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Assessment of soil fertility index for potato production using integrated Fuzzy and AHP approaches, Northeast of Iran

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Abstract

Considering the important role of soil fertility and nutrient management in the modern agriculture seems to be a key step in appropriate site-specific fertilizers management for crop production. The present study was conducted to prepare a soil fertility zonation map based on soil nutrient elements including total nitrogen, available potassium and phosphorus, magnesium, manganese and iron and soil chemical parameters comprising cation exchange capacity, organic carbon, salinity and pH by integrated Fuzzy and AHP approaches for potato production in Rokh plain, northeast of Iran. In this regard the most important soil chemical parameters and nutrient elements in 0-30 cm depth of the soil was analyzed and mapped. The S-shaped fuzzy membership function was subsequently defined for each factor to fuzzify soil fertility parameters. The soil fertility map was prepared by weighing factor layers by the AHP approach and summation of factor layers by IDW interpolation function in GIS. The values of the soil fertility index in the scale of 0 to 1 ranged from 0.104 to 0.574, classified the study area in very low (922.90 km^2), low (566.10 km^2) and moderate fertility (14.86 km^2) classes which comprises 61.37%, 37.64% and 0.99% of the surface area, respectively. A regression between soil fertility values and potato yield in the study area revealed a high correlation (R^2 = 0.91) between the observed results which validate the zonation of the fertility classes in the region.

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Introduction

The rapid growth of population demands higher land use efficiency to ensure food security. The most appropriate way to reach this goal is to increase yield per unit area rather than by expansion of cultivated areas. In this regard, evaluating soil fertility and productivity is of great importance in plant production. Determining the degree of soil fertility was done based on soil chemical parameters including cation exchange capacity (CEC) and Organic carbon (OC) as key indicators of soil quality, soil salinity (EC_e) and pH, as well as macro nutrient elements including nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) due to high rate of consumption and their great effect on crop yield and its quality, and micro nutrient elements comprising, manganese (Mn) and iron (Fe) because of their important role in conducting physiological processes in plant nutrition (Westermann, 2005). Nutrition of the potato (*Solanum tuberosum L.*) crop is characterized by its shallow rooting habit and rapid growth rate. Therefore, high yields necessitate an adequate supply of nutrients throughout the growth period. Nitrogen application promotes early development of the foliage and therefore, of the photosynthetic capacity during the growth period. However, excess N may delay tuber initiation and so reduce yield. The N requirement depends on many

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factors including soil type and cropping system. A preceding legume or another crop with high residual effects, or an application of organic manure, can reduce fertilizer N requirements by 40–50 kg.ha^{-1}. Potatoes utilize both ammonium and nitrate N, but show a preference for ammonium, especially in the early stages of growth. Usually, the entire N is applied to the seedbed. However, in high rainfall conditions, a split application may reduce leaching losses. N applications after the start of tuber development may delay crop maturity. Potatoes need a good supply of readily available Phosphorous because their root system is not extensive and does not readily utilize less available P forms. Water-soluble P is the most efficient source for potatoes. Potassium plays a major role in starch production by the potato crop. Potato plants well supplied with K are found to withstand frost better than low K plants. Fertilizer K requirement depends on soil type and organic manure application. Irrigation can improve the availability of soil K, and there can be varietal differences in susceptibility to K deficiency. Magnesium is the central part of the chlorophyll molecule, where photosynthesis occurs. It also helps the plant metabolize energy and form protein. Magnesium deficiency can occur on leached, sandy soils with low cation exchange capacities and may be intensified by large K fertilizer applications. It can be controlled by Mg applied in amendments such as dolomite or by Mg-containing fertilizer materials. Manganese (Mn) is involved in chlorophyll formation, nitrate assimilation, enzyme systems, and iron metabolism. Manganese deficiency is generally caused by a high soil pH, whereas Mn toxicities occur at low soil pH. Iron (Fe) is used in chlorophyll and protein formation, enzyme systems, respiration, photosynthesis, and energy transfer. Iron deficiency is believed to be caused by an imbalance of metallic ions, such as Cu and Mn; excessive amounts of P; and a combination of high pH, high lime, cool temperatures and high levels of carbonate in the root zone. Soil application or foliar sprays are the widely used methods for supplying micro-nutrients. The micro-nutrient needs of potato can also be met simply by soaking the seed tubers in nutrient solutions. The non-dormant seed tubers are soaked in 0.05% micro-nutrient salt solutions for three hours. The deficiencies of Mn and Fe are controllable by soil or foliar application. Potato cultivars can differ markedly with regard to their sensitivity to micronutrient deficiencies.

Fuzzy model is one of the most flexible models used to provide different kinds of soil maps (Cassel-Gintz et al., 1997). The model comprises high accuracy for preparing the soil attribute maps (Kremenová, 2004). Fuzzy set theory and concept of a linguistic variable is derived values of variables and made its use for expanded application area. Fuzzy logic makes conversion of imprecise information to precise one, consists of capability to design rational decisions containing imperfect information. Uncertainty, imprecision, incompleteness, risk management, partial true and vice versa is an attribute of information in Fuzzy systems. The fuzzy logic design is the best approach to get precise, accurate result and conclusions. Fuzzy set theory has been used in environmental sciences including land suitability evaluation, soil fertility classification, soil geo-statistics and soil quality indices (Burrough, 1989; McBratney and Odeh, 1997; McBratney et al., 2003; Zhang et al., 2004; Lagacherie, 2005). The development of fuzzy logic-based soil fertility mapping techniques is due to its ability to represent the continuous nature of soil spatial variation (Zhu et al., 2001; Yang et al., 2007). Fuzzy set theory has been widely used in soil fertility classification, mapping and land evaluation (McBratney et al., 2003; Zhang et al., 2004; Lagacherie, 2005; Sanchez Moreno, 2007). The analytical hierarchy process (AHP) developed by Saaty (1980) is a multi-criteria evaluation approach, used to enhance with fuzzy factor standardization. The AHP plays an important role in selecting alternatives (Dey and Ramcharan, 2008), (Vahidnia et al., 2009). AHP has become one of the most widely used methods for the practical solution of multi criteria decision making issues (Chan et al., 2000; Chang et al., 2007). AHP uses understanding and informed knowledge without the need of specific data (Bottero et al., 2011). But the main shortage of AHP is that it deals with people's expert judgment as a crisp number between 1and 9 and their Eigen values, this doesn't handle the uncertainty associating to these judgments. In order to overcome that incompetence, Fuzzy set integrated with AHP technique to determine the best alternative (Levary and Wan, 1998), (Chang et al., 2007). The combination of fuzzy set and AHP leads to more flexibility in judgment and decision making. The AHP reflects human thinking as it uses approximate information and uncertainty to generate decision in addition to inheritance of the advantages of AHP, ease of handling qualitative and quantitative data, use of hierarchical structure, pairwise comparison, reduce inconsistency, and generates priority vectors (Vahidnia et al., 2009). The main hypothesis behind our research is that there is a logical relationship between the soil chemical properties, soil fertility index and crop yield which can be defined as a modeling by integrating Fuzzy and AHP approaches. The aim of the present study is to evaluate soil fertility and classification for potato production in Rokh plain, northeast of Iran. In this regard integration between Fuzzy and AHP approaches and GIS was used to produce and classify soil fertility zonation map for the study area.

Material and Methods

General characteristics of the study area

The present study was conducted in Rokh plain, Khorasan-e-Razavi Province, Northeast Iran (Figure 1). The study area is located between latitude 35°28′51"N to 35°47′45"N and longitude 58°34′49"E to 59°35′39"E including lands less than 2933 m asl. The general physiographic trend of the plain extends in a west-east direction with a maximum length of 92 km. The total surface of the study area comprises 1503.86 km^2. The elevation values of the study area vary between 1386 m and 1901 m asl, with an average of 1643.5 m asl. The main land use practice in the study area is irrigated farming. The climate of the study area is semi-arid with mean annual precipitation of 267.7 mm and means annual temperature of 14.3°C (Figure 1).

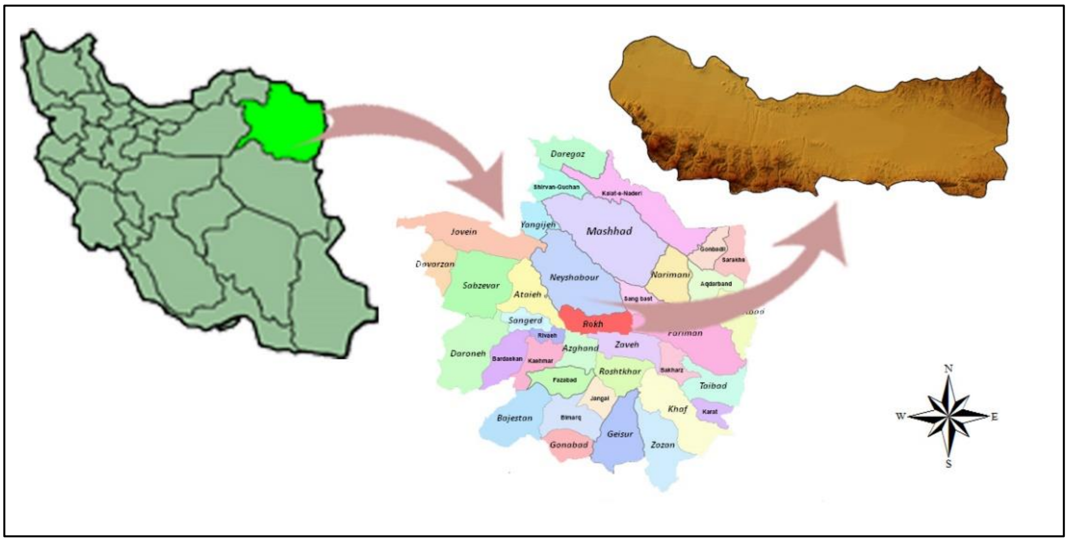


Figure1. the Geographical location of the study area

Soil analysis

Some 300 soil samples in depth of 0-30 cm were collected from current potato fields all over the study area. The values of Cation Exchange Capacity (CEC), Electro Conductivity of soil saturated extract (EC_e) and soil pH were determined by Ammonium Acetate method, Electro Conduct-meter and standard pH meter, respectively. The Soil organic carbon was measured using the Walkley Black method (Walkley and Black, 1934). The total N (%) was determined using the electro ultra-filtration (EUF) apparatus with an auto-analyzer, the available P was determined using the blue color method of Murphy and Riley (1962) and the absorbance measured on spectronic-20 equipment. The available K was determined by flame photometer approach and the Mg values were analyzed by spectrophotometer through CFA method. The atomic absorption spectrophotometer (AAS) was used for measuring manganese and iron. The cumulative quantities of the nutrients desorbed after 10, 30 and 35 min were subsequently calculated.

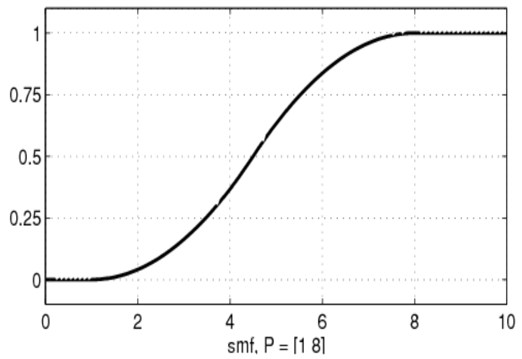
Fuzzy set theory

The fuzzy set theory originated by Zadeh (1965). Fuzzy set theory is a mathematical method used in data and functional relationships to characterize uncertainty and imprecision. To characterize uncertainty using standard statistical measures using a fuzzy set is useful (e.g., Mean, standard deviation, and distribution type). The fuzzy set theory includes fuzzy mathematics, fuzzy measures, fuzzy integrals, etc. One of the aspect of the field of fuzzy mathematics is fuzzy logic. In classical set theory, the membership of a set is defined as true or false, 1 or 0. Membership of a fuzzy set, however, is expressed on a continuous scale from 1 to 0 that μA =0 means that the value of *x* does not belong to A and μA=1 means that it belongs completely to A. A fuzzy set A, defined in the total space X, is a function defined in X which assumes values in the range [0, 1]. A fuzzy set (A) may be defined as follows (Burrough et al., 1992):

$$\text{For each } A = \{ x , \mu A(x)\}\ x \in X \quad \text{(Eq. 1)}$$

Where, X = {*x*} is a finite set of points and μA(*x*) is a membership function of *x* in A.

The membership function describes the variable's membership assigned to A and, therefore, it may quantify the influence of the variable x on the predicted phenomenon, as it is grasped by the developer (Burrough et al., 2015). There are several fuzzy membership function that in the paper was used Linear membership function. The Fuzzy Linear transformation function applies a linear function between the user-specified minimum and maximum values. Any value below the minimum will be assigned as 0 (definitely not a member) and any value above the maximum as 1 (definitely a member) (Sys et al., 1993; Sanchez Moreno, 2007). Fuzzy membership functions have been linear for the majority of soil factors, hence the S-shaped built-in membership function was defined as Equation 1 (Oberthur et al., 2000). This spline-based curve is a mapping on the vector x, and is named because of its S-shape. The parameters a and b locate the extremes of the sloped portion of the curve, as given by: y = smf(x,[a b]) (Figure 2).



$$f(x;a,b)=\begin{cases}0, & x\le a\\ 2\left(\frac{x-a}{b-a}\right)^2, & a\le x\le \frac{a+b}{2}\\ 1-2\left(\frac{x-b}{b-a}\right)^2, & \frac{a+b}{2}\le x\le b\\ 1, & x\ge b\end{cases}$$

Figure 2. The S-Shaped membership function and its equation

The applied function is asymmetrical linear where *a* and *b* are the critical and adequacy value limits used for each of the ten factors (Table 1).

Table 1. Soil fertility factors and the critical values (mangle and adequacy limits) in the fuzzy membership function (the values of *a* and *b* are calculated based on 40 $t.ha^{-1}$ potato production).

Fertility factors	units	*a*	*b*
CEC	meq/100g	7	18
OC	%	0.86	1.29
EC_e	dS m^{-1}	1.7	6
N_{total}	%	0.05	0.2
K	mg kg^{-1}	40	110
pH	-	5.2	8.2
P	mg kg^{-1}	6	15
Mg	mg kg^{-1}	10	20
Mn	mg kg^{-1}	3	6
Fe	mg kg^{-1}	2	4

Analytical Hierarchy process (AHP)

The AHP developed by Saaty (1990) considers a one-level weighting system through a pair wise comparison matrix between the parameters as described by Saaty (1990, 1994) and Saaty and Vargas (2001). The method employs an underlying nine-point recording scale to rate the relative preference on a one-to-one basis of each criteria (Malczewski, 1999). For better map presentation purposes, the scale assigns a linguistic expression to each corresponding numerical value (Table 2).

Table 2. The Saaty scale (2003) was used for generation of pairwise comparison matrix.

Intensity of importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Equally preferred
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong
9	Extreme importance

The weights of factors are calculated from the pair-wise comparison matrix undertaking specific values and vectors calculation. It has been demonstrated that the specific vector corresponding to the largest specific value of the matrix provides the relative priorities of the factors, i.e., if one factor has preference; its specific vector component is larger than that of the other. The components of the specific vector sum to unity. Thus, a vector of weights is obtained, which reflects the relative importance of the various factors from the matrix of paired comparisons. The complete pair-wise comparison matrix contains many multiple paths by which the relative importance of factors can be assessed; therefore, it is also possible to determine the degree of consistency that has been used in developing the judgments. In the construction of the matrix of paired comparisons, the consistency of the judgments should be revealed because this matrix is a consistent matrix. The results of the pair-wise comparison matrix and the factor weights are shown in Table 3.

Table 3. Pair-wise comparison matrix for calculating factor weights

Parameters	CEC	OC	EC_e	N	K	pH	P	Mn	Zn	Fe	Weight
CEC	1.00										0.282
OC	0.33	1.00									0.199
EC_e	0.33	0.50	1.00								0.154
N	0.33	0.33	0.50	1.00							0.122
K	0.20	0.33	0.33	0.33	1.00						0.076
pH	0.20	0.20	0.33	0.33	0.50	1.00					0.063
P	0.20	0.20	0.25	0.33	0.50	0.50	1.00				0.050
Mg	0.13	0.14	0.14	0.17	0.20	0.20	0.25	1.00			0.023
Mn	0.11	0.13	0.13	0.14	0.20	0.20	0.25	0.50	1.00		0.018
Fe	0.11	0.13	0.13	0.13	0.17	0.17	0.20	0.33	0.50	1.00	0.014

In AHP method, an index of consistency, known as the consistency ratio (CR), is a ratio between the matrix's consistency index and random index. CR is used to indicate the probability that the matrix judgments were randomly generated (Malczewski, 1999).

$$CR = \frac{CI}{RI} \qquad \text{(Eq. 2)}$$

where RI is the average of the resulting consistency index depending on the order of the matrix given by Malczewski (1999) and CI is the consistency index and can be expressed as

$$CI = \frac{\lambda \max - n}{n - 1} \qquad \text{(Eq. 3)}$$

Where, λmax is the largest or principal specific value of the matrix and can be easily calculated from the matrix, and n is the order of the matrix. CR ranges from 0 to 1. A CR close to 1 indicates the probability that the matrix's rating was randomly generated. A CR of 0.10 or less is a reasonable level of consistency (Malczewski, 1999). A CR above 0.1 requires revision of the judgments in the matrix. The calculated value of Cr in our study was 0.056. Once a satisfactory CR is obtained, the resultant weights are applied. The weights should add up to a sum of 1.0, as the linear weighted combination calculation requires. It was shown that the most important factor affecting soil fertility was cation exchange capacity (CEC) with the weight of 0.282 and the least important factor was defined as Iron with the weight of 0.014. Finally, in order to finalize soil fertility map the values obtained by AHP with the fuzzy values of each affecting parameters. In this procedure the values obtained by fuzzification of each parameter is multiplied in the factor weight of that parameter and the summations of the resultant values is used to produce the final soil fertility map as shown in the following equation (Kremenová, 2004):

$$\mu_A = w_i \mu_{A1} + \cdots + w_k \mu_{A1}$$

$$\mu_A = \sum_{j=1}^{k} w_j \, \mu_{Aj(\mathrm{x})} \qquad \mathrm{x} \in \mathrm{X} \qquad \text{(Eq. 4)}$$

$$\sum_{j=1}^{k} W_j = 1 \qquad \mathrm{W_j} > 0$$

Where; μ is the membership function related to each of the parameters and W is the specific weight given to each of the parameters. The analytical procedures in this study including interpolation, fuzzy mapping and final soil fertility map calculations have been done using Arc map (Version 10.5) software. The flowchart of the fuzzy AHP procedure used for soil fertility zonation in our study has been shown in Figure 3.

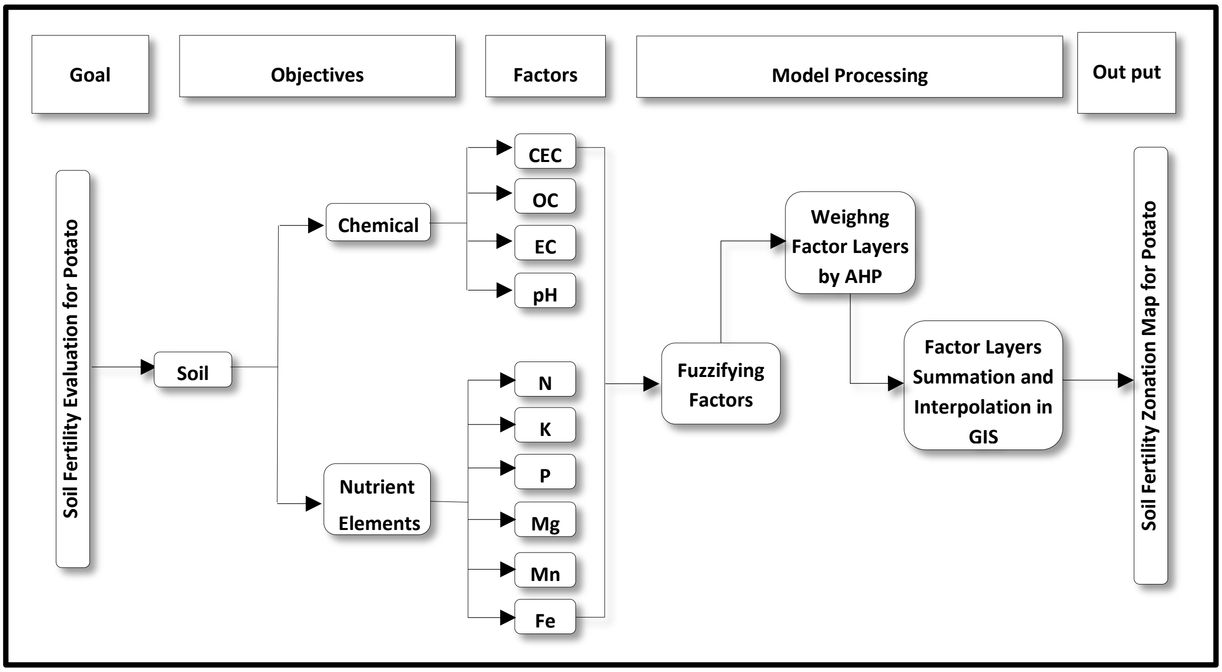


Figure 3. Schematic diagram of the Fuzzy-AHP Model for preparing soil fertility zonation

Results

Spatial distribution of factors affecting soil fertility

Soil chemical parameters including cation exchange capacity (CEC), organic carbon (OC), soil salinity (EC_e), pH and six nutrient elements including total Nitrogen (N), Potassium (K), Phosphorous (P), Magnesium (Mg), Manganese (Mn) and Iron (Fe) were analyzed and their spatial distribution in the upper 30 cm of the soil was mapped (Figure 4, 5).

The zonation of soil chemical parameters in the study area

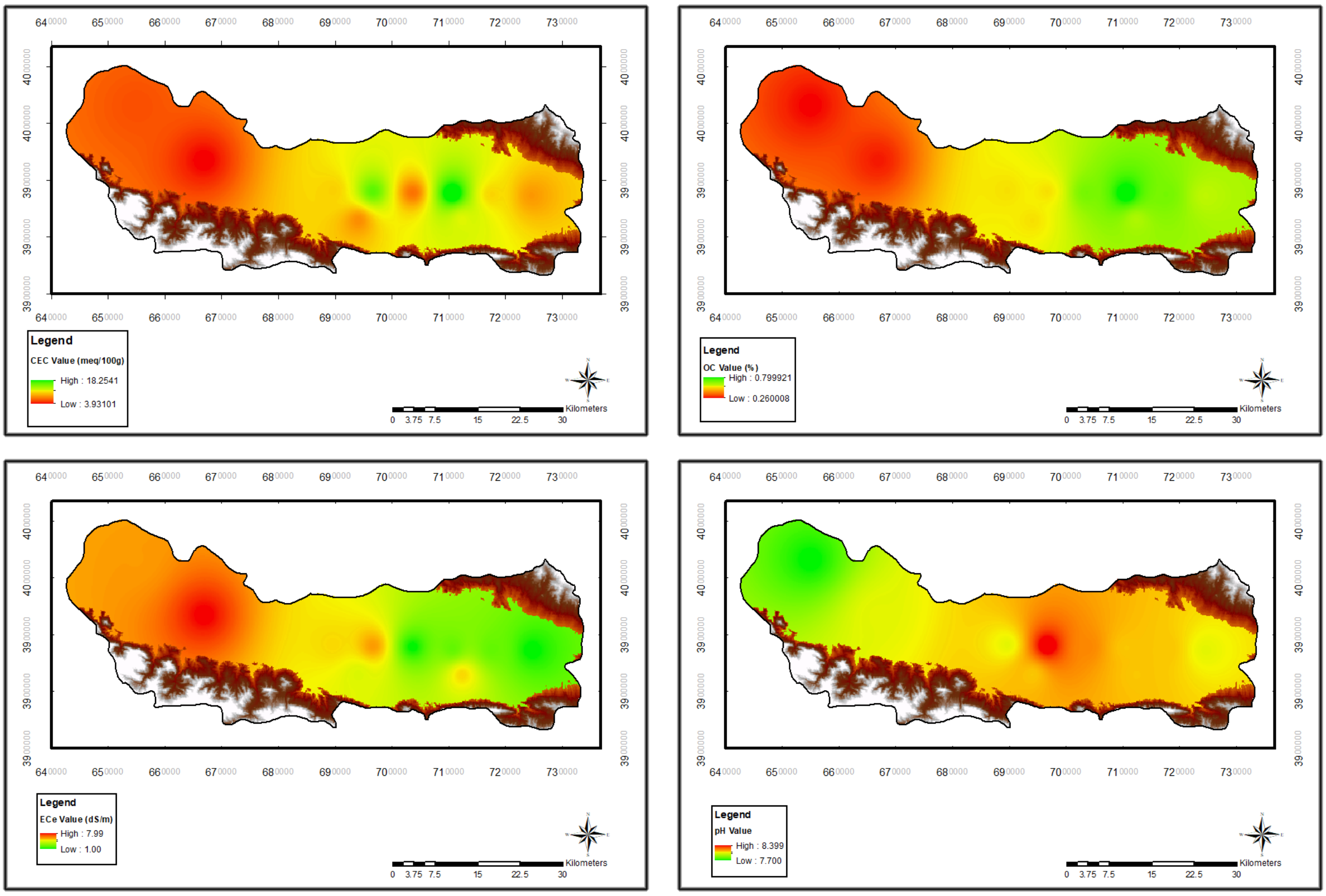


Figure 4. The zonation of soil chemical parameters in the study area

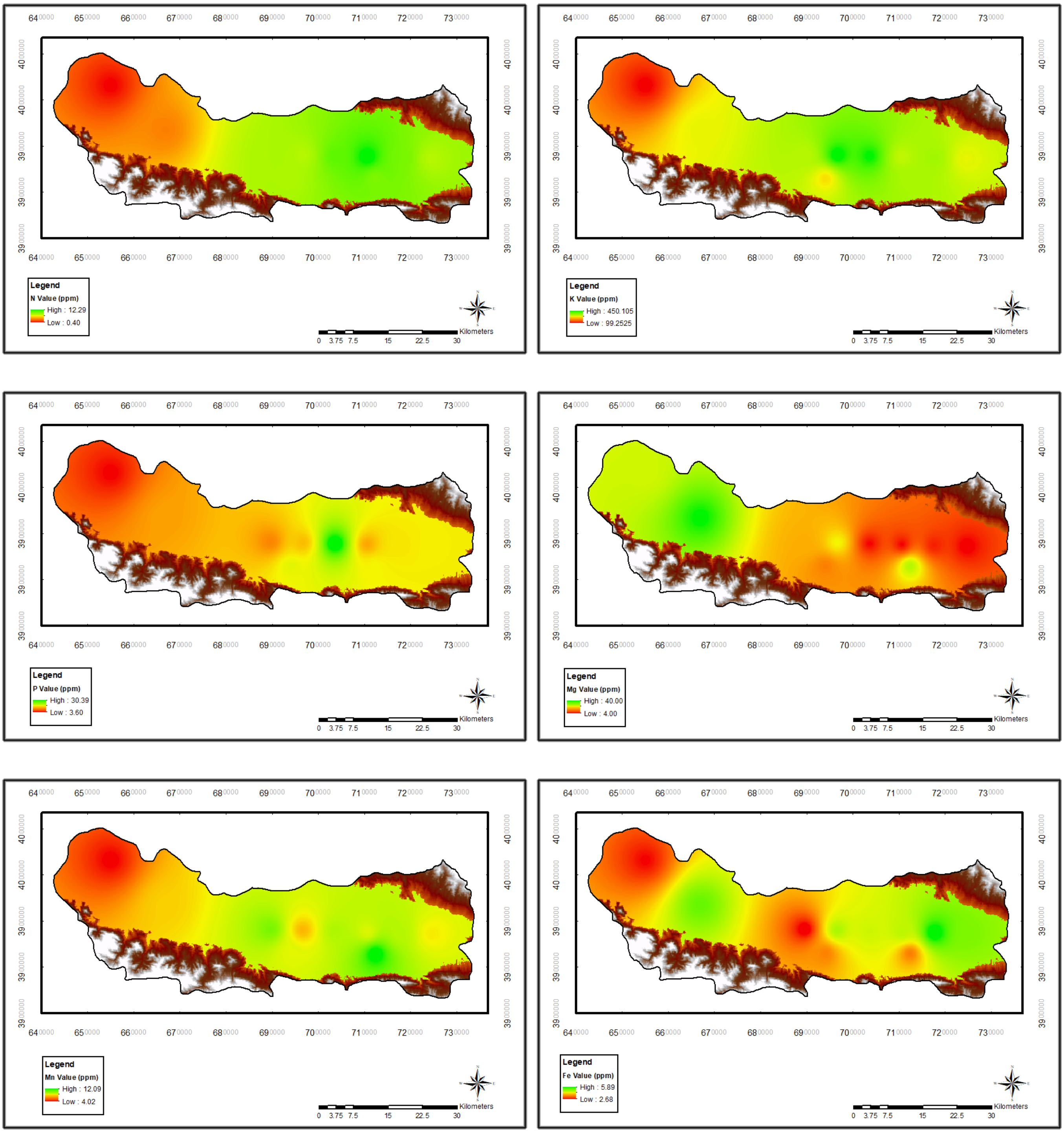


Figure 5. The zonation of soil nutrient elements in the study area

The main physiological functions of the selected nutrient elements in potato have been shown in Table 4. The values of cation exchange capacity in the study area varied between 6.23 and 13.8 meq/100g. The higher values of CEC were found mainly in west, while in east parts of the study area due to lower values of soil organic carbon and light texture of the soil the values of CEC were found as very low. The values of organic carbon in the study area ranged from 0.26 to 0.80%. The spatial distribution of soil organic carbon was followed the same pattern as CEC. The upper values of OC were observed in north and west, while the lower values were found mainly in the middle and south parts of the study area. The EC_e values ranged from 1 dS m^{-1} in some areas in the west to 8 ds m^{-1} in the north of the study area. It was revealed that the values of EC_e in west of the study area were in tolerance threshold for potato production; however to compensate the negative effects of high soil salinity and alkalinity on potato production a distinct amount of granulated sulfur were applied to soil before planting. The values of pH varied between 7.7 in west to 8.4 mainly in the middle of the study area. Potato grows best on slightly to moderately acid soils although it grows successfully in soils with a wide pH range, but in base soil reaction of our study area its negative effects on the availability of phosphorous and micronutrients such as manganese and iron cannot be ignored. It was revealed that the values of mineral nitrogen at the study area were very low, ranged from 0.4 to 12.3 mg.kg^{-1}. The upper values of total N (%) were found in east and the lower values were distributed mainly in west of the study area. The values of available phosphorous in the study area ranged from 3.6 to 25.2 mg.kg^{-1}. The lower values of available P were observed in the west and the higher values were found mainly in east parts of the study area. The values of available potassium varied between 99.24 and 450.15 mg.kg^{-1}. The lower values of available K were found in the west and the higher values were observed in the middle and east of the plain. The values of magnesium varied between 4.0 and 28.0 mg.kg^{-1}. The lower values of Mg were observed in the east and the higher values were found in west of the study area. The values of manganese ranged from 4.02 to 12.10 mg.kg^{-1}. The upper values of Mn were observed in the middle and east, while the lower values were found in west of the study area. The values of Iron ranged from 2.68 to 5.90 mg.kg^{-1}. The lower values of Fe were found in west and some parts in the middle of the plain and the upper values were observed mainly in east of the study area.

Table 4. The main functions of nutrients elements in Potato

Nutrient	Function
Nitrogen (N)	Synthesis of proteins (growth and yield).
Phosphorus (P)	Cellular division and formation of energetic structures.
Potassium (K)	Transport of sugars, stomata control, cofactor of many enzymes, reduces susceptibility to plant diseases.
Magnesium (Mg)	Central part of chlorophyll molecule.
Manganese (Mn)	Necessary in the photosynthesis process.
Iron (Fe)	Chlorophyll synthesis.

Soil fertility index zonation

The soil fertility factors including chemical and nutrient elements were fuzzified by S-shaped membership function (Figure 2). To determine the degree of membership for each factor the critical and adequacy values *a* and *b* were defined based on 40 t.ha^{-1} potato production. The pairwise comparison matrix was used by AHP approach to give the appropriate weight to each factor layer (Table 3). To determine the final soil fertility zonation for potato production the summation operator was used in GIS to combine the weighted layers in a final soil fertility map (Figure 6). The values of soil fertility index in the scale of 0 to 1 ranged from 0.104 to 0.574 which classified as very low to moderate fertility (Table 5). Based on our results the soil fertility classes were categorized in very low (922.90 km^2), low (566.10 km^2) and moderate fertility (14.86 km^2) which comprises 61.37%, 37.64% and 0.99% of the surface area, respectively. A linear regression between soil fertility values and the potato yield at each point study revealed a high correlation (R^2=0.91) between the observed results which verify the zonation of the fertility classes in the region.

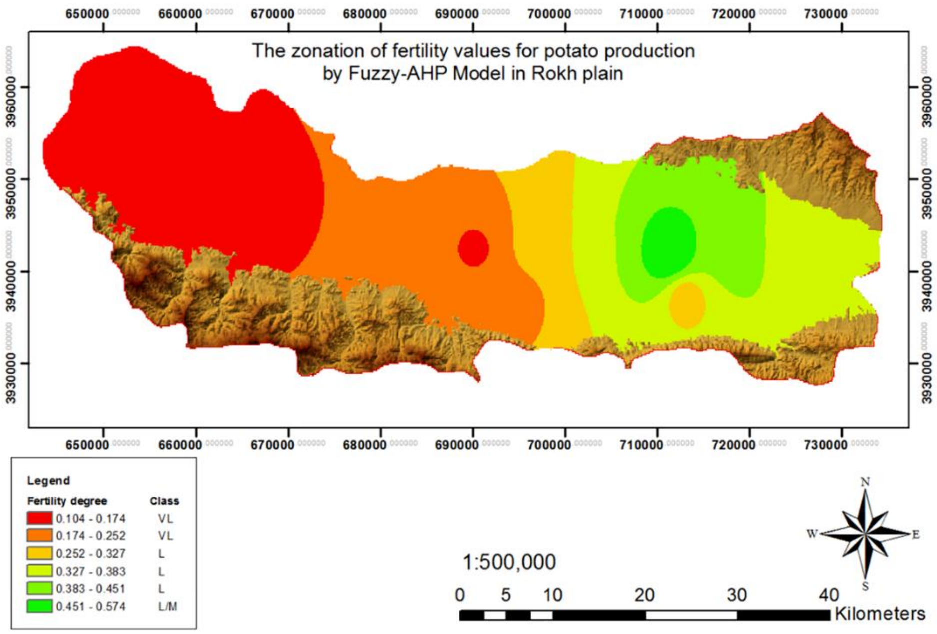


Figure 6. The zonation of soil fertility values for Potato production by Fuzzy-AHP approach in Rokh plain

Table 5. The values of soil fertility and the corresponding fertility classes

Fertility Value	Fertility Class
0.00 – 0.25	Very Low (VL)
0.25 – 0.50	Low (L)
0.50 – 0.75	Moderate (M)
0.75 – 0.90	High (H)
0.90 – 1.00	Very High (VH)

Discussion

To determine the soil fertility index and preparing a soil fertility zonation map for potato cultivation in Rokh plain, northeast of Iran, we applied an integrated Fuzzy and AHP approach. On this basis the most important soil chemical parameters and nutrient elements in 0-30 cm depth of the soil were analyzed and mapped. For fuzzifying each soil fertility parameter, a S-shaped fuzzy membership function was defined. The soil fertility map was prepared by weighing factor layers by the AHP approach and summation them by IDW interpolation function in ArcGIS. The values of the soil fertility index in the scale of 0 to 1 ranged from 0.104 to 0.574, which classified the study area in very low (922.90 km^2), low (566.10 km^2) and moderate fertility (14.86 km^2) classes which comprises 61.37%, 37.64% and 0.99% of the surface area, respectively. The spatial distribution of classes shows two areas in northwest and southeast as very low fertility zones, while great parts in north to east and some areas in west was demonstrated as low fertility zones for potato production. The poor values of soil fertility in the study area contributed mainly to very low amounts of soil organic carbon and mineral nitrogen which reduces potato yield to 35 t.ha^{-1} in the study area. Hence, to provide a desirable production of beet the consumption of nitrogen fertilizers as well as organic manures is inevitable. The results of the proposed model agreed with current conditions of potato production in the study area. The zonation of soil fertility for Potato production by integrating Fuzzy and AHP approach in the study area could be helpful in the potato production management decisions. It is proposed that exact fertilization program have to be done according to the specific crop needs, soil and water conditions and the farmers experiences. Our results revealed that the disaggregation of soil fertility variables allows direct evaluation of the contribution that individual components of soil fertility can make to potato yield. Worldwide, many studies have considered the impacts of environmental hazards such as climate change on future agricultural land use through scenario modelling and their consequent policy impacts (e.g. Ewert et al., 2005), but there is limited literature on the impacts of soil fertility rate on the crop production, a key factor influencing a region's ability to adapt agricultural practices to real conditions. But such analyses can play a critical role in formulating future land policies given the multi-functional role of agriculture and its importance for ecosystem services (Winter, 2009). The present study emphasized the importance of developing regional agricultural policy approaches that allow the transfer of indigenous knowledge to farmers, where they do not carry out routine soil nutrients analyses for potato production.

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