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Spatial Variability of Soil Physico-chemical Properties in Kadawa Irrigation Project in Sudan Savanna Agroecology of Nigeria

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ABSTRACT

Quantification of soil physical and chemical properties and estimation of their associated variability are essential for making site-specific decisions on soil and crop management practices. This study was conducted with the aim of determining the degree of spatial variability and variance structure of soil physical and chemical properties on about 20 ha in Kadawa Irrigation Scheme in Kano state, Nigeria, to observe changes in the variance structure caused by irrigation and to suggest future sampling designs for efficient management decisions. Forty eight soil samples were collected at 0-30 cm depth at a distance of 50 m intervals using Geographical Positioning System (GPS). The software package GS+ was used to model the variance structure of sand, silt, clay, soil bulk density, saturated hydraulic conductivity (Ks), Organic Carbon (OC), Total Nitrogen (TN), Available Phosphorus (AP), Cation Exchange Capacity (CEC), exchangeable bases, pH, Electrical Conductivity (EC), Exchangeable Sodium Percentage (ESP) and Sodium Adsorption Ratio (SAR). Results obtained revealed that the coefficient of variation ranged from 3.2% (bulk density) to 156% (exchangeable K). The semivariograms showed that the range of spatial dependence varied from 26 m (AP) to 911 m (exchangeable Na) for all measured soil properties. Cross-semivariograms showed that the particle size classes and soil hydraulic properties were spatially correlated; therefore, kriging or cokriging can be used to estimate hydraulic properties from available texture data. Correlograms with Moran's I indicated that a distance of 391 m was adequate to generate independent samples for measured soil physical and chemical properties. The kriged contour maps showed positional similarities. These contour maps of soil properties, along with their spatial structures, can be used in making better future sampling designs and management decisions.

Key words: Spatial structure, variogram, correlogram, soil physical properties, soil chemical properties

INTRODUCTION

Spatial and temporal variability of crop factors within a field can have a significant influence on agricultural production (Zhang *et al.*, 2002) by reducing yield and quality of product. Spatial variation in crops is the result of a complex interaction of biological (e.g., pests, earthworms, microbes), edaphic (e.g., salinity, organic matter, physical properties, chemical properties and depth), anthropogenic (e.g., leaching efficiency, soil compaction due to farm equipment), topographic (e.g., slope, elevation) and climatic (e.g., relative humidity, temperature, rainfall) factors (Stein *et al.*, 1997; Rockstrom *et al.*, 1999; Gaston *et al.*, 2001; Zhang *et al.*, 2002; Mzuku *et al.*, 2005). Water commonly has a leading role among the factors responsible for spatial and temporal yield variability and is a major input resource for precision management (Sadler *et al.*, 2000). When the application of water or water quality (salinity) is non-uniform in the field, the resulting soil moisture properties may be an important factor in causing spatial variations in crop yield (Sadler *et al.*, 2000). Yield variability within surface-irrigated fields has been related to the spatial variability of available soil water due to non-uniform irrigation (Palmer, 2005).

A search in the literature reveals that many studies have quantified the spatial variability of soil properties (Campbell, 1978; Vauclin *et al.*, 1983; Ovalles and Collins, 1988; Cambardella *et al.*, 1994; Shukla *et al.*, 2004; Worsham *et al.*, 2010). It has been reported that spatial dependence can occur at scales varying from a few meters to several kilometers. For example, Trangmar *et al.* (1987) found a short-range (3-4 m) spatial dependence of sand and clay contents, whereas Ovalles and Collins (1988) observed a long-range (16-35 km) spatial dependence for sand and clay. Variations in soil properties can also be expressed by dividing the coefficient of variation (CV) into different ranges, for example, least (<15%), moderate (15-35%) and most (>35%) (Wilding, 1985).

Quantification of soil physical and chemical properties and estimation of their associated variability are the first steps toward making site-specific decisions on soil and crop management practices, fertilizer applications and irrigation scheduling. Site-specific crop management aims to manage soils, pests and crops based upon spatial variations within a field (Larson and Robert, 1991). Specifically, site-specific crop management is the management of agricultural crops at a spatial scale smaller than the whole field by considering local variability with the aim of cost effectively maximizing crop production and making efficient use of agrichemicals to minimize detrimental environmental impacts.

Geostatistical analyses are considered valuable tools for analyzing and predicting the spatial structure of soil variables. Review of earlier conducted studies (Cambardella and Kalen, 1999; Machado *et al.*, 2000; Stenger *et al.*, 2002; Shukla *et al.*, 2004; Shahandeh *et al.*, 2005; Worsham *et al.*, 2010), revealed that the level of variability associated with an estimate of a soil property is scale dependent; therefore, assessing spatial variability of soil properties is of paramount importance prior to employment of site specific soil and crop management practices. Moreover, these studies were mostly performed either in the same field or in fields having the same crop. Only one study (Sharma *et al.*, 2011) has determined the spatial variability of soil properties in a field having different crops but under similar tillage practices.

Therefore, the objectives of this research were to quantify the spatial variability and determine the spatial variance structure of physical and chemical properties of an irrigated land to observe any change in the variance structure and also to suggest a future sampling design for improved management of the irrigation scheme.

MATERIALS AND METHODS

Location, topography and climate of the study areas: The survey was conducted during post-irrigation period of 2008 at the irrigation research farm of the Institute for Agricultural Research, Kadawa, Nigeria (11° 39', 08° 27' E). The study area is located at an altitude of 500 m above sea level in the Sudan Savanna Eological Zone of Nigeria. The rainfall pattern in the Kadawa is largely characterized by 6 wet and 6 dry months. The onset of the rains is in May-June, with monthly totals of 175 mm from May/June through September. August is the wettest month in the area. The mean monthly temperature in Kadawa ranges from 27.8°C in March up to maximum of 30.4°C in May.

Soil sampling and physical-chemical characterization: Forty eight sampling points were marked at a distance of 50 m intervals (north and east) using Geographical Positioning System (GPS). The sampling points were located on 6 transects perpendicular to one boundary of the farm considered as baseline. Soil samples were collected from each point at the depths of 0 to 30 cm using auger and core sampler. All the samples were collected during post-irrigation season before the commencement of rainy season in May 2008 (Dry season). The augered samples were air dried and ground to pass through a 2 mm-sieve for analysis of the following parameters:

Particle size analysis was performed by the Bouyoucos hydrometer method (Gee and Dr, 2002). Organic carbon determination was done by the standard Walkley-Black potassium dichromate oxidation method (Nelson and Sommers, 1982). Soil organic matter was calculated as 1.72x %OC (Walkley and Black, 1934). Bulk density was evaluated using the core method (Grossman and Reinsch, 2002). The saturated hydraulic conductivity (K_s) was measured using constant-head permeameter method (Klute and Dirksen, 1986). Soil moisture at field capacity (FC) (-33 kPa) and Wilting Point (WP) -1500 kPa was determined from undisturbed core samples using pressure plate extractors (Klute, 1986).

Soil reaction (pH) was determined by a pH meter using soil to water ratio of 1:2.5 as described by Peech (1965) whereas, total nitrogen determination was done by semi-micro Kjeldahl digestion (Bremner and Mulvaney, 1982) followed by ammonium distillation and titrimetric determinations. Exchangeable bases (Ca, Mg, K, Na) were determined as follows: Ca and Mg - by atomic absorption spectrophotometer (AAS); K and Na by flame emission photometry (Hesse, 1971); Cation Exchange Capacity (CEC) determination was done by the method proposed by Chapman (1965); Electrical Conductivity (EC) was measured by a conductivity meter from the soil solution directly following the procedure described by Piper (1942). Available Phosphorus (AP) was determined following the Olsen method of extraction (Olsen and Sommers, 1982). The extracted AP was then determined spectrophotometrically by reacting with ammonium molybdate using ascorbic acid as a reductant in the presence of antimony (Rodriguez *et al*., 1994). Exchangeable Sodium Percentage (ESP%) was obtained by dividing total exchangeable sodium by the cation exchange capacity multiplied by 100. Sodium Adsorption Ratio (SAR) and was computed as follows:

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{\mathrm{Ca}+\mathrm{Mg}}{z}}} \tag{1}$$

Statistical analysis: Data collected for all the measured soil physical and chemical properties were first subjected to classical statistical analyses to obtain descriptive statistics, including mean, range, maximum, minimum, skewness, kurtosis, S.D. and SE. The coefficient of variation was also calculated for each measured soil variable. Shapiro-Wilk test (Shapiro and Wilk, 1965) was conducted on data of all measured soil physical and chemical properties to check for normality of the data (Hintze, 2004). The Shapiro-Wilk test showed that most measured soil variables were significantly skewed (p = 0.05), with the exception of pH.

Skewed variables were transformed using a natural logarithm to a nearly normal distribution before using geostatistical analysis. A semivariogram shows autocorrelation as a function of distance (semivariance versus separation distance) and when plotted, represents spatial variability (Cohen *et al.*, 1990). In order to compare the spatial correlation of different semivariograms, one can use the ratio of the nugget and the sill after having fit a model to each semivariogram (Balasundram *et al.*, 2007). Low ratios indicate strong spatial dependence and vice versa (Henebry, 1993). This ratio, however was used to define three classes of spatial dependence for the measured soil variables (Cambardella *et al.*, 1994), (1) when the ratio was <0.25, the measured variable was considered strongly spatially dependent, (2) between 0.25 and 0.75, the soil variable was considered moderately spatially dependent and (3) if the ratio was >0.75, or the slope of the semivariogram was about 0, the variable was considered random or non spatially correlated (pure nugget). Therefore, the recommended model for higher R^2, low Reduced Sums of Squares (RSS) and high $C/(C_o+C)$ was then chosen for spatial autocorrelation process. A semivariogram was determined to calculate the degree of spatial variability between neighboring observations for each variable. The semivariogram function (Goovaerts, 1997) was calculated as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z\,(x_i) - Z(x_i + h)]^2 \qquad (2)$$

where, F (h) is the semivariance for interval class h, N (h) is the number of pairs separated by lag distance h (separation distance between sample positions), $Z(x_i)$ is a measured variable at spatial location i, $Z(x_i + h)$ is a measured variable at spatial location i + h. Samples separated by distances closer than the range are related spatially and those separated by distances greater than the range are not spatially related.

Theoretical variograms were obtained by fitting linear, spherical, exponential and Gaussian models. A best model was selected based on the least residual sum of squares between experimental and theoretical semivariograms and also by the square of the correlation coefficient (r^2) values for each soil property. The linear, spherical, exponential and Gaussian models shown below were fitted to the semivariograms.

- The linear variogram model

$$\gamma(h) = C_o + C_1 \frac{h}{a} \qquad (3)$$

- The exponential variogram model

$$\gamma(h) = (s-n)\ (1-\exp(-h/(ra))) + n1(0,\infty)(h) \qquad (4)$$

- The spherical variogram model

$$\gamma(h) = (s-n)\left(\left(\frac{3h}{2r} - \frac{3h^3}{3r^3}\right) 1_{(0,r)}(h) + 1_{(r,\infty)}\ (h)\right) + n1_{(0,\infty)}\ (h) \qquad (5)$$

- The Gaussian variogram model

$$\gamma(h) = (s-n)\left(1-\exp\left(-\frac{h^2}{r^2a}\right)\right) n1_{(0,r)}(h) + n1_{(r,\infty)}(h) \qquad (6)$$

where, h is lag distance, s is sill, n is nugget and r is range. The parameter a has different values in different references, due to the ambiguity in the definition of the range. E.g., a = 1/3 is the value used in (Chiles and Delfiner, 1999). The 1A(h) function is 1 if h∊A and 0 otherwise.

The degree of spatial variability for each measured soil variable was determined by geostatistical methods using semivariogram analysis, kriging and autocorrelation (Trangmar *et al.*, 1986; Iqbal *et al.*, 2005). The GS+software version 9.0 (Gamma Design Software, LLC) was used to obtain the semivariograms of each measured soil property.

RESULTS AND DISCUSSION

All the measured soil physical variables (except silt) were normally distributed in the site (Table 1). Conversely, non normal distribution of most of the measured soil chemical variables was observed with only exchangeable Mg, Cation Exchange Capacity (CEC) and Total Nitrogen (TN) normally distributed. Skewness was positive (ranging from 0.085 to 6.292) for most of the measured

Table 1: Results of Shapiro-Wilk Test of Normality

Variables	df	Test value	Prob. level
Sand (%)	47	0.9575	0.0802
Silt (%)	47	0.9426	0.0205
Clay (%)	47	0.9583	0.0808
ρd (g cm^{-3})	47	0.9747	0.3827
Ks (cm h^{-1})	47	0.9037	0.0008
FC (%)	47	0.9791	0.5422
PWP (%)	47	0.9590	0.0920
AWC (%)	47	0.9725	0.3162
pH (H_2O)	47	0.9411	0.0180
pH ($CaCl_2$)	47	0.8643	0.0001
SOC (g kg^{-1})	47	0.9144	0.0017
Total N (g kg^{-1})	47	0.9264	0.1264
Available P (mg g^{-1})	47	0.9009	0.0007
Ca^{2+} (cmol (+) kg^{-1})	47	0.9085	0.0012
Mg^{2+} (cmol (+) kg^{-1})	47	0.9814	0.6365
K^+ (cmol (+) kg^{-1})	47	0.2761	0.0000
Na^+ (cmol (+) kg^{-1})	47	0.7020	0.0000
SBR	47	0.6508	0.0000
CEC (cmol (+) kg^{-1})	47	0.9685	0.2209
ECe (dS m^{-1})	47	0.7079	0.0000
ESP	47	0.7192	0.0000
SAR	47	0.6791	0.0000
ESI	47	0.4074	0.0000

† df: Degree of freedom; SOC: Soil organic carbon; ρd: Bulk density; SBR: Sodium base ratio; CEC: Cation exchange capacity in (cmol(+) kg^{-1}); ECe: soil electrical conductivity in dS m^{-1}; ESP: Exchangeable sodium percentage; SAR: Sodium adsorption ratio; ESI: Electrochemical stability index; Ks: saturated hydraulic conductivity; FC: field capacity, volumetric water content at -33 kPa; PWP: Permanent wilting point, volumetric water content at -1,500 kPa; AWC: available water capacity, calculated as the difference between -33 and -1,500 kPa

physical and chemical parameters, but it was negative (-0.121 to -0.515) for silt and exchangeable Mg. Regarding the estimated values [Sodium Adsorption Eatio (SAR) and Exchangeable Sodium Percentage (ESP)], skewness was also positive and high (1.824-5.197). The exchangeable K values were highly skewed. In this study, the non-normally distributed data with significant skewness were transformed using natural logarithm to reduce skewness. Similar approach was employed in some studies (Trangmar *et al.*, 1987; Cambardella *et al.*, 1994; Bosch and West, 1998; Iqbal *et al.*, 2005; Sharma *et al.*, 2011).

Changes of non-normally distributed variables to normal after log transformation of most of the variable were not observed. However, log transformation of data for exchangeable Ca and Available Phosphorus (AP) changed the non-normal distribution to normal distribution which reduced skewness more than kurtosis. This is in conformity with earlier reports by Cambardella *et al.* (1994) and Sharma *et al.* (2011) which showed that variable failing to pass normality tests after the transformation could not reduce kurtosis as much as the skewness.

Spatial variability in distribution of parameters is measured by Coefficient of Variation (CV). Base on the CV values, saturated hydraulic conductivity (Ks), organic carbon (OC), TN, AP, exchangeable Ca and Na were the most variable soil measured parameters, with CV greater than 35%. All the estimated parameters were also among the category of the most highly variable in spatial distribution. Silt, clay, exchangeable Mg and CEC were moderately variable, with CV between 15 and 35%, while Sand, bulk density (ρd), soil water content at field capacity (-33 kPa or FC) and Wilting Point (WP) and pH measured in water (pH (H_2O)) were least variable

Table 2: Descriptive statistics for soil physical and chemical properties of kadawa irrigation research farm

Variables	Minimum	Maximum	Mean	Median	Kurtosis	Skewness	SE	CV (%)
Sand (%)	50.0	78.0	63.9	62.0	3.04	0.085	0.327	9.2
Silt (%)	10.0	24.0	19.4	20.0	2.94	-0.515	0.247	17.6
Clay (%)	9.0	26.0	16.6	16.0	3.17	0.373	0.221	23.6
ρd (g cm^{-3})	1.28	1.49	1.38	1.38	2.99	0.212	0.272	3.2
Ks (cm h^{-1})	1.32	6.85	3.27	2.79	3.42	1.033	0.254	40.9
FC (%)	0.254	0.346	0.295	0.297	3.07	0.271	0.284	6.9
PWP (%)	0.118	0.195	0.155	0.153	3.21	0.322	0.218	11.3
pH (H_2O)	6.5	10.0	7.83	7.75	3.58	0.786	0.217	10.3
SOC (g kg^{-1})	0.2	6.4	2.3	2.5	5.341	0.732	0.491	51.0
Total N (g kg^{-1})	0.007	0.09	0.044	0.039	2.564	0.435	0.229	43.9
Available P (mg kg^{-1})	2.5	19.3	6.9	6.1	3.98	1.114	0.324	55.1
Ca^{2+} (cmol (+) kg^{-1})	1.2	6.0	3.03	2.5	2.51	0.756	0.245	43.5
Mg^{2+} (cmol (+) kg^{-1})	0.8	4.0	2.5	2.6	2.24	-0.157	0.206	32.2
K^+ (cmol (+) kg^{-1})	0.03	1.13	0.099	0.07	42.29	6.292	2.946	156.6
Na^+ (cmol (+) kg^{-1})	0.10	1.65	0.43	0.23	5.11	1.799	0.415	98.6
CEC (cmol (+) kg^{-1})	4.2	9.2	6.3	6.3	2.95	0.38	0.200	18.8
ECe (dS m^{-1})	0.026	0.55	0.109	0.065	7.43	2.105	0.482	100.6
ESP	1.44	26.3	6.74	4.10	5.29	1.824	0.416	94.6
SAR	0.057	1.265	0.272	0.146	6.12	2.017	0.471	106.2
ESI	0.147	6.112	0.588	0.361	32.2	5.197	1.670	151.0

† CV: Coefficient of variation; SOC: Soil organic carbon; ρd: Bulk density; SBR: Sodium base ratio; CEC: Cation exchange capacity in (cmol(+) kg^{-1}); ECe: soil electrical conductivity in dS m^{-1}; ESP: Exchangeable sodium percentage; SAR: Sodium adsorption ratio; ESI: Electrochemical stability index; Ks: saturated hydraulic conductivity; FC: field capacity, volumetric water content at -33 kPa; PWP: wilting point, volumetric water content at -1,500 kPa; AWC: available water capacity, calculated as the difference between -33 and -1,500 kPa

(CV<15%). The descriptive analysis showed that exchangeable K had the largest variation (CV = 156.6%) while ρd data showed the lowest variation among the measured parameters (Table 2).

Conversely, the observations reported by Biggar and Nielsen (1976) and Shukla *et al.* (2004) indicated that Ks showed the largest variability. Other researchers (Aimrun *et al.*, 2007; Yost *et al.*, 1982; Tsegaye and Hill, 1998) reported a lower variance of soil pH compared to other soil chemical properties. Sun *et al.* (2003) documented that soil available P showed the highest while soil pH the lowest.

Using mean and media for estimating central tendency of the data for measured and estimated variables, the results showed that the mean and median values for most parameters were identical despite the skewness in their distribution. This indicates that distribution of most of the measured parameters was more or less symmetrical (homogeneous) with few extreme values present in the distribution of some parameters (Ks, exchangeable Ca, K and Na). Earlier reports by some researchers (Cambardella *et al.*, 1994; Iqbal *et al.*, 2005; Sharma *et al.*, 2011) showed similar extreme values for Ks.

Spatial structure analysis

Soil textural properties: Nugget (Co) is the error in estimation process caused by sampling intensity, positioning, chemical analysis and soil properties, while sill (Co+C) represents spatially independent variance, where the data locations were separated by distance beyond which semivarience did not change. The largest nugget variance (9.2) and sill (69.4) was found with clay, followed by sand (5.7 and 37.9, respectively). Nugget values for pH measured in water were lowest and this portends low sampling error for pH but highest for clay. All measured soil properties differed in their spatial dependence (Table 3) and showed a positive nugget effect.

The soil texture in the study site varied from sandy clay loam to sandy loam. Spatial structure analysis indicated spatial variability across the study area for all measured soil textural properties. All the particle size classes (sand, silt and clay fraction) were strongly spatially dependent with nugget to sill ratios [Co/Co+C)] <0.25. The variograms of sand indicated that it was best fitted to exponential (Fig. 1a) while that of clay was best fitted to Gaussian functions (Fig. 1b). The resulting semivariograms indicated a range of about 53 m for sand, 594.5 m for clay and 577.7 m for bulk density (ρd) (Table 3). Earlier studies conducted by Sharma *et al.* (2011) and Ozgoz (2009) showed a range value of 405 and 379 m for sand, 391 and 372 m for clay and 391 and 433 m, respectively for ρd at the 0- to 20-cm soil depth. The soil properties having large-range values might be a function of intrinsic variations in the soil texture and mineralogy.

Cross-semivariograms depict the spatial relationship between two variables. As seen from Table 4, the sand content depicted positive relationship with ρd (r = 0.890; p = 0000) up to the range of 46.5 m with strongly spatial dependence [Co/(Co+C) <0.25)]. The relationship between clay and ñd was negative (r = -0.95; p=0000) (Table 5) up to 41.6 m (Table 4). They also showed strong spatial dependence. The ρd map showed a weak positional similarity with both sand and clay contents (Fig. 1). This is contrary to the findings of Sharma *et al.* (2011) which indicated a strong positional similarity between sand and ρd.

Soil hydraulic properties: The Ks had a small nugget (0.90), a relatively high sill (7.81), nugget to sill ratio of <0.25 and large range (683 m). This indicated strong spatial variability and dependence of Ks (Table 3). A range of 683 m indicated the distance beyond which semivariance

Table 3: Semivariogram model parameters of soil physical and chemical properties

Variables	Model type	Nugget (Co)	Sill (Co+C)	Range (Ao, m)	Proportion C/(Co+C)	R^2
Sand (%)	Exponential	5.7000	37.870	53.0	0.151	0.343
Clay (%)	Gaussian	9.2000	69.400	594.5	0.133	0.668
ρd (g cm^{-3})	Spherical	0.0006	0.0038	577.7	0.158	0.716
Ks (cm h^{-1})	Gaussian	0.9000	7.8090	532.1	0.115	0.683
FC (%)	Spherical	2.4900	9.4000	832.3	0.265	0.597
PWP (%)	Gaussian	1.5900	10.189	531.8	0.156	0.691
SOC (g kg^{-1})	Gaussian	0.0010	1.5100	40.8	0.0007	0.900
Total N (g kg^{-1})	Linear	0.0004	0.0004	184.9	1.000	0.232
Available P (mg kg^{-1})	Gaussian	0.0100	13.180	25.8	0.0008	0.662
CEC (cmol (+) kg^{-1})	Linear	1.5788	1.5788	184.9	1.000	0.364
Ca^{2+} (cmol (+) kg^{-1})	Linear	0.1834	0.1834	426.0	1.000	0.015
Mg^{2+} (cmol (+) kg^{-1})	Gaussian	0.0010	0.6520	38.2	0.0015	0.552
K^{+} (cmol (+) kg^{-1})	Linear	0.3047	0.3047	426.0	1.000	0.269
Na^{+} (cmol (+) kg^{-1})	Exponential	0.3690	1.8210	910.9	0.202	0.539
pH (H_2O)	Gaussian	0.00001	0.01002	38.4	0.0010	0.789
ECe (dS m^{-1})	Gaussian	0.0010	0.6340	37.1	0.0016	0.376
ESP	Gaussian	0.0010	0.6340	38.8	0.0016	0.358
SAR	Gaussian	0.1380	0.6920	29.2	0.1990	0.152

† CV: Coefficient of variation; SOC: Soil organic carbon; ρd: Bulk density; SBR: Sodium base ratio; CEC: Cation exchange capacity in (cmol(+) kg^{-1}); ECe: soil electrical conductivity in dS m^{-1}; ESP: Exchangeable sodium percentage; SAR: Sodium adsorption ratio; ESI: Electrochemical stability index; Ks: saturated hydraulic conductivity; FC: field capacity, volumetric water content at -33 kPa; PWP: Permanent wilting point, volumetric water content at -1,500 kPa; AWC: available water content, calculated as the difference between -33 and -1,500 kPa

Table 4: Cross-semivariogram model parameters of soil physical and chemical properties

Variables	Model Type	Nugget (Co)	Sill (Co+C)	Proportion Co/(Co+C)	Range (m)	R^2	RSS
Sand×ρd	Gaussian	0.0082	0.2224	0.0369	46.5	0.940	1.616×10^{-3}
Sand×Ks	Exponential	1.9100	5.9740	0.3197	93.5	0.865	1.06
Sand×FC	Exponential	-0.0793	-0.1886	0.4205	482.2	0.443	1.270×10^{-3}
Sand×PWP	Exponential	-0.0525	-0.1472	0.3567	501.1	0.594	4.798×10^{-4}
Clay×ρd	Gaussian	-0.0001	-0.1462	0.0007	41.6	0.851	1.823×10^{-3}
Clay×Ks	Exponential	-0.0100	-0.4053	0.0247	37.8	0.746	1.30
Clay×FC	Exponential	0.0501	0.1049	0.4776	39.4	0.419	4.895×10^{-4}
Clay×PWP	Exponential	0.0359	0.0719	0.4993	162.8	0.586	2.809×10^{-4}
ρd×Ks	Gaussian	0.0001	0.0426	0.0023	42.9	0.836	1.923×10^{-4}
SOC×pH	Spherical	0.0000	0.0010	1.0000	24.6	0.000	0.721
SOC×ECe	Gaussian	0.0043	0.0923	1.0000	447.8	0.194	1.248×10^{-3}
SOC×CEC	Linear	0.0000	0.0010	0.0415	207.3	0.188	1.348×10^{-4}
SOC×TN	Linear	-0.0055	-0.0055	0.0009	910.9	0.324	3.67×10^{-2}
SOC×AP	Gaussian	0.0010	1.2870	0.0008	910.9	0.927	4.57×10^{-2}
ECe×TN	Linear	0.0000	0.0000	0.0000	510.9	0.359	5.822×10^{-7}
ECe×AP	Gaussian	-0.0001	-0.0662	0.0015	42.0	0.345	0.0184

† SOC: Soil organic carbon; ñd: Bulk density; CEC: Cation exchange capacity in (cmol(+) kg^{-1}); ECe: Soil electrical conductivity in dS mρ^{1}; TN: Total nitrogen; AP: Available phosphorus; Ks: Saturated hydraulic conductivity; FC: field capacity, volumetric water content at -33 kPa; PWP: Permanent wilting point; RSS:

for Ks became constant and the soil samples can be assumed to be spatially independent. Within the range, the measurements of the variable are correlated with each other. Various ranges for Ks

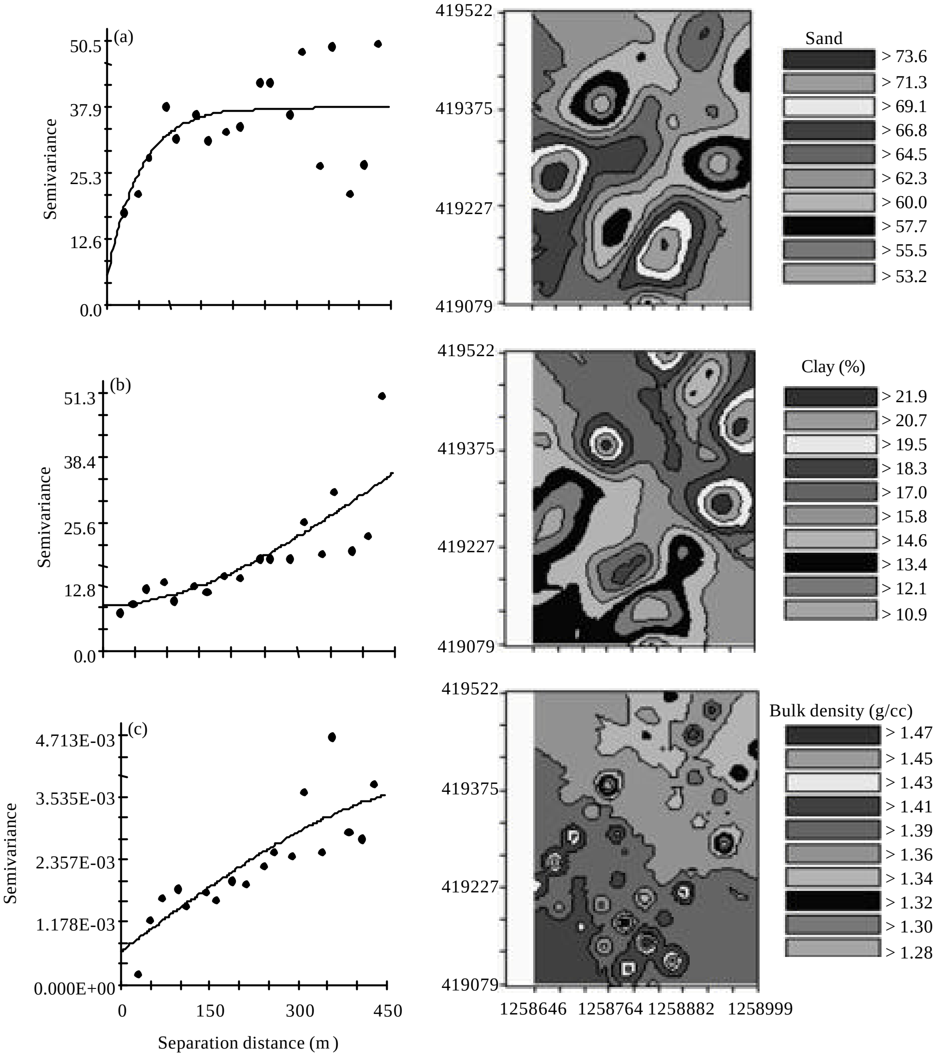

Fig. 1(a-c): Semivariogram and kriged maps of soil physical properties for (a) %sand, (b) %clay and (c) bulk density (g cm^{-3})

were reported in different studies in diverse locations. Studies conducted by Sharma *et al.* (2011) indicated that Ks had the largest spatial variability at a range of 563 m. Similar study conducted by Cemek *et al.* (2007) revealed spatial dependence in surface Ks, with a range value of 17,050 m. On the other hand, Bosch and West (1998) found structural variability in Ks, with range values that varied from 2 to 166 m for the soil samples collected at four horizons for two soil types.

The moisture content at -33 (FC) and -1,500 (PWP) kPa pressure heads showed structural variability with ranges of 832.3 and 531.8 m, respectively (Table 3). Based on the proportion of nugget (Co) to sill (Co+C) ratio, the moisture content at FC was moderately spatially dependent (Co/(Co+C) fell between 0.25-0.75) while the spatial dependence for PWP was strong (Co/(Co+C) <0.25). Iqbal *et al.* (2005) reported a long range of variability of 741 and 425 m for soil moisture at FC and PWP, respectively while Sharma *et al.* (2011) displayed ranges of 355, 297 and 134 m

Table 5: Pearson correlations between soil physical and chemical properties

	Sand	Silt	Clay	ρd	Ks	FC	PWP	AWC	pHw	SOC	TN	AP	Ca	Mg	K	Na	CEC	EC	ESP	SAR
Sand	-																			
Silt	-0.80	-																		
Clay	-0.86	0.39	-																	
ρd	0.89	-0.51	-0.95	-																
Ks	0.75	-0.33	-0.90	0.86	-															
FC	-0.95	0.60	0.96	-0.96	-0.83	-														
PWP	-0.83	0.35	0.99	-0.94	-0.91	0.94	-													
AWC	-0.70	0.89	0.29	-0.42	-0.12	0.54	0.23	-												
pHw	-0.11	0.04	0.14	-0.18	-0.19	0.12	0.15	-0.02	-											
SOC	0.02	0.02	-0.13	-0.00	-0.33	-0.01	-0.15	0.35	-0.09	-										
TN	0.20	-0.13	-0.18	0.14	0.12	-0.21	-0.19	-0.13	-0.00	-0.19	-									
AP	-0.14	0.14	0.11	-0.21	-0.14	0.11	0.09	0.07	0.00	0.02	0.14	-								
Ca	0.04	-0.07	0.02	-0.06	-0.01	0.03	0.03	0.02	-0.09	0.20	0.15	-0.16	-							
Mg	0.31	0.24	0.27	-0.36	-0.17	0.32	0.25	0.32	0.21	0.12	-0.21	0.17	0.12	-						
K	0.10	0.10	-0.05	0.04	0.05	-0.06	-0.05	-0.06	0.07	0.11	-0.04	-0.12	0.16	0.26	-					
Na	0.18	-0.26	-0.09	0.10	0.08	-0.13	-0.07	0.20	0.53	0.11	0.05	0.01	-0.13	-0.08	0.09	-				
CEC	0.00	-0.21	0.16	-0.17	-0.20	0.06	0.17	-0.24	0.19	-0.10	-0.13	0.14	-0.09	0.48	0.30	0.21	-			
Ece	-0.04	0.07	-0.03	-0.01	0.05	0.02	-0.04	0.14	0.36	0.10	0.15	-0.12	0.01	-0.05	-0.00	0.71	0.05	-		
ESP	0.19	-0.21	-0.13	0.14	0.11	-0.16	-0.11	-0.17	0.52	0.06	0.09	-0.0	-0.12	-0.18	0.03	0.98	0.04	0.71	-	
SAR	0.20	-0.28	-0.10	0.12	0.08	-0.15	-0.09	-0.23	0.50	0.09	-0.02	-0.01	-0.22	-0.16	0.04	0.98	0.16	0.70	0.97	-

SOC: Soil organic carbon; ρd: Bulk density; CEC: Cation exchange capacity in (cmol(+) kg^{-1}); ECe: soil electrical conductivity in dS m^{-1}; pHw: pH measured in water; ESP: Exchangeable sodium percentage; SAR: Sodium adsorption ratio; TN: Total nitrogen; AP: Available phosphorus; Ks: saturated hydraulic conductivity; FC: field capacity, volumetric water content at -33 kPa; PWP: Permanent wilting point, volumetric water content at -1,500 kPa; AWC: available water content, calculated as the difference between -33 and -1,500 kPa

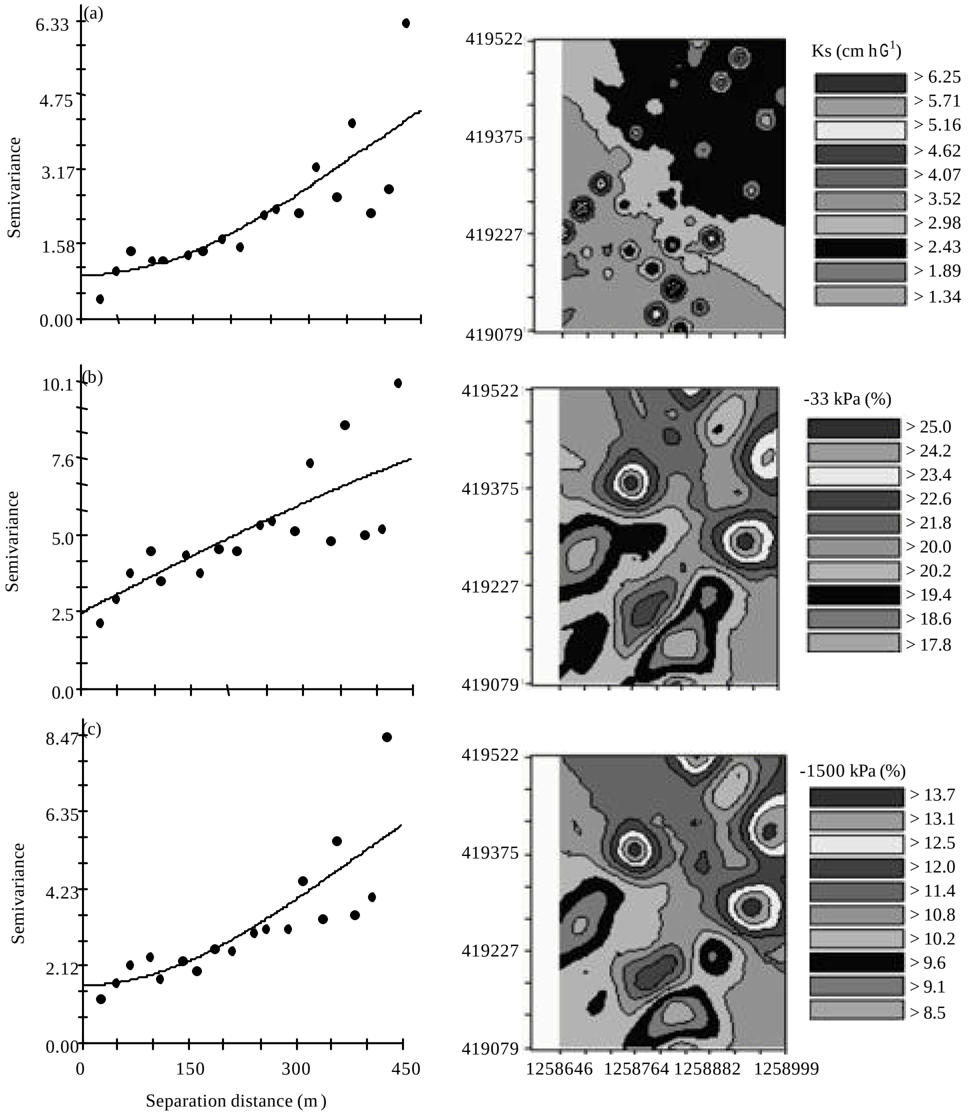

Fig. 2(a-c): Semivariogram and kriged maps of soil physical properties for soil water retention properties (a) Ks, percentage volumetric water content for (b) field capacity (-33 kPa pressure head) and (c) wilting point (-1,500 kPa pressure head)

for FC, PWP and AWC, respectively. Such wide differences in the ranges for the water retention parameters could be attributed to the differences in sampling interval which was dependant on the size of the surveyed area. As the nugget parameter is a measure of the amount of variance due to errors in sampling, measurement and other unexplained sources of variance, it corresponds to the spatial variation occurring at distances shorter than the measurement interval. The relatively high Co values in the present study confirm the relative heterogeneity of distribution of the water retention date in the surface soil layer.

Analysis of the cross-semivariograms revealed that values of Ks were positively correlated (r = 0.748) with sand content and negatively correlated (r = 0.904) with clay content (Table 4). The

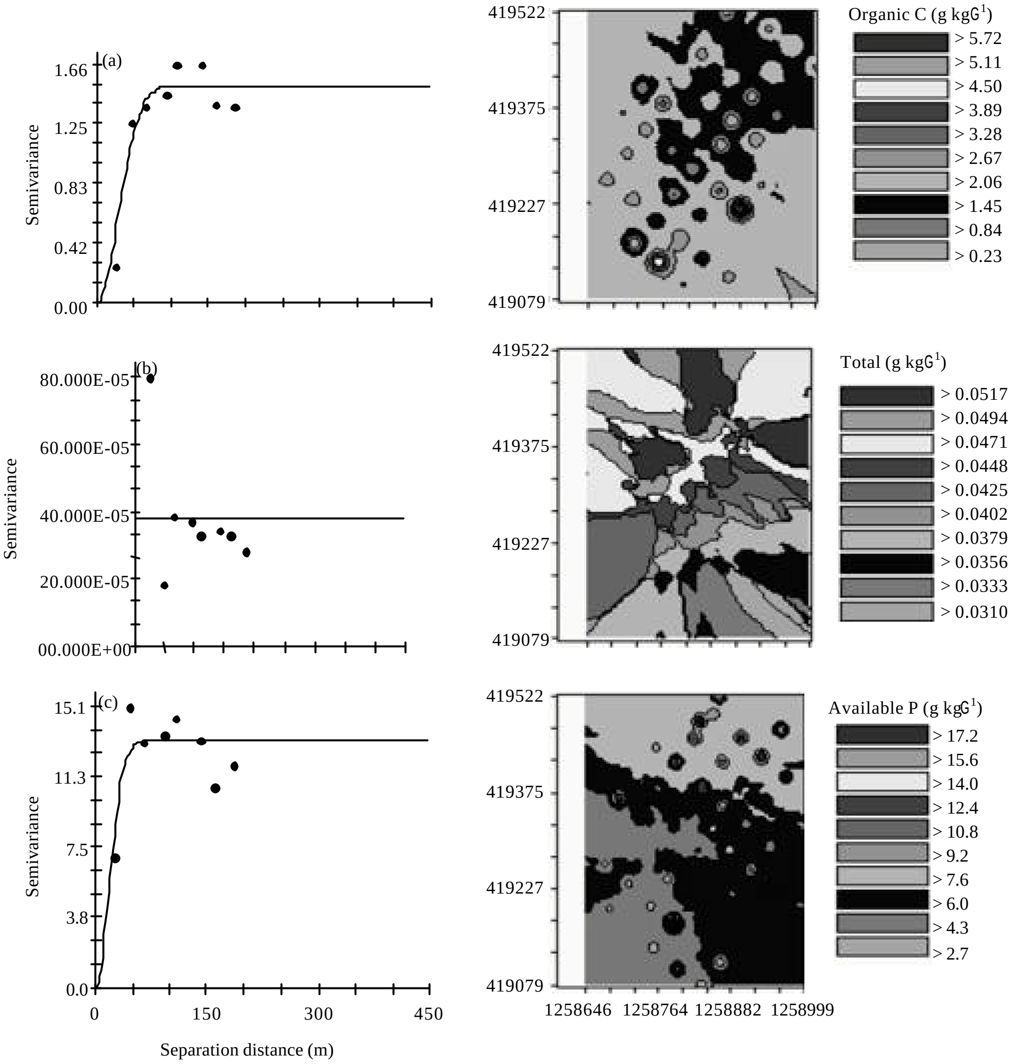

Fig. 3(a-c): Semivariogram and kriged maps of soil chemical properties for (a) organic carbon (g kg^{-1}), (b) total N (g kg^{-1}) and (c) available phosphorus (mg kg^{-1})

cross-semivariogram of Ks against sand content showed that Ks was positively correlated with sand content up to the range of 94 m within which they were moderately spatially dependent. The cross-semivariogram of Ks against clay content revealed a negative correlation up to the range of 38 m (Table 4). Strong spatial dependence was found between the parameters within this range. The implication of this is that Kriging or Co-kriging can be used to estimate the soil moisture values at FC and WP using the spatial structure of soil textural data and the associated correlation between hydraulic and textural properties.

The Ks was also found to be highly correlated to ρd ($r = 0.860$; $p<0.0001$) as well as moisture content at FC ($r = 0.826$; $p<0.0001$) and PWP ($r = -0.911$; $p<0.0001$) (Table 5). The moisture content at FC was highly negatively correlated to sand ($r = -0.949$; $p<0.0001$), clay ($r = 0.948$; $p<0.0001$) and ρd ($r = -0.951$; $p<0.0001$). Similarly, moisture content at PWP was also found

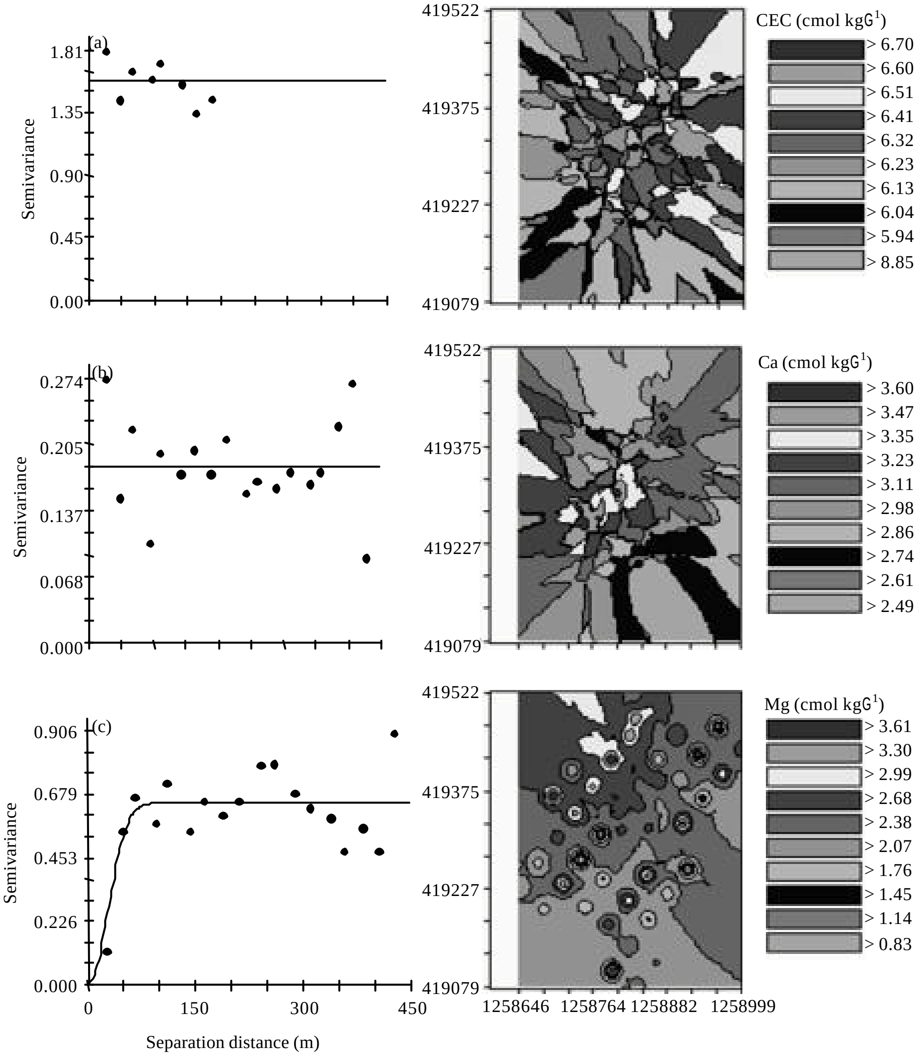

Fig. 4(a-c): Semivariogram and kriged maps of soil chemical properties for (a) cation exchange capacity (CEC, cmol(+) kg^{-1}), (b) Ca (cmol(+) kg^{-1}) and (c) Mg (cmol(+) kg^{-1})

correlated to sand (r = -0.804), clay (r = 0.982) and ρd (r = -0.917) (Table 5). Vauclin *et al.* (1983) also found the strongest correlation between moisture content at -33 kPa (FC) and sand (r = -0.83). Similarly, Sharma *et al.* (2011) reported high correlation between soil moisture at FC and sand (r = -0.90), clay (r = 0.88) and ρd (r = -0.93) as well as between moisture at PWP and sand (r = -0.79), clay (r = 0.87) and ρd (r = -0.89).

Kriged maps of soil moisture at FC (Fig. 2b) and PWP (Fig. 2c) had the best positional similarity with the clay content.

Chemical properties: The spatial structure analysis of pH measured in water (pH(H_2O)) indicated that it had the smallest nugget variance (0.00001) of all the studied chemical properties with relatively small sill of 0.01002 (Table 3). Similarly, the distribution data of all the other

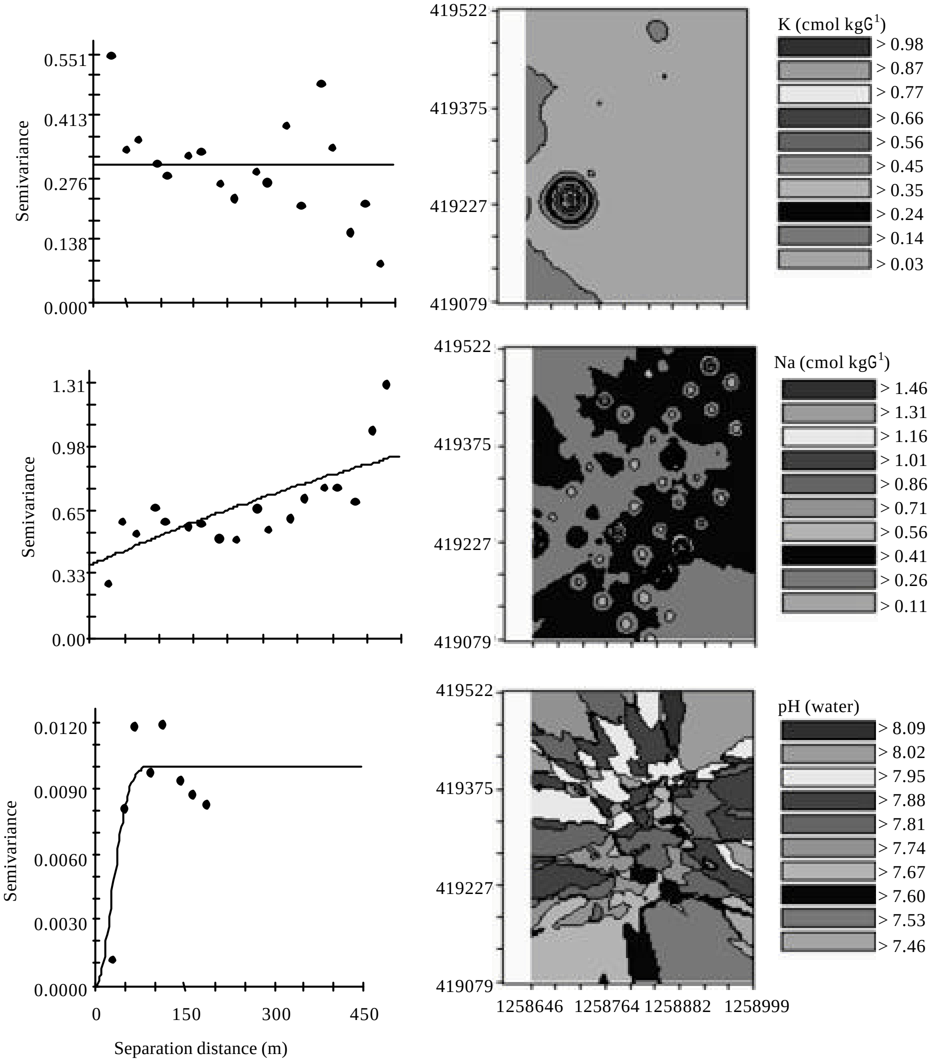

Fig. 5(a-c): Semivariogram and kriged maps of soil chemical properties for (a) potassium (cmol(+) kg^{-1}, (b) sodium (cmol(+) kg^{-1}) and (c) pH measured in water

measured and estimated chemical parameters also showed a low nugget variance and sill with range values varying from 26 to 911 m. The semivariograms of the measured soil chemical properties revealed that Na had the largest range while Available Phosphorus (AP) had the lowest (Table 3). Most of the measured and estimated soil chemical variables were strongly spatially dependent with nugget to sill ratio of <0.25. However, the distribution of exchangeable total N, Ca, K and CEC showed non spatial dependence. The Pearson correlation analysis revealed significant positive pH(H_2O) correlation with exchangeable Na (0.549, $p<0.0001$), electrical conductivity ($r = 0.394$, $p<0.01$), ESP ($r = 0.521$, $p<0.01$) and SAR ($r = 0.519$, $p<0.001$). Similarly, a significant positive Pearson correlation was found between pH ($CaCl_2$) and Na ($r = 0.604$, $p<0.0001$), ESP ($r = 0.565$, $p<0.0001$), SBR ($r = 0.524$, $p<0.001$) as well as CEC ($r = 0.299$, $p = 0.039$). The CEC data also showed significant positive correlations with exchangeable Mg ($r = 0.483$, $p<0.001$) and K ($r = 0.298$, $p<0.05$).

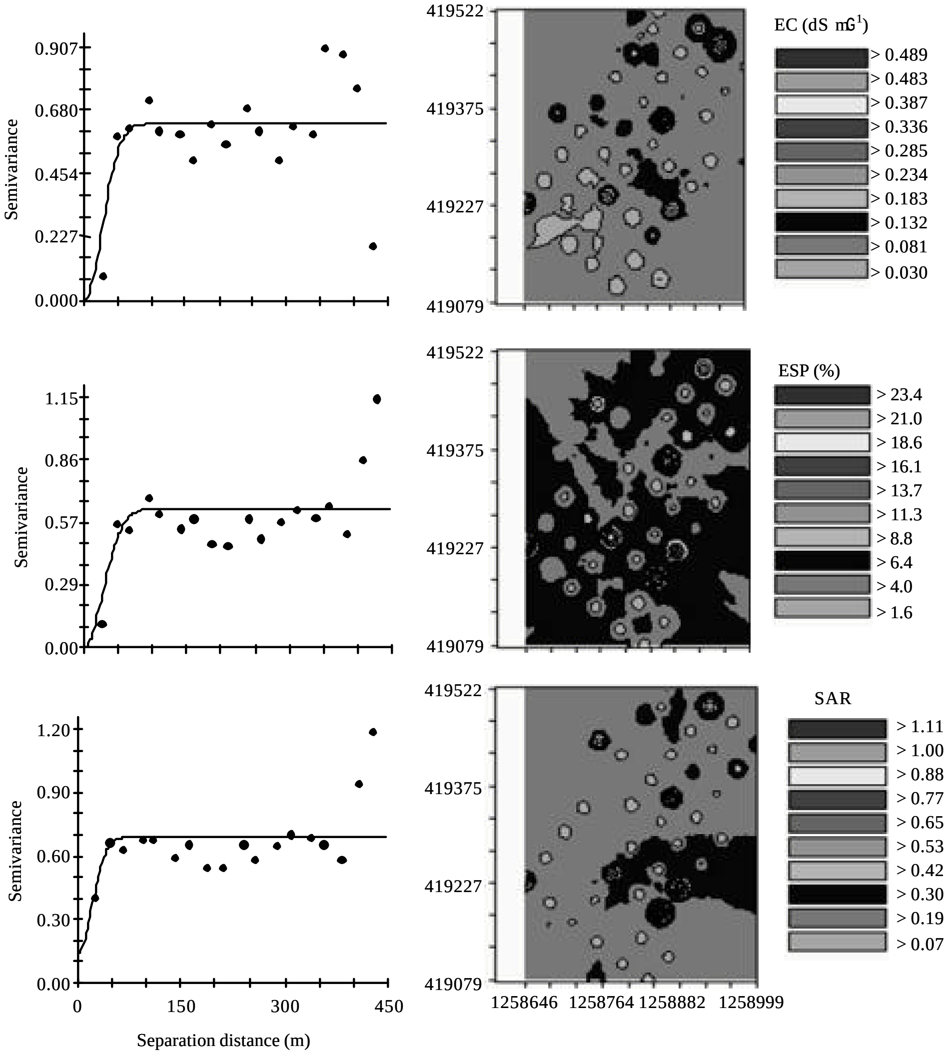

Fig. 6(a-c): Semivariogram and kriged maps of soil chemical properties for (a) electrical conductivity (dS m^{-1}), (b) exchangeable sodium percentage (%) and (c) sodium adsorption ratio

The cross-semivariogram between SOC and TN as well as AP showed a positive correlation up to range of 911 m (Fig. 3). Similarly, electrical conductivity values correlated with TN and AP up to the ranges 511 and 42.0 m, respectively (Table 4). Kriged maps of CEC (Fig. 4a). Ca (Fig. 4b) and pH (H_2O) (Fig. 5c) showed similar distribution pattern of the chemical properties in the site.

The variability of these properties (TN, EC) seemed to be controlled by extrinsic factors, such as irrigation water and fertilizer application (Fig. 6). Similar observations were also reported by Cambardella *et al.* (1994), Shukla *et al.* (2004) and Sharma *et al.* (2011).

Spatial autocorrelation, Moran I: The correlograms showed the spatial autocorrelation for soil physical (Fig. 7 and 8) and chemical variables (Fig. 9 and 10). Figure 7 presents the correlograms of soil texture and bulk density. The analysis of Moran'I statistics revealed that sand content

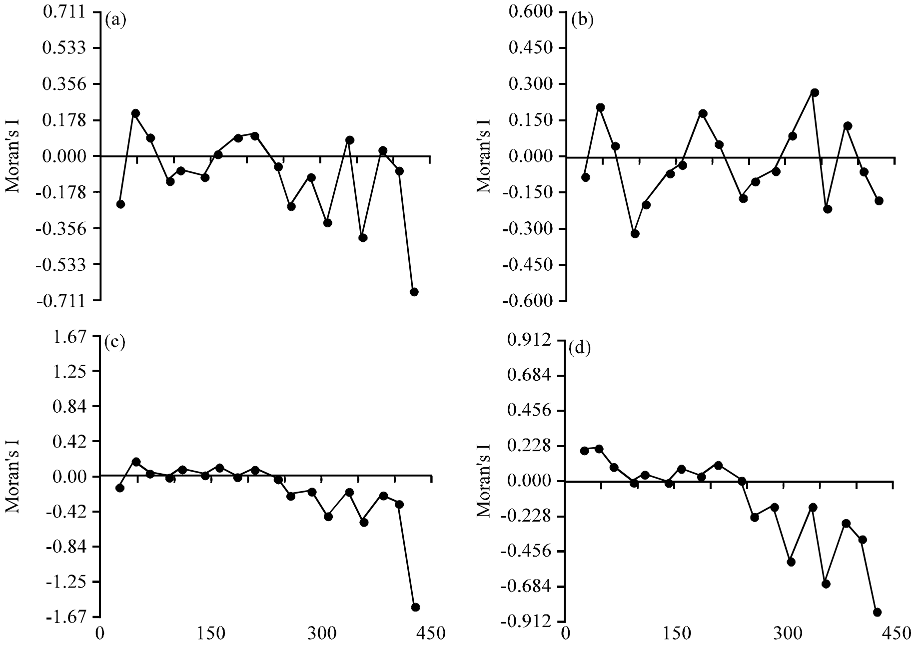

Fig. 7(a-d): Spatial autocorrelation, Moran's I, of soil textural properties(%) (a) Sand, (b) Silt, (c) Clay and (d) bulk density (g cm^{-3})

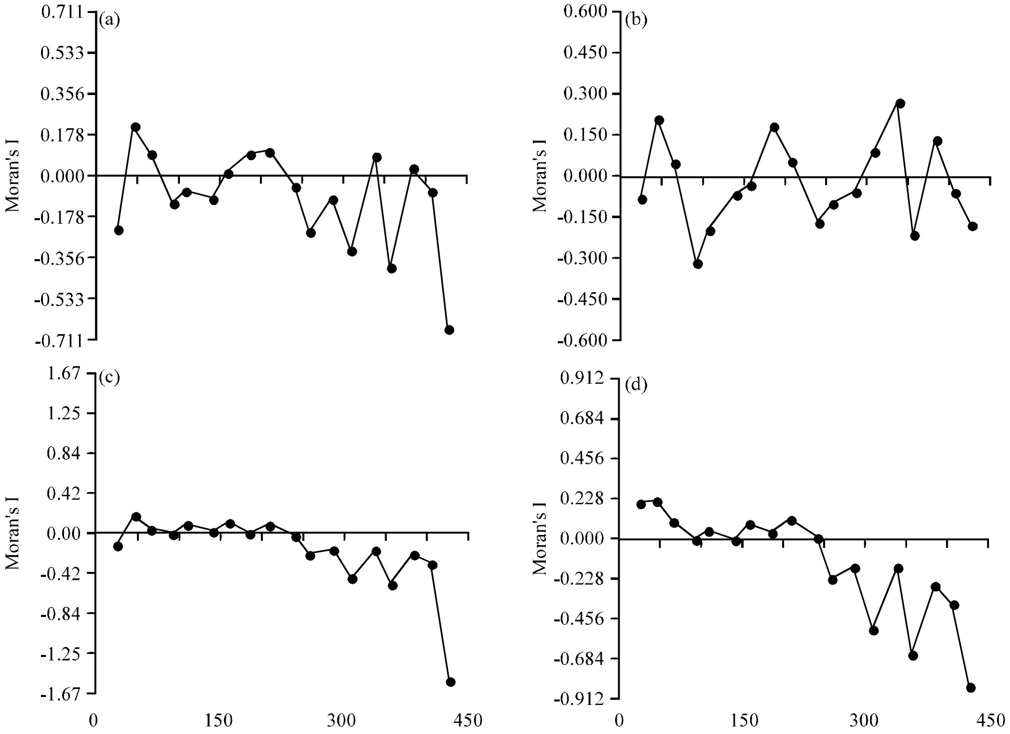

Fig. 8: Spatial autocorrelation, Moran's I, of soil hydraulic properties. (a) KS, (b) -33 kpa (FC), (c) -33 kpa (FC) and (D) -1500 KPA (NP) -33 kPa and -1,500 kPa represent volumetric water content (cm^3 cm^{-3}, expressed as a percentage) at field capacity and wilting point, respectively. Ks: saturated hydraulic conductivity (cm h^{-1})

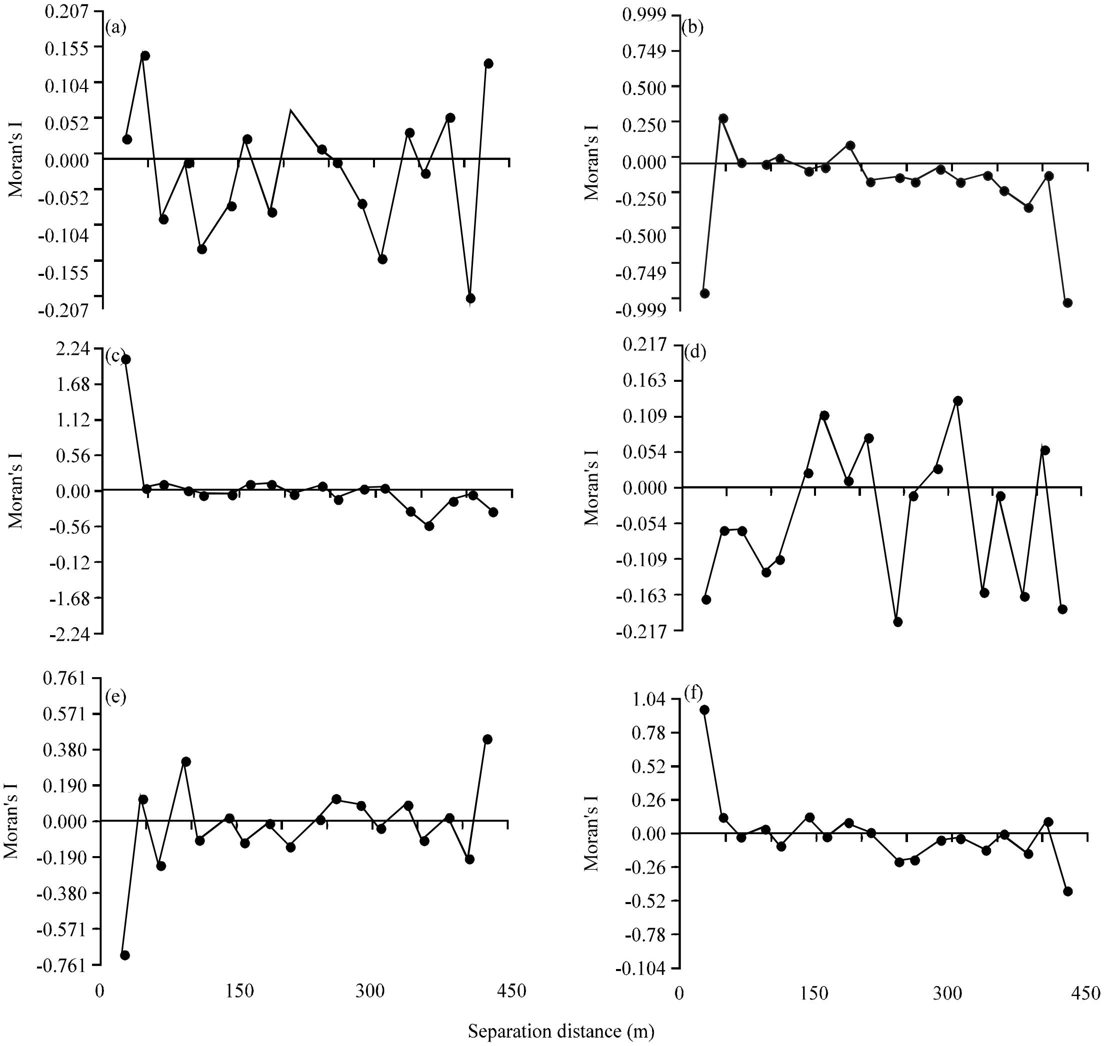

Fig. 9(a-f): Spatial autocorrelation, Moran'I of some soil chemical properties. (a) Orgain c, (b) Total N, (c) Availabe P, (d) CEC, (e) Ca and (f) Mg. CEC: cation exchange capacity (cmol(+) kg^{-1})

significantly (p = 0.009) autocorrelated up to a lag distance of 391 m with Moran's I value of 0.1951). Correlograms of silt and clay content also revealed significant (p = 0.019 and 0.017, respectively) autocorrelation at a lag distance of 172 and 237 m, respectively with Moran's I values of 0.1749 and 0.1822, respectively. Similarly, ρb had a significant (p = 0.004) Moran's I of 0.2568 at a lag distance of 242 m.

The correlograms of soil hydraulic properties are presented in Fig. 8. The Ks, soil water content at FC and WP also had significant (p = 0.003, 0.023 and 0.008) Moran's I (0.2575, 0.1822 and 0.1908, respectively) at spatial lag distances of 197, 247 and 244 m, respectively. Soil water at FC and clay content showed similar autocorrelation patterns each of which had Moran's I value of 0.1822. Similarly, soil water at FC and WP depicted as well as clay content had identical autocorrelation pattern. Iqbal *et al.* (2005) reported significant Moran I (p = 0.05) values at a lag distance of less than 400 m for soil physical properties and less than 100 m for soil hydraulic properties and ρb.

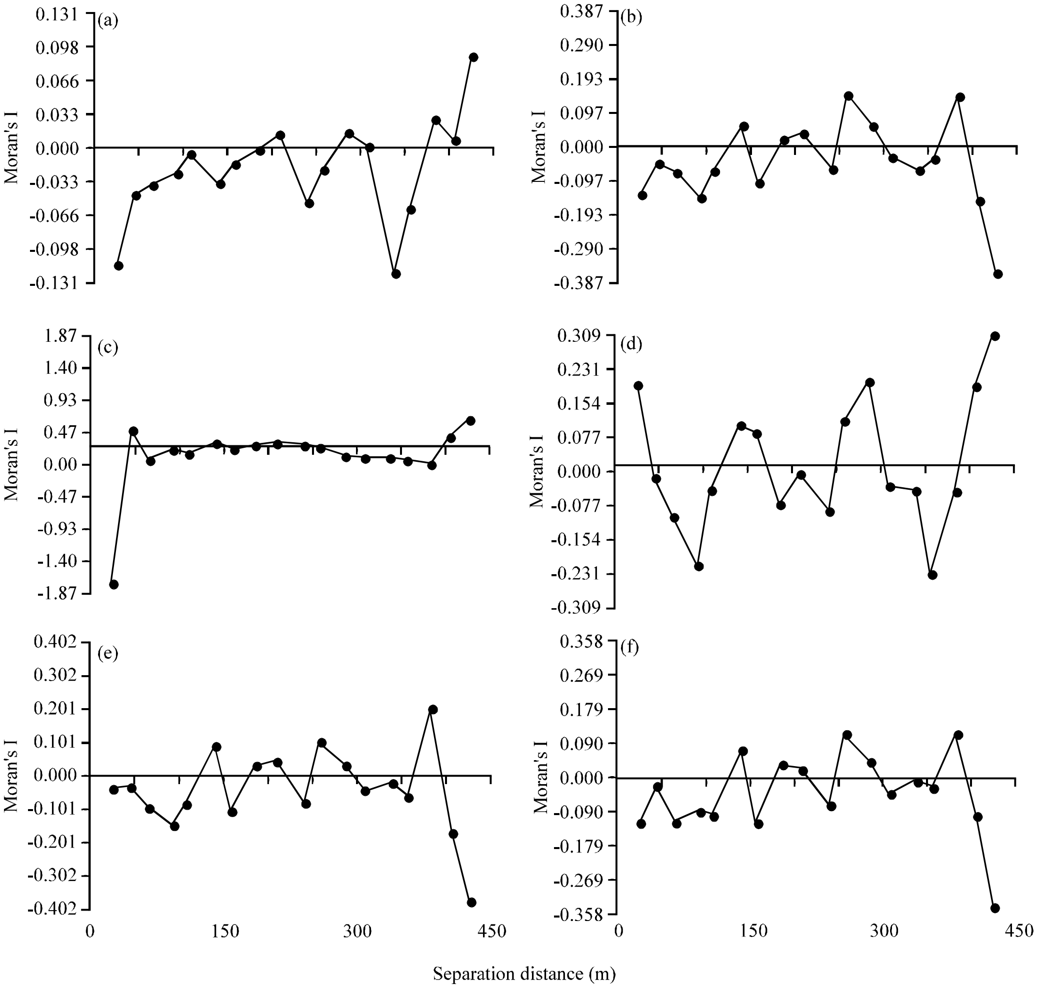

Fig. 10(a-f): Spatial autocorrelation, Moran'I of some soil chemical properties. (a) k, (b) Na, (c) pH water (d) EC, (e) ESP and (f) SAR. EC: electrical conductivity (dS m^{-1}); ESP: exchangeable sodium percentage; SAR: sodium adsorption ratio

Among the studied soil chemical properties, only pH measured in water had significant ($p = 0.048$) Moran's I (Fig. 8d) with a value of 0.1395 and lag distance of 271.3 m.

Management strategy: As it was revealed from the analysis of the contour maps of soil properties, the entire study site has different soil textural classes and water retention capacities. Besides, the distribution pattern of spatial variability of soil texture was nearly similar to the spatial variability pattern of water-holding capacities in the study site. During the dry season, crops such as maize, wheat, sorghum, sugar cane, carrots, tomatoes, etc. are cultivated either under furrow irrigation system or basin type irrigation system. The textural differences and water-holding capacities of the soils are not often put into consideration when applying water in the site. The portion with coarse texture and low water-holding capacities require frequent application of water in small amounts using more efficient irrigation systems like the drip irrigation. For site-specific management, it is necessary to apply different water depths at different time intervals, N fertilizer and other inputs taking into consideration the soil textural and volumetric water content at FC and WP maps.

CONCLUSIONS

The descriptive statistics showed that most of the measured soil chemical variables were skewed and nonnormally distributed. The total N data were highly variable (0.007 -0.09 g kg^{-1}) because of the coarse-textured soils in the greater parts of the study site. Exponential, Gaussian, Spherical and Linear models were fitted to the semivariograms of the soil variables. The semivariograms revealed spatial variability in the spatial structures of soil physical and chemical properties across the study area. Cross-semivariograms revealed spatial correlation within soil physical and chemical properties. Pearson correlation also showed that soil textural properties, especially sand and clay data, were highly correlated to the water retention. The kriged contour maps of measured soil variables showed positional similarities with each other. The correlograms showed similar spatial structures of clay, volumetric water content at FC and WP. Correlograms generated for soil physical properties indicated that samples collected for the study of soil physical properties should be separated by a distance of 391 m. Samples would be independent when collected at a separation distance of 270, 296, 369, 271 and 222 m for organic C, TN, CEC, pH(H_2O) and EC, respectively. Therefore, a sampling distance of 391 m would be sufficient to design a future sampling scheme to investigate the soil physical and chemical properties in the study site. Contour maps of sand and clay contents and water content at -33 or -1,500 kPa pressure head can be used for better irrigation management in the site. The more efficient irrigation systems like drip irrigation system can be considered in the portion with coarse-texture to supply small and frequent water applications.

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