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Towards a new framework for land suitability evaluation: Application of matter element quantifier-based on Multi-Criteria Decision Analysis

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The problem of selecting the suitable land for the cultivation of a certain agriculture crop is a long-standing and empirical issue. Although many researchers, organizations, institutes and governments have tried to provide a framework for optimal agricultural land use, however, agricultural land is used below its optimal capability. Land suitability evaluation is a prerequisite for land use planning and development. The aim in integrating Multi Criteria Decision Analysis (MCDA) with Geographical Information Systems (GIS) is to provide more flexible and more accurate decision in order to evaluate the effective factors. Furthermore, by changing the parameters, a wide range of decision strategies or scenarios can be generated. Matter-element theory, which was first put forward by the Chinese mathematician Cai Wen, has shown potential for solving incompatibility problems. The objective of this research is to take the advantage of incorporation of matter-element quantifier into GIS-based land suitability analysis by Analytic Hierarchy Process (AHP). In this study, nine land characteristics including climatic, topographic (relief and slope) and soil-related (texture, $CaCO_3$, OC, coarse fragment, pH, gypsum) factors were used in modeling land suitability for rainfed barley and economic factors have been excluded and moderate management was assumed. The results showed that the most important limiting factors for rainfed barley cultivation are topographic and climatic conditions and 84.38% (~4303 ha) of total lands was classified as N_1 class (currently not suitable), whereas remaining 15.62% (~797 ha) was classified as S_3 class (marginally suitable). The coefficient of determination (R^2) between land index and observed barley yield was 0.86 for new hybrid method. From results, it is concluded that this study is helpful in planning and decision making about lands for crop suitability.

Capsule Summary: Multi criteria Decision Analysis and Geographical Information Systems were used to evaluate land suitability for barley using soil characteristics and analysis provide better information for decision making and planning.

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INTRODUCTION

Over the last decade, land suitability problems have increasingly been conceptualized in terms of the GIS-based multi criteria evaluation procedures (Barredo et al., 2000; Mohamed et al., 2000; Bojorquez-Tapia et al., 2001; Dai et al., 2001; Malczewski, 2004; Mokarram and Aminzadeh, 2010; Keshavarzi et al., 2010; Keshavarzi et al., 2011). Land suitability analysis is a multi criteria evaluation, which aims to identify the most appropriate spatial pattern for future land uses according to specify requirements, preferences or predictors of some activity (Collins et al., 2001; Mokarram and Aminzadeh, 2010). Geographic information systems (GIS) serve the multi criteria evaluation function of suitability assessment well, providing the attribute values for each location and both the arithmetic and logical operators for combining attributes (Jiang and Eastman, 2000). Furthermore, multi criteria evaluation may be used to develop and evaluate alternative plans that may facilitate compromise among interested parties (Malczewski, 1996). In general, the GIS-based land suitability analysis assumes that a given study area is subdivided into a set of basic unit of observations such as polygons or rasters. Then, the land suitability problem involves evaluation and classification of the units according to their suitability for a particular activity.

In recent years, the methods such as analytic hierarchy process (AHP), principal component analysis, grey correlation method, fuzzy comprehensive evaluation, linear regression and artificial neural network method have been often used for soil and land evaluations (An et al., 2007; Gong et al., 2012; Victor et al., 2004; Wang et al., 2007; Yang and Wang, 2005). All methods have their own advantages and disadvantages. The principal component analysis, linear regression and grey correlation method can reduce the evaluation factors and have high veracity, but their workloads are higher. The workload of AHP is low, but it needs more expertise. In addition, many of them ignore the influence of various factors on the collectivity of land evaluation. The critical concept in extension set casts off binary restriction of "either this or that" in classical mathematical theory, which indicates the transition state in the natural world. Matter-element model has been widely used in the comprehensive evaluation of the environmental quality and product quality classification as well as agricultural resources evaluation (Xiang and Xiang, 1999; Wu et al., 2000; Gong et al., 2012), But there are few reports on soil and land evaluation using matter-element model.

To best of our knowledge, the land suitability assessment using AHP and matter-element model has not previously been used for the modeling of cultivated barley. The main objective of this study was to investigate the potential use of this new hybrid model for land suitability analysis for rainfed barely in a hilly plateau region of Iran.

MATERIAL AND METHODS

Study area description

A hilly area in the northwestern province of Qazvin (Kouhin region), Iran was selected for this study (Fig. 1). Height amplitude varies from 1300 - 1540 m above sea level with 1 to 25 percent slope. This belt covers about 5100 hectares, situated between latitudes 36° 20' and 36° 23' north and longitudes 49° 34' and 49° 38' east. The climate is semi-arid in nature. Soil temperature and moisture regimes are mesic and xeric, respectively (Newhall and Berdanier, 1996). The soils have been developed on alluvial deposits of marl and brown to grey limestone parent materials and are plateau from east to west direction. According to US Soil Taxonomy system, the soil has been classified as Entisols and Inceptisols (Soil Survey Staff, 2006) and is used for rainfed farming. During 1993-2006, the average annual rainfall and average annual temperature were recorded to be 327 mm and 11.2 °C, respectively (Iran Meteorological Organization).

Sampling design and data acquisition

As sampling is constrained by financial resources, therefore, efficient sampling strategies are desirable. In this paper, Soil-Land Inference Model (SoLIM) with respect to environmental covariates (soil and terrain attributes) was used for sampling design optimization (Yang et al., 2012). A Digital Elevation Model (DEM) with grid size of 10×10m was extracted from a paper-based topographic map using GIS platform with scale of 1:25000 and contour lines interval of 10 meter (National Cartographic Center, 2010). A total of 120 soil samples were collected from different horizons of thirty two representative soil profiles located in Kouhin region in Qazvin Province, Iran. Geographical location of sampling points was recorded by Global Positioning System (GPS). The soil samples were air dried, crushed and sieved using 2 mm sieve size and subjected to laboratory analysis using standard methods (Sparks et al., 1996).

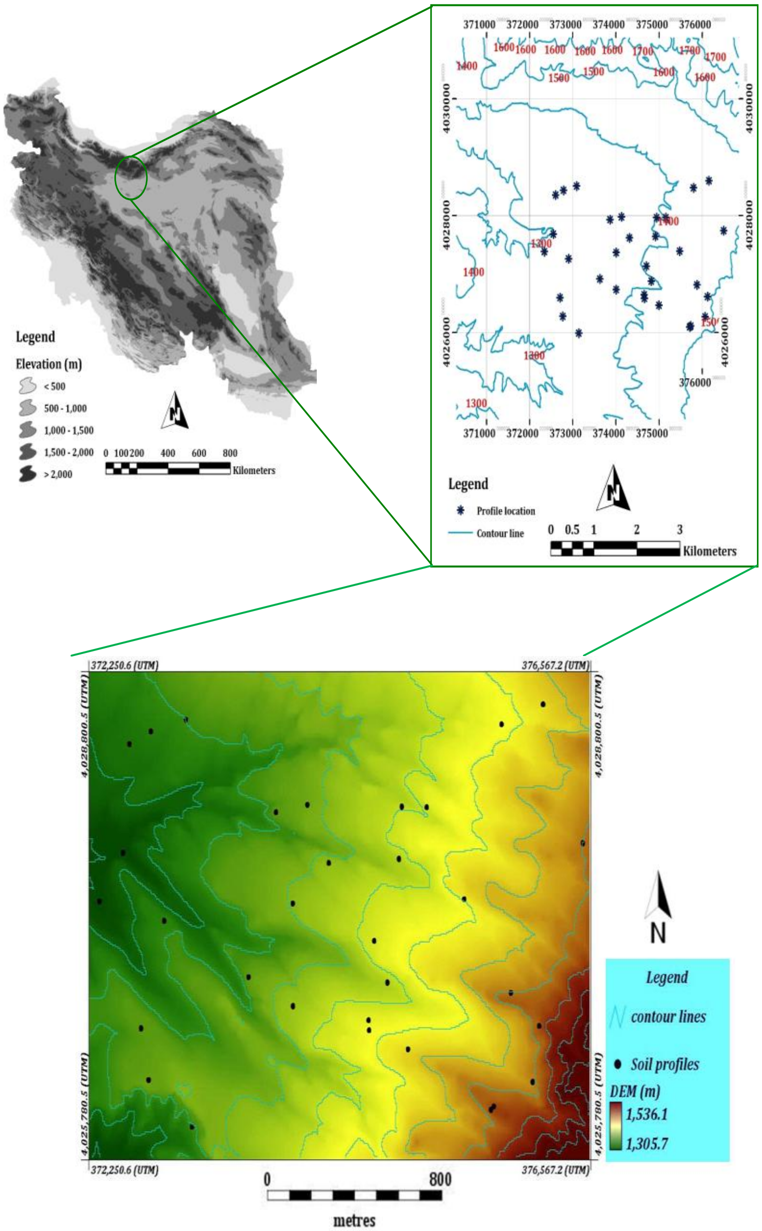

Fig. 1: Location of study area, representative soil profiles and Digital Elevation Model (DEM)

Table 1: Modified land suitability indices and classes based on matter-element model

Land index interval	Land suitability class
85~100	S_1
60~85	S_2
40~60	S_3
25~40	N_1
0~25	N_2

Land allocation and crop requirements

A requirement table for rainfed barley is established using the structure of the FAO framework for land evaluation. Both previously established requirement tables (Sys and Debaveye, 1991) and conditions proper to Kouhin area were considered. Moreover, based on the matter-element model, the land suitability indices and land suitability classes are modified as following table (Table 1).

Land suitability evaluation based on matter element quantifier

The basis of the present methodology lies in the traditional qualitative land evaluation, and land qualities/ characteristics are matched with each specific crop requirements in order to find the suitable class of land for the same crop (FAO, 1976). The methodology comprises two key steps: Step 1 is to identify land units with a similar topography and soil conditions, Step 2 is to match the properties of the land units with crop requirements including the traditional matching process, as described in the FAO qualitative land evaluation system (FAO, 1976, 1983, 1985) used to compare land qualities/ characteristics of topography, erosion hazard, wetness, soil physical properties, soil fertility and chemical properties, soil salinity and alkalinity with each specific crop requirements developed by Sys et al. (1991). The physical land suitability evaluation consists of a model that assigns a score to every land quality and characteristic. Land quality is a complex attribute of land, which in a distinct manner influences its suitability for a specific kind of use, while land characteristics are any measurable features of land that can be used to characterize a land unit.

Matter-element theory was first introduced for solving incompatible problems in the 1980s by the Chinese mathematician Cai Wen (Cai, 1994; Cai et al., 2000). Since then matter-element theory has been applied not only to mathematics but also system theory, noetic science, and other disciplines. New methods of system matter-element analysis were created and adapted to suit its applications in system theory. Systems were considered as a set of matter-elements, with each element consisting of objects, characteristics and values which participate in a range of processes and transformations (Jiang et al., 2000; Tang et al., 2008). Following this idea, matter-element analysis now includes the following basic steps: firstly, the

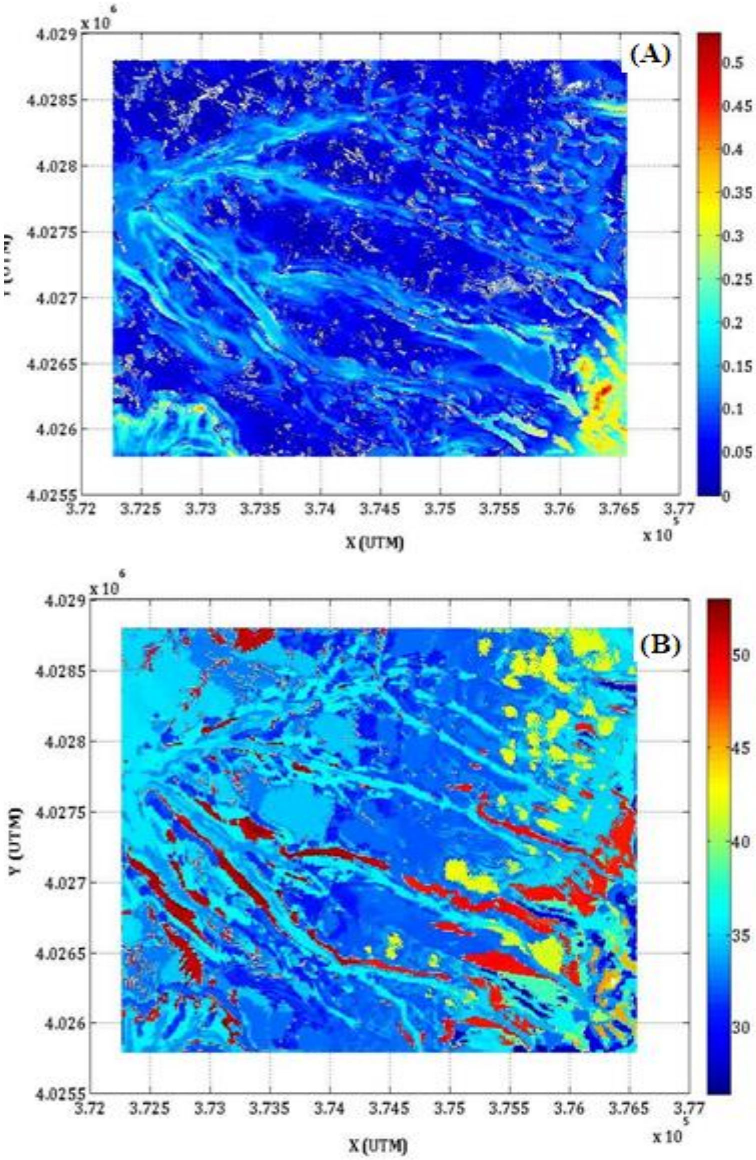

Fig. 2: Uncertainty map (A) and variation of land suitability index (B) in Kouhin region

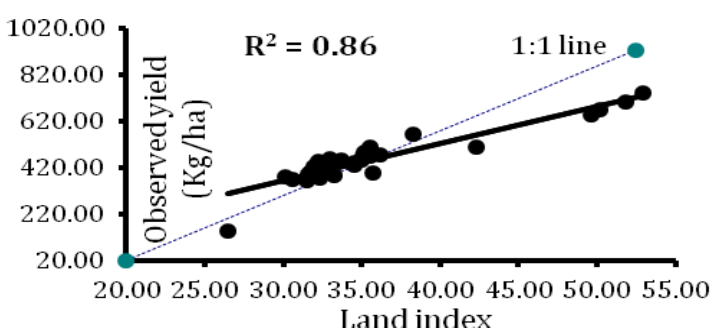

Fig. 3: Linear regression between land suitability index and observed barley yield (Kg.ha^{-1})

system is divided into matter elements (objects). Analysis or evaluation factors are then selected and classes are defined. Class intervals for each factor are then also defined. For each class the range of values is called the classical domain, while the whole range of values for all classes is called the segmented domain. Thirdly, the correlation degree for each single factor (in other words how well each factor matches the criteria for the category) is calculated. Finally, the integrated correlation degree of matter-elements for each class is calculated through model integration methods such as the AHP method. The class defines the average grade of the matter-element falls within. In this study, MATLAB 8.2 (The MathWorks, Inc.) software was used for calculating of AHP weights and for modeling of matter-element analysis. For more details about AHP and performance of matter-element analysis, one can refer to Gong et al. (2012).

RESULTS AND DISCUSSION

Land characteristics and soil mapping units

Based on SoLIM approach, the study area was divided into thirteen soil mapping units (with thirty two representative soil profiles) and nine land characteristics including climatic, topographic (relief and slope) and soil-related parameters (texture, $CaCO_3$, OC, coarse fragment, pH, gypsum) were considered to be relevant to rainfed barley. Similarly, Van Ranst et al. (1996) and Sanchez (2007) used seven and eight land characteristics, respectively. Only one low parameter is enough to reduce the suitability from high to moderately suitable or not suitable, even if the relevance of this parameter is low compared to the others. The selection of land characteristics and their limits are a sensitive issue when performing the evaluation. Elevation alone did not affect land suitability, because this factor affected on climatic, soil and agronomic management variables (Ghaffari et al., 2000). The crop requirements in terms of soil and land characteristics are depicted in Table 2. In present study, economic factors have been excluded and moderate management has been assumed. Soils classification in the study area is presented in Table 3. As it is highlighted in Table 3, 7.69% of soil is classified as Entisols order, whereas the remaining 92.31% is classified as Inceptisols order. Kamkar et al. (2014) studied a GIS-based plan to assess the possibility and performance of a canola- soybean rotation in Golestan province, one of the most important agricultural productions in the regions of Iran. They used precipitation, temperature, aspect, slope, texture,

Table 2: Soil and land characteristics for rainfed barley in Kouhin region

Profile No.	Soil and land characteristics								
	Texture (class)*	**$CaCO_3$ (%)**	**OC (%)**	**Slope (%)**	**pH**	**Gypsum (%)**	**Coarse fragment (%)**	**Relief (code)**	**Climate (index)**
1	C.L	12.43	0.87	11.18	7.85	0.00	0.00	3	41
2	C	19.00	0.90	3.95	7.98	1.58	0.00	3	41
3	C	12.79	0.85	5.00	7.95	0.00	0.00	0 to 1	41
4	C	17.77	0.78	5.30	7.68	0.00	0.42	0 to1	41
5	S.C.L	22.82	0.83	10.00	8.04	0.00	14.50	0 to 1	41
6	S.C.L	16.13	0.74	15.21	8.03	0.00	16.32	0 to 1	41
7	C	12.86	0.82	9.01	7.95	0.00	7.00	0 to 1	41
8	S.C.L	12.67	0.59	23.25	7.87	0.00	33.00	2	41
9	C	14.17	0.78	5.00	7.86	0.00	0.00	0 to 1	41
10	C.L	10.70	0.85	1.77	7.99	0.00	0.00	0 to 1	41
11	C	13.84	0.66	5.30	7.74	0.00	0.00	1 to 2	41
12	C	15.82	0.65	14.25	8.00	0.00	0.00	2	41
13	C	14.20	1.03	5.00	7.70	0.00	1.63	1	41
14	C	13.22	0.89	11.18	7.81	0.00	6.60	0 to 1	41
15	S.C.L	11.26	0.75	14.25	8.00	0.00	15.00	1	41
16	C.L	13.34	0.75	24.04	7.90	0.00	3.00	2	41
17	C	7.14	0.98	1.77	8.06	0.00	4.00	0 to 1	41
18	C	14.23	1.02	5.30	8.16	0.00	0.00	0 to 1	41
19	C	14.80	0.85	3.95	7.97	0.00	3.30	0 to 1	41
20	C	15.38	0.93	5.59	7.97	0.00	0.00	0 to 1	41
21	C.L	16.88	0.70	11.18	7.84	0.00	0.00	2	41
22	C.L	14.88	0.80	13.81	7.95	0.00	3.75	1	41
23	C	8.77	1.04	23.25	7.92	0.00	15.00	2	41
24	C.L	15.97	1.12	3.95	7.85	0.00	6.50	2	41
25	C	15.35	0.74	11.18	7.85	0.00	10.00	0 to 1	41
26	S.C.L	14.40	0.94	8.84	8.09	0.00	27.00	0 to 1	41
27	S.C.L	14.24	0.87	9.52	7.81	0.00	8.50	3	41
28	C	15.97	0.63	22.36	8.08	0.00	2.00	2	41
29	S.C.L	19.90	0.81	10.00	7.89	0.00	16.38	2	41
30	S.C.L	19.71	0.93	5.00	8.07	0.00	5.63	1	41
31	C.L	16.48	0.49	25.00	7.65	0.00	9.96	1	41
32	C.L	17.30	0.68	7.07	7.80	0.00	4.36	0 to 1	41

*C=Clay, C.L= Clay Loam, S.C.L= Sandy Clay Loam

pH and EC layers in GIS platform. According to their results, 11.82% of total land found to be suitable to rotate soybean after canola, whereas most agricultural lands in the study area fell into the moderate and low suitable classes.

Multi-criteria decision analysis using AHP method

Analytic Hierarchy Process (AHP) was employed to obtain the different weights for the soil and land characteristics.

Table 3: soils classification in the study area (Soil Survey Staff, 2006)

Soil mapping unit	Soil classification
1	Fine-loamy, mixed, superactive, mesic Gypsic Haploxerepts
2	Fine, mixed, actice, mesic Gypsic Calcixerepts
3	Fine, mixed, active, mesic Typic Calcixerepts
4	Fine-loamy, mixed, active, mesic Typic Calcixerepts
5	Fine-loamy over fragmental, mixed, active, mesic Typic Calcixerepts
6	Clayey over loamy-skeletal, mixed, active, mesic Typic Calcixerepts
7	Loamy-skeletal, mixed, superactive, mesic Typic Calcixerepts
8	Loamy-skeletal, mixed, active, calcareous, mesic Typic Xerorthents
9	Fine, mixed, active, mesic Vertic Calcixerepts
10	Fine, mixed, superactive, mesic Typic Haploxerepts
11	Fine-loamy, mixed, superactive, mesic Typic Calcixerepts
12	Fine-loamy over sandy-skeletal, mixed, superactive, mesic Typic Calcixerepts
13	Fine-loamy, mixed, superactive, mesic Typic Calcixerepts

Table 4: The Saaty scale (2003) was used for generation of pair-wise comparison matrix

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

AHP relies on pair-wise comparison between different parameters to assign importance levels.

This process may be subjective and requires expertise knowledge and common sense. For this reason different land evaluators may assign different importance and different weights, which may result in different suitability maps. Our results showed that use of AHP method can regard all of land characteristics and more efficiency for explanation of different criteria in land suitability. In order to generate weighting factors, pair-wise comparison matrix and normalized pair-wise comparison matrix are developed. Firstly, judging matrix is built by 1~9 scale (Saaty, 2003) and supposed that comparison matrix was reverse and reciprocal that means if a criterion A in comparison with criteria B has a double priority, it could be inferred that criteria B has a priority half of criteria A. The criteria priorities are defined according to expert's judgments (Table 4).

After generation of pair-wise comparison matrix, the criteria weights were calculated that includes sum of each column of pair-wise comparison matrix and division of each component by the result of each relevant column sum. The resulted matrix is knows as normalized pair-wise comparison matrix. The average of each row of the pair-wise comparison matrix is calculated and these average values indicate relative weights of compared criteria. The result of AHP method is depicted in Table 5. Due to higher weight, relief factor was the most significant characteristic (criteria) and the soil gypsum was the least significant criteria among all effective criteria in rainfed barley cultivation.

Table 5: Weight of soil and land evaluation factors in Kouhin region based on AHP method

Criteria	Texture	$CaCO_3$	OC	Slope	pH	Gypsum	C. fragment	Relief	Climate
Weight	0.011	0.013	0.018	0.02	0.019	0.005	0.008	0.575	0.331

Performance and evaluation of AHP-matter element model

Table 6: Land suitability classes, land indices and observed yield based on the new hybrid model in Kouhin region

Profile No.	Land index (AHP-matter element model)	Suitability class	Observed yield ($Kg.ha^{-1}$)
1	52.92	S_3	738.91
2	51.81	S_3	699.50
3	32.97	N_1	456.22
4	32.24	N_1	446.27
5	31.78	N_1	400.60
6	32.44	N_1	399.53
7	33.68	N_1	452.38
8	26.42	N_1	147.49
9	35.55	N_1	470.74
10	34.50	N_1	438.65
11	33.00	N_1	422.12
12	31.60	N_1	392.18
13	30.12	N_1	380.63
14	35.53	N_1	507.41
15	31.47	N_1	362.72
16	50.16	S_3	670.19
17	35.06	N_1	470.64
18	35.14	N_1	482.58
19	32.71	N_1	430.83
20	34.55	N_1	430.27
21	30.61	N_1	370.03
22	32.33	N_1	373.95
23	33.25	N_1	385.63
24	42.34	S_3	506.71
25	34.95	N_1	452.55
26	35.68	N_1	396.39
27	49.65	S_3	644.25
28	38.24	N_1	560.65
29	36.13	N_1	473.02
30	31.76	N_1	403.36
31	31.97	N_1	426.48
32	35.41	N_1	491.24

Using the extension set concept (Cai et al., 2000), the performance of land suitability analysis with emphasis on soil and land weighting factors was carried out. The land suitability classes and land indices in Kouhin region are shown in Table 6. According to Tables 2 and 5, the most important limiting factors for rainfed barley cultivation are topographic and climatic conditions and 84.38% (~4303 ha) of total land is classified as N_1 class (currently not suitable), whereas remaining 15.62% (~797 ha) is classified as S_3 class (marginally suitable). Figures 2 (A, B) show the variation of land suitability index and uncertainty map in the study area, respectively. Emphasis should be placed on soil management techniques that conserve organic matter and enhance nutrient and water-holding capacity of the soil.

Table 6 shows the observed rainfed barley yield, land suitability classes and land indices obtained by combined AHP-matter-element model for different soil profiles in Kouhin region. The maximum and minimum observed yield was ~739 and ~148 (Kg.ha^{-1}), respectively. In order to assess the combined AHP-matter element model performance, the coefficient of determination (R^2) between land index and observed barley yield (Fig. 3) was plotted. The plot approximates a straight line and angle close to 45 degrees also indicates a high accuracy of this new hybrid method. The coefficient of determination (R^2) between land index and observed barley yield was 0.86 for combined AHP-matter element model.

There are limited published studies dealing with the use of matter-element model in soil science, especially in soil and land evaluations. Similar to this study, Gong et al. (2012) performed the land suitability evaluation using a matter-element model in Zengcheng, Guangzhou, China. They used land use, roads, water bodies, population density, distance from center of the city, geodetic height, and slope as factors in modeling land suitability for development. According to both the classification map created using the matter-element model and the statistics on the land suitability classes, the study area was found to have a considerable amount of land which is highly suitable for development. Moreover, the results demonstrated the advantage of matter-element model over fuzzy theory, as it provide much more information. Jing et al. (2013) studied the groundwater quality based on matter-element extension Model. Their investigation showed that parameters of groundwater are basically within the permissible limits and meet the requirement of drinking water standards. By comparing the evaluation results obtained from matter-element extension method, osculating value method based on entropy weight and principal component analysis method, it was proved that matter-element extension is an effective and reasonable method for groundwater quality assessment.

In comparison to this new hybrid method in land evaluation, the earlier fuzzy model has been used by many researchers in land suitability evaluation (Keshavarzi and Sarmadian, 2009; Tang et al., 1991; Van Ranst et al., 1996). Most of the researchers have been compared the results of this evaluation with other conventional methods such as maximum limitation, parametric and multiple regression methods in order to predict production yield. The weakest part of the fuzzy set methodology for land evaluation is the way in which membership functions, class centers, cross-over values and weight values are chosen (Keshavarzi and Sarmadian, 2009). The problem of how to define the parameters of the fuzzy membership functions is more complicated than the boolean equivalent because it requires not only specifications of what kind of membership function and class boundary values, but also the widths of the transition zones.

CONCLUSIONS

The optimal use of reserved land resources for agriculture is a complex problem that involves subjective assessments with multiple criteria. This paper was presented a GIS-based multi criteria land suitability evaluation using AHP with matter element quantifier approach for effectively solving this problem. The evaluation criteria showed that the coefficient of determination (R^2) between land index and observed barley yield was 0.86 for combined AHP-matter element model. Additionally, this research confirmed that climatic and topographic components proved to be useful in the identification of suitable areas for barley production, within a GIS environment. This investigation is a climatologically evaluation that provides information at a regional level that could be used by farmers to select their crop pattern. As well, decision-making regarding adequate crop patterns could be based not only on the information provided by this approach, but also on other aspects such as: production supports, marketing, technological level, and economic evaluation, in addition to local customs, which are also highly important. According to the advantages associated with the use of this new hybrid model over this research, it appears that the combined AHP-matter element model approach could be a suitable alternative to performance of land suitability scenarios and studies on this approach should continue in an effort to relate soil properties to the basic soil characteristics and its advantages should motivate soil scientists to work further on it in the future.

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