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RESEARCH ARTICLE

GIS-based assessment of land suitability for alfalfa cultivation: a case study in the dry continental steppes of northern China

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Abstract

Alfalfa (*Medicago sativa* L.) is the most valuable perennial forage grass in northern China. We selected 12 ecological criteria and 4 socioeconomic criteria to calculate the suitability of land for alfalfa cultivation in the Xilingol League of the Inner Mongolia Autonomous Region. We combined ecological suitability assessment with fuzzy analysis to standardize the criteria. We used the analytical hierarchy process to determine the weight of these criteria, and used multi-criterion decision analysis (MCDA) to aggregate the criteria. We then calculated the suitability score for each evaluation unit. The suitability was divided into highly, moderately, and marginally suitable, or unsuitable, using the geoprocessing module of ArcGIS 9.3 according to the FAO land suitability classification. We found that highly suitable areas covered 10,799.84 km^2, accounting for 5.3% of the total area, and unsuitable areas covered 99,235.87 km^2, accounting for 48.9% of the total area. Combining the fuzzy analysis method with the theory of ecological suitability and the MCDA method to evaluate the suitability of land for alfalfa cultivation provided insights that can guide decisionmakers and farmers to make more practical and scientific decisions.

Additional key words: land suitability; GIS; MCDA; Fuzzy analysis; AHP; *Medicago sativa*; dry continental steppes.

Introduction

Alfalfa (*Medicago sativa* L.) is one of the main forage legumes around the world. Currently more than 30 million hectares of alfalfa are grown throughout the world as monocultures or in pasture mixes with various grasses (FAO, 2012). Alfalfa plays a significant role in the development of China's animal husbandry industry, especially in northern China (Li X. *et al.*, 2007; Wang *et al.*, 2011). However, alfalfa cultivation requires a rational spatial distribution based on identifying conditions that are suitable for this species, but such a system is currently lacking in China. At present, the regions where alfalfa can be cultivated are restricted by law and custom, and the scientific basis for these restrictions is weak. The suitability of land for alfalfa crops should therefore be evaluated objectively and quantitatively to identify the sustainability of alfalfa planting in a given region.

The FAO (1976) first developed a common framework for land evaluation that was based on biophysical factors and the socioeconomic characteristics of an area. However, this approach was difficult to apply over large areas before the development of geographical information systems (GIS), which permitted the use of computerized techniques for assessing and mapping land suitability. These techniques have become increasingly important as integral components of urban planning (Marull *et al.*, 2007), agricultural utilization (Olivas *et al.*, 2007), habitat selection (Manton *et al.*, 2005), and environmental planning (Oleszczuk, 2007). Many studies have assessed the potential suitability of land and guide the selection of areas that are suitable for a particular use. One of the most important methods is multi-criterion decision analysis (MCDA; Malczewski, 2006). In addition, «fuzzy» land evaluations can be used to define continuous suitability classes rather than using binary

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Abbreviations used: AHP (analytical hierarchy process); CR (consistency ratio); DEM (digital elevation model); GIS (geographical information systems); MCDA (multi-criterion decision analysis); TM (thematic mapper).

("true" or "false") suitability assessments (Burrough, 1989; Burrough *et al*., 1992). Fuzzy set methodology has the potential to provide better land evaluations than the commonly used discrete approaches because this approach can accommodate the effects of attribute values and properties that are close to category boundaries (Stoms *et al*., 2002).

A number of fuzzy MCDA approaches that combine the advantages of these two methods have been developed for assessing land suitability (Ruger *et al*., 2005; Sicat *et al*., 2005; Zuther *et al*., 2005). In addition, Mendas & Delali (2012) developed a spatial decision-support system that enabled the preparation of agricultural land-use suitability maps by integrating GIS with the ELECTRE Tri multi-criterion analysis method. The analytical hierarchy process (AHP) method is a sort of multi-attribute MCDA method. It can be employed to derive the weights associated with the layers in suitability maps. The weights can then be combined with the suitability map layers by means of linear additive combinations (Malczewski, 2004). This approach is of particular importance for problems involving a large number of alternatives that are represented by means of a raster data model, as in the case of GIS software. AHP has been used in many land evaluation problems (Elaalem *et al*., 2011; Akinci *et al*., 2013).

To the best of our knowledge, the land suitability assessment approach has not previously been used for the analysis of cultivated alfalfa. In this paper, we developed a combined fuzzy-MCDA method and used it to assess the ecological characteristics of land in the Xilingol League of China's Inner Mongolia Autonomous Region and its suitability for alfalfa cultivation.

Material and methods

Research area

The Xilingol League is located near the center of Inner Mongolia, where it covers an area of 20.3×10^4 km^2, of which 19.7×10^4 km^2 is grassland (97% of the total study area). The region lies between 41°28' N and 46°40' N latitude and between 111°16' E and 119°51' E longitude (Fig. 1). The altitude ranges from 662 m to 1916 m asl. The region has a dry continental climate, with a mean annual precipitation ranging from 150 mm in the northwest to 430 mm in the southeast. The mean annual temperature ranges from –0.5°C at higher latitudes to 4.5°C at lower latitudes. The dominant soil types are chestnut soils, aeolian sandy soils, and meadow soils. The study area has a wide range of grassland types, including meadow steppes, typical steppes, and desert steppes.

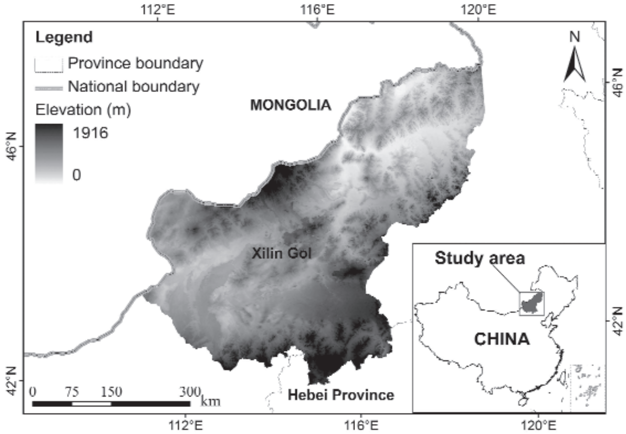

Figure 1. The location of the study area.

Based on the terrain structure and ecological environment, Xilingol can be divided (at a latitude of about 43.5° N) into northern and southern regions. The northern region is dominated by typical steppes, with grassland as the main land-use and cover type, and many large areas of grassland could potentially be developed for alfalfa cultivation despite the low rainfall. The southern region belongs to the agro-pastoral ecotone, with farmland as the main land-use and cover type; most of that land could potentially be planted with alfalfa. In 2010, the land-use and cover types in this area included artificial grassland (200 km^2), land cultivated for annual forage production (630 km^2), and improved grassland (330 km^2).

In this study, we used a fuzzy-MCDA approach to assess the suitability of the land for alfalfa cultivation. Based on local data and a literature review, we identified the key environmental criteria that would affect the growth of alfalfa, and defined a suitability range for each of these environmental criteria. We converted the precipitation and temperature data into GIS layers by means of the ordinary kriging interpolation method, with a uniform Lambert projection system. We used fuzzy analysis to standardize the various ecological criteria, and used the analytical hierarchy process (AHP) to determine the weight of each criterion. Then we calculated an integrated final suitability score for each evaluation unit. As our primary data, we obtained a land-use map from Land-

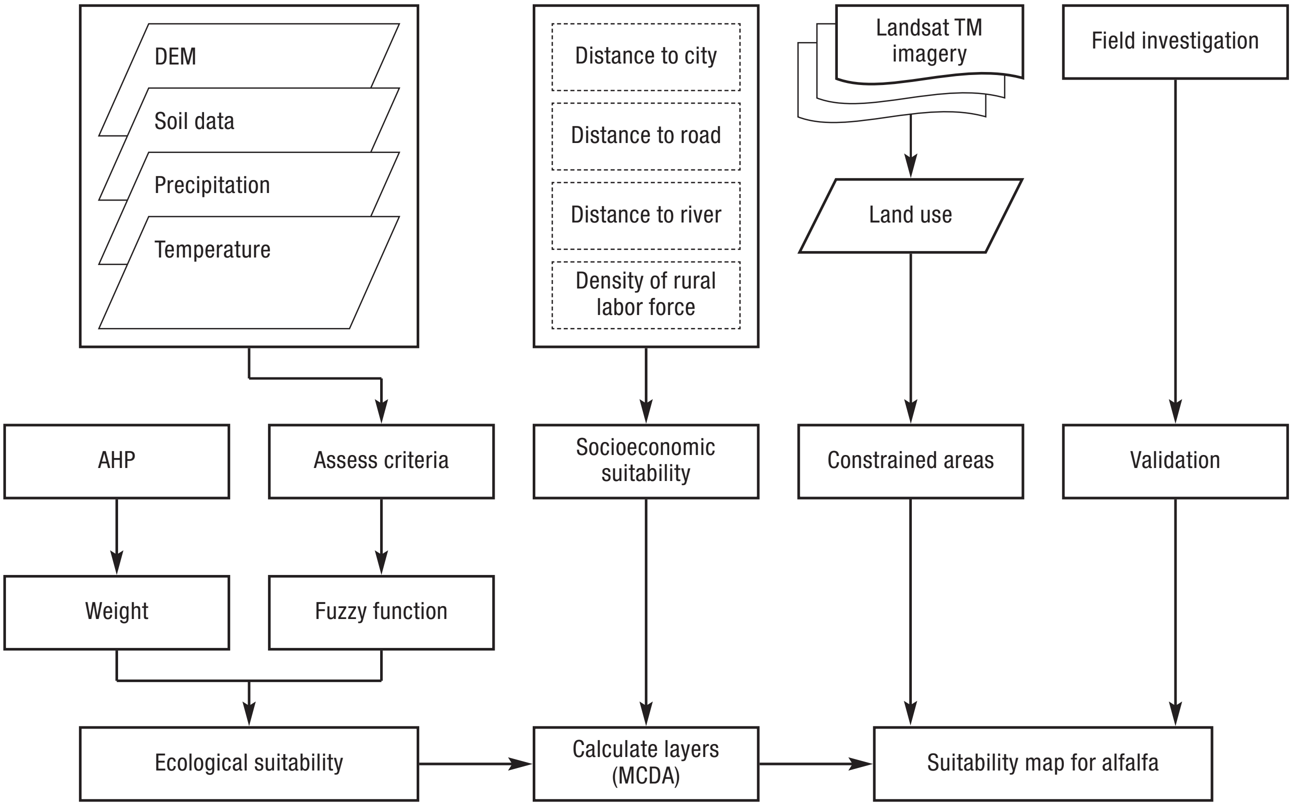

Figure 2. Framework for assessment of the suitability of land for alfalfa cultivation. AHP, analytical hierarchy process; DEM, digital elevation model; MCDA, multi-criterion decision analysis; TM, Thematic Mapper.

sat 5 TM images, and identified restricted planting areas (including bodies of water, urban land, and woodland). We eliminated these areas from our suitability map, and determined a final suitability evaluation map for alfalfa in the remaining areas. Fig. 2 summarizes our approach.

Identification of criteria influencing the land's suitability

The selection of appropriate evaluation criteria is essential for successfully developing a land suitability evaluation method. For a living organism such as alfalfa, attention should focus on the biological and ecological characteristics of the land's suitability rather than the criteria that might be used in a more general land suitability assessment. The evaluation criteria we selected in this research were based on an extensive literature review.

First, we found that soil properties such as the soil type, pH, organic matter content, and soil depth significantly affect alfalfa yields. For instance, the yield of alfalfa is highest in deep, permeable soil with a good soil moisture-supply capacity or with irrigation during the growing season (Meyer *et al.*, 2007). In contrast, poor drainage and compacted soil restrict root growth. Thus, loams or loamy soils, which are well drained and have good moisture-holding capacity, are the best soil types for alfalfa growth. Coarse sand could increase the permeability of soil and is convenient for alfalfa growth (Xian, 2006). Neutral or alkaline soil (pH from 7.3 to 8.1) is most suitable for alfalfa growth (Orloff, 2007). Organic matter content is also important, because a high content improves plant growth by increasing the soil's fertility (Becker *et al.*, 1994). The root system of alfalfa is well developed, and its taproot can reach depths of 3 to 6 m. This means that alfalfa could obtain nutrients from deep in the soil (Hall, 1998). In addition, the plow layer's thickness could potentially influence the quality and productivity of alfalfa (Anonymous, 1990).

Weather conditions are also important for plant growth in artificial pastures. The optimal precipitation for alfalfa growth ranges from 400 to 600 mm (Xian, 2006), but growth can be acceptable at lower levels of precipitation, particularly if supplemental irrigation is provided. In addition, the optimal mean annual temperature is about 6°C, with a minimum extreme low temperature of –38°C, an optimal mean temperature of 15 to 20°C during the growing season, a mean temperature higher than –4°C during the growth period, and a relative humidity of 53 to 57% during flowering (Xian, 2006).

Furthermore, the topographic factors of slope and elevation not only affect the suitability of land for alfalfa cultivation, but also affect the distribution of moisture and temperature. To facilitate planting and harvesting, the slope should be less than 15° (Orloff, 2007).

Finally, socioeconomic factors, including transportation, irrigation, and the agricultural labor force, also significantly affect the land's suitability. We chose the distance from each pixel in our satellite map images to the nearest roads and cities to measure the convenience for transportation, and the distance of each pixel from a river to measure the convenience for irrigation. We used the rural labor population density, based on data provided by each county, to represent the agricultural production capacity.

Data processing and evaluation units

We obtained 30 years of meteorological data (from 1971 to 2011), the duration recommended by the World Meteorological Organization (Li *et al*., 2012), from 30 meteorological stations in or near the study area (Fig. 3). From these data, we extracted the average annual rainfall, annual average temperature, annual extreme low temperature, Mean temperature during the growth period (June to September), low temperature during the greening stage (May), and relative humidity during the flowering stage (August). All of these values were mapped to GIS layers, with interpolation by means of ordinary kriging, in ArcGIS 9.3 (http://www.esri.com/software/arcgis/arcgis-for-desktop). We obtained a 1:1,000,000-scale digital soil map of Xilingol that was produced during the Second General Soil Survey of China (Shi *et al*., 2002). We created a land-use and cover map of Xilingol from Landsat TM 5 images obtained during July to August of 2010 (paths 123 to 126, rows 028 to 030, 30-m resolution), using a combination of automated and supervised classification. The classification was field-verified, and the accuracy was about 90%, which is

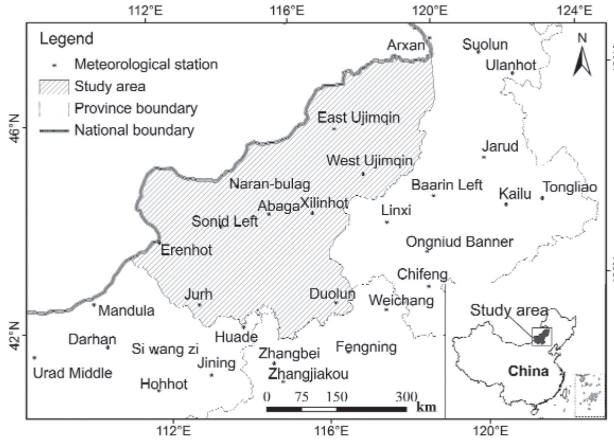

Figure 3. Meteorological stations in or near the study area that provided data for constructing the climatic layers in the GIS.

adequate for the purposes of our study. We used a digital elevation model (DEM) provided by the International Scientific & Technical Data Mirror Site (http://datamirror.csdb.cn/dem/files/ys.jsp). The raster data for elevation and slope were derived from the 30-m-resolution DEM dataset. Road data and river data were generated from the digitized map of the study area, and the labor force data came from the statistical yearbook of Xilingol. We used the spatial analyst tools provided by ArcGIS to calculate the distances and labor density, respectively.

In the final step, we resampled all layers to a raster format with a resolution of 100 m × 100 m using a uniform Lambert projection. We chose the raster cells as the evaluation unit, and all calculations based on these cells had the same resolution (100 m × 100 m).

Standardization of criteria

The theory of fuzzy sets was first introduced by Zadeh (1965), who provided a mathematically meaningful method to quantify the degrees of imprecision and uncertainty in non-discrete data. In the modern use of this approach, a fuzzy set is described using a series of fuzzy membership functions with values that range from 0.0 to 1.0, representing a continuous increase from non-membership (0) to complete membership (1) (McBratney & Odeh, 1997). Burrough *et al*. (1992) were the first to apply fuzzy logic to the evaluation of land suitability for agricultural crops. In the present study, we employed two models (A and B) to create membership functions

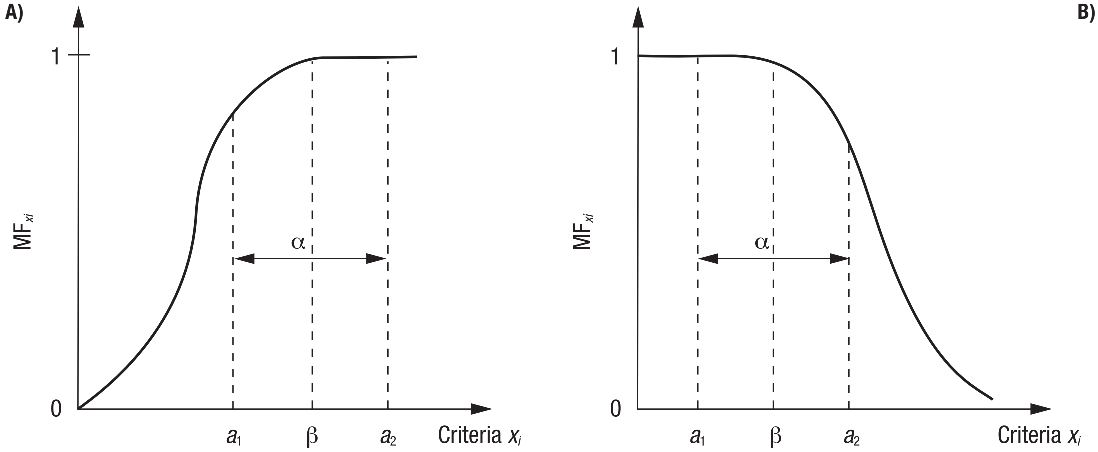

Figure 4. The fuzzy membership function of two asymmetrical models.

Table 1. Descriptive statistics for the factors that influence alfalfa growth

Factors	Criteria	Optimal values	Variable type	Fuzzy model type
Climate	Average annual rainfall (mm)	400 to 600	Continuous	A
	Mean temperature during the growth period (°C)	15 to 20	Continuous	B
	Extreme low temperature (°C)	–38	Continuous	A
	Annual average temperature (°C)	6	Continuous	A
	Low temperature during the greening stage (°C)	–4	Continuous	A
	Relative humidity during the flowering stage (%)	53 to 57	Continuous	A
Topography	Slope (°)	<15°	Continuous	B
	Elevation (m)	<2300	Continuous	B
Soil	Soil depth (cm)	100	Continuous	A
	Soil pH	7.3 to 8.1	Continuous	A
	Organic matter (%)	0.18 to 8.55	Continuous	A
	Coarse sand (%)	15.0 to 20.0	Continuous	A

"Optimal values" in this table were derived from the section "Identification of criteria influencing the land's suitability".

for the criteria that were associated with land suitability (Fig. 4). We used the optimal ecological conditions identified earlier in previous sections to construct these models.

Model A (Equation [1]) is used when the suitability increases with increasing value of a criterion:

$$\begin{cases} MF_{xi} = \dfrac{1}{1+\dfrac{(\varphi-\beta)^2}{\alpha^2}} & \varphi < \beta \\ MF_{xi} = 1 & \varphi \geq \beta \end{cases} \quad [1]$$

where MF_{xi} is the suitability of criterion x_i, α is the range of the suitability values ($\alpha = a_2 - a_1$), φ is the actual value of criterion x_i, and β, is the ideal level for alfalfa growth.

Model B (Equation [2]) is used when the suitability decreases with increasing value of a criterion:

$$\begin{cases} MF_{xi} = \dfrac{1}{1+\dfrac{(\varphi+\beta)^2}{\alpha^2}} & \varphi \geq \beta \\ MF_{xi} = 1 & \varphi < \beta \end{cases} \quad [2]$$

Table 1 lists the range of optimal values for all of the evaluation criteria, their variable type, and the fuzzy model (A or B) used for the criterion.

For the socioeconomic criteria (factors), we used the following standardization methods in this study, with the membership degree (E_j) of the density of the rural labor force calculated using the following Equation [3]:

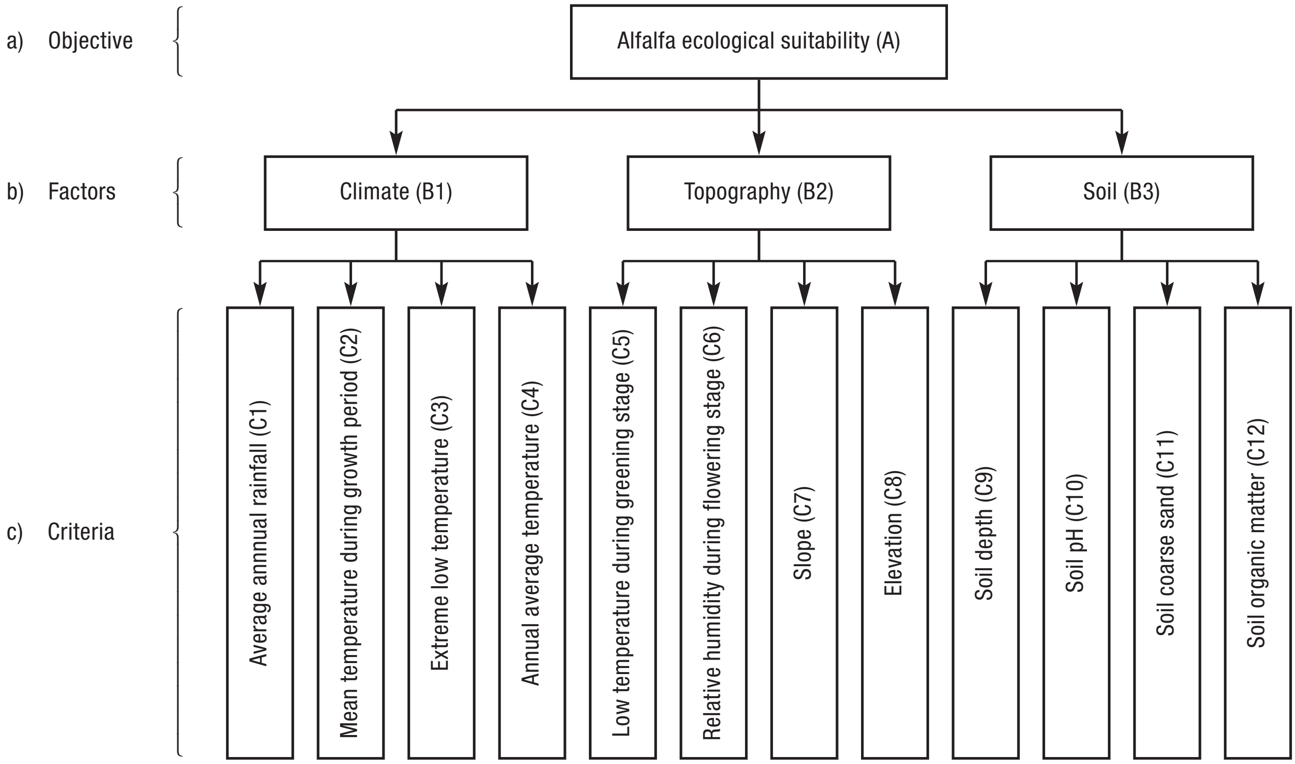

Figure 5. Hierarchical structure in the analytical hierarchy process used to determine the ecological suitability evaluation index for alfalfa cultivation.

$$E_j = \frac{X_j - X_{\min}}{X_{\max} - X_{\min}} \quad [3]$$

where X_j is the value in pixel j, $X_{\min}$ is the minimum value of the rural labor force density, and $X_{\max}$ is the maximum value.

The membership degree (E_j) of the distance to roads, rivers, and cities was given by Equation [4]:

$$E_j = (1 - \frac{X_j}{X_{\max}}) \quad [4]$$

where X_j is the distance to roads or rivers or cities in pixel j, and $X_{\max}$ is the maximum distance to a road.

Weights of the criteria

Different environmental factors have different effects on the growth of alfalfa based on our review of the literature on the criteria that affect forage grass cultivation. Therefore, determination of criteria weights is an important step in the development of a suitability model. There are many methods to determine the weight of criteria, such as the Delphi method (Hayati *et al*., 2013) and the AHP method (Bagheri *et al*., 2013). To account for the influence of subjectivity, we chose the AHP method to determine the weight of each criterion (Fig. 5).

The AHP method was first proposed by Saaty & Vargas (1980) as an appropriate decision-making approach to handle complex problems with numerous factors involved. This process can be used to assess both intangible qualitative criteria and objective quantitative criteria (Badri, 2001). To assign weights to the criteria used in our analysis, we first organized the criteria into a hierarchical structure (Fig. 5). We then generated a pairwise comparison matrix that compared each pair of criteria. In these comparisons, each of the criteria was assigned a weight ranging from 1 to 9. To assign this weight based on local conditions in the study region, we consulted the relevant literature and nine specialists with relevant expertise. We combined these inputs to determine the relative weight of each criterion using the eigenvector method provided by the Expert Choice software environment (http://expertchoice.com/).

To examine the rationality of the AHP, it is necessary to determine the level of consistency that has been used

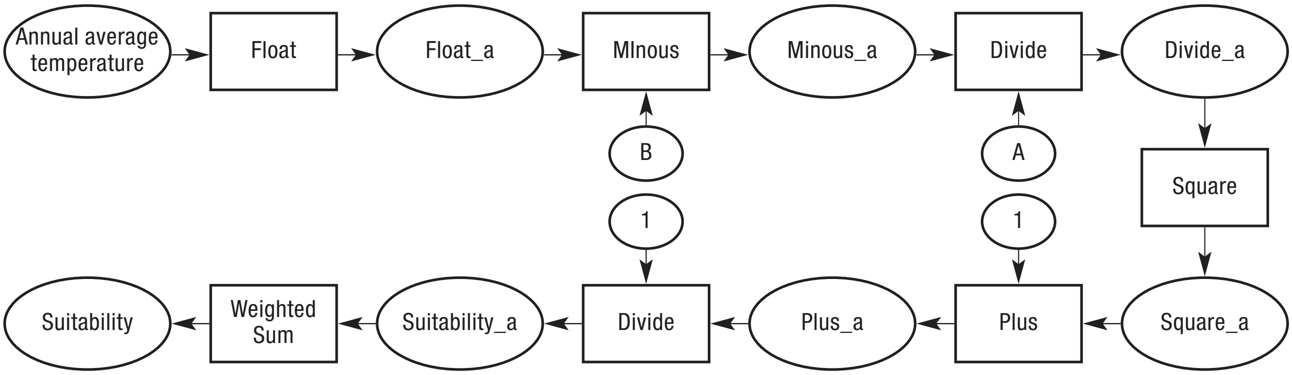

Figure 6. Structure of a typical geoprocessing model used to determine the ecological suitability of land for alfalfa cultivation. This specific example is for the annual average temperature.

in developing the judgments. An index known as the "consistency ratio" (CR) can be used to indicate the probability that the matrix of judgments were randomly generated (Saaty, 1977).

$$CR = \frac{CI}{RI} \qquad [5]$$

where RI is the random index given by Saaty (1977), and CI is the consistency index:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad [6]$$

where $\lambda_{\max}$ is the principal eigenvalue of the matrix, and n is the order of the matrix.

Saaty (1977) noted that matrices with CR > 0.1 require revisions of the judgments in the matrix. In this study, we obtained a CR = 0.089 (*i.e.*, CR < 0.1), suggesting that the judgments had a reasonable level of consistency.

Land suitability model

In a GIS context, we first calculated the ecological suitability and the socioeconomic suitability independently. We then overlaid the layers for the two criteria, and chose the minimum of the two values as the suitability of the land in a given pixel. The final suitability value (S) was generated using the following equation:

$$S = min(\sum_{i=1}^{m} W_i MF_i + \sum_{j=1}^{n} W_j E_j) \qquad [7]$$

where S is the suitability score, W_i is the weight of ecological criterion i (and $w_1 + w_2 + \ldots + w_m = 1$); MF_i is the membership function value for the suitability of ecological criterion i, and m is the number of ecological criteria (here, $m = 12$); W_j is the weight of socioeconomic criterion j (and $w_1 + w_2 + \ldots + w_n = 1$); E_j is the value for suitability of socioeconomic criterion j; and n is the number of socioeconomic criteria (here, $n = 4$).

We used the ArcGIS 9.3 model builder tool to develop a model of the alfalfa suitability. We used Equations [1] to [4] to calculate the suitability of each influencing factor for the growth of alfalfa, and Equation [7] to integrate the effects of the various factors and calculate an overall weighted suitability score for each evaluation unit. Fig. 6 shows the structure of a typical geoprocessing model for one criterion of alfalfa suitability.

Based on the land suitability characteristics for different crops, FAO (1976) proposed a land suitability evaluation in terms of two broad classes: suitable regions and unsuitable regions. They further divided these categories into five classes: highly suitable, moderately suitable, marginally suitable, currently unsuitable, and permanently unsuitable. The main purpose of the present study was to find land that would be suitable for the growth of alfalfa, so we combined the currently and permanently unsuitable regions into a single "unsuitable" category.

Results

Suitability value and weight of each criterion

Fig. 7 shows the suitability value maps for twelve ecological criteria and four socioeconomic criteria, which present the distribution of the suitability value

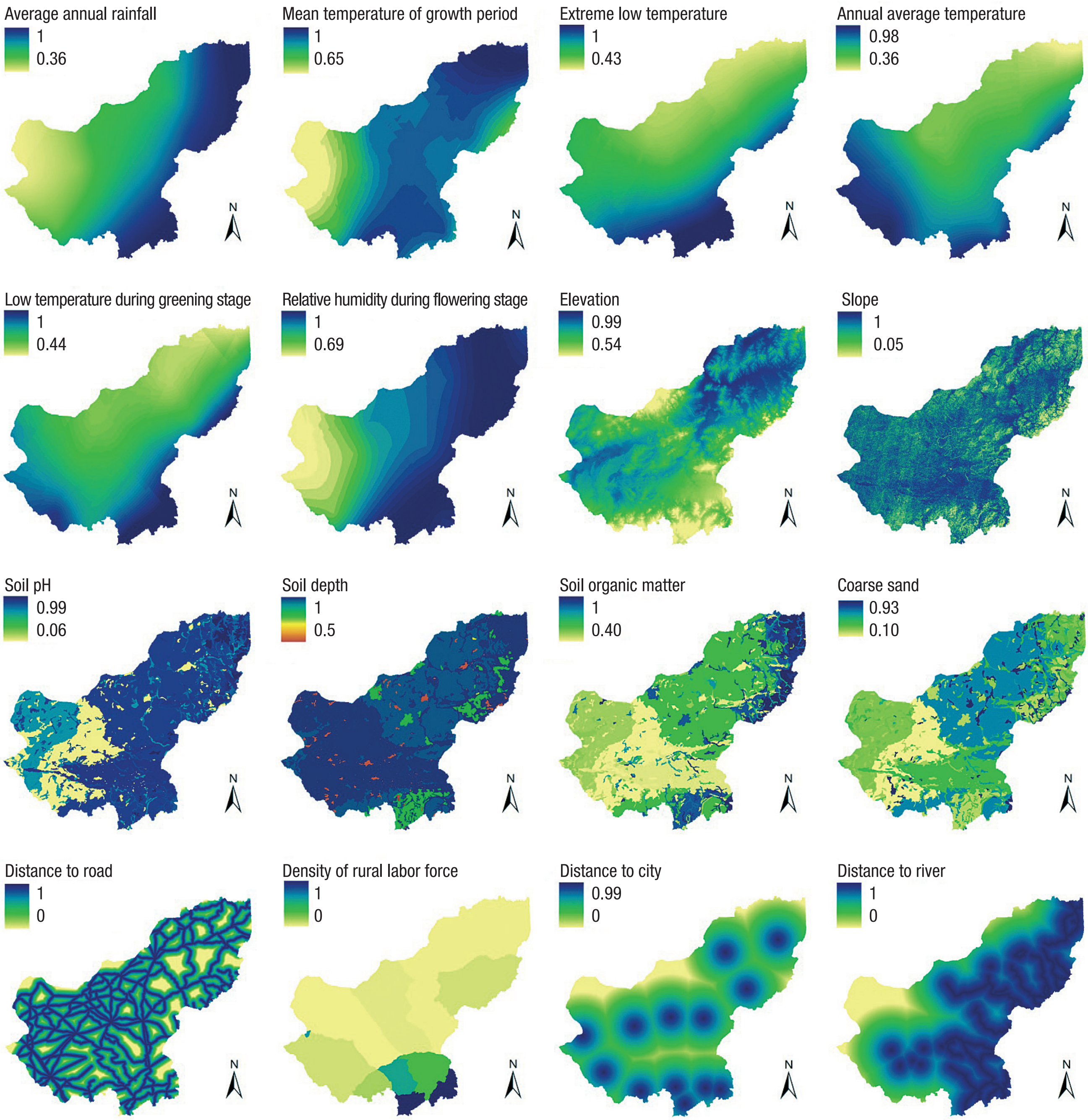

Figure 7. Suitability value for each evaluation criterion in the study area.

within our study region using a continuous scale with values ranging from 0 to 1.

Table 2 shows the weights of twelve ecological criteria determined based on a literature review and expert consultations, with the weights calculated using the Expert Choice software. Table 3 shows the weights of the four socioeconomic criteria, which were based on a consultation with experts.

Land suitability of alfalfa

Fig. 8 showed the spatial distribution of the suitability classification for alfalfa cultivation, that using the natural-breaks classification method. Table 4 shows the suitability classification of alfalfa, that sort the comprehensive suitability scores for all grid units into four classes (Table 4), plus a “constrained” class

Table 2. Weights of the 12 ecological criteria determined based on a literature review and expert consultations, with the weights calculated using the Expert Choice software

Factors	Weight	Criteria	Weight
Climate (B1)	0.6099	Average annual rainfall (C1)	0.2280
		Mean temperature during the growth period (C2)	0.1027
		Extreme low temperature (C3)	0.0605
		Annual average temperature (C4)	0.0385
		Low temperature during the greening stage (C5)	0.1209
		Relative humidity during the flowering stage (C6)	0.0593
Topography (B2)	0.1655	Slope (C7)	0.1379
		Elevation (C8)	0.0276
Soil (B3)	0.2246	Soil depth (C9)	0.0166
		Soil pH (C10)	0.1152
		Soil organic matter (C11)	0.0309
		Soil sand (C12)	0.0619

Table 3. Weights of the four socioeconomic criteria, which were determined by expert consultations

Socioeconomic criteria	Weight
Distance to road	0.15
Distance to river	0.40
Distance to city	0.20
Density of rural labor force	0.25

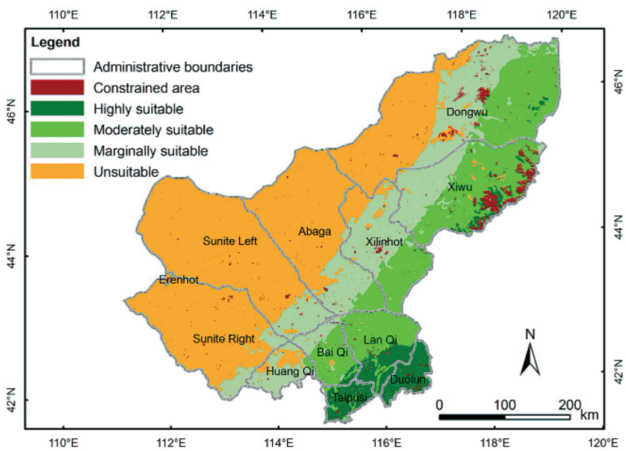

Figure 8. Spatial distribution of the suitability for alfalfa cultivation.

in which alfalfa cultivation would not be permitted, and the area and percentage of each class were presented.

We defined the forest, body of water, and urban land uses and cover types as completely unsuitable for alfalfa cultivation based on the current land-use policy in China. Therefore, we labeled these regions as "constrained" areas in the land-use map and eliminated them from our evaluation procedures. On this basis, we eliminated 4493.07 km^2 of the study area as unsuitable for alfalfa cultivation, amounting to 2.2% of the total area. The regions that are highly suitable for the cultivation of alfalfa occupied 10,799.84 km^2 (5.3% of the total land in Xilingol) versus 42,983.03 km^2 (21.2%) for moderately suitable, 45,488.19 km^2 (22.4%) for marginally suitable, and 99,235.87 km^2 (48.9%) for unsuitable.

Highly suitable regions covered only 5.3% of the total study area. They were mainly located in the

Table 4. Suitability classification for alfalfa cultivation in the Xilingol League

Suitability classification	Score	Total pixels	Area (km^2)	% of total area
Highly suitable	0.80 to 1.00	1,079,984	10,799.84	5.3
Moderately suitable	0.75 to 0.79	4,298,303	42,983.03	21.2
Marginally suitable	0.70 to 0.74	4,548,819	45,488.19	22.4
Unsuitable	0.42 to 0.69	9,923,587	99,235.87	48.9
Constrained area	—[1]	449,307	4,493.07	2.2
Total		20,300,000	203,000.00	100.0

[1] "Constrained area" is unsuitable, based on current land-use policy in China.

southern and southeastern regions of Xilingol (Fig. 8), which included Duolun, Taipusi, Lan Qi, and southeastern Xiwu. The annual rainfall in these regions was between 350 and 430 mm, the annual average temperature was from 2.9 to 3.5°C, the relative humidity during the flowering stage was from 70 to 77%, the mean temperature during the growth period was from 18 to 20°C, the lowest temperature during the greening stage ranged from –5.0 to 7.2°C, and the extreme low temperature ranged from –33 to –37°C. The soil thickness was more than 90 cm, and the soil pH ranged from 6.8 to 7.5. The growth of alfalfa in these regions could be enhanced by a stable interannual climate under natural rainfall conditions.

Moderately suitable regions accounted for 21.2% of the total study area. These sites were mainly located in the south-central and southeastern parts of the study area, including eastern Huang Qi and Bai Qi, northern Lan Qi, southeastern Xilinhot, and southeastern Xiwu and Dongwu (Fig. 8). The annual rainfall in these regions was between 299 and 350 mm, the annual average temperature ranged from 2.0 to 2.8°C, the relative humidity during the flowering stage was from 64 to 70%, the mean temperature during the growth period was from 18 to 20°C, the lowest temperature during the greening stage was from –6.9 to –8.1°C, and the extreme low temperature ranged from –33 to –35°C. The soil pH was from 7.5 to 8.0. The cultivation of alfalfa in these regions may be possible if local water resources are sufficient to permit sustainable irrigation that will not jeopardize the security of the local water resources.

Marginally suitable regions accounted for 22.4% of the total study area. These sites were mainly located near the center of the study area, in a region running from southwest to northeast that included northern Huang Qi and Bai Qi, southern Sunite Left and Abaga, northern Xilinhot, western Xiwu, and south-central Dongwu (Fig. 8). The annual rainfall in these regions was between 250 and 299 mm, the annual average temperature was from 1.6 to 2.3°C, the relative humidity during the flowering stage was from 61 to 64%, the mean temperature during the growth period was from 17 to 19°C, the lowest temperature during the greening stage was from –8.1 to –9.0°C, and the extreme low temperature ranged from –34 to –36°C. The soil pH was from 7.4 to 7.9. Some of this area may be suitable for growing alfalfa, but because of the difficulty (*e.g.,* the requirement for significant irrigation inputs), most of this land use should be limited.

Unsuitable regions accounted for 48.9% of the total study area. They were mainly located in the central and western parts of the study area (Fig. 8). Precipitation was low (140 to 150 mm), the annual average temperature ranged from 2.3 to 4.5°C, the relative humidity during the flowering stage ranged from 50 to 61%, the mean temperature during the growth period was from 18 to 21°C, the lowest temperature during the greening stage was from –9.0 to –10.1°C, and the extreme low temperature ranged from –36 to –38°C. The soil pH was from 8.5 to 9.8.

Discussion

Land suitability evaluation can be designed to evaluate the land for a particular purpose, such as agriculture or urban expansion, or to evaluate the optimal land use for a particular region. In the present study, we performed the first type of assessment. Because the suitability of land for specific crops depends on many physiological and ecological characteristics, as well as on characteristics of the regional ecological environment, it is necessary to use a multi-criterion evaluation method to account for this complexity; in similar studies, the AHP has been commonly used. Because this method can comprehensively consider the range of factors that affected crop growth in our study region, the AHP method was able to highlight the dominant factors. Our assessment results indicated that the combination of the AHP with modified fuzzy analysis successfully assessed the potential for alfalfa cultivation in Xilingol.

To standardize the evaluation criteria, we combined the fuzzy analysis method with a measure of ecological suitability to calculate the suitability of the land based on each of 12 criteria, and replaced traditional discrete classification methods (Ziadat & Sultan, 2011) with a continuous interval [0, 1]. Because continuous intervals can convert the values of environmental criteria with different orders of magnitude into the same range of values, it can provide a better expression of how the environmental criteria affect the suitability for a given crop by capturing the more realistic continuous change in the values of these criteria, and therefore provides a better reflection of the actual suitability.

Our research area is the largest area of typical steppes in northern China. However, due to the impacts of both human activities and climate change, the production capacity of this area appears to be declining (Li W.J. *et al.*, 2007). This is a problem given the socioeconomic and environmental contexts in which the study area exists. On the one hand, the demands for meat and milk are increasing due to ongoing improvement of standards of living in China, and this is driving the development of animal husbandry, leading to a requirement for increasing quantities of fodder. On the other hand, national conservation measures such as grazing prohibition to protect degraded land will greatly hamper the development of animal husbandry. Therefore, it will be necessary to develop artificial grassland in regions with suitable environmental conditions in our study area to solve this problem by providing sustainable local sources of fodder. Alfalfa is sometimes called «the king of forage grass» because of its high protein and nutrient contents, and it therefore appears to be an excellent choice as a perennial forage grass. However, there has been insufficient experience with alfalfa planting in this area. Some economic and ecological losses have resulted from planting failures caused by a lack of systematic research to identify the most suitable locations for planting alfalfa in this area.

Our use of FAO's land suitability assessment method was based on climate, soil, and remote-sensing data, combined with a DEM, which let us perform a GIS-based evaluation of the suitability of each part of our study area for planting alfalfa. Our method provided a good depiction of the spatial distribution of the suitability for alfalfa, suggesting that our method has high potential to support decision-making related to alfalfa planting. In the highly suitable areas, it may be possible to plant large areas under rain-fed conditions, and with appropriate management, this should provide good forage production. In the moderately suitable areas, irrigation (where sufficient water is available to allow sustainable irrigation) and appropriate management may also permit the planting of large areas of alfalfa. In the marginally suitable areas, planting would be risky and should be limited. In the unsuitable areas, the poor ecological conditions suggest that natural steppes should be preserved, and that alfalfa planting should be strongly discouraged. Because of decreasing water availability in many areas of northern China, it will be crucial to ensure that sufficient renewable supplies of water are available to sustain widespread planting of alfalfa, particularly in the drier parts of the study area. In addition, regional managers should identify areas that are too fragile to support intensive cultivation and areas that are important reservoirs of biodiversity. Even if these areas appear to be suitable for alfalfa cultivation based on the criteria used in our study, they should be protected against cultivation to protect their ability to provide ecological services.

Alfalfa is a highly productive legume, and can improve the protein content of milk. It is therefore an important plant for the creation of artificial grasslands designed to support grazing animals. Based on the results of our analysis, it will be worthwhile to develop integrated approaches that can account for the evaluation factors in our study during the decision-making process to determine the suitability of land for alfalfa cultivation. However, as noted earlier, other criteria such as the ecological services value of land, should also be considered in this evaluation.

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References

Akinci H, Ozalp AY, Turgut B, 2013. Agricultural land use suitability analysis using GIS and AHP technique. Comput Electron Agr 97: 71-82.

Anonymous, 1990. Alfalfa: the crop for the soil. Certified Alfalfa Seed Council. Kennewick, WA, USA.Badri MA, 2001. A combined AHP-GP model for quality control systems. Int J Prod Econ 72: 27-40.

Bagheri M, Sulaiman WNA, Vaghefi N, 2013. Application of geographic information system technique and analytical hierarchy process model for land-use suitability analysis on coastal area. J Coast Conserv 17: 1-10.

Becker RD, Cosgrove J, Doll C, Grau K, Kelling N, Martin M, Rice M, Schmitt D, Wedberg J, 1994. Alfalfa management guide. Am Soc Agron, Madison, WI, USA.

Burrough PA, 1989. Fuzzy mathematical methods for soil survey and land evaluation. J Soil Sci 40: 477-492.

Burrough PA, Macmillan RA,Vandeursen W, 1992. Fuzzy classification methods for determining land suitability from soil-profile observations and topography. J Soil Sci 43: 193-210.

Elaalem M, Comber A, Fisher PA, 2011. A comparison of fuzzy AHP and ideal point methods for evaluating land suitability. T GIS 15(3): 329-346.

FAO, 1976. A framework for land evaluation. Food and Agricultural Organization of the United Nations, Rome.

FAO, 2012. Crop yield response to water. Food and Agriculture Organization of the United Nations, Rome.

Hall M, 1998. How an alfalfa plant develops. Certified Alfalfa Seed Council. Kennewick, WA, USA.

Hayati E, Majnounian B, Abdi E, Sessions J, Makhdoum M, 2013. An expert-based approach to forest road network planning by combining Delphi and spatial multi-criteria evaluation. Environ Monit Assess 185: 1767-1776.

Li B, Zhang F, Zhang LW, Huang JF, Jin ZF, Gupta DK, 2012. Comprehensive suitability evaluation of tea crops using GIS and a modified land ecological suitability evaluation model. Pedosphere 22: 122-130.

Li WJ, Ali SH, Zhang Q, 2007. Property rights and grassland degradation: a study of the Xilingol Pasture, Inner Mongolia, China. J Environ Manage 85: 461-470.

Li X, Su D, Yuan Q, 2007. Ridge-furrow planting of alfalfa (*Medicago sativa* L.) for improved rainwater harvest in rainfed semiarid areas in Northwest China. Soil Till Res 93: 117-125.

Malczewski J, 2004. GIS-based land-use suitability analysis: a critical overview. Progress in Planning 62: 3-65.

Malczewski J, 2006. GIS-based multicriteria decision analysis: a survey of the literature. Int J Geogr Inf Sci 20: 703-726.

Manton MG, Angelstam P, Mikusinski G, 2005. Modelling habitat suitability for deciduous forest focal species. A sensitivity analysis using different satellite land cover data. Landscape Ecol 20: 827-839.

Marull J, Pino J, Mallarach JM, Cordobilla MJ, 2007. A land suitability index for strategic environmental assessment in metropolitan areas. Landscape Urban Plan 81: 200-212.

McBratney AB, Odeh IOA, 1997. Application of fuzzy sets in soil science: fuzzy logic, fuzzy measurements and fuzzy decisions. Geoderma 77: 85-113.

Mendas A, Delali A. 2012. Integration of multicriteria decision analysis in GIS to develop land suitability for agriculture: application to durum wheat cultivation in the region of Mleta in Algeria. Comput Electron Agr 83:117-126.

Meyer RD, Marcum DB, Orloff SB, Schmierer JL, 2007. Alfalfa fertilization strategies. In: Irrigated alfalfa management for mediterranean and desert zones (Summers CG & Putnam DH, eds). Chapter 6. Univ Calif Agr Nat Resour, Oakland, CA, USA, Publication 8292.

Oleszczuk P, 2007. The evaluation of sewage sludge and compost toxicity to *Heterocypris incongruens* in relation to inorganic and organic contaminants content. Environ Toxicol 22: 587-596.

Olivas GUE, Valdez LJR, Aldrete A, Gonzalez GMdJ, Vera CG, 2007. Suitable areas for establishing maguey cenizo plantations: definition through multicriteria analysis and GIS. Rev Fitotec Mex 30: 411-419.

Orloff SB, 2007. Choosing appropriate sites for alfalfa production. In: Irrigated alfalfa management for mediterranean and desert zones (Summers CG & Putnam DH, eds), Chapter 2. Univ Calif Agr Nat Resour, Oakland, CA, USA. Publication 8288.

Ruger N, Schluter M, Matthies M, 2005. A fuzzy habitat suitability index for *Populus euphratica* in the Northern Amudarya delta (Uzbekistan). Ecol Model 184: 313-328.

Saaty TL, 1977. A scaling method for priorities in hierarchical structures. J Math Psychol 15: 234-281.

Saaty TL, Vargas LG, 1980. Hierarchical analysis of behavior in competition: prediction in chess. Behav Sci 25: 180-191.

Shi XZ, Yu DS, Warner ED, 2002. A framework for the 1:1,000,000 soil database of China. Proc 17th World Congress of Soil Science, Bangkok, 1757: 1-5.

Sicat RS, Carranza EJM, Nidumolu UB, 2005. Fuzzy modeling of farmers' knowledge for land suitability classification. Agr Syst 83: 49-75.

Stoms DM, McDonald JM, Davis FW, 2002. Fuzzy assessment of land suitability for scientific research reserves. Environ Manage 29: 545-558.

Wang X, Yang X, Chen L, Feng G, Zhang J, Jin L, 2011. Genetic diversity among alfalfa (*Medicago sativa* L.) cultivars in Northwest China. Acta Agriculturae Scandinavica, Section B - Soil & Plant Science 61: 60-66.

Xian W, 2006. Forage cultivation. China Environmental Science Press, Beijing.

Zadeh LA, 1965. Fuzzy sets. Information and Control 8: 338-353.

Ziadat FM, Sultan KA, 2011. Combining current land use and farmers' knowledge to design land-use requirements and improve land suitability evaluation. Renew Agr Food Syst 26: 287-296.

Zuther S, Schulz HK, Lentzen GA, Schulz R, 2005. Development of a habitat suitability index for the noble crayfish *Astacus astacus* using fuzzy modelling. Bulletin Français de la Pêche et de la Pisciculture 376-377: 731-742.