Assessment of Spatial Variability of Soil Properties Using Geospatial Techniques For Sustainable Agricultural Production

Abstract

Soil is an important source of available nutrients. Either shortage or surplus of available nutrients in the soil would limit growth of crops. Understanding the spatial variability and distribution patterns of soil available nutrients is essential for management of the soil and application of fertilizers. A total of 111 geo-referenced soil samples were collected on 300 m x 300 m grid at a depth of 0–15 cm, processed and analyzed for pH, EC, soil organic carbon (SOC), available nitrogen (AN), available phosphorus (AP), available potassium (AK), available sulphur (AS), available iron (Fe), available manganese (Mn), available zinc (Zn) and available copper (Cu). Soil properties coefficients of variation (CVs) widely varied from low (5.22%) to moderate (49.28%). The geostatistics and geographic information system (GIS) techniques were applied. Ordinary kriging and semivariogram analysis showed differed spatial variability patterns for the studied soil properties with spatial dependence ranged from moderate to strong. The semivariograms for the soil properties were best fitted with spherical model. The range of influence for available N, P, K and S were 268.287, 497 and 706 m, respectively. The spatial ranges of available Fe, Mn, Zn and Cu were 1050, 1150, 1470, and 1430 m, respectively. The spatial dependence class was strong for EC, SOC, available P, K and was moderate for available N, S, Fe, Mn, Zn and Cu. The available N and P is categorized as low (<280 kg ha^{-1}) and low (<11 kg ha^{-1}) to medium (<22 kg ha^{-1}), respectively were the main limiting factors in crop production. The availability K was categorized as medium (118-280 kg ha^{-1}) to high (> 280 kg ha^{-1}). The soil nutrient maps would help to provide precise fertilizer recommendations for sustainable production and environmental conservation.

Key words: Spatial variability, Geostatistics, soil properties, site specific nutrient management

Introduction

Crop management in India has been driven by increasing use of external inputs for the past four decades. Fertilizer nutrients have played a major role in improving crop productivity. In the early 1950s, total fertilizer consumption in India was just 0.069 mt, which has increased to 2.25 mt in 1970–71 and 32.5 mt at present. This about 14.4 times rise in fertilizer consumption since the 1970s level to the present highlights the role of fertilizers and nutrient management in Indian agriculture (Raj Gupta et al. 2021). The food grain production for past 3-4 years is hovering around 234 million tonnes (Firdos Ahmad and Shaukat Haseen, 2012). Not with standing these impressive developments, food grain demand is estimated to increase to about 300 million tonnes yr^{-1} by 2025 (Johnston *et al.*, 2009). Hence in the next 15 years, production of food grain needs to be increased at the rate of 4.5

million tonnes annually. With ground water tables declining, there is growing pressure to increase the yield. The key factor behind high yield growth could be the development of new technology that will produce higher yield per hectare, and fertilizer remains a key factor in managing the task. However, fertilizer application should be optimum in quantity to meet the crop‘s nutrient requirement so as to achieve the yield target.

In addition, the growing concern about poor soil health and declining nutrient use efficiency has raised concern on the productive capacity of agricultural systems in India. Major factors contributing to the low and declining crop responses to fertilizer nutrients are (a) continuous nutrient mining due to imbalanced nutrient use, which is leading to depletion of some of the major, secondary and micro nutrients like P, K, S, Zn, Mn, Fe and B, and (b) mismanagement of irrigation systems leading to serious soil quality degradation. Furthermore, such low efficiency of resources and fertilizer inputs has impacted the production costs with serious environmental consequences.

Research conducted in various countries including India (Dobermann *et al.*, 2002; Wang *et al.*, 2001 and Wopereis *et al.*, 1999) has demonstrated limitations of the blanket fertilizer recommendations practiced across Asia. Cassman *et al.* (l996 a, b) observed that indigenous N supply of soils was variable among fields and seasons, and was not related to soil organic matter content. On-farm research has clearly demonstrated the existence of large field variability in terms of soil nutrient supply, nutrient use efficiency and crop responses. Thus, it was hypothesized that future gains in productivity and input use efficiency will require soil and crop management technologies that are knowledge-intensive and are tailored to specific characteristics of individual farms or fields to manage the variability that exists between and within them (Katyal, 2019).

An approach, which considers between – field variations to guide individual farmers to a rational nutrient management practice, instead of applying a general recommended dose seems more appropriate. Such methods are known as Site – Specific Nutrient Management (SSNM), and precision farming (precision agriculture).

Precision agriculture is the application of technologies and principles to manage spatial and temporal variability associated with all aspects of agricultural production for improving production and environmental quality (Jin and Jiang, 2002). The generation of maps for crop and soil properties is the most important and first step in precision agriculture. These maps will measure spatial variability and provide the basis for controlling spatial variability .

Assessing variability, managing variability and evaluation are the steps involved in SSNM, of which assessing spatial variability is the critical step in SSNM (Mc kinion et al., 2001). Spatial variability in soils occurs naturally from pedogenic factors (Goovaerts, 1998). Natural variability in soils results from complex interaction between geology, topography, climate as well as land use. Soil property varies not only between regions and between farms but also from plot to plot and within a field or plot. Accurate representation of spatial variability in field requires taking and analyzing many samples. Sampling is normally done on a grid or on places whose spatial coordinates were recorded by Global Positioning System (GPS).

Spatial data analysis is being carried out using a variety of techniques. Geostatistics is basically a technology for estimating the local values of properties that vary in space from sample data. Geostatistics has been applied to map soil nutrient contents to understand interaction between soil formation and agronomic processes or to assess the effect of long term cultivation on general soil properties (Liu et al. 2004). Geostatistical techniques can be used to characterize the spatial variability of soil properties through structure recognition and optimal interpolation. Kriging is a geostatistical estimation technique for optimal, unbiased estimation of properties at unsampled location with minimum estimation variance. Geographical Information System (GIS) is referred as the brain of precision agriculture. The ability of GIS to perform spatial operations on the data enables precision agriculture. Integration of geostatistics and GIS to map fertility properties of soil provide a helpful tool for SSNM (Jiang et al., 2012).

In India, the general agronomic practices follow a standard management option for a large area irrespective of the variability occurring within and among the fields. Under such circumstances, GIS based soil fertility mapping appeared as a promising alternative. Use of such maps as a decision support tool for nutrient management will not only helpful for adopting a rational approach over farmer's fertilization practice or state fertilizer recommendations, but will also reduce the necessity for elaborate individual field based soil testing activities.

However, information on soil properties spatial variability in southern India is still limited. Thus, the present study was carried out i) to analyse the spatial dependence and to explain the variation mechanism of available nutrients in paddy soils, ii) to map the spatial distribution of available nutrients using geostatistics.

2. Material and Methods

Site details

The spatial variability study was conducted in the cultivated fields of Thirunavalur village, Thirunavalur block, Villupuram district (Fig.1) The study area lies between 11° 44’N to 11° 46’N Latitude and between 79° 22’E to 79° 25’ E Longitude. The annual rainfall of the region is 1070 mm. The mean maximum and minimum temperatures are 38°C and 21°C, respectively. The soils were clay loam in texture belonging to Vertic Haplustepts.

Soil sampling and their analysis

Grid wise (300 x 300 m grids) soil samples were collected from 111 locations. Soil samples (0-15 cm) were taken before fertilizing and planting the fields. Soil samples were collected before monsoon using a soil core sampler (8cm diameter, 15 cm length) litters, organic debris are removed. The location coordinates of each sampling site were recorded using global positioning system (GPS) unit. Samples were air dried in shade and passed through 2 mm sieve and analyzed for physic-chemical properties.

Soil pH and electrical conductivity was measured in soil-water suspension (1:2.5) using pH meter (Jackson,1973) The soil organic carbon was determined by Walkley and Black method (1934), available nitrogen was analysed by alkaline $KMnO_4$ method (Subbiah and Asija, 1956). Available Phosphorus by Olsen method (1954), the available Potassium was determined by NH_4OAC method (Stanford and English, 1949) and the available sulphur by $CaCl_2$ 0.15% extract (Williams and Steinbergs, 1959). The micronutrients were extracted by diethylene triamine penta acetic acid (Lindsay and Norvell, 1978) followed by analysis using atomic absorption spectrophotometer (Varian Spectr AA 55B).

Descriptive statistics

The descriptive statistics including mean, standard deviation (SD), minimum, maximum, coefficient of variation (CV), skewness and kurtosis were calculated for each properties in SPSS 9.2. A correlation analysis was conducted to determine the relationship among ten soil properties under study.

Geostatistical analysis

Geostatistical analysis of soil properties was carried out by Geostatistical analyst of ArcGIS 9.1 for modelling semivariogram and fitting the best semivariogram model. Before fitting the semivariogram models, skewed soil properties were transformed to a nearly normal distribution using natural logarithm. The data was back transformed using back transformation. Different variogram models *viz,* Spherical and exponential were fitted to the empirical semi-variance. Selection of semivariogram models was made based on the coefficient of determination (R^2) and residual sum of squares (RSS) The fitted models were then used in an ordinary kriging procedure to estimate different properties at non-measured points as interpolated values for mapping (Krig, 1981). The cross validation analysis was conducted for evaluating kriging interpolation bias and accuracy in which each point measured in a spatial domain is individually removed from the domain and estimated via kriging as though it were there (Schepers et al., 2004). In this way, a comparison can be made of estimated vs actual values for each sample location.

Results and Discussion

Exploratory data analysis

Soils were neutral (pH 7.01) to alkaline (pH 9.56) in reaction and nonsaline (EC 0.17 to 1.65 dS/m) in character with the mean value of 8.22 for soil pH and 0.59 dS/m for EC (Table 1). The SOC content varied from 0.26% to 0.97% with average value 0.71%. The results support the findings of Reddy et al. (1996) and Satyavathi and Reddy (2004) who reported wide ranges for soil pH, EC, and SOC in the region. This may be ascribed to varied soils, prevailing climatic conditions and various crop husbandry practices followed in the region.

The available nitrogen ranged from 134.40 to 280 kg ha^{-1} with a mean of 207.21 kg ha^{-1}. The available phosphorus and potassium values ranged from 8.10 to.40 kg ha^{-1} and 204 to 552 kg ha^{-1} with mean of 13.55 kg ha^{-1}, 348.90 kg ha^{-1}, respectively. Available S content of soil had values from 4.10 to 9.80 ppm and it showed moderate variability with a mean of 6.19 ppm.

Available Fe, Mn, Zn and,Cu concentrations varied widely with mean values of 2.59, 0.04, 0.38 and 0.05 mg/kg, respectively.

Soil pH had the lowest CV (5.22 %) while available Zn had the highest CV (49.28%). Electrical conductivity recorded high variability with a CV of 40.22 per cent and similar result was reported by Yuqi Li *et al.* (2012). The organic carbon recorded CV of 25.10 per cent. Rice followed by black gram is the cropping pattern followed in the study area. The addition of manures and application of fertilizers might be attributed to the variation in organic carbon. Available P exhibited moderate variability with a CV of 22.04 per cent. Available K showed moderate variability with a CV of 29.71 per cent. This was in line with Lopez Granados *et al*. (2002). The variation in the mineral composition of the soil might have been the reason for relatively higher variation of K when compared to P. Available S had a medium variability with a CV of 23.63 per cent.

The available Mn and Zn exhibited high variability which was in accordance with the results reported by Sen *et al.* (2007). The observed CV of Fe, Mn, Zn and Cu were 25.37, 41.78, 49.28 and 34.67 per cent, respectively.

Correlation between soil properties

Table 2 shows the degree of correlation between soil properties. Almost all of the variables except few were significantly correlated among each other. Correlation coefficient values indicated negative correlation of pH with soil Fe and Cu. Soil available N and Fe were positively correlated with SOC, in which SOC was an important portion of the soil which affected soil chemical, physical and biological properties influencing soil nutrients' availability (Behera et al. 2018). The correlation of EC with SOC available N, S and Fe was negative. The available Fe was positively correlated with organic carbon but negatively correlated with pH,electrical conductivity. The available Cu was positively correlated with electrical conductivity but negatively correlated with pH, SOC, available N, P and S

Soil Properties Spatial Distribution

As shown in Table 1, distributions of all the studied variables were lightly skewed (skewness < 1),and their means were close to their medians, except soil EC and Mn which skewed with a value of 1.20 and 1.10 respectively, so that before performing geostatistical analysis its values were log-transformed. All the soil properties were best fitted by Spherical models. Also, several authors found that most of the soil properties were best modeled by using spherical models (Lopez Granados et al., 2002; Liu et al., 2008 and Jiang et al 2012). The results indicated that soil properties had spatial autocorrelation due to human induced factors, such as soil crop management practices, fertilizer application, and farming systems in the study area

Spatial class ratios (Nugget/Sill ratio) similar to those presented by Cambardella et al. (1994) were adopted to define distinctive classes of spatial dependence. A variable is considered to have a strong spatial dependency if the ratio is less than 25 %, moderate spatial dependency if the ratio is between 25 - 75 % and weak spatial dependency if the Nugget/Sill ratio is greater than 75 %. The spatial dependence class was strong for EC, SOC, available P, K and was moderate for available N, S, Fe, Mn, Zn and Cu. Strongly spatially dependent properties may be controlled by intrinsic variation in soil characteristics such as texture and mineralogy, which was reported by Cambardella *et al.* (1994). The stronger the spatial correlation, the more accurate the soil property map that could be obtained using kriging. The majority of the measured properties exhibit moderate spatial dependency. These suggest the extrinsic factors such as fertilization, ploughing and other soil management practices weakened their spatial correlation after a long history of cultivation.

The maximum distance in which spatial dependence or autocorrelation exists was defined as the range value of semivariogram. The range of soil properties in the study area ranged between 268 m for available N and 1470 m for available Zinc. The short range indicates that continuous measurement of available phosphorus is essential in proper characterization of variability. Larger than the obtained range values, spatial dependence does not exist for these soil properties. Lopez-Granados et al. (2002) reported that a large range value indicated that estimated soil properties were influenced by anthropogenic and natural factors over larger distances than the other soil properties which have smaller ranges. The range of influence for available P, K and S were 287, 497 and 706 m, respectively. The spatial ranges of available Fe, Mn, Zn and Cu were 1050, 1150, 1470, and 1430 m, respectively.

Implementing these best fit theoretical models and corresponding semivariogram parameters, spatial variability maps for various soil properties were created using ordinary kriging. Spatial distribution maps for all soil properties are shown in Fig.3. The soil available nitrogen was low in most parts of the study area because of the tropical climatic condition. Soil available Nitrogen was lowest in east part of the study area because of coarse textured soil. Soil available phosphorus was low to medium. The soil available potassium was medium to high. The distribution of available Nitrogen AN was similar to distribution pattern of OC. The available sulphur content in entire portion of the study area was in low category. Among the micronutrients, the available iron content ranged from low to medium and the available Mn, Zn and Cu were deficient in the study area.

Conclusion

The current study used geostatistical tool to study the spatial variation in soil properties and available nutrients in cultivated soils. The information evolved from the spatial variability analysis can be best utilized for precise management of nutrients. Spatial variability based fertility mapping could provide an alternative avenue for assessing and managing nutrient variability in agricultural holdings. Integrating geostatistics and GIS to study spatial variability and map soil fertility properties provides an opportunity to assess variability in the distribution of native nutrients and other yield limiting / building soil parameters across a large area and thus aid in strategizing appropriate management of nutrients leading to better crop yield and environmental protection. These information could be helpful to give recommendations for soil site specific nutrient managing, for getting maximum output and increasing the income by reducing the cost of the inputs paired with the best management practices.

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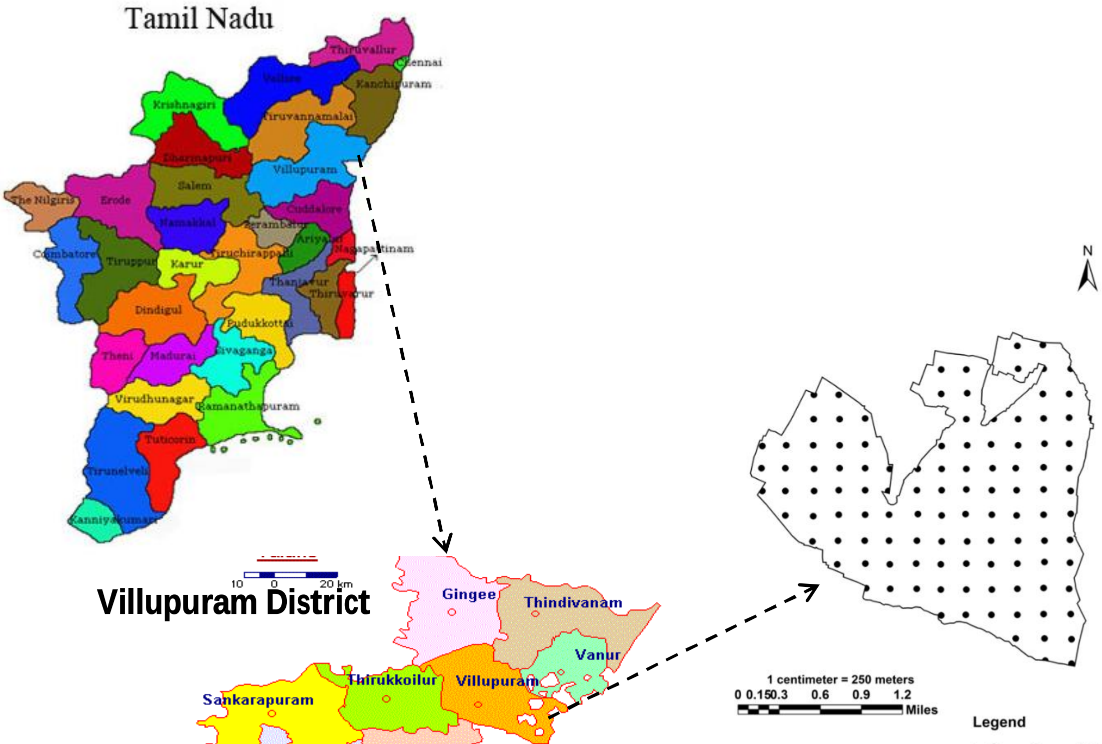
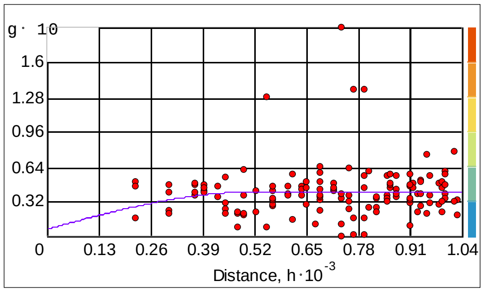


Figure 1. Study area located in Thirunavalur Village of Villupuram District in Eastern Tamil Nadu, India and soil-sampling points.



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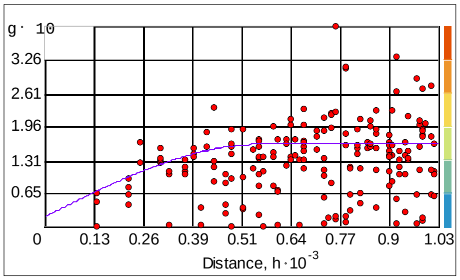

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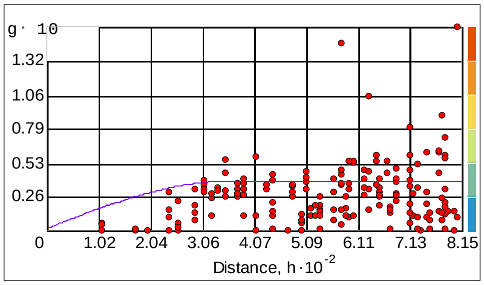

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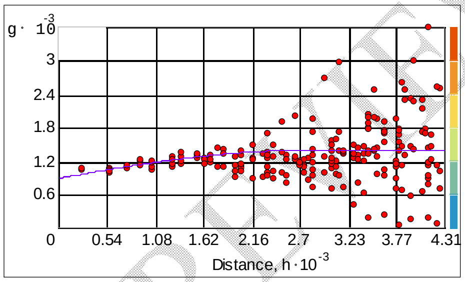

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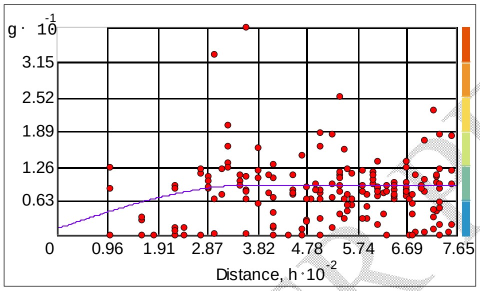

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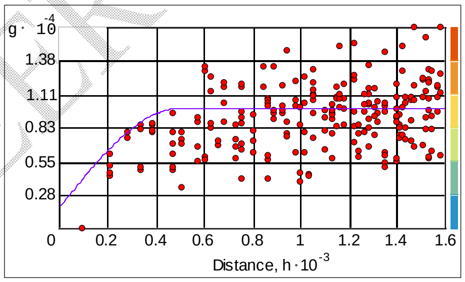

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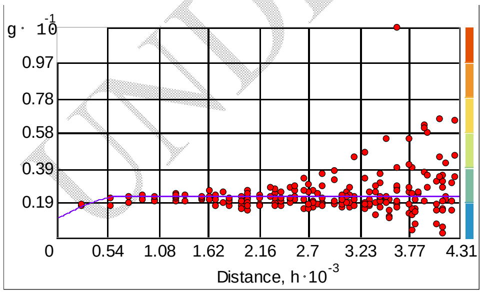

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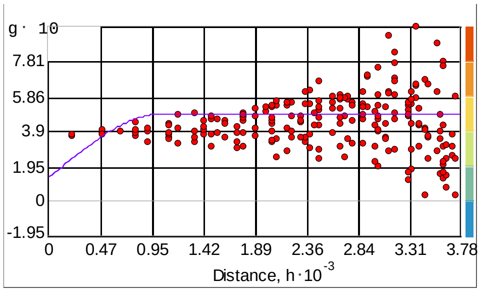

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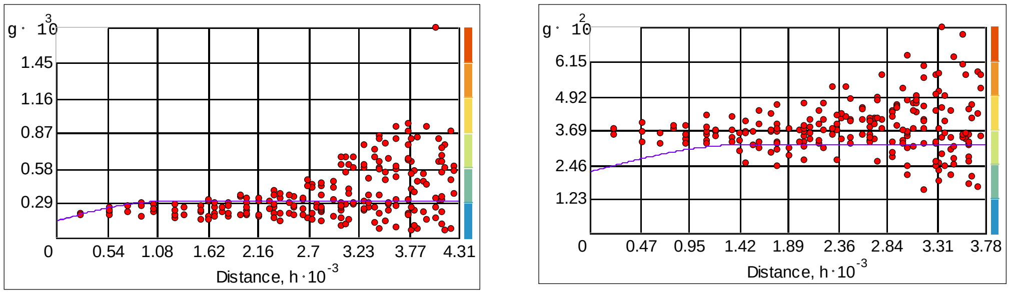

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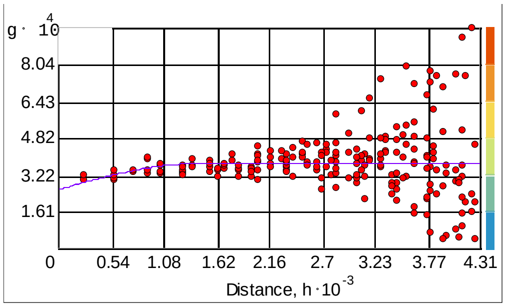
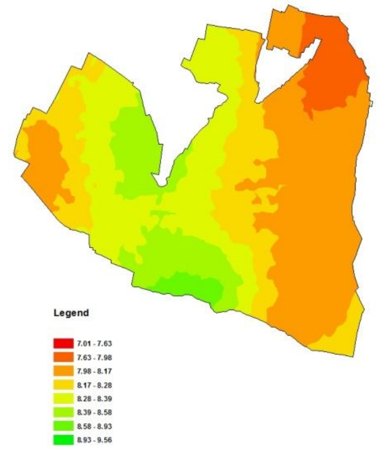


Cu

Figure 2. Semi-variograms and fitted models of soil properties



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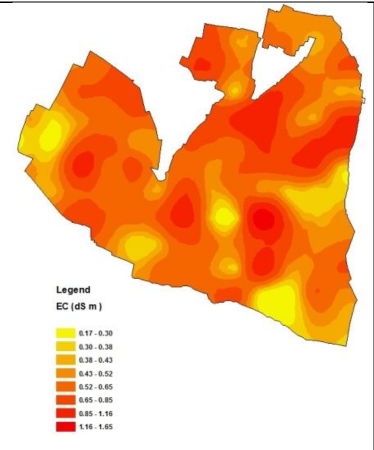

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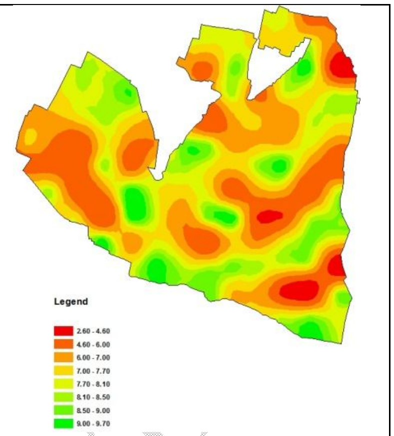

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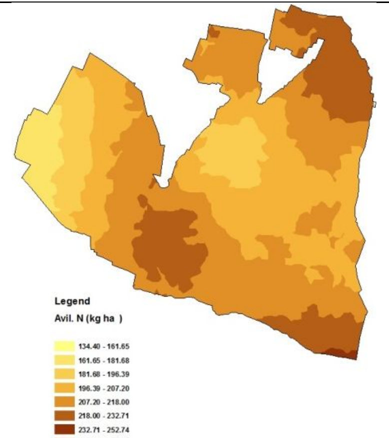

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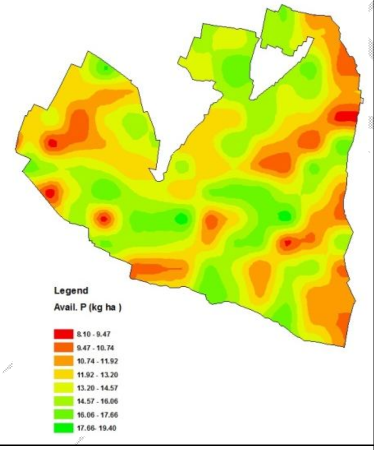

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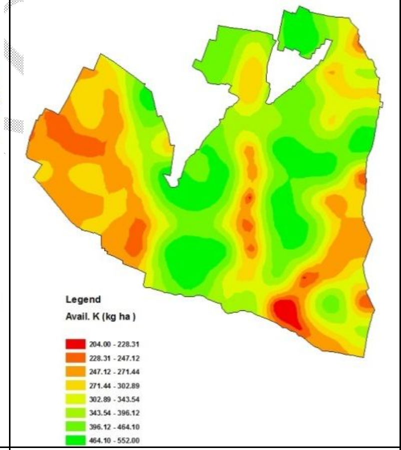

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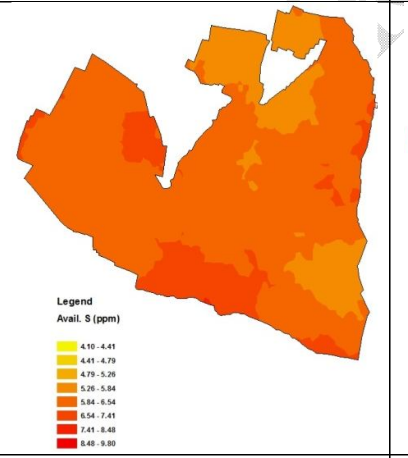

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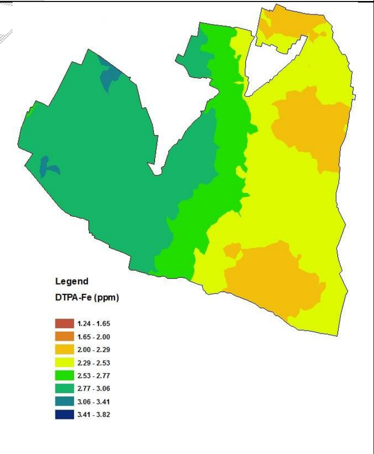

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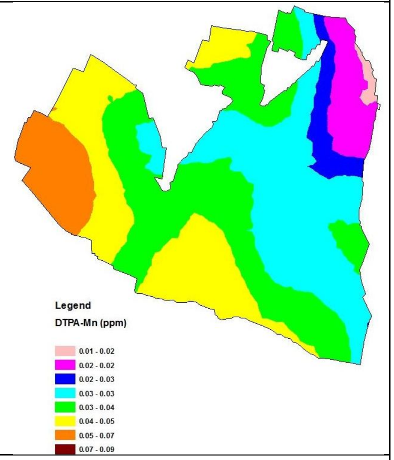
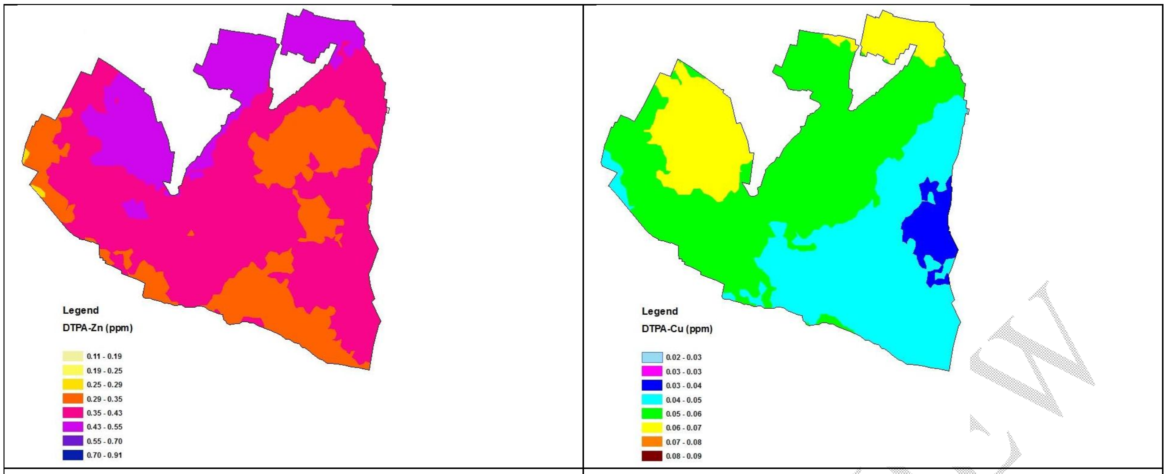


Mn



Zn

Cu

Figure 3. Map of spatial distribution for eleven soil properties in the study area. EC: soil electrical conductivity; SOC:soil organic carbon AN: available nitrogen; AK: available potassium: AP: available phosphorous AS: Available Sulphur;; Fe, Zn, Mn and Cu are DTPA extractable iron, zinc, manganese and copper in soil

Table 1. Descriptive statistics of soil properties in study area

S.No	Soil Properties	Min	Max	SD	Median	Mean	CV (%)	Skewness	Kurtosis
1.	pH	7.01	9.56	0.43	8.30	8.22	5.22	-0.61	1.39
2.	EC (dS m^{-1})	0.17	1.65	0.23	0.55	0.59	40.22	1.20	2.79
3.	SOC (%)	0.26	0.97	0.17	0.78	0.71	25.10	-0.77	-0.17
4.	AN (Kg ha^{-1})	134.40	280.00	34.55	210.00	207.21	16.65	0.03	-0.86

5.	AP (Kg ha^{-1})	8.10	19.40	2.98	13.60	13.55	22.04	-0.03	-1.01
6.	AK (Kg ha^{-1})	204.00	552.00	103.66	319.00	348.90	29.71	0.46	-1.16
7.	AS ((ppm)	4.10	9.80	1.46	6.30	6.19	23.63	0.30	-0.90
8.	Fe (mg kg^{-1})	1.24	3.82	0.65	2.61	2.59	25.37	0.07	-0.92
9.	Mn (mg kg^{-1})	0.01	0.09	0.01	0.04	0.04	41.78	1.10	1.18
10.	Zn (mg kg^{-1})	0.11	0.91	0.19	0.34	0.38	49.28	0.57	-0.68
11.	Cu (mg kg^{-1})	0.02	0.09	0.01	0.06	0.05	34.67	0.18	-1.06

EC: electrical conductivity; AK: available potassium ; AP: available phosphorous; AN: available nitrogen AS: available Sulphur; Fe,Zn, Cu and Mn represent DTPA extractable iron, zinc, copper and manganese in soil respectively.

Table 2. Correlation matrix for soil properties in study area.

	pH	EC	SOC	AN	AP	AK	AS	Fe	Mn
pH	1								
EC	0.066	1							
SOC	0.061	-0.160	1						
AN	0.089	-0.088	0.256^{**}	1					
AP	0.141	0.033	-0.028	0.076	1				
AK	0.146	0.450^{**}	-0.050	0.079	-0.067	1			
AS	0.697^{**}	-0.135	0.031	0.074	0.048	0.040	1		
Fe	-0.363^{**}	-0.108	0.197^{*}	0.016	0.037	-0.067	0.250^{**}	1	
Mn	0.166	0.008	-0.097	-0.133	0.057	-0.103	0.050	0.207^{*}	
Zn	0.147	0.005	-0.038	-0.110	0.124	0.013	-0.040	0.091	0.0
Cu	-0.127	0.075	-0.083	-0.025	-0.042	0.137	-0.152	-0.127	0.0

EC: electrical conductivity; AK: available potassium ; AP: available phosphorous; AN: available nitrogen AS: Available sulphur; Fe,Zn, Cu and Mn represent DTPA extractable iron, zinc, copper and manganese in soil respectively.

**. Correlation is significant at the 0.01 level

*. Correlation is significant at the 0.05 level

Table 3. Semivariogram models for soil properties in the study area.

Soil property	Model	Sill	Nugget	Nugget /Sill	Range (m)	Spatial Dependence class
pH	Spherical	0.091	0.133	59.2	425	Moderate
EC	Spherical	0.142	0.019	11.7	610	Strong
SOC	Spherical	0.036	0.001	3.6	352	Strong
AN	Spherical	497.8	886.01	64.0	268	Moderate
AP	Spherical	8.044	1.144	12.4	287	Strong
AK	Spherical	8670	1598.6	15.5	497	Strong
AS	Spherical	1.238	1.052	45.9	706	Moderate
Fe	Spherical	0.362	0.122	25.2	1050	Moderate
Mn	Spherical	0.016	0.013	46.1	1150	Moderate
Zn	Spherical	0.009	0.021	69.3	1470	Moderate
Cu	Spherical	0.011	0.025	69.1	1430	Moderate

EC: electrical conductivity; AK: available potassium ; AP: available phosphorous; AN: available nitrogen; AS: Available sulphur Fe,Zn, Cu and Mn represent DTPA extractable iron, zinc, copper and manganese in soil respectively.