both factors including geology, management practices, soil texture, among others. Figure 4 shows the kriged contour map of the spatial variability and classification of the sand content of the field. For the cowpea plot, it was observed that there was slightly high sand content. Also for sole maize plot, there was slightly high sand content. For maize/cassava intrecrop, there was moderately high sand content. Figure 5 shows the kriged contour map of the spatial variability and classification of the clay content. For the cowpea plot, the kriged contour map showed that there was very low to low clay content in the northeastern region of the map. It was noted that for sole maize plot, there was low clay

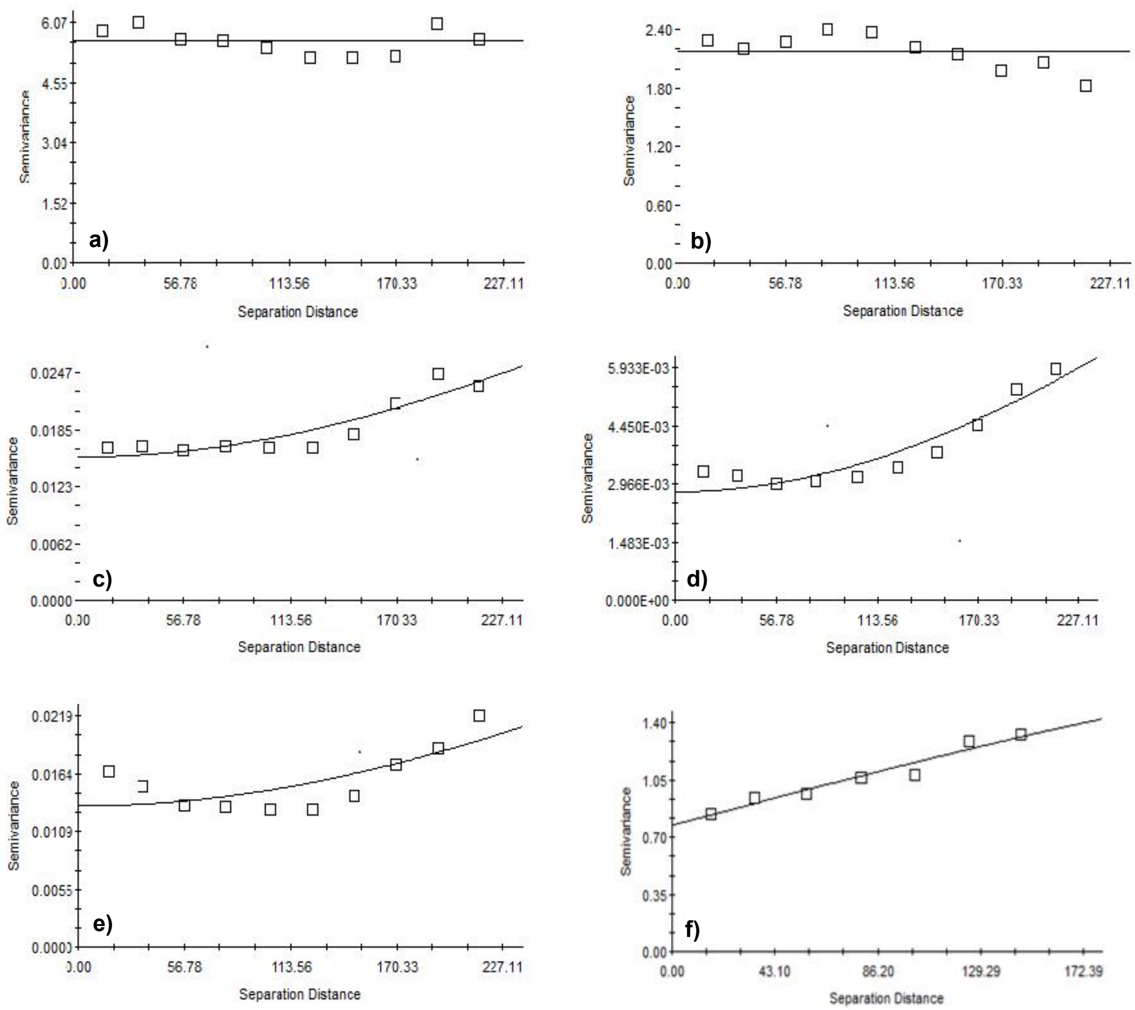

Figure 3. Semivariogram of a) sand content, b) clay content, c) soil bulk density (BD), d) total porosity (Pt), e) particle density (Pd), and f) log transformed saturated hydraulic conductivity (LnKs) of the field.

content due to inherent soil factors such as soil type and environmental factor. For maize/cassava, it was observed that there was very low clay content in this area of the field. The differences in the sand and clay contents are attributed to geology and intrinsic soil forming factors and the differences in these textural properties have implications in terms of pore space, water and nutrient retention and availability. Figure 6 shows the kriged contour map of the

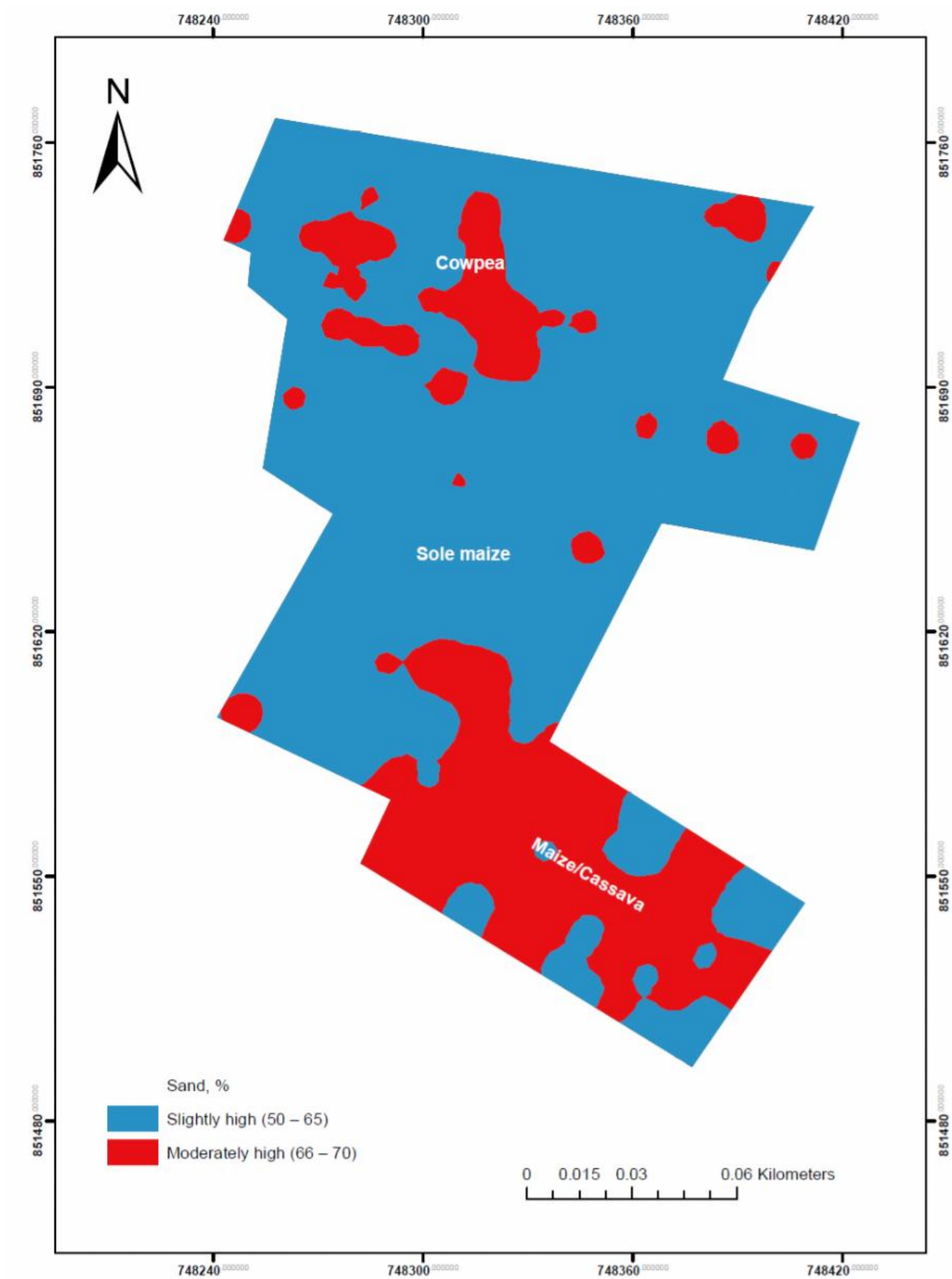

Figure 4. Kriged contour map showing the spatial variability and classification of the sand content of the field.

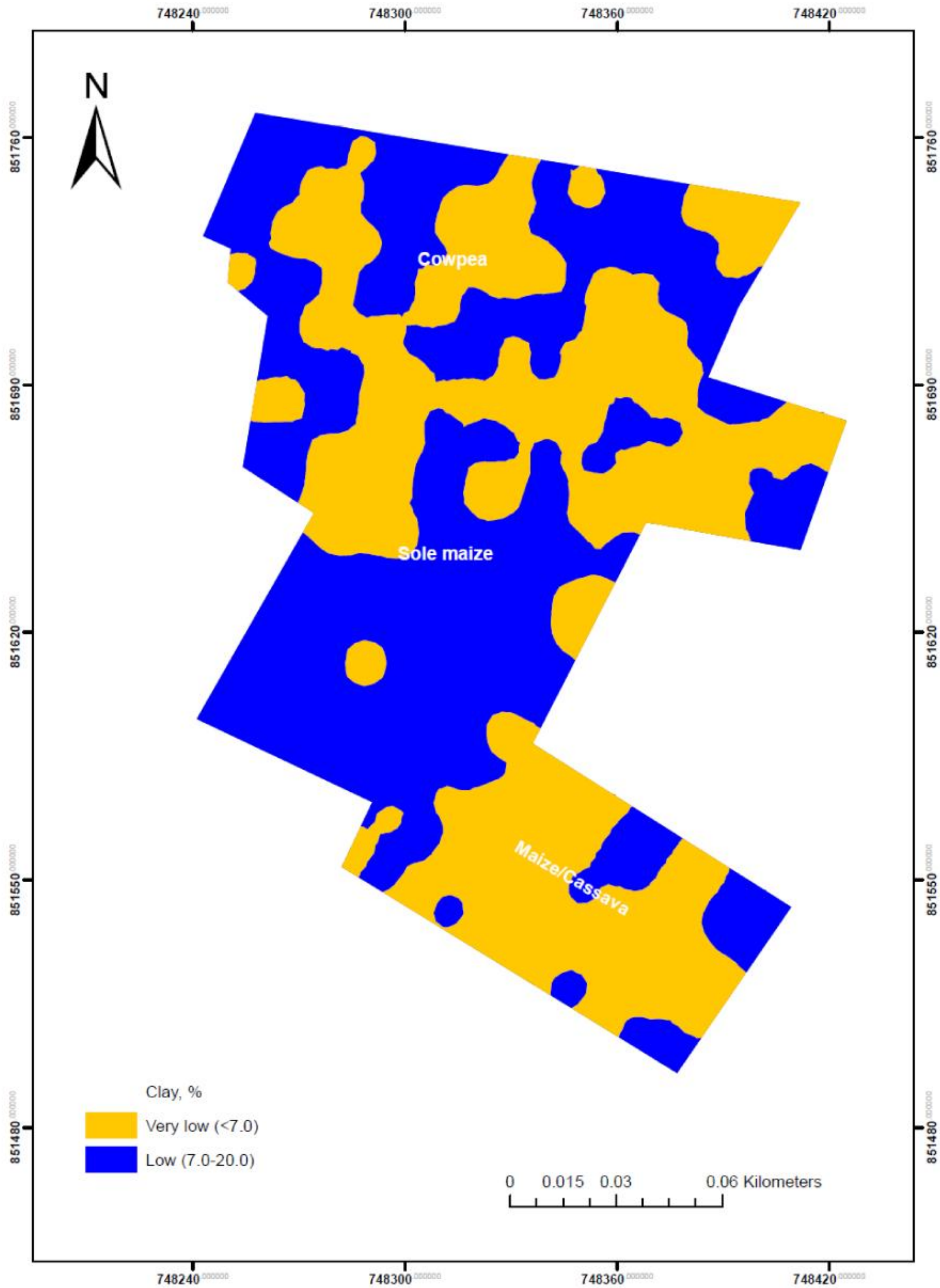

Figure 5. Kriged contour map showing the spatial variability and classification of the clay content.

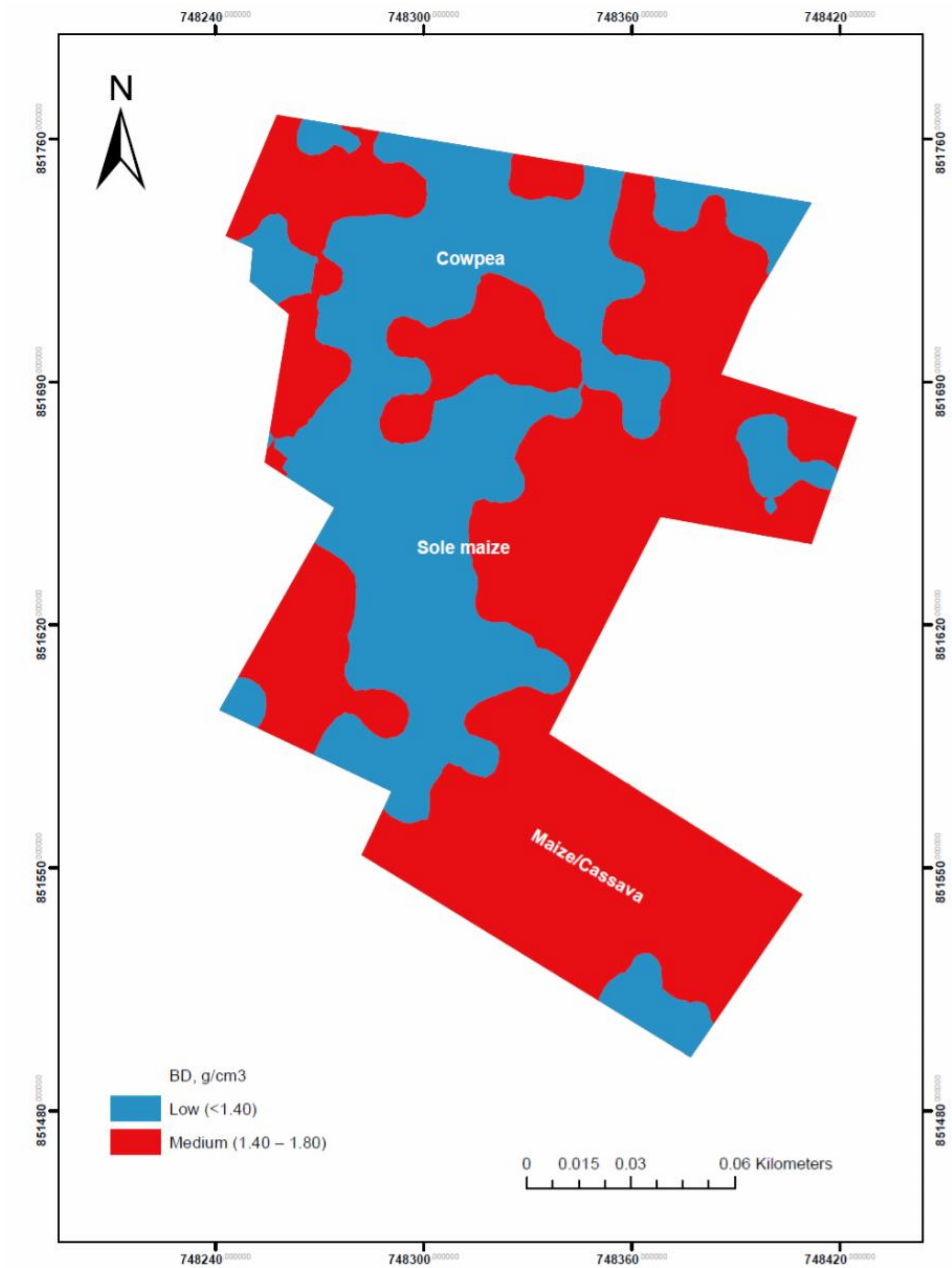

Figure 6. Kriged contour map showing the spatial variability and classification of the soil bulk density (BD) of the field.

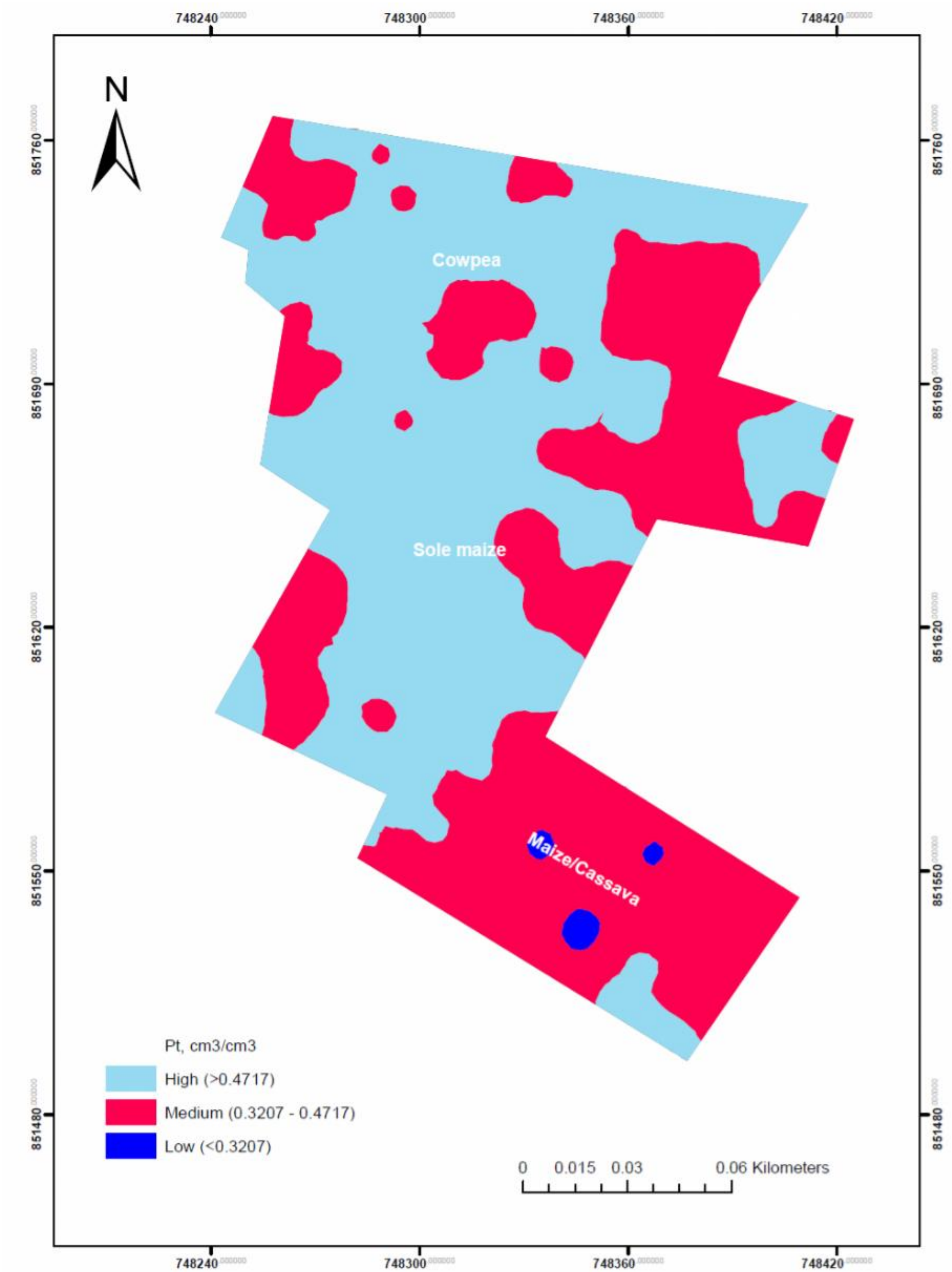

Figure 7. Kriged contour map showing the spatial variability and classification of the soil total porosity (Pt) of the field.

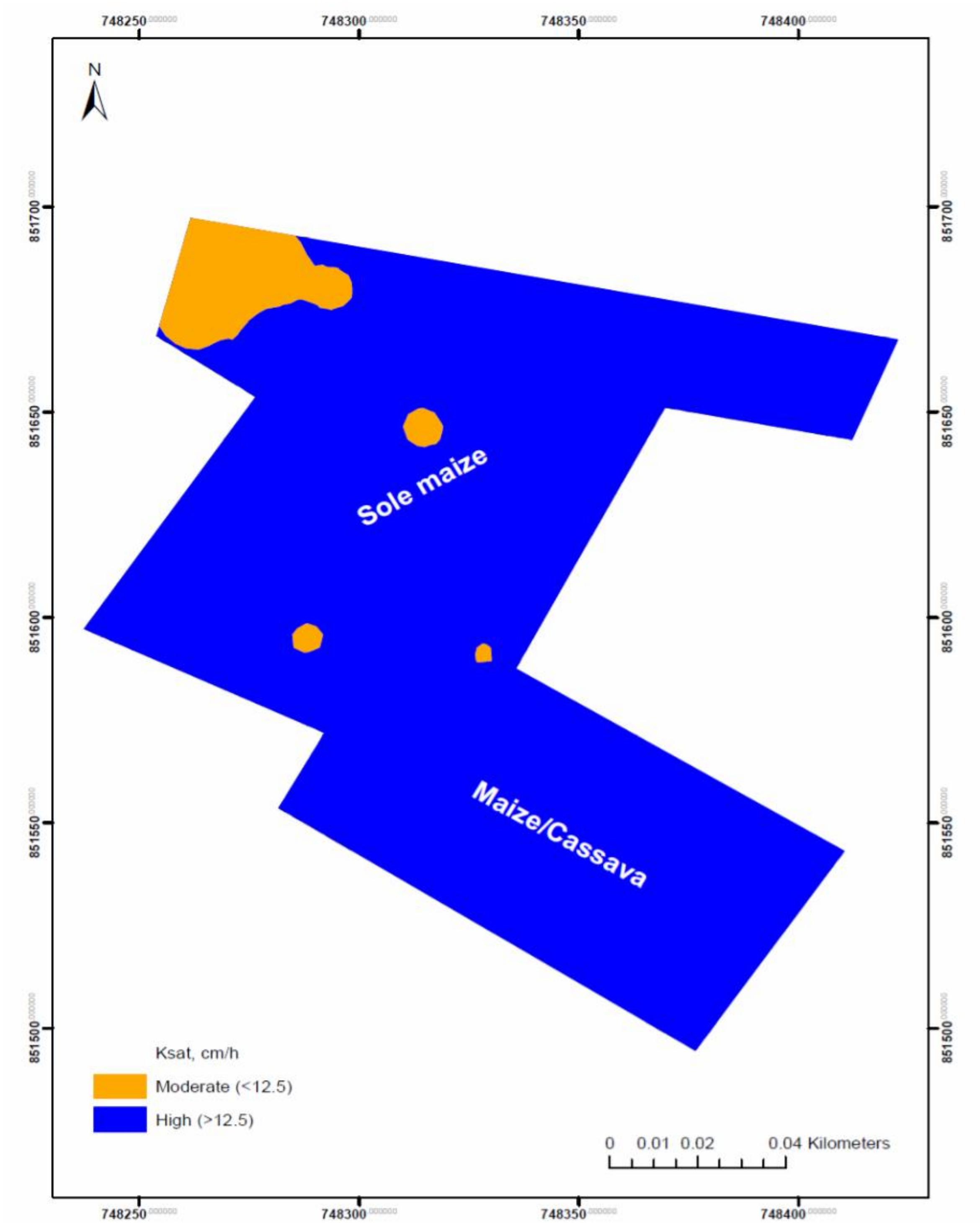

Figure 8. Kriged contour map showing the spatial variability and classification of the soil saturated hydraulic conductivity (Ksat) of sole maize and maize/cassava intercrop area of the field.

variability and classification of the soil bulk density (BD) of the field. For the cowpea plot, it shows that there was low BD. Also from the sole maize plot, it was observed that there was low BD. The low bulk density indicates that the degree of compaction is low due to recent ploughing, harrowing and ridging operations conducted on the soil. For maize/cassava intercrop, the bulk density (BD) was medium (a bit higher) compared to cowpea and maize plots which may be attributed to crop intensification. The higher sand content in this region is also an avenue for the increased BD as more pore volume is available for compression.
Figure 7 shows the kriged contour map of the spatial variability and classification of the soil total porosity (Pt) of the field. For both cowpea and sole maize plots, the total porosity (Pt) is classified as high. The high Pt observed may be as a result of low bulk density which is attributed to better aggregation and improved pore space. Conversely, maize/cassava intercrop had Pt classified as medium to low. This may be attributed to the relatively higher BD due to crop intensification.

Figure 8 shows kriged contour map of the spatial variability and classification of the soil saturated hydraulic conductivity (Ksat) for sole maize and maize/cassava intercrop only. For sole maize plot, the Ks is classified as moderate to high while it was classified as high for maize/cassava intercrop. The high Ks observed in maize/cassava intercrop may be due to high volume of macropore due to high sand content. The saturated hydraulic conductivity is a dynamic property of soil and its behavior is determined by the degree of compaction that the soil offers [31] as well as the quantity and continuity of pores, mainly macro spores.

The results of test of cross-validation of the kriging procedure checked using performance parameters of MAE and MSE are shown in Table 3. While the MAE indicates the bias, the MSE determines the prediction accuracy (Utset et al. 2000). Both the MAE and MSE values are very low, indicating that the kriging procedure was acceptable. Regardless of what factors caused the spatial variability observed, the magnitude of the soil properties may be expected to influence the spatial distribution of crop growth and yield, thus having considerable implications regarding the implementation of soil sampling schemes and site-specific management practices.

CONCLUSIONS

The geostatistical methods showed spatial variability of the soil physical properties across the field. The variability of these properties is not random, revealing weak to strong spatial dependence.

The BD, Pd, Pt and Ksat could be well described using either Gaussian or spherical models. The semivariogram for sand and clay contents shows a small range of spatial dependence and purely nugget effect.

Crop intensification of maize/cassava intercrop influenced soil physical properties.

Spatial variability of soil physical properties across the field is attributed to a combination of previous sand mining activities and farming practices, parent material, and weather conditions.

The documentation of these physical properties in field scale distribution maps will allow derivation of zones of physical and mechanical sensitivity. This will further help define management zones, which can be combined with minimum soil samples to provide a more accurate prediction of spatial variability of soil properties for site-specific soil management.

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