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Providing a soil fertility map using geographic information system, geostatistical techniques and fuzzy logic

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Abstract. Soil resources monitoring and evaluation of its status leads to specific and systematic plans related to agricultural production. By providing the soil fertility map in terms of land status, nutrient for cultivation by farmers would be determined. This leads to the correct application of fertilizers to achieve optimal conditions in productivity of the soil resources. In this study, evaluation of soil fertility using geostatistical techniques and fuzzy logic in a Geographic Information System was conducted for a part of agricultural land of Amol city, Iran. In field studies, 201 points from 0 to 30 cm depth were sampled. After laboratory analysis, values of soil available phosphorus, available potassium, organic matter, Electrical conductivity (EC) and soil reaction (pH) were measured followed by statistical processing of the points interpolation using Kriging model in the GIS environment. Then, for map providing, a fuzzy membership function defined according to soil parameters critical levels. Finally, to achieve the final map the fertile layers were combined.
Key Words: mapping soil fertility, modern agriculture, fuzzy logic, soil.

Introduction. One of the main goals of modern agriculture is the correct use of fertilizers. The amount of consumption of these fertilizers depends on soil fertility. Regardless of soil fertility, application of chemical fertilizer leads to imbalance in soil nutrients and environmental problems. Soil fertility map of an agricultural area allows providing recommendation for the amount of chemical fertilizer requirements based on spatial variation of nutrients structure needed for plants of the region. Today, regular soil sampling and analysis of spatial variability of elements by using fertility maps play an important role in soil fertility management (Loghavi 2004). In recent years, there have been several studies on soil fertility in different parts of the world including quantitative evaluation of soil fertility in Gao of China using fuzzy and AHP techniques in GIS environment (Zhang et al 2004) and soil fertility study for rice cultivation in the Philippines (Dobermann & Oberthur 1998). Fuzzy model is one of the best models used to provide different kinds of soil maps (Cassel-Gintz et al 1997). This model requires fewer parameters and in turn, it possesses high accuracy for preparing the soil attribute maps (Kremenov 2004).

Soil as the main constituent of an ecosystem is the bed for agriculture and food supplies and keeps the plant stable and provides a rich source of nutrients for crop productivity, when it is well managed (Miller & Donahue 1990). Regarding lack of soils uniformity, applying the chemical fertilizers and other input requirements without considering soil fertility variability cannot be yielded in high quality-quantity products. Therefore, the site specific management of the study area needs high-quality soil fertility map. The main objective of this study was to examine the distribution of some of the factors affecting soil fertility and providing a soil fertility map using geostatistical and fuzzy logic techniques in some agricultural lands in Amol city, Iran.

Material and Method. The study area was the central part of the Amol District, which is located in the Haraz river plains of Mazandaran province in Iran (Figure 1). This region has an area of 304.83 km^2 and is situated in the North part of Iran between 36^o34'43'' and 36^o22'16'' N latitudes and 52^o11'34'' and 52^o26'54'' E longitudes. Amol city and 135 villages that are in the study area comprise an overall population of approximately 272844 populations (Iranian Census Centre 2011). Elevations range from 20 to 500 meters above sea level. Agriculture is one of the main sources of income for the population. Based on weather data the average annual temperature of the region is 17.47^{o}C and the mean annual relative humidity is 78%. Consequently, the annual average rainfall is recorded to be 800 mm, mostly falling in December (Meteorological Mazandaran Province Administration). Different types of land uses in this area included rice lands, forests, pasture and residential.

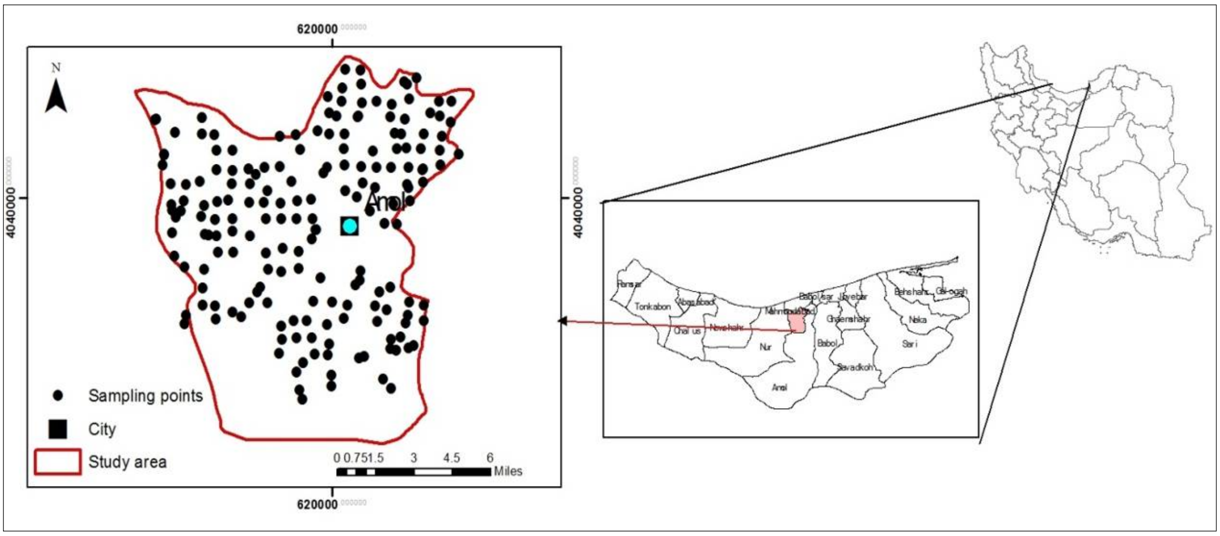

Figure 1. Location of case study area and sampling points in the Mazandaran province, Iran.

After investigation of the initial maps of region considering different forms of land, the best sampling network was determined. Total 201 soil samples from the surface depth of soil (0 to 30 cm) with recorded GPS latitude and longitude were collected. Then, all samples were air dried for lab operations and passed through a sieve of 2 mm.

Available P was measured by Olsen method (Olsen & Sommers 1990) and to determine the available K the ammonium acetate adjusted at pH = 7 were used (Westerman 1990). Soil organic matter was measured using the Walkley Black method (Walkley & Black 1934). The electrical conductivity (EC), as indicator of soil salinity, was determined from the saturation soil paste extract by EC meter device. Soil reaction (pH) was determined by the Electrometric method (Chung & Fabbiri 2001).

The logarithmic transformation method was used to normalize the data distribution of phosphorus, potassium, organic matter and EC. Bax-Cox method was used to normalize the data distribution of pH. After conversion of variables that had an abnormal frequency distribution, linear correlation of variables determined. SPSS software was used for descriptive statistics and regression analysis.

Results and Discussion. First initial data consisted of the frequency distribution of data and statistical indicators such as mean, median, mode, variance, standard deviation, skewness and kurtosis was calculated as the results shown in Table 1. Main condition for using variogram analysis was normality of the data. The Kolmogorov-Smirnov (K-S) test was used for normality of the data and it was evaluated by considering the coefficient of skewness. Normalization methods are required if the skewness of the data to be more than 0.5 (Bregt et al 1992).

Table 1

Statistical analysis of the measured quantities

Statistical results	*P mg kg^{-1}*	*K mg kg^{-1}*	*organic matter %*	*EC dsm^{-1}*	*pH Log[H+]*
Minimum	5	60	0.12	0.10	6.10
Maximum	100	630	11.68	3.38	8.26
Mean	24.22	148.63	3.21	0.73	7.60
Median	22.50	126	2.79	0.65	7.70
Mode	7.5	125	2.01	0.50	7.80
Standard deviation	13.82	76.06	1.79	0.40	0.38
Variance	191.16	0.66	3.23	0.16	0.15
Skewness	1.88	2.53	1.19	2.58	1.30
Kurtosis	7.27	10.01	2.46	11.94	2.05
Kolmogorov-Smirnov Z	1.368	2.651	1.398	1.583	1.998
Asymp. Sig. (2-tailed)	0.047	0.000	0.040	0.013	0.001

Geostatistical method can be used to estimate the amount of the soil elements in the unknown points (Goovaerts 1999; Xiaopeng et al 2014). Analysis of the structure of spatial variability would be conducted using Variogram. Variogram represents changes in the structure of spatial variability of a particular variable while basic tools of geostatistics used for assessment of spatial variability of soil properties. Moreover, the most natural method to compare two quantities, such as two value of Z (x + h) and Z (x) at two points, with coordinates of x and x + h at a distance of h from each other is to examine their differences. Obviously, the sign of this difference and the mean value of Z (xi + h)-Z (xi) will be considered for the analysis. Therefore, the mean value of Z (x)-Z (x + h) should be calculated and considered for all positions of x and x + h. Since the mean value of this quantity is zero or close to zero, practically the root mean square will be considered (Utset et al 2000). If it is assumed that there are a total number of N (h) pairs of samples at a distance of vector h, based on this data Variogram might be as follows:

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[Z(X_i+h)-Z(X_i)\right]^2$$

Data obtained from the variogram of elements as input values of Kriging method will be used to estimate values in the unknown points. Before application of the variogram in the estimation process the best theoretical model must fit. In this study, several theoretical models allocated to fitting. After investigation of data anisotropy, Variogram models including linear, spherical, exponential and Gaussian model were examined. Results from cross-validation for each of the five factors indicated that exponential model due to lower Rss error recognized as the best model compared with other models. Low piece effect value in this fitted model on the one hand and low rate of estimation errors including mean error (ME) and root mean square error (RMSE) on the other hand confirms this assumption. The components of best variogram model fitted to variables studied were presented in Table 2.

Table 2

The components of variogram model fitted to variables

Type of variable	*Model*	*Nugget effect*	*Sill*	*Range*	*Mean error*	*Root mean square error*	*Root mean square standardized*
P MgKg^{-1}	Exponential	0.05	0.290	7112	0.41	2.69	1.01
K MgKg^{-1}	Exponential	0.08	0.089	6238	0.71	8.92	1.14
O.M %	Exponential	0.17	0.270	6111	0.079	1.54	0.82
EC dsm^{-1}	Exponential	0.17	0.048	5134	0.003	0.36	0.68
pH.Log[H+]	Exponential	0.05	0.066	2619	0.007	0.31	0.96

Spatial distribution of phosphorus, potassium, soil organic matter, EC and pH by Kriging method in the ArcGIS software was plotted with selection of the best fitting model (Figure 2).

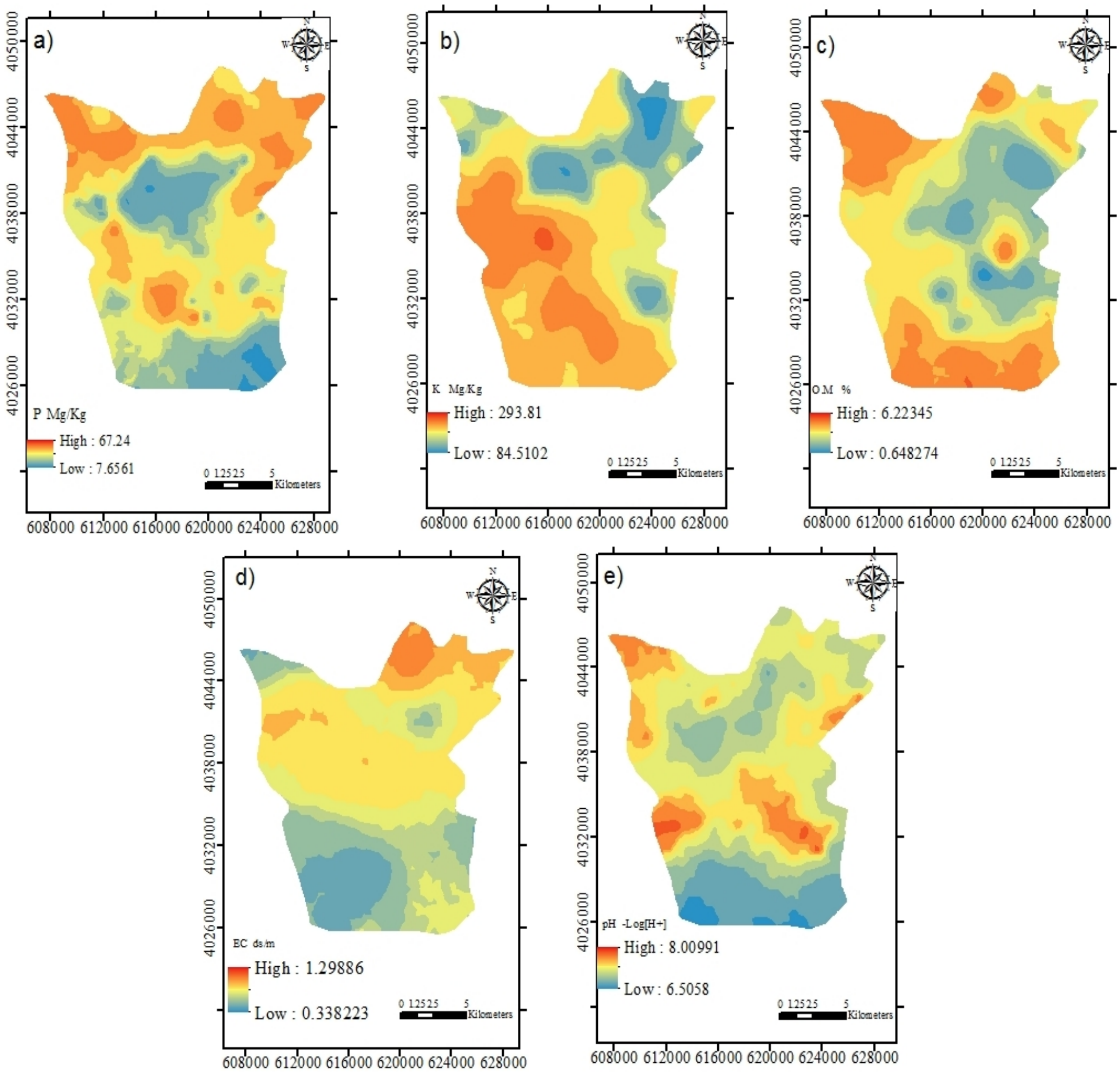

Figure 2. Map of the statistical distribution of (a) soil available P (Mg Kg^{-1}), (b) soil available K (Mg Kg^{-1}), (c) soil organic matter (%), (d) soil EC (dsm^{-1}) and (e) soil pH (-Log [H+]).

In the fuzzy logic, the membership function specifies the value of a fuzzy collection. In fact, a function that represents the membership degree of members to a collection is called membership function (Koorehpazan Dezfuli 2008). This means that each area with higher the value of membership has a higher desirability. The uncertainty of Boolean logic cannot be found in the fuzzy logic and each layer is graded in a scale from zero to one. It means that number 1 has the highest desirability while zero has no desirability. In addition to the choice of scale for providing fuzzy map, the fuzzy function should be also examined to select more suitable function for the desired criteria. Among the famous functions are Triangular, Sigmodial, bell-shape, Linear and Gaussian functions. Another factor contributing to the standardization of fuzzy maps is determining thresholds which are also called control points. But the point that needs to be considered in the selection of function is its decreasing or increasing type. By increasing we mean maximizing or ascending function. For example, in relation to organic matter, the more amount of increase leads to more appropriate productivity. Therefore, an increasing function will be used here. Fuzzy membership functions have been linear for the majority of soil factors and are defined as equation 1 (Oberthur et al 2000):

$$\mu(x) = f(x) = \begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a \le x \le b \\ 1 & x \ge b \end{cases} \qquad (1)$$

The a and b value for soil organic matter in the study area considered as 1 and 3, respectively. The a and b value for EC considered as 2 and 1, respectively. Fuzzy membership function has been reducing linear for pH in the study area and is defined equation 2:

$$\mu(x) = f(x) = \begin{cases} 1 & x \le a \\ \frac{b-x}{b-a} & a \le x \le b \\ 0 & x \ge b \end{cases} \qquad (2)$$

The a and b value for pH in the study area considered as 7 and 9, respectively. The triangular membership function with three parameters of a, b and c for the standardization of phosphorous factor is defined as equation 3:

$$\mu(x) = f(x) = \begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a \le x \le b \\ \frac{c-x}{c-b} & b \le x \le c \\ 0 & c \le x \end{cases} \qquad (3)$$

Parameters of a, b and c determine the coordinates for the corners of the triangle that were considered as 8, 25 and 52 for phosphorous in the study area, respectively. The Trapezoidal membership function with four parameters of a, b, c and d for the standardization of Potassium factor is defined as equation 4:

$$\mu(x) = f(x) = \begin{cases} 0 & x \le a \\ \frac{x-a}{b-a} & a \le x \le b \\ 1 & b \le x \le c \\ \frac{d-x}{d-c} & b \le x \le c \\ 0 & c \le x \end{cases} \qquad (4)$$

Parameters of a, b, c and d determine the coordinates for the corners of the trapezoid that were considered as 100, 150, 200 and 250 for K in the study area, respectively.

The primary attribute maps and equations 1, 2, 3 and 4 have been used to prepare fuzzy maps for the five mentioned factors (Figure 3).

Process evaluation is done by combining layers after standardization of criteria maps. Variety of combination rules have been investigated (Zimmerman 1996). Five operators that are used, namely the fuzzy and, fuzzy or, fuzzy algebraic product, fuzzy algebraic sum and fuzzy gamma operator (Bonham-Carter 1994). In this study, the fuzzy gamma operator was used for combining the fuzzy membership functions. The fuzzy gamma operator adjusted and closer to reality the very high sensitivity of fuzzy multiplication operator and low sensitivity of fuzzy sum operator. Select the correct gamma value is very useful to improving the accuracy. According to studies (Chung & Fabbiri 2001; Rather & Andrabi 2012) and compared different results $\gamma = 0.7$ was used. Composite index map was extracted in the fuzzy value ranging from zero to one. According to the map and column chart of the pixel values, limited area with low fertility were determined. Accordingly, the more pixel value causes better conditions in terms of productivity. Then divisions of the final map were determined using histogram of values of composite index map (Figure 4).

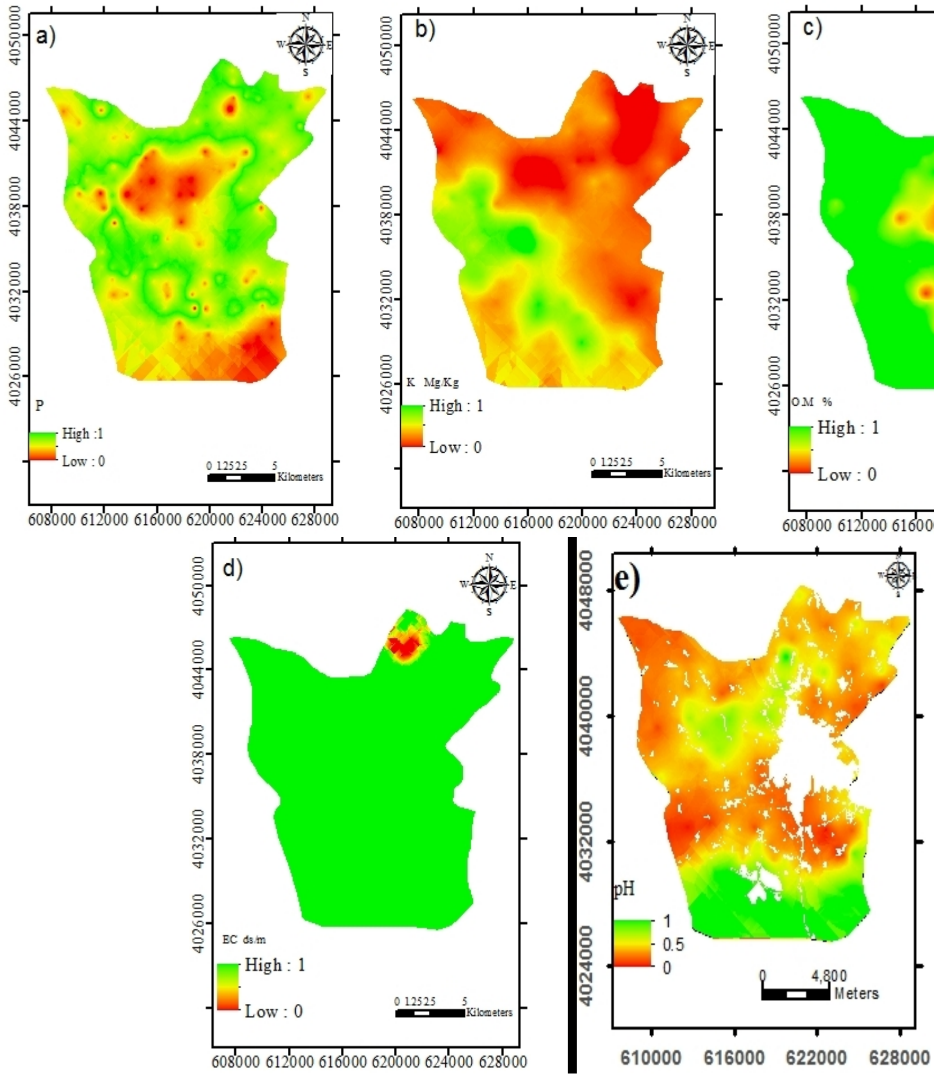

Figure 3. The produced fuzzy map of (a) soil available P (Mg Kg^{-1}), (b) soil available K (Mg Kg^{-1}), (c) soil organic matter (%), (d) soil EC (dsm^{-1}) and (e) soil pH (-Log[H+]).

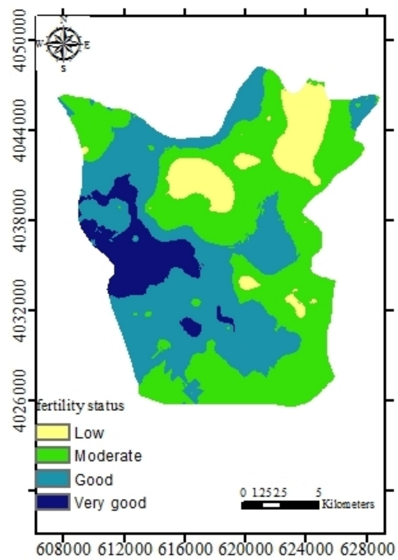

Figure 4. Separated map of soil fertility.

Surface map of elements of phosphorus, potassium, soil organic matter, EC and pH were prepared separately in Figure 2, through interpolation of studied points. Finally, after defining membership functions for each factor and standardization of layers by using fuzzy method, layers were combined and the final map was produced (Figures 3 and 4).

Fuzzy maps of effective distribution in fertility indicate that how much and what kind of fertilizer is required for the soil in each area. Thus, rationing and distribution of fertilizer will be fair and based on consumer needs. In the region of interest, a large part of the lands in terms of available phosphorus was higher than the threshold and there is no need to increase the phosphorus in these areas. For proper fertilizer management actions it is necessary to have complete information about soil nutrient levels to achieve better performance. Lack of awareness of soil changes in different parts and uniform application of the fertilizers causes some soils receive more or less fertilizer than what they require (Sokouti & Mahdian 2011). Based on the final classified map, 10.27% of the lands in the area were in the low classes, 43.30% in medium, 37.25% in good and 9.18% in very good classes in terms of fertility. This means that about 46.43% of the land was suitable for cultivation in terms of fertility and only 53.57% of the land area (163 km^2) has a low potential for the cultivation. Therefore, to increase the efficiency of production, fertilization based on soil test is required. To determine the accuracy of separation groups by the mentioned method, 8 points (two points selected randomly from each group) were selected. Mentioned areas were identified and re-sampling of the soil was carried out using GPS. Then, in the laboratory the amount of potassium, organic matter and phosphorus were determined again. Comparing sampling results with the separated groups shows that these random points according to the values were put exactly in separated groups with regard to the limits set by them in the final map of fertility. Therefore, it is evident that the prepared map can be of good accuracy to determine soil fertility in the region. Also use of fuzzy logic is of a very high accuracy to prepare map of fertility. This method is suggested for preparation of soil fertility map.

Conclusions. Agricultural soils are valuable resources and their protection and fertility management play an important role in the sustainable agriculture. One of the suitable tools that make it possible to manage the soil fertility is the use of soil fertility map. This study produced a high-quality soil fertility map for applying the site-specific management of crop cultivation in study area. The geostatistical techniques and fuzzy logic were incorporated for mapping soil fertility in GIS based on soil OC, K, P, EC and pH factors. The final soil fertility map indicated that most of the studied soils have moderate potential for cultivation. In brief, it can be concluded that using integrated geostatistical techniques and fuzzy logic techniques in GIS, changes in soil characteristics could be identified in the same soil uniform mapping units over a very short distance. This method can easily present the limitation factors of the different soil fertility classes for cultivation.

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