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GIS and multi-criteria decision-making analysis assessment of land suitability for rapeseed farming in calcareous soils of semi-arid regions

Yaser Ostovari[1], Afshin Honarbakhsh[2*], Hamed Sangoony[3], Farhad Zolfaghari[4], Kimia maleki[5], Ben Ingram[6]

Chair of Soil Science, TUM School of Life Sciences Weihenstephan, Technical University of Munich, Freising, Germany

Associate Professor in Watershed Engineering, Department of Rangeland and Watershed Engineering, Faculty of Natural Resources and Earth Science, Shahrekord University, Shahrekord, Iran.

Invited Lecturer at Range and Watershed Management Department, Tarbat-e-Heydarieh University, Tarbat-e-Heydarieh, Iran

Assistant professor, Higher educational complex of Saravan.

Instructor and research associate of urban physical development group. ACECR (academic center for education, culture and research), Markazi Province, Iran.

Cranfield Soil and Agrifood Institute, Cranfield University, UK

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Abstract

To reverse the negative environmental properties effect on fertile lands for agriculture, land suitability evaluation is the first step in the designing the most sustainable land use and management systems. The aim of present study was to develop and evaluate a model to determine land suitability for rapeseed farming using environmental data including topography, ecological and remote sensing data in calcareous soils of semi-arid regions northwestern Iran. For this purpose, stratified random sampling was used to select a set of 92 soil samples of agricultural land use from 0 to 30 cm depth. For land suitability assessment, the opinions of 19 local experts were used to make a decision for the weight of topography, ecological and remote sensing data factors by an analytic hierarchy process (AHP) from multi-criteria analysis. The environment factors included were climate, topography, soil and remote sensing data that are related to rapeseed production. The results indicate the highest specific weight belongs to the soil texture (0.341), calcium carbonate equivalent (0.171) and elevation (0.114). Land suitability evaluation based on the United Nations Food and Agriculture Organization classification system indicated that 0.81% (420.8 ha) of the studied area was for high suitable (S1), 42.33% (21940.2 ha) was for moderately suitable (S2) and 11.78% (6104 ha) was for marginally suitable (S3) class. The 39.72% (20586.4) and 0.95% (492.1 ha) of studied area were located as currently not-suitable and permanently not-suitable for rapeseed productions, respectively.

Key words: Environment factors, Modeling, Topography, Ecological, Remote sensing data

1. Introduction

In order to the best manage agricultural land resources, considering the environmental components and understanding the main limitations of local biophysical conditions could help to select certain crops to farm (Kazemi et al., 2016; Mendas & Delali, 2012). Land suitability evaluation is a key approach to promoting the sustainable development of agriculture and conducting scientific land use planning (Baroudy, 2016; Falasca et al., 2012). Land suitability varies for an especial crop in each part of a field because of their soil properties, topo-position, and land use. It is necessary to classify and manage land units according to the most effective environmental factors (FAO, 1990). Land resources in Iran, on the other hand, have been degraded gradually by human activity since the industrial revolution. Therefore, it is necessary that attention be focused on predicting the potential and limitation of the land for sustainable crop production especially on semi-arid calcareous soils conditions.

A critical step in land use planning is land suitable evaluation (FAO, 1993). For increasing land productivity, land suitable evaluation enables decision makers to create the best crop management system. Some qualitative methods such as a framework for land use planning developed by FAO (1976) based on two methods developed in Iran and Brazil are still widely used (Recatal & Zinck, 2008; Fontes et al., 2009). The large number of the effective environmental factors makes land use suitability evaluation increasingly complex for managing the long-term sustainable use without land degradation (Bandyopadhyay et al., 2009; Akinci et al., 2013). Hence, agro-ecological innovations are necessary to develop, determine and manage a specific use on land according to agro-ecological potentialities and limitations to be ensure the food supply, without deterioration (Uphoff, 2002). In recent decades, numerous studies have used multi-criteria analysis to develop and predict land evaluation models. The analytical hierarchy process (AHP) method developed by Thomas Saaty (1980) was used in the Gonbad-Kavous region, north of Iran (Kazemi et al., 2016), in the Maharashtra, India (Zolekar & Bhagat 2015) and in the Yusufeli district, Turkey (Akinci et al., 2013) for selecting the best use of a land unit.

Remotely sensed data and geographic information systems (GIS) as reported by several recent studies results have a great potential to improve land suitability evaluation (Baroudy 2016; Zolekar & Bhagat 2015). Mirzaee et al., (2016, 2017) showed that auxiliary data including remote sensing data are potential variables to improve the prediction of difficult-to-measure soil properties.

In Iran, the main field crops are wheat, barley and rapeseed during the winter season and corn, soybean and cotton during the summer season. Wheat occupies approximately 6, corn 0.3, barley 0.64, soybean 0.1, cotton 0.09 and rapeseed 0.2 million ha (FAO, 2005). Rapeseed (*Brassica napus L.*) is the most important crop in Iran due to increasing in demand for oil production. Rapeseed oil is the second largest oil source around the world (Rosillo-Calle et al., 2006). Rapeseed, which is low in both glucosinolates (<30 mmol g^{-1}) and erucic acid (<2%) in the oil (Boyles et al., 2012), contains both high oil (40-45%) and protein content (about 40%) (Grassano et al., 2011). Rapeseed has also become a valuable rotational crop in a region with continuous cereal or cereal-fallow based cropping systems (Boyles et al., 2012) as well as a creating alternative weed management strategies. Therefore, rapeseed could be a good alternative crop for the region. In addition, a field study to investigate land suitability evaluation for rapeseed production under calcareous conditions are still lacking and need to be quantified. Calcareous soils are known for high pH (pH>7.5) and calcium saturation which can affect the soil quality (Ostovari et al., 2016). The objectives of this study were i) to evaluate the land suitability of studied area for winter rapeseed crop; ii) to drive and evaluate AHP and ANN-based model that allows selecting the most suitable land units for winter rapeseed production in the calcareous soils of northwest Iran, a region dominated by cereal-fallow cropping systems.

2. Material and methods

2.1. Study Area

The general landscape of the study region is shown in the northeast part of East Azerbaijan province, Iran. The study site with an area of approximately 51831 ha is located between latitudes 39° 0.55′-39° 16.4′ N and longitudes 47° 15.3′-47° 32.8′ E (Fig. 1). Wheat and barley are the main land uses in this area. In recent years, rapeseed production has undergone a rapid increase in this region.

The parent material is easily visible on the surface where the terrain is rough. Also, accumulation of the materials has been transported through streams results in the formation of the alluvial soils. According to the American soil classification Entisols, Inceptisols and Mollisols (USDA, 2010) are widely distributed in this area. This region has parent materials of limestones and Quaternary deposits which are enriched by carbonates (Mirzaee et al, 2018).

Insert Fig 1

2.2. Climate factors

The region is characterized by a semi-arid climate and has an annual average temperature and precipitation of 14.2 °C and 383.5 mm, respectively. The distribution of average monthly temperature and precipitation presented in Fig. 2 in the period 2005-2018.

Insert Fig 2

2.3. Topography factors

The digital elevation model (DEM) (with 30 × 30 m resolution) of the studied area was gotten from the agricultural research center of East Azerbaijan province. Other territorial factors including elevation, slope and aspect were derived from the DEM. Elevation from sea level varies between 239 and 1194 m (Fig. 1). With changing elevation factor, all of the environmental factor including radiation, precipitation and temperature will change. Elevation factor has a great effect on the distribution and growth of a certain crops. In 1.8, 11.8, 27.4, 18.1 and 40.9% of the study area, the slope is 0-2, 2-6, 6-12, 12-16 and >16%, respectively (Fig. 3). Slope degree is the most effective factor for determining type of agricultural practices and irrigation, drainage and erosion status. Generally, a land more suitable for farming has low slope (Fu et al., 2011). In this area, dominated aspects are north and east 38.5 and 18.1%, respectively (Fig. 3). This parameter plays an important role on the farming practices and crop yield by influencing soil temperature and soil water content (Niezen et al., 1998).

Insert Fig 3

2.4. Remote sensing data

A Landsat 8 satellite image on July 2017 was acquired from the NASA server, that was used to generate remote sensing data. Global positioning system (GPS) points were used to correct spatial distortion of the Landsat 8 image data. After that, the noise of the image pixels by the effect of micro-topography and film processing is decreased using a low-pass filter in ILWIS 3.7 (Unit Geo Software Development, 2001). The NDVI (Normalized difference vegetation index) was calculated to estimate vegetation cover (Eastman & Fulk, 1993) (Eq. 1).

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}$$

Where NIR is the near-infrared reflectance band and Red is the Red band. The NDVI negative values show lakes and rivers, a the NDVI zero value present no vegetation, 0.2–0.3 indicates bare soils and close to +1 present the green leaves on landscape. The NDVI map is presented in Fig. 4.

Land use data and map were interpreted from Landsat 8 image on July 2017 by supervised classification technique i.e. Bayesian Maximum likelihood. The land use data were corrected further by Google Earth. Six dominant land use classes are agriculture (12040 ha), water body (102 ha), range lands (16313 ha), rain-fed land (20645 ha), rocky land (2542 ha) and forest (189 ha) (Fig. 4).

Insert Fig 4

2.4. Soil Sampling and Analysis

92 soil samples were taken using a stratified random sampling method at depth of 0-30 cm (Fig. 1). The soil samples were air-dried and the particles less than 2 mm were used for soil analyses. The soil pH and Electrical conductivity (EC) was measured in extracted saturated soil. The optimum pH value is between 6.5 and 7.0 (Thompson & Troeh, 1973). Sand (0.05 –2 mm), silt (0.05 - 0.002 mm) and clay (< 0.002 mm) content was measured using hydrometer method (Gee & Bauder, 1986). The most soil properties including salinity, pH, nutrients, organic carbon, soil structure and microbial biomass are varying with soil texture (Mustafa et al., 2011; Bhagat, 2014). The calcium carbonate equivalent (CCE) contents was determined using back-titration methods (Nelson & Sommers, 1986). Thematic maps of soil properties were provided by Inverse Distance Weighting (IDW) interpolation method and ordinary kriging in ArcGIS v, 10.3. In this method, the weight factor is calculated as following:

$$\lambda_i = \frac{D_i^{-\alpha}}{\sum_{i=1}^{n} D_i^{-\alpha}} \tag{2}$$

Where λ_i, D_i, α and i are the weight of point, the distance between point, the power ten of weight and the unknown point, respectively (Ngetich et al., 2014). In ordinary kriging method the experimental semivariogram (Eq. 3) is (Webster & Oliver, 2001):

$$\Upsilon(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \tag{3}$$

Where $Z(x_i)$ is measured soil properties at location of x_i, $\Upsilon(h)$ represent the variogram for a lag distance h between $Z(x_i)$ and $Z(x_i + h)$, and $N(h)$ is the number of data pairs. The general equation of ordinary kriging (Eq. 4) method is (Webster & Oliver, 2001):

$$\hat{Z}(x_i) = \sum_{i=1}^{N} \lambda_i Z(x_i) \tag{4}$$

Where λ_i, $\hat{Z}(x_i)$ and $Z(x_i)$ are the weight of point, predicted and measured soil properties, respectively.

2.3. Land suitability assessment

The environmental and ecological requirements of rapeseed were used to evaluate the land suitability in the studied area. Schematic diagram of the land suitability evaluation is presented in Fig 5. At first, the environmental and ecological requirements for rapeseed crop growth were identified from scientific resources (Table 1). After that, 19 local expert's opinions were collected about rapeseed production at studied area and then classified. The United Nations Food and Agriculture Organization (FAO) classification system was used for classifying land suitability at studied area i.e. highly suitable (S1), moderately suitable (S2), marginally suitable (S3), currently not-suitable (N1) and permanently not-suitable (N2) according to requirements of the rapeseed crop (Table 2).

Analytical Hierarchy Process (AHP) is the best method where factors are arranged in a hierarchy structure. Some factors i.e. climate, topography, remote sensing data and soil factors were selected and used in order to identify the most suitable area for rapeseed production (Fig. 5). The factors were ranked based on the fundamental scale suggested by Saaty (2000) with values 1–9 (Table 2). The 19 local expert opinions were used to determine the weight of factors for land suitability evaluation, by a pairwise comparisons statistical analysis in Expert Choice 2001 software. Weights were within the range of 0–1 (Malczewski, 1999). The weights of factors were determined by expert opinions and the allocation of AHP weights for any factors and by weighted overlay (WO) method in ArcGIS 10.0. The WO method is useful to solve multi-criteria decision-making analysis spatial problems in land suitability (Girvan et al., 2003). Therefore, a land suitability map for rapeseed production was extracted by WO method based on multi-criteria decision-making analysis and AHP. The land suitability map in ArcGIS was calculated as:

$$S = \sum_{i=1}^{n} Wi\,Xi \qquad (5)$$

where S = total land suitability score including S1, S2, S3, N1 and N2, Wi is the weight factors, Xi is the sub-factor score of i factors and n is the total number of factors to assessment of land suitability.

Insert Table 1

Insert Table 2

Insert Fig 5

2.5. Performance Criteria

In this study, the cross-validation method was used for validating geostatistical methods. The accuracy of predictions was investigated by R^2 (coefficient of determination) (Eq. 6) and the RMSE (root mean square error) (Eq. 7).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Y_i - \widehat{Y}_i)^2}{\sum_{i=1}^{N}(Y_i^2) - \frac{(\sum_{i=1}^{N} Y_i)^2}{N}} \tag{6}$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}\left(\widehat{Y}_i - Y_i\right)^2}{N}\right]^{0.5} \tag{7}$$

where N is the number of data, Y_i and $\widehat{Y}_i$ are measured and predicted values of soil properties.

3. Results and discussion

3.1. The characteristics and mapping of soil properties

The descriptive statistics for soil properties are presented in Table 3. Some soil properties showed a slight positive (Clay, sand, CCE and EC parameters) and negative (pH parameter) skewness in the data. However, according to Kolmogorov-Smirnov (K-S) test, all of soil parameters were normally distributed at the 5% level of significance. In addition, a CV (Coefficient of variation) categorized by Wilding (1985) (high variability: CV > 35%, moderate variability: 15 < CV < 35% and low variability: CV < 15%), Clay, EC and CCE parameters indicated high variability (Table 3). The silt and sand showed moderate variability and pH parameter showed low variability in studied area. Therefore, soil properties have a broad range of values in the studied soils that can be an important characteristic to note for land suitability for rapeseed productions.

Insert Table 3

According to the results in Table 4, ordinary-kriging model with larger R^2 and lower RMSE values performed better than IDW method to map the CCE and pH. Based on the result of the models in Table 4, the IDW method is the best for the interpolation of EC parameter. One of the advantages of ordinary kriging is by far the most common type of kriging, which uses weighted averages to estimate un-sampled locations as a linear combination of neighboring observations (Webster & Oliver, 2001; Mirzaee et al., 2016). The map of soil properties provided by the best interpolation method are presented in Fig 6.

Insert Table 4

Insert Fig 6

3.2. Land suitability assessment

Based on the expert's pairwise comparisons, the weights of factors that include climate, topography, soil and remote sensing data are presented in Table 5. The results showed the best factor for assessment of land suitability was soil texture which had the highest specific weighting (0.341). After this, it belongs to CCE (0.171) and elevation (0.114), respectively. As can be seen from Table 5, soil texture, CCE and elevation play an important role in the determining of suitable areas for rapeseed productions. In this way, some studies have been shown that the AHP method is the best method to determine the weighting of several factors (Lai et al. 2002; Zhang et al. 2015; Kazemi et al. 2016). The weighting of factors in Table 5 are comparable to those reported by Kazemi et al. (2016) that presented for faba bean productions the soil properties were the effective factors for deriving a good land evaluation model. Basically, soil texture or the bed of rapeseed growth plays a significant role in attaining high yields.

Insert Table 5

Suitable area for rapeseed production were identified according to important climate, soil, topography and remote sensing data factors, and an optimum land suitability map was generated using overlaying of 10 raster layers. A final map of land suitability for rapeseed production in studied area is presented in Fig. 7. The highly suitable land units (S1) are located at the east and northeast part of studied area (Fig. 7). The highly suitable land, 420.8 ha, is characterized by: soil texture loam, clay loam, sandy clay and clay, EC 0-4 dS/m, pH 6.5 -7, CCE 0-15, elevation <400 m, slope <2% and etc. (Table 1). Moderately suitable (S2) land described by: soil texture sandy loam and sandy clay loam, EC 4-8 dS/m, pH 6-6.5 and 7-7.5, CCE 15-30 and others in Table 1. The land area in this class is 21940.2 ha (Table 6) and is located mostly in north and east parts of the studied area (Fig. 7). The final map of land suitability (Fig. 7) showed that about 11.8% of study area (6104 ha) are situated in marginally suitable class for rapeseed production (Table 6). These classes are in the south and southwest of the studied area (Fig. 7). A summary of these land suitability classes is presented in Table 1.

The results of land suitability analysis showed that the large parts of the studied area were classified as currently not-suitable 39.72% (20586.4 ha) and permanently not-suitable 0.95 (492.1 ha) (Table 6). The results in final map (Fig. 7) showed these classes mostly are located in the central and southern parts of studied area. In general, after soil parameters, topography factors (Elevation and slope with weighting 0.114 and 0.057, respectively) are the most important in the studied area. Elevation influences can be related to the cooler temperatures and consequent reduction in soil microbiological activity at elevations, the land suitability degree decreased with increasing elevation. In the study area, increasing elevation increases the possibility of frost occurrence. A frost occurrence in the range of sowing and rosette stages of plant growth months can be very harmful to rapeseed and cause yield losses (Boyles at al. 2012). In addition, there is snow cover during March at higher elevation (about >1000 m) that can be a main restrictive factor for rapeseed production.

The difference between the result of this study and other studies about land suitability assessment might be due to the unique influence of calcareous materials on soils (Ostovari et al. 2016). The high calcium saturation tends to keep the calcareous soils in well-aggregated form. However, the high calcium saturation creates high nutritional problems in studied area. In calcareous soil, carbonate hydrolysis controls soil pH and produce a soil pH as high as 7 (Foth 1990). The analysis of pH map showed the soil pH factor is as high as 7.0 for 98.1% of the studied area. This suggests that land suitability models need to be calibrated for the variable field conditions that exist in different areas.

Insert Table 6

Insert Fig 6

4. Conclusion

In the present study, the application of GIS and multi-criteria decision-making analysis in assessment of land suitability for rapeseed farming using environmental data is investigated in calcareous soils of semi-arid regions northwestern Iran. Land suitability evaluation is a first step to obtain optimum use of environmental data and other resources for the most sustainable rapeseed production at studied area. Based on experts' opinions, the highest specific weight belongs to soil texture (0.341), CCE (0.171) and elevation (0.114). Land suitability analysis indicated that 0.81% (420.8 ha) of the studied area was of high suitable class for rapeseed production, 42.33% (21940.2 ha) were moderately suitable class, and 11.78% of the study area (6104 ha) were located in marginally suitable class. The 39.72% (20586.4) and 0.95% (492.1 ha) of studied area were classified as currently not-suitable and permanently not-suitable for rapeseed productions, respectively. The results could be useful for future decisions in northwestern Iran. Future work could concentrate on quantifying at other crops on calcareous soils.

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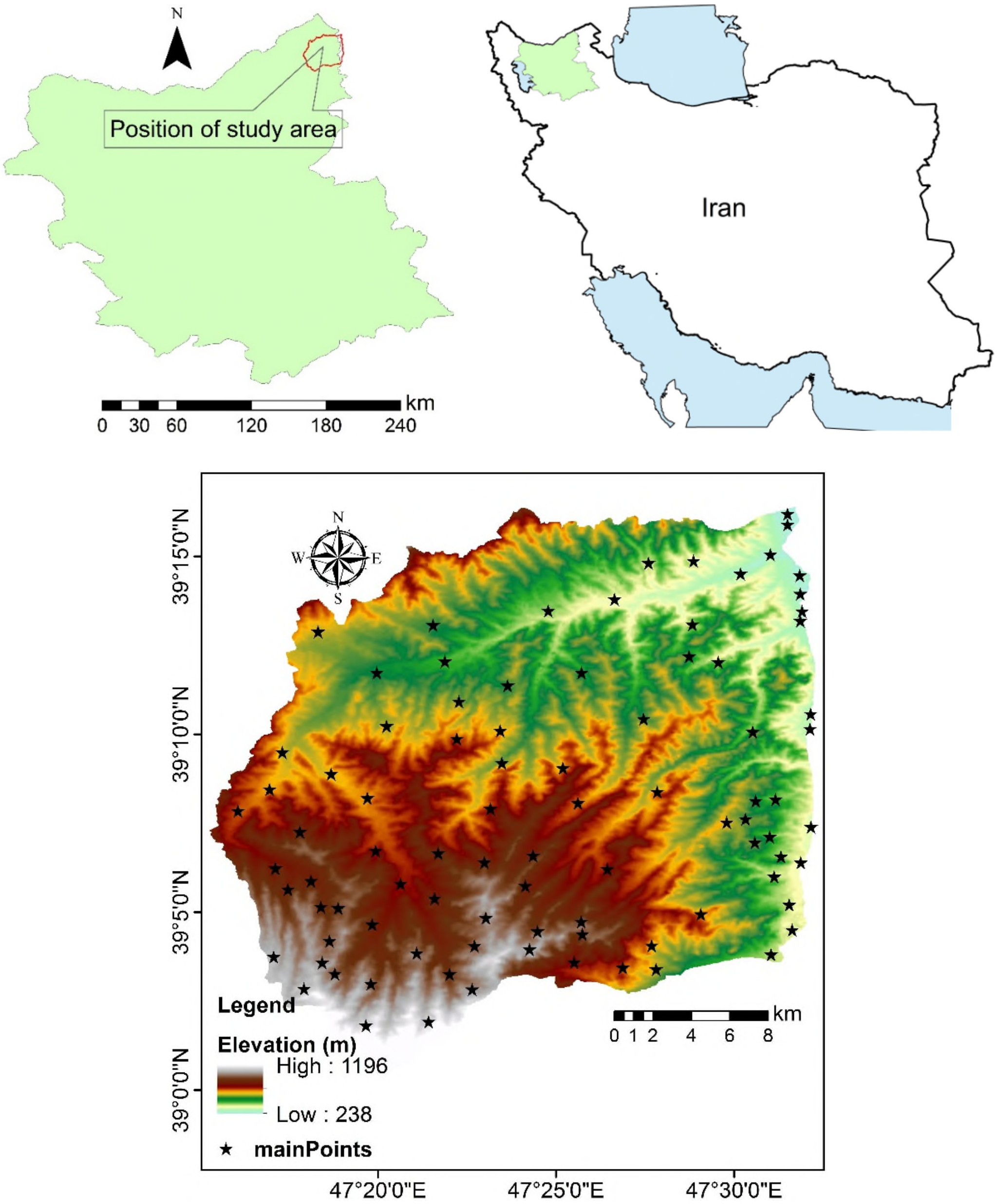

Fig 1. Location of study area northwest Iran and distribution of studied points.

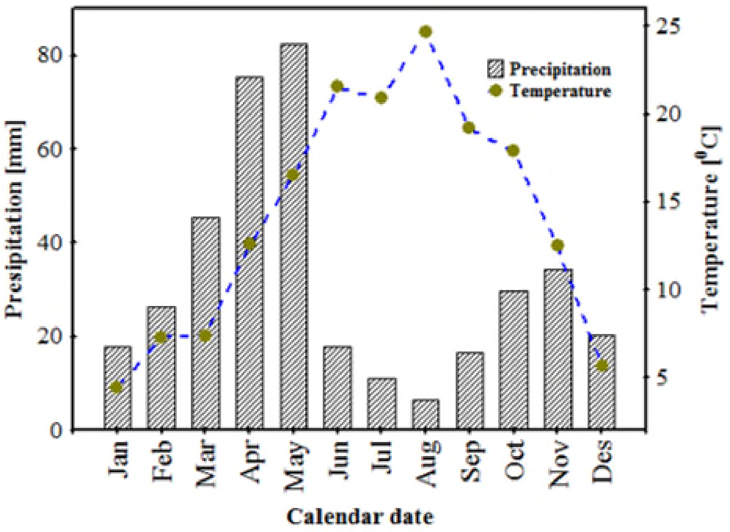

Fig 2. Average monthly precipitation and temperature (from 2005 to 2018)

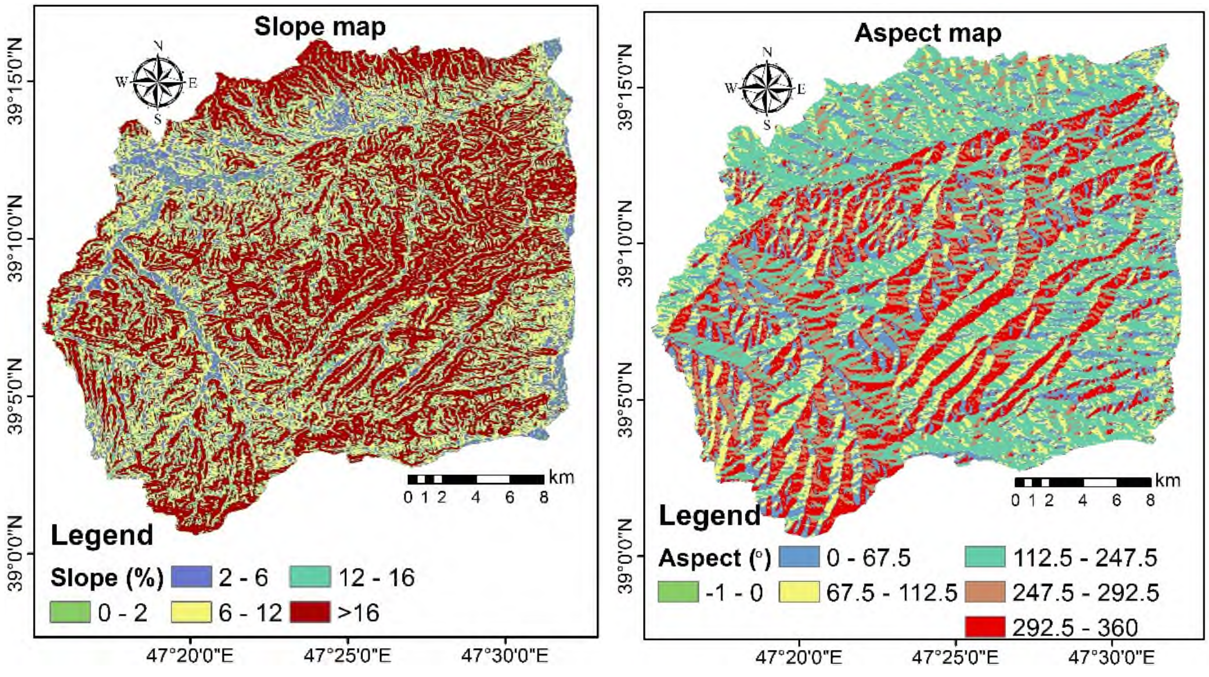

Fig 3. Topographic maps of studied area: Slope and aspect maps

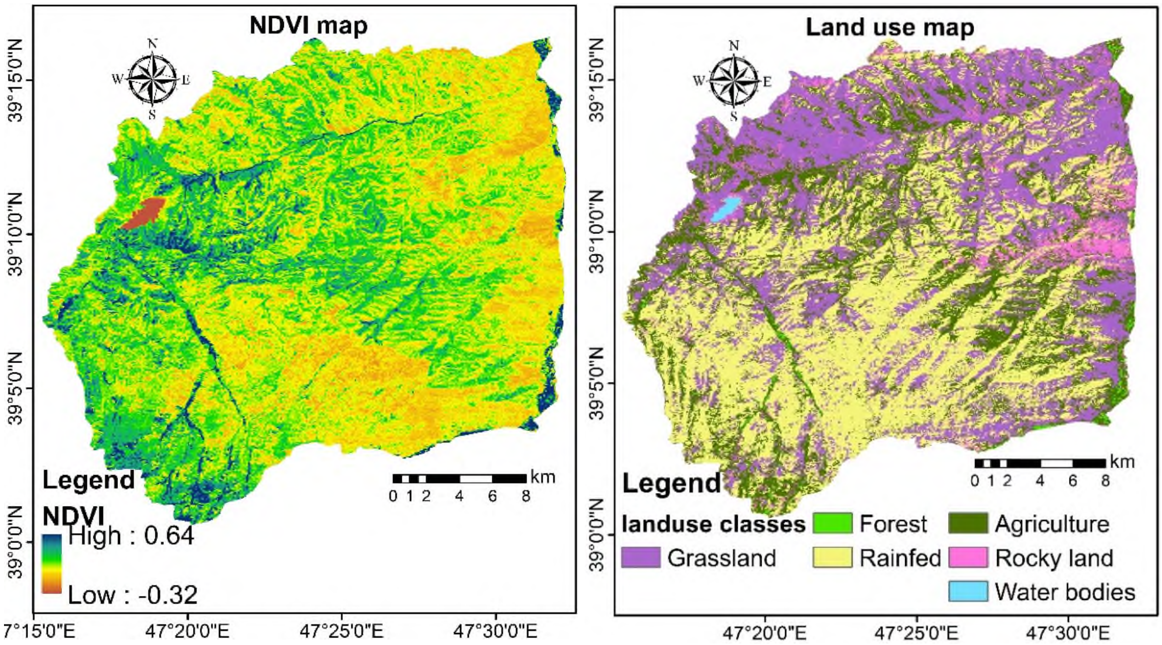

Fig 4. NDVI and land use classes maps of study area.

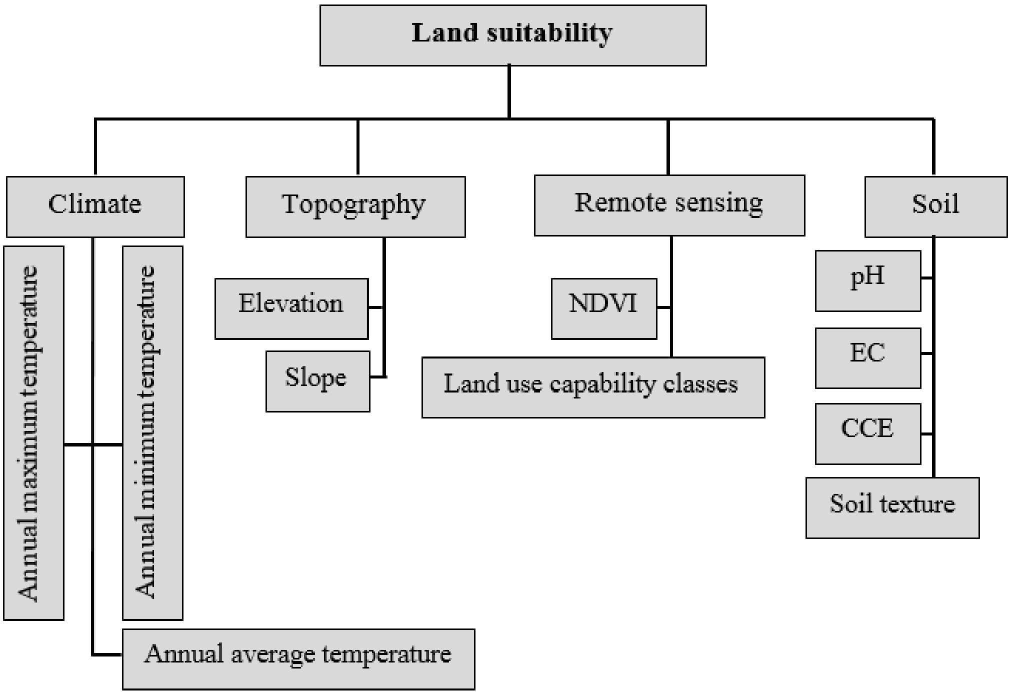

Fig 5. Hierarchy structure of evaluation factors of rapeseed.

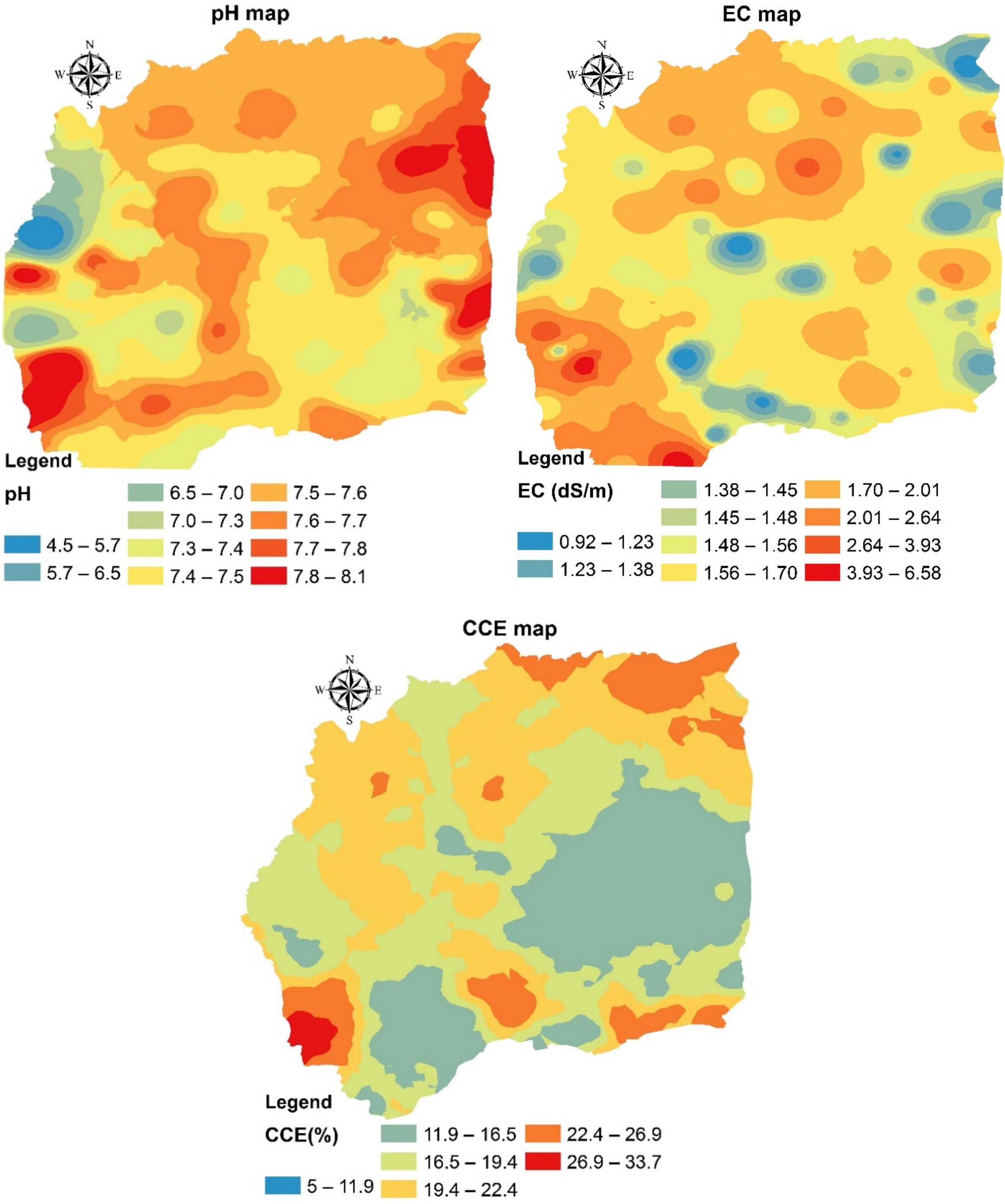

Fig 6. Soil properties map of study area

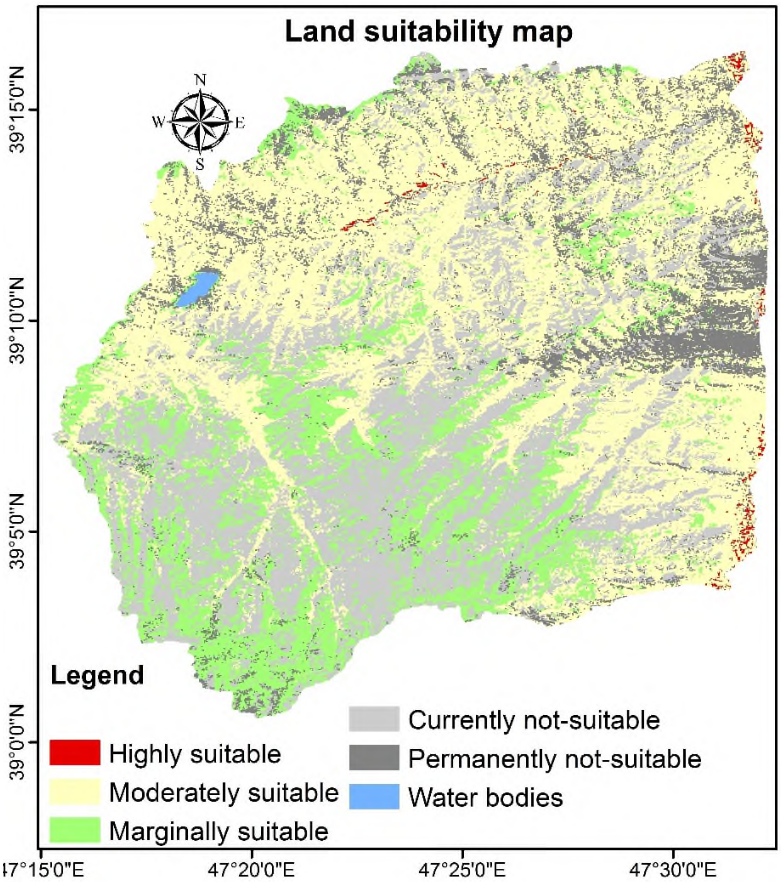

Fig. 7. Land suitability map for rapeseed in northwest Iran.

Table 1. Criteria for delineating land suitability of rapeseed crop in northwest of Iran.

parameters	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Currently not-suitable (N1)	Permanently not-suitable (N2)
Climatic factors					
Annual average temperature (°C)	20-25	15-20 and 25-27	12-15 and 27-30	10-12 and 30-35	<10 and >35
Annual minimum temperature (°C)	10-15	8-10	6-8	4-6	<4
Annual maximum temperature (°C)	20-25	25-27	27-30	30-35	>35
Topography factors					
Elevation (M)	<400	400-600	600-800	800-1000	1000>
Slope (%)	0-2	2-6	6-12	12-16	>16
Remote sensing data					
NDVI	0.2-0.3	0.3-0.5	0.1-0.2 and 0.5-0.6	0-0.1	<0 and >0.6
Soil factors					
PH	6.5-7	6-6.5 and 7-7.5	5.5-6 and 7.5-8	8-8.5 and 5-5.5	>8.5 and <5
EC (dS m^{-1})	0-4	4-8	8-11	11-16	>16
CCE (%)	0-15	15-30	30-50	50-60	>60
Soil texture	Loam, clay loam, sandy clay and clay	Sandy loam and sandy clay loam	Loam sandy, silty loam and silty clay loam	Silty clay	sandy and silty

References: Sys et al. (1991), Goudriaan & Van Laar (1994), Morrison & Stewart (2002), Francois (1994), Boyles at al. (2012) and Weiss (1983)

Table 2. The fundamental scale for pairwise comparison used for the AHP

Intensity of importance	Definition of preference score
1	Two attributes preferred equally
3	Judgment slightly favors one attribute over another
5	Judgment strongly favors one attribute over another
7	Judgment very strongly favors one attribute over another
9	Extreme preference of one attribute over another
2, 4, 6 and 8	Intermediate values between the two adjacent judgments

Table 3. Descriptive statistics of studied soil.

Properties	Min	Max	Mean	Median	Std. dev	CV
Clay (%)	6.0	46.0	25.0	24.0	9.93	35.6
Silt (%)	20.0	60.0	38.0	38.0	7.52	19.8
Sand (%)	18.0	55	36.9	36.0	8.21	22.2
CCE (%)	0.5	33.7	19.0	18.9	6.85	36.0
pH	4.5	8.1	7.5	7.6	0.38	4.98
EC (dS m^{-1})	0.93	6.5	1.7	1.6	0.76	43.84

CV: Coefficient of variation; CCE: Calcium carbonate equivalent; EC: Electrical conductivity.

Table 4. The best-fitted interpolation methods for mapping of soil properties

Properties	Interpolation methods	R^2	RMSE	Interpolation methods	R^2	RMSE
CCE	Ordinary Kriging- Spherical	0.68	6.56	IDW	0.56	5.78
pH	Ordinary Kriging- Spherical	0.57	0.405	IDW	0.52	0.369
EC	Ordinary Kriging- Pure-nugget	0.38	0.98	IDW	0.48	0.64

Table 5. The results of AHP method in land suitability for rapeseed cropping

Parameters	Weight	Rank
Climatic factors		
Annual maximum temperature (˚C)	0.049	7
Annual average temperature (˚C)	0.038	9
Annual minimum temperature (˚C)	0.034	10
Topography factors		
Elevation (M)	0.114	3
Slope (%)	0.057	6
Soil factors		
PH	0.068	5
EC (dS m^{-1})	0.085	4
CCE (%)	0.171	2
Soil texture	0.341	1
Remote sensing data		
NDVI	0.043	8

Table 6. The distribution of land suitability analysis results for rapeseed in northwest Iran.

Suitability degree	Area (ha)	Area (%)
Highly suitable	420.8	0.81
Moderately suitable	21940.2	42.33
Marginally suitable	6104.0	11.78
Currently not-suitable	20586.4	39.72
Permanently not-suitable	492.1	0.95
Water bodies	97	0.19