Case Study

The use of fuzzy- AHP methods to assess fertility classes for wheat and its relationship with soil salinity: east of Shiraz, Iran: A case study

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Abstract

Fuzzy membership function is an effective tool to reveal the relationship between soil and environment to predict soil fertility mapping. This research was conducted to evaluate the capability of a combined Fuzzy- AHP method for soil fertility evaluation of wheat in the east of Shiraz, Fars Province, Iran. A set of membership functions was conducted to reveal the soil fertility classes, which were derived from 64 field samples collected through a purposive sampling approach. Seven soil parameters [soil texture, potential of hydrogen (pH), cation exchange capacity (CEC), nitrogen (N), phosphorus (P), potassium (K) and organic content (OC) of the soil] were chosen for the soil fertility analysis and thematic maps were developed for each of these parameters with kriging method. Different fuzzy membership functions obtained from the literature were employed. Finally, in order to finalize soil fertility map and weight of the layers, AHP method was used. With the fuzzy approach, it is possible to find lowly fertility areas for wheat with values between 0.25 and 0.5. The results of the Fuzzy-AHP method in this study showed that 15% of the lands had highly fertility, 23% medium fertility, 45% low fertility and 16% very low fertility. In the study area, in regions with less fertility, CEC was a major factor. The comparison of soil yield and CEC on 20 points of the study area showed that soil salinity had a high correlation (R²=0.82) with wheat yield. Also, significant relationship was observed between soil salinity and fertility. Generally, in Fars Province, saline areas had low fertility compared to non saline areas.

Keywords: Fuzzy-AHP method, kriging method, salinity, soil fertility, wheat yield.


Introduction

Fuzzy set theory has been used in soil science for soil classification and fuzzy soil geostatistics, soil quality indices (Burrough, 1989; Zhu et al., 1996; McBratney and Odeh, 1997; McBratney et al., 2003; Zhang et al., 2004; Lagacherie, 2005). The development of fuzzy logic-based digital soil mapping techniques is due to its ability to represent the continuous nature of soil spatial variation (Zhu, 1997; Zhu et al., 2001; Yang et al., 2007). Fuzzy set theory has been widely used in soil science for soil fertility classification, mapping and land evaluation (McBratney et al., 2003; Zhang et al., 2004; Lagacherie, 2005; Sanchez Moreno, 2007). In fuzzy logic approaches, soil spatial parameters are expressed as spatial parameters of membership in soil classes (McBratney et al., 2000), which is then used to produce conventional soil class maps and to forecast spatial parameters of specific soil properties (Zhu et al., 1996). Lagacherie (2005) proposed a procedure based on fuzzy pattern matching to translate soil class description in soil database into a set of membership functions. Qi et al. (2006) developed a prototype-based fuzzy soil mapping approach to represent soil-environment knowledge as fuzzy membership functions. Qi et al. (2008) developed a data mining method using the Expectation Maximization (EM) algorithm to define membership functions based on the information extracted from conventional soil class maps. Liu and Zhu (2009) developed a mapping with words approach based on computational theory of perceptions to define membership functions. Membership functions in soil fertility classes were established based on FAO and expert knowledge (Sanchez Moreno, 2007). The topic principal in this knowledge-based method to the fuzzy membership function definition is the determination of class limits and membership gradation within these class limits (Zhu et al., 2010). Lagacherie (2005) suggest fuzzy pattern matching to soil class description in soil database into a set of membership functions. In 2007, it became clear that the fuzzy AHP method in the land suitability is one of the best methods (Sanchez Moreno, 2007; Mokarram et al., 2010). Nevertheless in this method, a lot of factors such as primary slope, secondary slope, micro-relief, wetness, salinity (EC), alkalinity (ESP), soil texture, fertility slope, soil depth, CaCO3, pH (H2O) and gypsum should be assessed and measured (Sys et al. 1993). In 2006, soil mapping was developed with a fuzzy approach which were also constructed based on the knowledge obtained from soil experts (Qi et al, 2006). In order to predict soil map, Liu and Zhu (2009) and Zhu et al., (2010) used membership functions under fuzzy logic. Dobermann and Oberthür (1997) used fuzzy method for mapping of soil fertility. The method has been successful in mapping spatial variation of discrete soil classes. However, to be able to map spatial continuity of soils using the soacquired descriptive knowledge under fuzzy logic. This paper presents a method to construct fuzzy membership function from descriptive knowledge (Bui et al., 1999; Qi and Zhu, 2003) for predictive soil mapping. Soil
Table 1. Pairwise comparison matrix for soil fertility of wheat field.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CEC</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>OC</th>
<th>PH</th>
<th>Texture</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEC</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>0.35</td>
</tr>
<tr>
<td>N</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>0.24</td>
</tr>
<tr>
<td>P</td>
<td>0.33</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>0.16</td>
</tr>
<tr>
<td>K</td>
<td>0.25</td>
<td>0.33</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>0.11</td>
</tr>
<tr>
<td>OC</td>
<td>0.2</td>
<td>0.25</td>
<td>0.25</td>
<td>0.33</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>0.07</td>
</tr>
<tr>
<td>Texture</td>
<td>0.14</td>
<td>0.16</td>
<td>0.2</td>
<td>0.25</td>
<td>0.33</td>
<td>0.5</td>
<td>1</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Fig 1. Kriging method was used in order to prepare Raster maps for each of the parameters. a: Organic Content (OC), b: Cation-Exchange Capacity (CEC), c: potential of hydrogen (pH), d: Nitrogen (N), e: Phosphorus (P), f: Soil texture, g: Potassium (K).

Fertility degradation has become a problem for agricultural management in Fars Province, Iran. So the main purpose of the study is the use of fuzzy membership for predictive soil fertility map.

Results and Discussion

In order to make soil fertility map soil texture, soil pH, CEC (dS/m), nitrogen, phosphorus and potassium applied to the soil (ppm) and organic content of the soil (%) were used (Fig 1). Based on Fig 1, most of surface soil in the study area had medium texture (from silt to loam). Most of case study soil had CEC lower than 10 dS/m. Soil pH in the study area was medium acid (pH is between 5 to 6). Because of light texture, the soil was quite porous in the surface horizon, and had strong mineralization, consequently soil was poor in organic matter. Most of soils contained organic carbon lower than 1%. The soil in the study area was poor in nitrogen (N<0.19). Degraded soil in the study was phosphorous poor. Potential potassium of degraded soil in the study area was low. In general, most of the soil had total K₂O lower than 400 (ppm) (0.4%) (Fig 1). To evaluate of soil fertility status from Sangamer area in India pH, EC, organic matter, available Nitrogen, Phosphorus and potassium were applied by Deshmukh (2012). Neppel et al. (2004) used pH, EC, phosphorus, organic carbon, potassium, and total nitrogen for
Table 2. The area (%) for each of the classes for soil fertility.

<table>
<thead>
<tr>
<th>Class</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>25.2</td>
</tr>
<tr>
<td>Low</td>
<td>72.85</td>
</tr>
<tr>
<td>Medium</td>
<td>38.36</td>
</tr>
<tr>
<td>High</td>
<td>24.51</td>
</tr>
</tbody>
</table>

Fig 2. Fuzzy maps were used for each parameter for determining the soil fertility for wheat that assumes values in the range $[0, 1]$. a: Organic Content (OC), b: Cation-Exchange Capacity (CEC), c: potential of hydrogen (pH), d: Nitrogen (N), e: Phosphorus (P), f: Soil texture, g: Potassium (K).

assessing soil fertility in the South Fork Watershed of the Iowa River and results showed that nitrogen and potassium amount of soil had key elements in yield improvement. In total 64 surface soil samples were taken in the study area. In ArcGIS software raster maps using Kriging model were prepared (Fig 1). In the fuzzy classification the fertility was given between 0 and 1, being 1 a high fertility area and 0 a not fertility area (Equations 1 and 2). In the study area with the fuzzy approach it was possible to find low fertility areas both for wheat with membership values between 0.25 and 0.5. The fuzzy model for each of the parameters was shown in Fig 2. In the study area, deficient N and organic materials and in terms of salinity were a critical condition (Fig 2).

Next, the AHP method was applied on the fuzzy parameter maps. The pairwise comparison matrix used for preparation of the weights for each parameter in the AHP method (Table 1). As was shown in Table 1, the most important factor in soil fertility was soil salinity and the least important factor was soil texture in the study area while in Lao PDR area in China, the most important factor was soil salinity (EC) and the least important factor was available potassium (Sanchez Moreno, 2007). Soil fertility maps based on the Fuzzy-AHP were shown in Fig 3. After reclassifying the fuzzy map prepared in the four classes that consist of very low, low, medium and high (Fig 4). Area for each of the classes was shown in Table 2. The results of the Fuzzy-AHP method showed that 15% of the lands had highly fertility, 23% medium fertility, 45% low fertility and 16% very low fertility. Soil fertility in the study area was influenced by soil salinity (Sears et al., 2005; Kravchenko et al 2003). After
that. According to Equation 1 relative yield and final wheat yield (kg/m²) was calculated (Maas and Hoffman 1977).

\[
\frac{Y}{Y_m} = 100 - b \left( EC_s - a \right) \quad \text{Eq.1}
\]

Where, \( Y/Y_m \) is the relative yield (%)

\( Y_m \) is maximum yield obtained with good water

\( EC_s \) is the electrical conductivity of a saturated soil paste extract (dS/m)

\( a \) = Salinity threshold value

\( b \) = Yield loss per unit increase in salinity

Results showed that \( a \) and \( b \) parameters were 2.1 and 2.5, respectively. Wheat yield response to different degree of salinity was given in Table 3. Wheat yield was reduced with higher salinity. The reduction was high beyond EC value 4.

Fig 5 indicates that there was a high correlation between soil salinity and wheat yield. The relationship between soil salinity and wheat yield resulted the following significant (R²= 0.98) mathematical yield model. The equation could be applied to estimate wheat yield in the study area. Also the results achieved by Yadav (2005) showed that a significant relationship exists between crop yield and soil salinity (R² = 0.8). Francois et al., (1986) gained a positive relationship between crop yield and soil salinity (R² = 0.86). The result in Fig 5 showed that suitable areas for the production of wheat crops were under different degree of salinity. Therefore, it could be applied in managing salinity for the wheat crops in the study area. Wheat yield collected from the measured samples were closely related to estimated yield (R²=0. 82)(Fig 6). Generally, yield from measured 20 point varied from 3.5 to 6 ton/ha which correlate well to yield map obtained from the simulation. So measured yield in average that could be used to validate the results.

Materials and methods

Case study

The study area was located in the Fars Province in the southwest of Iran, between latitudes 29° 33’ 00” N-29° 43’ 11” N and longitudes 52° 49’ 12” E- 52° 57’ 00”E with an area 161 km² (Fig 7); elevation 1810 m above mean sea level. The dataset was extracted from a land classification study done by the Fars Soil and Water Research Institute in the year 2010 and soil pH (0 – 8.27), CEC (0.11 – 18.4) (dS/m), N (0.01- 0.19), P (2 - 30) and K applied to the soil (147 - 666) (ppm), OC (0.18 – 2.04) (%) and consists of soil texture (0 – 6) that values of soil texture were reclassified between 0 to medium texture to 6 for best texture for wheat ([Table 4], Department of Natural Resources and Watershed of Fars Province, 2009)). In the current study fuzzy-AHP procedure was used for determination of soil fertility map (Fig 8):

Fuzzy set theory

The fuzzy set theory originated by Lotfi Zadeh (1965). According to Lotfi Zadeh “The theory of fuzzy sets is, in effect, a step toward a rapprochement between the precision of classical mathematics and the pervasive imprecision of the real world - a rapprochement born of the incessant human quest for a better understanding of mental processes and cognition”. 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 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 \( \mu_A = 0 \) means that the value of \( x \) does not belong to \( A \) and \( \mu_A = 1 \) 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): (Eq. 1)

For each \( A = \{ x, \mu_A(x) \} \in X \)
Table 4. Summaries of effective parameters for land suitability of the study area.

<table>
<thead>
<tr>
<th>ROW</th>
<th>Parameter</th>
<th>STDEV</th>
<th>AVERAGE</th>
<th>MAX</th>
<th>MIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CEC(dS/m)</td>
<td>2.88</td>
<td>2.86</td>
<td>18.40</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>PH</td>
<td>1.00</td>
<td>7.60</td>
<td>8.27</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>OC (%)</td>
<td>0.38</td>
<td>1.04</td>
<td>2.04</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>N (%)</td>
<td>0.03</td>
<td>0.10</td>
<td>0.19</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>P (ppm)</td>
<td>6.57</td>
<td>13.03</td>
<td>30.00</td>
<td>2.00</td>
</tr>
<tr>
<td>6</td>
<td>K (ppm)</td>
<td>99.87</td>
<td>321.10</td>
<td>666.00</td>
<td>147.0</td>
</tr>
<tr>
<td>7</td>
<td>Soil texture*</td>
<td>1.35</td>
<td>3.68</td>
<td>6.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Fig 4. Map of the fuzzy classification. High fertility is in the north area with blue color and very low fertility located in the south area with red color.

Table 5. Reclassified probability values for soil texture (Sanchez Moreno, 2007).

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>New value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loam</td>
<td>8</td>
</tr>
<tr>
<td>Silty Loam</td>
<td>6</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>9</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>9</td>
</tr>
</tbody>
</table>

Fig 5. Relationship between EC (dS/m) and wheat yield (kg/m²) in the study area.

\[ y = -0.0004x^2 - 0.0092x + 0.6115 \]
\[ R^2 = 0.98 \]
where $X = \{x\}$ is a finite set of points and $\mu_A(x)$ 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 and McDonnell, 2000). 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. Anything below the minimum will be assigned a 0 (definitely not a member) and anything above the maximum a 1 (definitely a member). fuzzy membership function variables are divided into two fuzzy values based on categories and ranges that are shown in Equations\(1\) and \(2\). For potassium (\(K_2O\)), soil texture, soil organic matter (OC), Nitrogen (N), Phosphorus (\(P_2O_5\)) considered only two fuzzy values: For example, used two fuzzy values for organic matter: low organic matter and high organic matter that in fuzzy set, $\mu_A = 0$ is value of $x$ does not belong to $A$ and $\mu_A = 1$ is belongs completely to $A$ (Sanchez Moreno, 2007; Sys et al., 1993):

\[
\mu_A(X) = f(x) = \begin{cases} 
0 & x \leq a \\
\frac{x-a}{b-a} & a < x < b \\
1 & x \geq b 
\end{cases}
\]

\[
\mu_A(X) = f(x) = \begin{cases} 
1 & x \leq a \\
\frac{b-x}{b-a} & a < x < b \\
0 & x \geq b 
\end{cases}
\]

Fig 6. Relationship between observed yield and estimated yield (kg/m²) so that there is a direct relationship between observed yield and estimated yield.

Fig 7. Location of the study area in the Iran. (a): Iran country, (b): Fras county, (c): Watershed study and Position of the profiles in the area.
the input data and a, b are the limit values. For cation exchange capacity (CEC), and pH values, the following function was used. So that in fuzzy set, $\mu_A(x) = 1$ is value of $x$ does not belong to A and $\mu_A(x)=0$ is belongs completely to A. (Sanchez Moreno, 2007; Sys et al., 1993) : (Eq. 3)

**AHP method**

In order to prepare the soil fertility map, it was necessary to calculate the convex combination of the raster values containing the different fuzzy parameters. $A_1, \ldots, A_i$ was fuzzy subclasses of the defined universe of objects $X_i$, and $W_1, \ldots, W_i$ is non-negative weights summing up to unity. The convex combination of $A_1, \ldots, A_i$ is a fuzzy class A (Burrough, 1989), and the weights $W_1, \ldots, W_i$ were calculated using AHP and fuzzy method parameters had been calculated in ArcGIS. Analytic Hierarchy Process (AHP) was developed by Thomas Saaty in the 1980. When there are a limited number of choices, the AHP facilitates the selection of weighting criteria and admits the decision making.

**Conclusion**

Given the non-discrete characteristics of soils, fuzzy theory suits well to the analysis of soil fertility. With fuzzy representation the boundaries between suitability classes were not so strict and map units that were more or less suitable can be described properly. With fuzzy theory, the spatial entities were associated with membership grades that indicate to which extent the entities belong to a class. In this study fuzzy-AHP were used for soil fertility. Using fuzzy-AHP method was defined membership function for each parameter. In this study area, results showed that fuzzy-AHP method is useful for determining soil fertility. Using fuzzy-AHP method, fertility classes was given between 0 and 1, being 1 a hihgery fertility area and 0 a not fertility where soil fertility was low or soil salinity was high. On the other hand total and marketable wheat yields decrease with the increase of EC rates. The correlation between soil salinity and wheat yield resulted the following significances. It is well known that salinity has adverse effect on crop yield (wheat) through affecting the osmotic potential balance between soil and plant. The simulation result showed that the crop yield decreases with increasing salinity. So crop yield with different degree of salinity in relation to soil fertility can be predicted by crop yield model This results is integrated in GIS environment for further manipulations. Also using different methods such as leaching should reduce the amount of salt and also using different manure should be increased soil fertility. Finally, it was concluded that the Fuzzy-AHP method has a higher accuracy for predictive soil fertility maps and it is recommended that fuzzy-AHP method use in soil fertility modeling.

**Acknowledgements**

The authors would like to acknowledge the Fars Soil and Water Research Institute for their assistance during the study and providing dataset.

**References**


