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Geostatistical Assessment of the Spatial Variability of Acid Soils Properties in the Southeastern Highlands, Arsi Zone, Ethiopia

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Authors' contributions

This work was carried out in collaboration between all authors. Author DHH designed the study, carried out the field and laboratory work, performed the geostatistical and data analysis and wrote the first draft of the manuscript. Authors FK and BB managed the analyses of the study and draft manuscript evaluation. Author LW managed the literature searches and draft manuscript evaluation. All authors read and approved the final manuscript.

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ABSTRACT

This research was conducted with the objective of generating quantified information on the spatial variability of soil properties and apply them to improve the planning and management of acid soils in the highlands of Arsi zone, Ethiopia. In this research, the spatial variability of soil pH-H_2O, pH-K, percent organic carbon (% OC), cation exchange capacity (CEC), exchangeable acidity, and exchangeable aluminum is studied. Four kriging and 3 deterministic interpolation methods were evaluated for their prediction accuracy. Hence, Ordinary Kriging (OK) and Empirical Bayesian Kriging (EBK) were found to be superior for prediction of pH-H_2O and pH-K; while Universal Kriging (UK) for CEC and % OC; and UK and Local Polynomial Interpolation (LPI) for exchangeable acidity and exchangeable aluminum. Finally, OK was applied for analysis and interpretation of pH-H_2O and

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pH-K; UK for CEC, % OC, exchangeable acidity and exchangeable aluminium. Soils in the range of pH-H_2O:4.49-5.3 cover about 82% of the total area. About 56% have pH-H_2O less than 5.1 and CEC values between 2.96 and 20.01 meq/100 g. Generally, the CEC varied from 2.96 in the very strongly acidic to 37.1 meq/100 g soil. The % OC content is generally good, and varied with altitudinal gradations. Exchangeable acidity varied from 0.1–4.28 meq/100 g. Kriging interpolation based on the data range of 0.1 - 2.4 meq/100 g showed that 68% of the total area has exchangeable acidity greater than 0.5 meq/100 g. These results are found to be very useful for improving research and development planning, management, and evaluation of the effectiveness of measures to be taken to address productivity problems on the studied area.

Keywords: Geostatistical assessment; spatial variability; kriging; deterministic interpolation.

1. INTRODUCTION

Acid soils with pH values of < 5.5 cover about 30% (3.95 billion ha) of the world's ice free land area, of which 4.53% (179 milllion ha) is used for arable land [1]. Comparing the 179 million with 1.56 billion ha of globally cultivated land [2], the proportion of acid soils is about 11.47%. In Ethiopia, information on the full extent and level of acidity is scarce; especially, with respect to the total cultivated land. Schlede [3] estimated that soils with pH values of less than 5.5 occupy about 13.2% of the total area. The Agricultural Transformation Agency report [4] indicates that strong acidity (pH < 5.5) affects 28.1% of soils in the country.

The potential productivity of acid soils is very high, provided that they are well managed. The management of such soils, however, remained to be one of the weak links in the quest for sustainable agricultural development in Ethiopia [5]. Soil properties highly vary in space and time [6]. "The variability in any landscape is an inherent natural phenomena conditioned by geological setting, pedology, and climate. However, some of this variability may also be induced by tillage and other soil management practices" [7]. Thus, the design and development of site specific crop management requires a multifaceted approach, which includes spatial analysis of soil properties [5]. However, such approach has not been practically applied in soil science research of Ethiopia.

The most important soil physical, chemical and biological properties related to soil acidity and affect the effectiveness of liming are soil pH, soil organic matter (SOM), exchangeable acidity, exchangeable aluminum, cation exchange capacity (CEC), and soil texture. Soil pH, which has often been called a measure of soil acidity and alkalinity, greatly affects numerous soil chemical processes [8]. Exchangeable acidity measures the sum of hydrogen and Aluminum ions adsorbed on soil colloids [9]. Soils that have values below about pH: 5.5 are likely to contain exchangeable Al that may be present at sufficiently high levels to be toxic to plants [10,11]. Generally, soil pH is simply a measure of an intensity factor and not a capacity factor. The total amount of acidity is influenced by other properties like CEC, SOM content, soil texture, and exchangeable Aluminum [9]. Exchangeable Al in soils appears to decrease exponentially as pH increases [10]. At a given pH, the concentration of Al in the soil solution also decreases with an increase in soil OM [11]. Organic matter affects the CEC and pH of soils too, while soil texture affects the CEC. Hence, for soils with differing CEC, pH does not indicate the amount of acidity present. Different CEC values have different buffering capacity and lime requirements [10]. Therefore, the effectiveness of liming to decrease soil acidity and improve crop growth and yields is affected by the complex nature of the interrelationship between the different soil properties. As a consequence of this fact, development of proper planning and management of acid soils requires spatial analysis and interpretation of different soil chemical and physical properties. Geostatistics provides quantified information on geospatial patterns of environmental variables of interest with more precision and accuracy at lower cost than the classical methods [12,13,14]. Continuous surface properties of soils can be predicted or generated from geographically referenced point samples using different interpolation techniques. The method can be used to analyse any number of soil properties and some scenarios (e.g. land reclamation scenarios) can be tested with corresponding estimates of the uncertainty of the results [15].

The spatial properties of acid soils in the southeastern highlands of Ethiopia are not studied so far. The attention given to management of acid soils in the areas is very poor. Hence, this research was conducted with the main objective of generating sufficient information on the levels, spatial patterns and distributions of soil properties that can be applied to develop improved planning and management of acid soils in the highlands of Arsi zone, Ethiopia. The specific objectives were: *i*) to analyze and describe the spatial variability of acid soil properties; *ii*) to describe the spatial patterns of soil properties using prediction maps with associated uncertainty of estimates; iii) to evaluate the performance of different kriging and interpolation models under different data structure.

2. METHODOLOGY

2.1 Description of the Study Area

The study is conducted in Arsi zone, Oromiya regional state, southeastern highlands of Ethiopia in 2017 and 2018. The area is located between 170 and 240 km south of Addis Ababa (capital city) along "Adama" – "Bale Robe" road. The geographic coordinates of the boundaries lie within the ranges of 7° 21'32''- 7° 57'3.3'' N and 39° 04'47.8''-39° 18'58.46'' E (Fig. 1). The study area is located mostly in the agricultural lands of Tiyo, Digelu-Tijo, and Bokoji districts of Arsi zone; and, covers about 102,000 ha of land. The altitude ranges from 2440 - 3200 m.a.s.l. from west to east and is bounded by Chillalo Mountain. The geological formations of the mountain and its adjacent agricultural areas are associated with the huge shield volcanoes of basaltic and trachytic composition formed during the mid and late tertiary period, Miocene - Pliocene [16]. The parent materials contain Trachyte, trachy- basalt, peralkaline rhyolite with subordinate akaline basalt [17]. The 2 major soil types in the 3 districts are Vertisols and Luvisols [18].

The climate of the study area is presented in Fig. 2. Based on long term (1979 - 2015) weather data collected by Kulumsa Agricultural Research Center (KARC) from two sub-stations, the mean annual rainfall ranges from 821 mm in the north to 1047 mm in the south, with uni-modal rainfall pattern. In most years about 50-75% of the annual rain falls during the months of June to September (main cropping season). Long term mean monthly highest temperature ranges from 20.9°C in Aug to 25°C in March and from 16.85 (in July) to 21.3°C (in Feb/March), to the north and south, respectively. Mean monthly lowest temperature ranges from 7.72°C (in Dec/ Jan) to 11.72°C (in April) and from 6.03°C to 8.5°C, to the north and south of the study area, respectively (Fig. 2).

The climate of Arsi zone is highly suited to production of many grain crops. The total area covered for production of cereals in 2015 was 522,763 ha, and produced 1,368,985 metric tons [19]. Wheat production in the area is by far the highest in Ethiopia.

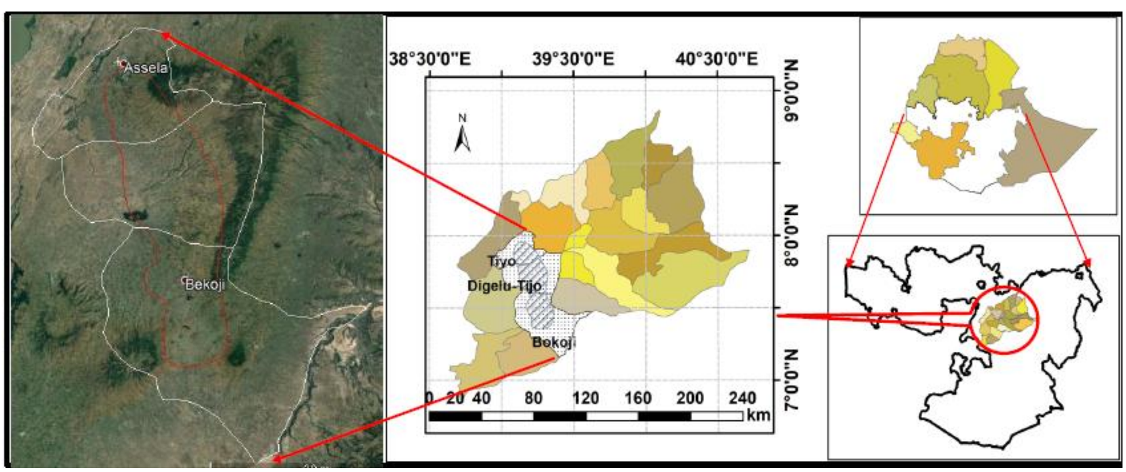

Fig.1. Landsat image of the Study area (Google Earth, 2018) relative to Chilalo Mountain; and, map of its location in 3 districts ("woreda") of Arsi zone, Oromiya region, Ethiopia

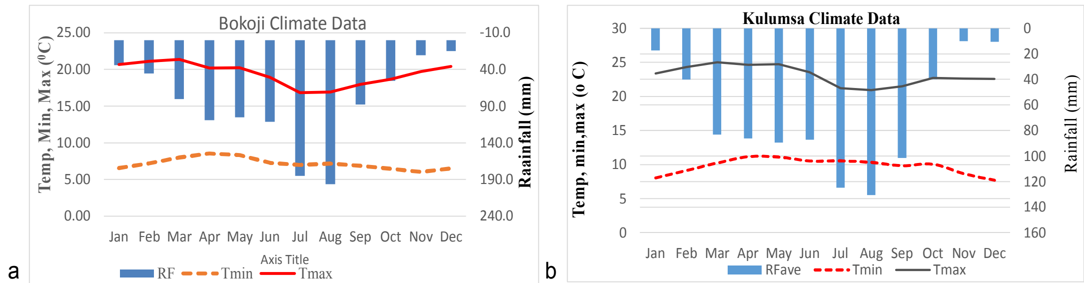

Fig.2. Long term mean monthly rainfall, monthly min, and monthly max temperature records for southern (a) and northern (b) part of the study area (data from KARC, EIAR: 1979 to 2015 GC)

2.2 Soil Sampling and Laboratory Determination of Soil Properties

Geographically referenced surface (0-20 cm depth) samples were collected using a combination of random and multistage sampling methods. The selection of point sampling sites was based on topographic gradations and availability of accessible roads. Sub-samples were collected randomly from as few as 5 to as many as 10 points to make about 1.5 kg composite sample per sampling point. During the first stage, composite samples were collected from 74 point sites. A second and third sampling plan was generated after the model is approximated using prediction variances of the analytical results of pH-H_2O [14]. Hence, additional samples were collected from 91 sites. The sampling intervals, generally, range from 0.5 to 2 km in the east – west, in the direction of altitudinal gradations. The total area covered was about 102,000 ha, giving an average sampling density of 0.162/km^2. The spatial coordinates of all sampled sites were taken using eTrex Garmin GPS receiver. The collected samples were handled with polythene bags for transport to KARC, air dried, crushed using pestle and mortar, and passed through 2mm sieve before analysis.

The samples were analyzed for soil Organic carbon content (% OC), pH-H_2O, pH-K, cation exchange capacity (CEC), exchangeable acidity, and exchangeable aluminum. Soil pH was determined based on the procedures outlined in Ethiopian Institute of Agricultural Research soil chemistry laboratory manual; and, measurements made in both distilled water and 0.1N KCl in 1:2.5 soil: solution ratio, potentiometrically using a glass-calomel combination electrode. Organic carbon was determined by [20], CEC by ammonium acetate method at pH: 7 [21], exchangeable acidity and aluminum by the procedures of [22]. Each sample was analyzed 2, 3 and in some cases 4 times for % OC, pH-water and pH-K. Exchangeable acidity, exchangeable Al, and CEC were analyzed 2 times (in two rounds). Finally, the mean results of repeated analysis of each sample were used for geospatial analysis.

2.3 Geostatistical Analysis

The statistical properties and data structure were assessed using the exploratory spatial data analysis (ESDA) tool of the geostatistical Analyst extension of ArcGIS 10.1 [23]. To create precise predictions of soil properties for continuous surfaces, different interpolation and kriging methods were tested to select the best predictor for each data set. Initially, models available on the geospatial Analyst tool of ArcGIS 10.1 were tested for their prediction map outputs and prediction errors. The kriging and interpolation models selected for further evaluation were: Simple Kriging (SK), Ordinary kriging (OK), Empirical Bayesian Kriging (EBK), Universal Kriging (UK), Kernel Smoothing (KS), Radial Basis Function (RBF), and Local Polynomial Interpolation (LPI).

The models were evaluated by cross-validation and validation procedures of the ArcGIS 10.1. Cross-validation used prediction error statistics to compare the performance of models. Validation was done using subset features of the test dataset to check the validity of the analysis and cross validation results. Maps developed using subset features were used for prediction and validation of the test data set analytical results. The total number of data used for subset feature was 75 % of the test data set of each parameter. After comparing the different kriging and deterministic interpolation models for their prediction accuracy, the best selected models were applied to map the spatial patterns and distribution of each measured soil property. Finally, OK was applied for analysis and interpretation of pH-H_2O and pH-K; UK for CEC, % OC, exchangeable acidity and exchangeable aluminium. Based on the best model predictions, standandard error maps were also produced. To improve the accuracy of predictions of highly skewed data, data transformations were used based on the level of improvements made in the prediction error outputs. Hence, the normal score transformation type was applied to predict exchangeable acidity and exchangeable Al by SK and log transformation for prediction of exchangeable acidity by OK.

3. RESULTS AND DISCUSSION

3.1 Descriptive Statistical Analysis

Descriptive statistical properties: the mean, median, minimum (Min), maximum (Max), and standard deviations (SD) of the measured soil property values is presented in Table 1. The data distributions of pH-H_2O and pH-K are normal or near normal with coefficient of skewness as shown in the table. But, the coefficient of skewness of % OC, CEC, exchangeable acidity and exchangeable Al are higher than the normality required for kriging interpolation. The coefficient of kurtosis of pH-H_2O and pH-K are normal. For the other 4 variable values, some outliers were removed before analysis of the data (Table 1). The outliers removed represent from 0.6% for CEC to 2.4% for OC, exchangeable acidity and exchangeable Al of the data sets. Their exclusion from analysis improved the degree of normality of the frequency distributions and the kriging interpolation results.

3.2 Cross Validation and Validation of Model Predictions

Four models from kriging interpolation (SK, OK, UK, and EBK) and 3 from deterministic interpolation methods (LPI, KS, and RBF) were evaluated using cross validation and validation procedures of the geostatistical analysis tool of ArcGIS 10.1 [23]. Mean prediction error (ME), standardized mean prediction error (MSE), root mean-squared prediction error (RMSE), standardized root mean-squared prediction error (RMSSE), and average standard prediction error (ASE) values were used for prediction error assessment and evaluation of models (Table 2). Better prediction of a model was determined by ME and MSE values nearest to 0, RMSSE nearest to 1, smallest RMSE, and ratio of ASE to RMSE nearest to 1. But more weight is given to RMSE than to ME and RMSSE and ratio of ASE to RMSE than to the other values. Similarly, validation procedure used to check the model predictions to have ME and MSE near to zero, a small RMSE, and ASE near to the RMSE.

Based on this evaluation criterion and prediction error data (Table 2), OK and EBK have shown superior performance for prediction of pH-H_2O and pH-K values, while UK and KS for CEC and % OC. For the highly skewed data, the superior models were UK and LPI. The next good predictors were SK and UK for pH-H_2O; LPI for pH-K; KS and LPI for exchangeable acidity; OK, KS and LPI for exchangeable Al; and EBK for CEC and % OC.

Validation was done for all kriging and interpolation methods using subset data of each parameter (Table 3). The ME and MSE values by all predictors of all variables are near to 0. The RMSE values of all parameters by all predictors are also near to their respective ASE values. The RMSE values recorded for all parameters and predictors in the validation data (Table 3) are also near to the values recorded in the cross-validation data (Table 2). Hence, these results demonstrate that there is no bias in the prediction process of the spatial variability of different soil properties and the cross-validation and validation analysis results are consistent.

Table 1. Statistical data of measured soil parameters (n=165)

Parameter	Min	Max	Mean	Median	SD	Skewness	Kurtosis	1^{st} Q	3^{rd} Q
pH-H_2O	4.493	5.653	5.051	5.077	0.240	-0.013	2.619	4.866	5.211
pH-K	3.96	4.977	4.435	4.432	0.235	0.266	2.096	4.235	4.616
%OC	1.66	5.7	3.438	3.33	0.676	0.633	4.210	3.078	3.75
CEC	2.96	37.1	14.84	13.30	6.171	0.942	4.433	11.515	18.02
Ex. Acidity	0.1	4.28	0.795	0.65	0.638	2.242	10.226	0.36	0.985
Ex. Ac(log)						-0.097	2.860		
Ex. Al.	0.01	1.68	0.350	0.24	0.339	1.584	5.702	0.09	0.528

Ex. Al(log)	-0.762	3.166

Table 2. Summary of prediction errors statistics for different models

Soil properties	Prediction errors	Kriging and interpolation models						
		SK	OK	UK	EBK	KS	RBF	LPI
$pH\text{-}H_2O$	ME	-0.0046	-0.0014	-0.0074	-0.0007	-0.0086	-0.0105	-0.0110
	RMSE	0.1866	0.1854	0.1895	0.1865	0.1891	0.1930	0.1888
	MSE	-0.0197	-0.0032	-0.0346	-0.0004	-0.0432		-0.0554
	RMSSE	0.9976	1.0032	1.0056	1.0035	0.9897		0.9907
	ASE	0.1873	0.1855	0.1877	0.1870	0.1934		0.1929
pH-K	ME	-0.0046	-0.0007	-0.0115	-0.0031	0.0114	0.0077	0.0059
	RMSE	0.1523	0.1501	0.1527	0.1527	0.1518	0.1557	0.1519
	MSE	-0.0235	-0.0008	-0.0727	-0.0124	0.0792		0.0436
	RMSSE	1.0429	1.0232	1.0224	0.9928	0.9945		0.9986
	ASE	0.1476	0.1470	0.1496	0.1542	0.1542		0.1534
CEC	ME	-0.0079	-0.0136	-0.0562	-0.0553	-0.0438	-0.1699	-0.0619
	RMSE	3.8572	3.8425	3.8138	3.8329	3.8099	4.0168	4.0505
	MSE	-0.0048	-0.0057	-0.0059	-0.0021	-0.0051		-0.0022
	RMSSE	1.0383	1.0420	0.9852	0.9283	1.0084		1.0199
	ASE	3.8829	3.6604	3.8893	4.129	3.8191		3.8783
%OC	ME	-0.0109	-0.0037	-0.0074	-0.0002	-0.0006	-0.0219	0.0001
	RMSE	0.5789	0.5666	0.5482	0.5694	0.5843	0.5728	0.5800
	MSE	-0.0113	-0.0024	-0.0100	-0.0017	0.0001		0.0032
	RMSSE	1.0265	1.0812	1.0131	1.0355	1.0248		1.0516
	ASE	0.5497	0.5166	0.5345	0.5301	0.5592		0.5379
EX. Acid	ME	0.0184	0.0162	-0.0017	0.0040	-0.0085	0.0055	0.0100
	RMSE	0.4576	0.4396	0.4752	0.4518	0.4602	0.4829	0.4626
	MSE	0.0014	-0.0273	-0.0007	0.0086	-0.0211		-0.0240
	RMSSE	1.0157	1.0714	1.0057	1.0516	0.9937		1.0009
	ASE	0.5400	0.5374	0.4708	0.4311	0.4654		0.4626
Ex Al	ME	0.0086	0.0007	0.0006	0.0069	0.0054	0.0067	0.0075
	RMSE	0.3069	0.3009	0.2863	0.2966	0.3074	0.3190	0.3065
	MSE	-0.0228	0.0021	-0.0018	-0.0319	0.0153		0.0228
	RMSSE	1.0673	1.0467	1.0081	1.1165	1.0011		1.0004
	ASE	0.2892	0.2884	0.2846	0.3463	0.3068		0.3066

ME = Mean prediction Error, MSE= Mean Standardized prediction Error, RMSE = Root Mean-Squared prediction Error, RMSSE= Standardized Root Mean-Squared prediction Error, ASE= Average Standard prediction Error, Ex. Acid=Exchangeable Acidity, Ex. Al=Exchangeable Al, SK=Simple Kriging, OK=Ordinary Kriging, UK=Universal Kriging, EBK=Empirical Bayesian Kriging, KS=Kernel Smoothing, RBF=Radial Basis Function, LPI=Local Polynomial Interpolator

The comparison using cross-validation data did not include RBF, because the prediction error outputs of this model are ME and RMSE only, in contrast to the other models which have 5 error outputs. However, comparison of the maps produced by the model, based on the size and position of the different categorized levels of soil properties, with the maps produced by the best predictors for this study indicates that RBF is not only comparable to the superior models, but also versatile with high prediction accuracy under different data structure. This conclusion is confirmed by Pearson correlation coefficient data (Table 4). Correlation analysis was done to assess the goodness of fit of the predicted to the measured data sets using prediction outputs of the subset data sets. The results of the analyses showed that the correlation between the measured values and predicted outputs by RBF is highest for all variables data.

3.3 Spatial Variability of Soil Properties

The spatial variability of soil properties like soil pH, CEC, percentage of soil organic carbon (% OC), exchangeable acidity, and exchangeable aluminum are shown in Fig. 3. The soils are all acidic and varied between $pH\text{-}H_2O$: 4.49 - 5.65. The map (Fig. 3a) indicates that extremely acidic soils (pH: 4.49 - 4.9) are found in the northern tip and some parts of the east. Strong to moderately strong acid soils (pH: 5.3 - 5.65) are found in the southern and some areas in the northern central part. Almost all of the soils in the intermediate areas, with the exception of some patches of high and low pH, are within the range of 4.9 - 5.3

(very strong to strongly acidic) and cover about 82 % of the total area.

The highest and lowest pH classes are predicted in the highest altitudinal areas to the south and north, respectively (compare Figs. 3a with 5a). Hence, altitude is not the major factor to influence pH levels in the study area. These highest elevation areas receive long rains (based on my personal observation for 7 years). Knowledge of the soils class can lead to better explanation of the level of acidity. The map (Fig. 5b) derived from Harmonized World Soil Database (HWSD) ver 1.1 [24] clearly shows the patterns of soil associations. The physical boundaries of the major soils mostly align with the boundaries of the soil map (Fig. 5b); though, overlaying polygon map of the study area to the soil map (Fig. 5b) shows that Luvisols in the middle and northern top of the western boundary is somehow contracted to the east. Comparison of the soil map with the spatial patterns and distribution of pH-H_2O levels (Fig. 3a) shows that the predicted pH-water values in the range of 4.49 - 5.1 fall on Luvisols. The light and dark blue colored areas in the upper part of the map (pH: 5.1 - 5.65) are typical Vertisols areas. Similarly, the lower light and dark blue colored areas fall on Vertisols. Therefore, Soils with the higher pH level are Vertisols and most of the areas with predicted pH-H_2O values less than 5.1 are Luvisols. The pH-K map also show similar distribution and pattern. Soils predicted in the lower pH range of 3.96 – 4.55 (Fig. 3b) are located on Luvisols, while soils in the range of 4.55-4.977 on Vertisols. The middle parts of the Vertisols area fall in the low pH ranges, indicating that the soil properties in the middle Vertisols areas are similar to the Luvisols.

The spatial patterns and distribution of CEC is shown in Fig. 3c. High and moderately high CEC (20.0 - 37.0 meq/100 g) soils are located in the northwest central and moderately high CEC (20.0–25.7 meq/100 g) in the southern half. Low CEC (2.96 - 8.65 meq/100 g) are predicted in some parts of north. The remaining areas are low to moderate (8.65 - 20.0 meq/100 g soil). The northwest central part with high and moderately high CEC values are typical Vertisols with high swelling and cracking properties. The CEC generally decreases to the southern part of Vertisols. The other soils with predicted values of 8.65 - 20.0 meq/100 g have pH-H_2O values of less than 5.1 (Fig. 3a and b). They are mainly Chromic and Haplic Luvisols [24] and cover a very large proportion of the study area.

Table 3. Validation using error statistics based on maps developed from subset data

Soil properties	Prediction errors	Validation data						
		SK	OK	UK	EBK	KS	RBF	LPI
pH-H_2O	ME	-0.0101	-0.0095	-0.0090	-0.0099	-0.0205	-0.0071	-0.0195
	RMSE	0.1558	0.1563	0.1611	0.1427	0.1639	0.0901	0.1589
	MSE	-0.0516	-0.0459	-0.0430	-0.0474	-0.0998		-0.0983
	ASE	0.1923	0.1943	0.1989	0.1846	0.2001		0.1998
pH-K	ME	-0.0012	0.0050	0.0045	0.0048	0.0111	0.0053	0.0072
	RMSE	0.1213	0.1340	0.1305	0.1282	0.1384	0.0739	0.1313
	MSE	0.0124	0.0361	0.0332	0.0328	0.0718		0.0454
	ASE	0.1600	0.1543	0.1533	0.1653	0.1627		0.1651
CEC	ME	-0.2500	-0.2438	-0.2242	-0.2206	-0.0546	-0.2253	-0.0904
	RMSE	3.1231	2.5756	3.040	2.4544	2.9018	2.1448	3.2185
	MSE	-0.0260	-0.0549	-0.0528	-0.0465	-0.0149		-0.0229
	ASE	3.7480	3.5434	3.826	3.5931	3.7665		4.0165
%OC	ME	-0.0018	-0.0125	0.0046	-0.0155	-0.0367	-0.0129	-0.0263
	RMSE	0.4428	0.4430	0.5390	0.4018	0.5229	0.3188	0.4872
	MSE	-0.0192	-0.0261	0.0086	-0.0303	-0.0633		-0.0438
	ASE	0.4794	0.4860	0.5643	0.4934	0.5485		0.5399
EX. Acid	ME	0.0273	0.0338	0.0144	0.0371	0.0131	0.0248	0.0383
	RMSE	0.4119	0.4034	0.3907	0.3690	0.4194	0.2226	0.4217
	MSE	0.0979	0.0732	0.0281	0.0857	0.0238		0.0790
	ASE	0.4468	0.4490	0.2857	0.4450	0.4848		0.4713
Ex Al	ME	0.0044	0.0239	0.0083	0.0130	0.0172	0.1429	0.0176
	RMSE	0.2590	0.2390	0.1391	0.2661	0.2685	0.1432	0.2702
	MSE	0.0099	-0.0062	0.1033	0.0466	0.0518		0.0528
	ASE	0.2591	0.3596	0.0833	0.3018	0.3159		0.3164

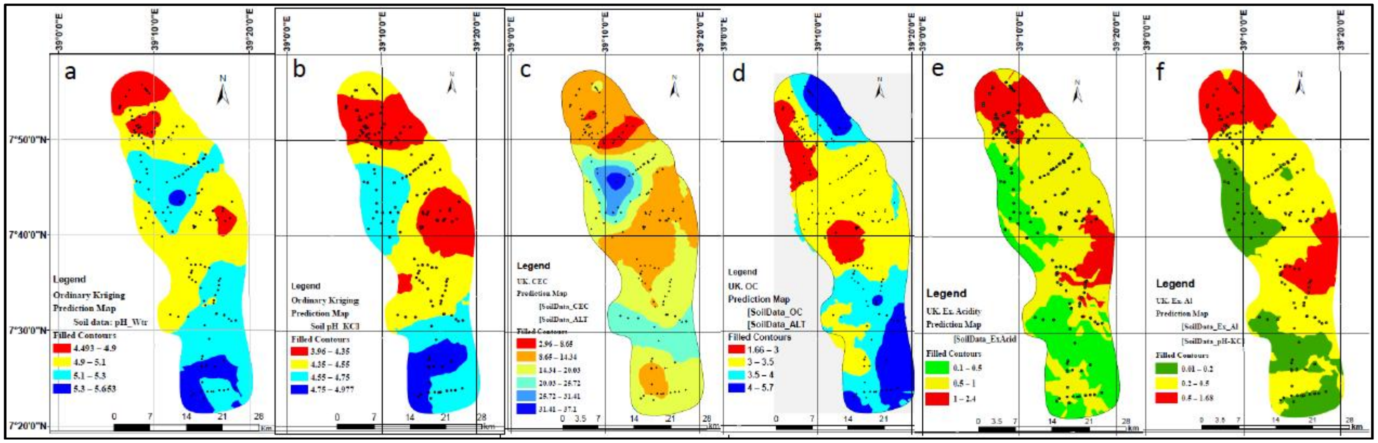

Fig. 3. Map of spatial patterns of soil properties for the study area: pH-water (a), pH-K (b), CEC (c) in meq/100g soil, %OC (d), Ex. Acidity (e) and Ex. Al (f) both in meq/100g soil

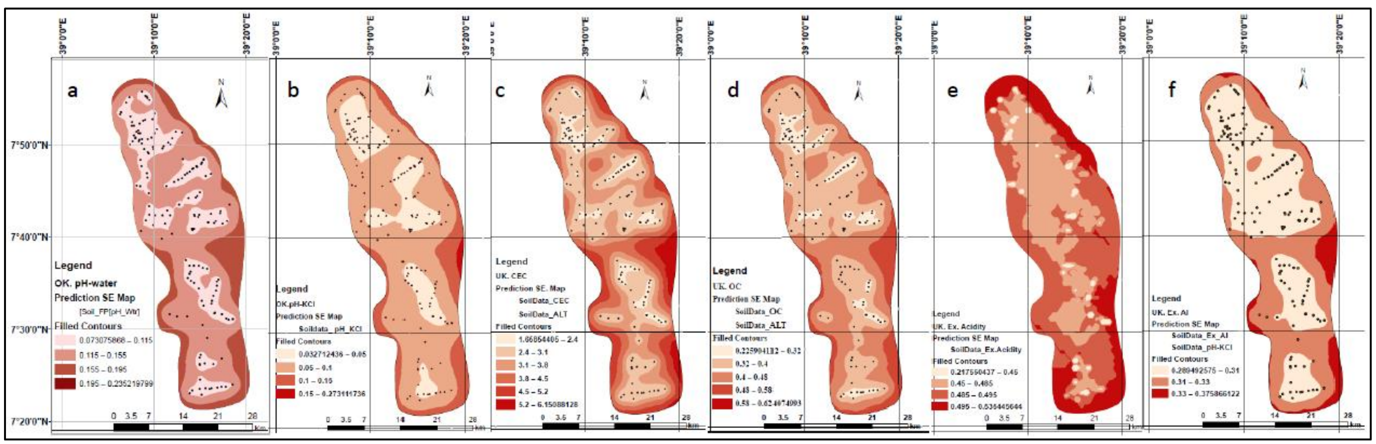

Fig. 4. Maps of standard error predictions for pH-water (a), pH-K (b), CEC (c), %OC (d), Ex. Acidity (e), and Ex. Aluminium (f)

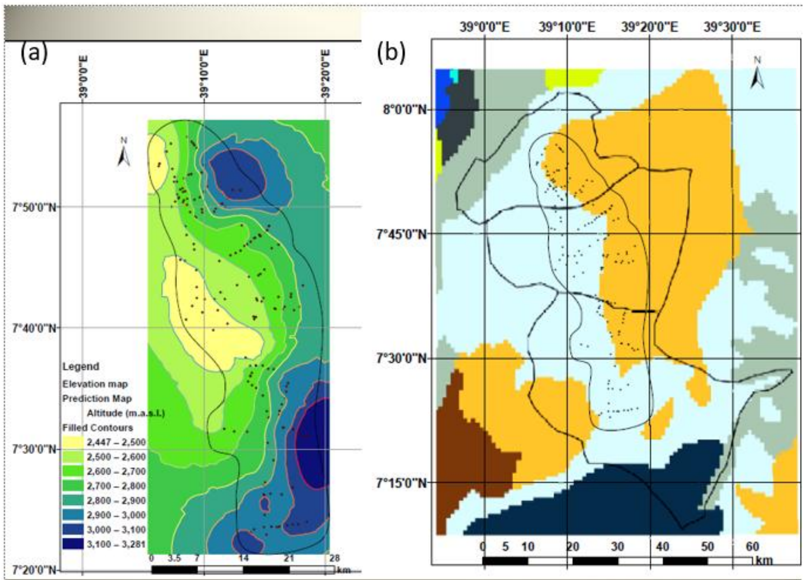

Fig. 5. Contour map (a) from point coordinates data and Soil map (b) derived from HWSD (2009). The two soil colors in the study area (inner polygon) represent Luvisols (orange) and Vertisols (light grey)

Table 4. Pearson correlation coefficient values of model predictions

Variables	Predictor models						
	SK	**OK**	**UK**	**EBK**	**KS**	**RBF**	**LPI**
pHW	0.765^{**}	0.761^{**}	0.743^{**}	0.806^{**}	0.736^{**}	0.927^{**}	0.753^{**}
pH_KCl	0.863^{**}	0.821^{**}	0.831^{**}	0.839^{**}	0.812^{**}	0.949^{**}	0.834^{**}
CEC	0.870^{**}	0.914^{**}	0.876^{**}	0.926^{**}	0.881^{**}	0.939^{**}	0.863^{**}
%OC	0.776^{**}	0.766^{**}	0.614^{**}	0.824^{**}	0.635^{**}	0.881^{**}	0.698^{**}
Ex.Acidity	0.602^{**}	0.607^{**}	0.837^{**}	0.705^{**}	0.551^{**}	0.897^{**}	0.561^{**}
Ex.Al	0.650^{**}	0.721^{**}	0.912^{**}	0.623^{**}	0.614^{**}	0.907^{**}	0.607^{**}

Soils with the highest OC content (4.0 - 5.7%) are located in the northeast and southeast, the highest elevation areas (compare Fig. 3d with 5a). Soils with % OC levels less than 3, categorized as low for this work, are located in the central and northwest margin. They are part of the lower elevation areas, 2447 - 2600 m.a.s.l, (Fig. 5a). The remaining part of the study area (yellow and light blue) has OC content between 3.0 and 4.0 %. When the spatial pattern of OC content (Fig. 3d) is compared with elevation map (Fig. 5a), the OC content decreases with altitudinal gradation. There is a significant decrease in the northeast to northwest and southeast to southwest direction. The trend is also apparent in the central east to west direction. The low range of % OC cover about 11% of the total area only. Hence, the OC stock is, generally, good.

The spatial patterns of exchangeable acidity and exchangeable aluminum are presented in Fig. 3e and f. High values are predicted to the north and mid-east, while lower values to the south and western parts. Comparison of the spatial patterns of the two acid soil properties (Fig. 3e and f) with the soil map (Fig. 5b) shows that the soils with exchangeable acidity of 0.5 - 2.4 meq/100 g soil) and aluminum (0.2-1.68 meq/100 g soil) are Chromic Luvisols and those in the lowest ranges are located on Vertisols. Generally, soils with exchangeable acidity ranges specified above cover about 68% and exchangeable Al values greater than 0.5 meq/100g soil) cover about 22% of the total. Therefore, the proportion of area that require intervention is very high.

4. CONCLUSION AND RECOMMENDATION

The spatial patterns of soil pH, CEC, % OC, exchangeable acidity, and exchangeable Al were examined. To select the best models for prediction of different soil properties, 4 kriging and 3 deterministic interpolation methods were evaluated. Hence, the superior predictors were OK and EBK for prediction of pH-H_2O and pH-K; while UK and KS for CEC and % OC and UK and LPI for the highly skewed data. Finally, the models selected for analysis and interpretation were OK for pH-H_2O and pH-K; UK for the remaining data sets (Fig. 3). However, correlation analysis between measured and predicted data sets indicated that RBF can provide predictions with the highest accuracy under different data structure.

The study helped identify that the majority of the soils are very strongly to strongly acidic (pH-H_2O: 4.49 - 5.3), and cover about 82% of the total area. Very strongly acidic areas (pH < 4.9) cover about 10.6 %. The CEC values range from 2.96 in the very strongly acidic to 37.1 meq/100 g in the Vertisols area. Soils with low to moderate CEC levels (2.96 - 20.01 meq/100 g) cover 79.8% of the total area, among which soils within the range of 2.96 - 8.65 meq/100g cover 3.1% only. About 55,700 ha of the low to moderate CEC level areas have pH-H_2O values less than 5.1.

The study also helped identify that the soil OC content is, generally, good for the whole area; and, the amount vary in the east west direction following altitudinal gradations. About 89% of the studied area has OC content more than 3.0%. Exchangeable acidity in the low (0.1-0.5 meq/100 g) and high (1.0 - 2.4 meq/100 g) ranges, cover about 32 and 17 % of the total area, respectively. The intermediate level cover about 51%. The land coverage of exchangeable Al levels within each category follow similar pattern. Therefore, the proportion of area that require intervention, based on exchangeable acidity levels, could reach as high as 68% of the total.

Generally, geostatistical analysis is found to be a very useful tool for visualization and proper quantification of continuous surface soil properties, for proper understanding and interpretation of their spatial patterns and distributions, and the relationship between the different interrelated factors. Thus, the quantified information generated is found to be very useful for improving research and development planning, management, and evaluation of measures to be taken on acid soils of the area. However, the study has some limitations. The distribution of point sample sites was irregularly spaced due to poor accessibility. This can affect estimates in some areas, although the level of uncertainty of estimates at any location can be understood from standard error prediction maps (Fig. 4). The topography of the study area vary from near flat plain to undulating and rugged topography, especially to the east. There are also a number of valleys running in the east-west direction. Such variability cannot be represented well by an average sampling density of 0.162/km^2. So, the influence of local topographic variability on the predicted outputs at any location should be recognized when interpreting the map outputs.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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