Land Suitability Evaluation for Sorghum Based on Boolean and Fuzzy-Multi-Criteria Decision Analysis Methods

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***Abstract*—The objective of this paper was to compare two approaches to land suitability evaluations, Fuzzy MCDA and Boolean, to model the opportunities for sorghum production in the north-western region of Jeffara Plain, Libya. In this paper a number of soil and landscape and climate criteria were identified and their weights specified as a result of discussions with local experts. The Fuzzy MCDA approach was found to be better than the Boolean approach. Boolean logic indicted that the study area has only four suitability classes (highly suitable, moderately suitable, marginally suitable and currently not suitable). In contrast, the results obtained by adopting the Fuzzy MCDA approach showed that the area of study has a greater degree of subdivision in land suitability classes for sorghum. The richer overall picture provides an alternative type of land suitability evaluation to Boolean approaches and allows subtle variations in land suitability to be explored.**

***Index Terms*—Fuzzy, MCDA, boolean, uncertainty.**

I. Introduction

Land suitability evaluation is classification of lands in terms of their suitability for a specific land use. The main object of the land evaluation is prediction of inherent capacity of the land units without deterioration [12]. Land evaluation can be carried out on the basis of biophysical factors and/or socioeconomic conditions of an area [3]. Physical land evaluation is a prerequisite for land-use planning, because it guides decisions on optimal use of land resources [7]. In multi-criteria decision making which is utilized for determination of optimum land use type for an area, unequal importance of different land criteria is taken into consideration. This method could be perceived as a collection of concepts, models and methods that aim an evaluation according to some factors. Investigation a number of alternatives in respect to multiple criteria and conflicting objectives is the main goal of multi-criteria decision analysis approaches (MCDA).

In recent years, there has been increasing interest in integrating geographic information system capability with multi-criterion decision analysis techniques for spatial planning and management [6], [11], [19], [22]. The use of the MCDA methods is still a new task in land suitability evaluation for agricultural crops. The MCDA approaches have the capacity for addressing and exploring the uncertainties associated with land resources, especially if they are integrated with fuzzy set models [1], [4], [9].

Fuzzy set theory has been extensively utilized in soil science for land suitability evaluation, soil classification and soil quality indices [14]. In using the fuzzy set models, observations are grouped into continuous classes, instead of classifying them into hard classes (Boolean classification).

The implicit assumption in Boolean approaches is the absence of any uncertainty or vagueness associated with the suitability model, measurement, vagueness in the concepts that are specified. In reality these assumptions may be invalid. Fuzzy set methodologies have been proposed as a method for overcoming problems related to vagueness in definition and other uncertainties. The use of fuzzy set methodologies in land suitability evaluation allows imprecise representations of vague, incomplete and uncertain information. Fuzzy set methodologies have the potential to provide better land evaluations compared to Boolean approaches because they are able to accommodate attributed values and properties which are close to category boundaries. Fuzzy land evaluations define continuous suitability classes rather than 'true' or 'false' categories as in the Boolean model [1], [4].

The objective of this paper was to assess land suitability for sorghum in the north-western region of Jeffara Plain, Libya, using FAO crop specific land suitability classification for sorghum and Multi- Criteria Decision Analysis approaches with fuzzy set models in GIS context.

II. Background

A. Boolean Logic Theroy

Boolean logic was introduced by the English mathematician and logician, George Boole. It has been mostly used where the attribute of any cell can only be an integer, 1 (True) or 0 (False), and the boundaries between these integers or classes are clearly defined. The Boolean method takes no account of measurement errors or uncertainties; because it is inflexible for estimating real ambiguity [15].It takes no consideration of partial membership of an object in a set [16].

B. Multi-Criteria Decision Analysis Approches

Multi- criteria decision analysis approaches tackle real world problems that are multi-dimensional in nature. MCDA is used to combine qualitative and quantitative criteria and to specify the degree and nature of the relationships between those criteria in order to support spatial decision-making. In a GIS context MCDA is used to combine layers of spatial data representing the criteria in the model.

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The model specifies how the layers are combined, for example the relative weighting given to each individual criterion, and how the data are combined [10]. It is argued that the combination between GIS and MCDA gives the decision makers support in all steps of decision making [17].

The Analytical Hierarchy Process **(**AHP) method is one of the MCDA approaches and it was applied to derive land suitability model for sorghum in this paper. The AHP was developed by [21] and it seeks to consider the context of the spatial planning decision, identifying and arranging the criteria into different groups [5], [18]. It has three major steps:

1) Develop the analytical hierarchy process procedure: At this step the most and least important elements of the decision problem should be defined and entered into the AHP procedure.

2) Perform a pairwise comparison of decision elements**:** The pairwise comparison is considered the fundamental input for the AHP method. The pairwise comparisons matrix was developed by [21] in the context of the AHP procedure. It is based on forming judgments between two particular criteria rather than attempting to prioritize an entire list of parameters [21], and is designed to determine the weights of criteria for the parameters of a composite suitability map layers. It includes three main stages [13], [20].

Stage 1: The first step is developing the pairwise comparison matrix by using scale ranges from 1 to 9: equal importance, equal to moderate importance, moderate importance, and moderate to strong importance, strong importance, strong to very strong importance, very strong importance, very to extremely strong importance and extreme importance.

Stage 2: The second step comprises three main operations: (A) add the values in columns of the pairwise comparison matrix; (B) divide each element in the pairwise comparison matrix by its column total; and (C) calculate the average of the elements in each row of the standardized matrix: i.e., divide the sum of standardized scores for each row by the number of variables.

Stage 3: The final step comprises the calculating of the Consistency Ratio of the pairwise comparison matrix. The Consistency Ratio is a measure of how much difference is acceptable and must be ≤ 0.1.

3) Construct an overall priority rating**:** At this step the composite weights are created. The composite weights are derived by multiplying the relative weights matrix at each level of the hierarchy. The composite weights show the rating of alternatives with respect to the overall goal and also represent decision alternatives scores.

C. *Fuuzy Logic Theroy*

Fuzzy logic theory is preferred to Boolean logic for land suitability evaluation, because fuzzy approaches lead to estimates for land use suitability on a continuous scale and can therefore, be more informative than the Boolean classification. Land suitability based on fuzzy logic helps to cope with vagueness and uncertainty [2], [7], [8], [14]

In this paper, three fuzzy set models were used to create fuzzy membership values for land characteristics that affect the growth of sorghum in the study area. According to [12], these models are:

1) An asymmetrical left model "(1)" is used when decreases in quality function of the criteria improves the suitability.

$$MF\ (xi) = [1/\{1 + 1/d^2\ (x - b)^2\ \}] \quad (1)$$

2) An asymmetrical right model "(2)" is used when increases in quality function of criteria decreases the suitability.

$$MF\ (xi) = [1/\{1 + 1/d^2\ (x + b)^2\ \}] \quad (2)$$

where is d is the width of the transition zone, while b is for an ideal point level and χ is the value of land characteristics.

3) A symmetrical or optimum range model "(3)" is used when suitability is indicated by being within a range or plateau of values.

$$MF\ (xi) = 1\ if\ (b_1 + d_1\ ) \leq \chi_i \leq (b_2 - d_2\ ) \quad (3)$$

where is d is the width of the transition zone, while b_1 and b_2 are for an ideal point level and χ is the value of land characteristics.

III. Materials and Methods

The study area is sited within north-west of Jeffara Plain region, Libya and it is located between Tripoli and the AZ-Zahra city; between longitudes 12° 45' and 13° 15' east and latitudes 31° 52' and 32° 52' north; and has total land area of about 309, 396 hectares (Fig. 1).

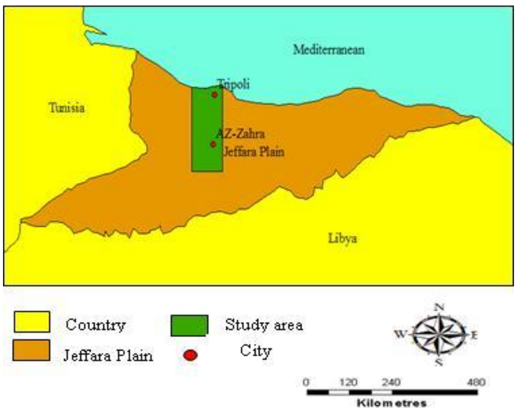

Fig. 1. Study area location

The mean annual rainfall in the area is 200 mm whilst mean annual temperature is 19.33 C°. The area has Mediterranean climate and arid climate. Aridsols and Entisols are the major soils in the study area [12].

IV. Land Suitability Evaluation Models for Sorghum

Land suitability evaluation model for sorghum in the study area are divided into main four steps. These steps are:

A. Factors Affecting Sorghum Prroduction in the Study Area

Land characteristics affecting the growth of sorghum crop was defined on the basis of literature reviews [7] and discussions with relevant experts. These factors include physical and chemical soil characteristics, soil erosion, slope steepness and mean temperature in the growing season (Table I).

TABLE I: LAND SUITABILITY CLASSES AND THEIR THRESHOLD VALUES FOR SORGHUM

	Suitability classes[1]			
Land Characteristics	S1	S2	S3	N1
Mean temperature in the growing season	24-30	20-24	15-20 24-35	< 15, > 35
Rootable depth(cm)	>80	80-50	>50-30	<30
Soil texture class	1	2	3	4
AWHC (mm/m)	>150	110-150	110-75	<75
Soil pH	>6-8	>5.5-8	5-5.5	< 5.0, > 8.5
% organic matter	>1.5	>1-1.5	1-0.5	> 0.5
CEC (me/100g soil)	>16	> 8–16	5-8	<5
soil salinity (EC)	0 – 6.8	>6.8 -8.4	>8.4 -10	> 10
Soil Alkalinity (%ESP)	0-10	10-20	20-30	>30
% $CaCO_3$ in root zones	0-15	15-20	20-35	>35
% stones at surface	0-3	3-9	9-20	>20
Soil drainage classes (mm/h)	>125	125-42	42-17	<17
Infiltration rate (mm/h)	>12	>8	>6	<6
% slope steepness	0-2	> 2-4	>4-8	> 8
Soil erosion (classes)	N	S	M	H

Suitability classes[1]: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and currently not suitable (N1). Soil texture classes*: (1) silt, silty clay loam, clay, loam, clay loam; (2) sand clay, sandy, clay loam; (3) loamy sand; (4) sand. Soil Erosion classes*: (N) no erosion, (L) low or slight erosion, (M) moderate erosion, (H) high or severe erosion.

B. Weighting Factors

Weights for the model criteria were obtained using the pairwise comparison analysis. The pairwise comparison analysis was selected because it allows the decision makers to assign different levels of importance to the different factors involved in land suitability. Different weights were assigned to land properties and these weights resulted from discussion with local experts (Table II). The weights used for the pairwise comparison analysis have a consistency ratio (CR) ≤ 0.1. The consistency ratio ≤ 0.1 shows that the comparisons of land characteristics were perfectly consistent, and the relative weights are appropriate for use in land suitability evaluation for sorghum.

C. Boolean Land Suitability Model for Sorghum

The FAO framework for land evaluation based on Boolean theory for the study area selected under irrigation conditions has been divided into five main steps in this work. These steps are:

1) Generation of suitability map for soil characteristics.
2) Generation of suitability map for topography.
3) Generation of suitability map for climate.
4) Generation of suitability map for erosion.
5) Using weighted overlay technique to produce the final land suitability map.

D. Fuuzy-Mcda Land Suitability Model for Sorghum

The Fuzzy MCDA approach was dived to four steps:

1) Hierarchical organization of the land characteristics for sorghum production (Fig. 2).

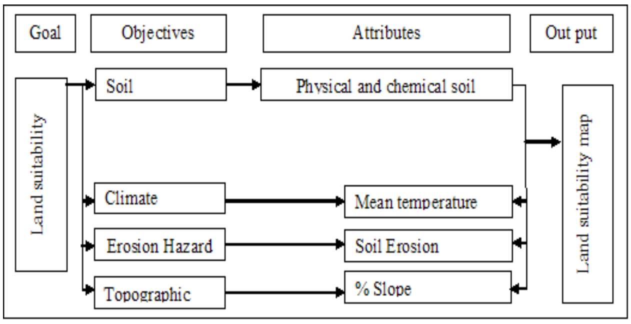

Fig. 2. Hierarchical organizations of the land characteristics for sorghum production.

2) Normalization or standardization land characteristics using fuzzy set models.
3) Generation of the weighted criterion map layers.
4) Generation of the overall land suitability map layers.
5)

V. RESULTS

A. Weighting Factors Results

The results showed that soil characteristics have higher weights than climate, erosion and slope and therefore soil characteristics measured the main significant parameters in the study area. The accuracy of these weights is mainly dependent on local staff experience (Table II).

TABLE II: THE WEIGHTS (EIGEN-VALUES) FOR THE SORGHUM

Land characteristics	Weights / eigenvalues for the sorghum
Soil characteristics	0.75
Climate	0.20
Erosion	0.04
Slope	0.01

The weights used for the pairwise comparison analysis have a consistency ratio (CR) ≤ 0.1. The consistency ratio ≤ 0.1 shows that the comparisons of land characteristics were perfectly consistent, and the relative weights are appropriate for use in land suitability evaluation for sorghum.

B. Boolean and Fuzzy Mcda Results

The results indicated that the area under consideration has good potential for sorghum production when the Boolean logic is applied, while the Fuzzy MCDA approach showed that no locations in the study area is mapped with highly suitable; areas which are highly suitable (1) (TABLE III and IV).

TABLE III: SUITABILITY RESULTS FOR SORGHUM USING BOOLEAN MODEL

Suitability Class	Overall suitability	
	Ha	%
S1 (Highly suitable)	139650	45.1
S2 (Moderately suitable)	106879	34.5
S3 (Marginally suitable)	28413	9.2
N1(currently not suitable)	18930	6.1
No data	15524	5.0

TABLE IV: SUITABILITY RESULTS FOR SORGHUM USING FUZZY MCDA MODEL

Suitability Class	Overall suitability	
	Ha	%
0.0 – 0.10	0.0	0.0
0.10 – 0.20	0.0	0.0
0.20 – 0.30	0.0	0.0
0.30 – 0.40	1840	0.6
0.40 – 0.50	20593	6.7
0.50 – 0.60	75999	24.6
0.60 – 0.70	182077	58.8
0.70 – 0.80	2129	0.7
0.80 -0.90	11234	3.6
0.90 – 1.0	0	0.0
No data	15524	5.0

The comparison between the Fuzzy MCDA and Boolean methods shows that each suitability class from the Boolean method is associated with high and low membership function values. The variability of the range of the MFs comes from the variation of the membership function values (Fig. 3).

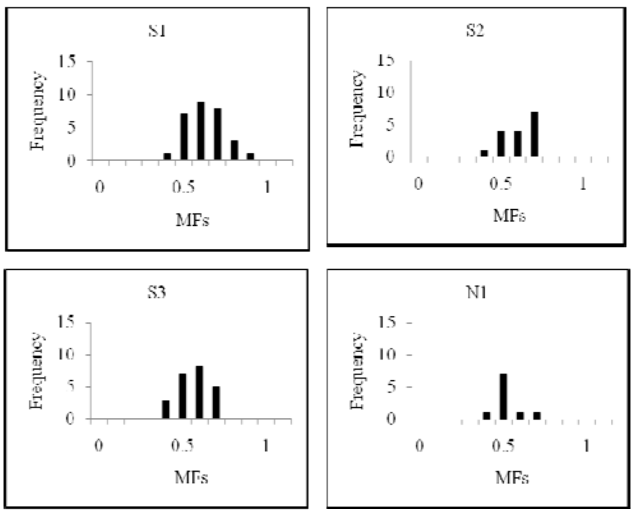

Fig. 3. The range of the overall suitability derived from the application of the Fuzzy MCDA approach for sorghum, classified for each suitability class (S1, S2, S3 and N1) as mapped by the Boolean method

VI. DISCUSSION

According to the decision of the local expert's, soil criteria are the most important parameters in the suitability classification for sorghum in the study area. Therefore, the local experts assigned larger weights to soil parameters than climate, slope and erosion. The results of the Boolean model depend on the rules which can simply be applied in GIS environment and this is in agreement with [9]. Consequently, eigen-values given in Table II, which have been given to thematic maps on the basis of the weighted overlay function, were utilized to create the overall land suitability classes for sorghum. This means application of Boolean model to land evaluation model which was used in this study is not a straightforward procedure. The problem that land characteristics under the application of the Boolean method may have the same eigen-values, as many authors discussed, can be sorted out by given different weights based on local opinion to different thematic maps and this is also in agreement with [2],[[12].

The problem of land characteristics associated with the use of Boolean model having the same eigen-values is easy to resolve, as discussed earlier, but the main problem in the application of the Boolean model, as many researchers reported [1], [14], [15] is that it failed to classify the values close to class boundaries. As a result, this paper adapted the Fuzzy MCDA method to the model of land suitability evaluation for sorghum in the study area.

The results of the Fuzzy MCDA revealed that no location in the study area selected was classified with suitability classes equal to 1. In the Fuzzy MCDA approach, number of land characteristics has been assigned with membership function values equal to 1. The Fuzzy MCDA approach is not only based on the membership function values assigned to the thematic map layer, but also to the weights given to each thematic map layers. This means that the Fuzzy MDCA approach reveals the interaction between the fuzzy membership function values and the weights for the selected land properties for the sorghum, and does not only reveal the fuzzy membership function values for sorghum.

The main advantages resulting from the use of the Fuzzy MCDA approach to land suitability evaluation in the study area are the capability to describe the uncertainties associated with describing the phenomenon itself and the capability to take into account the effect of land characteristics which happen to have values close to class boundaries. Another advantage found in this paper is that all land properties that affect sorghum production are very well-organized in the hierarchy, and this has facilitated the incorporation of expert knowledge into the model of decision making (i.e. Fuzzy MCDA). More so, the results were derived as a continuous classification, which is considered a more realistic classification in nature.

VII. CONCLUSION

The results of land evaluation derived from the use the Boolean model indicated that the most locations of the study area was mapped as highly suitable for sorghum, while with Fuzzy MCDA classification few locations highly suitable have been mapped for sorghum. In land suitability evaluation using Boolean model, only one low factor is sufficient to decrease the suitability of lands from highly suitable classes to not suitable classes (N1). Land criteria in land suitability evaluation using Boolean model may have the similar eigenvalues and this will create the classification quite strict.

An alternative to ovoid this problem is to apply the Fuzzy MCDA approaches. The Fuzzy MCDA can deal perfectly with the case of land suitability analysis by assigning different weights to the parameters according to their importance for the suitability.

From this work a number of conclusions can be reported. First, land characteristics affecting sorghum production was very well organized into the hierarchy to fit into the framework of decision-making. Second, the use of the Fuzzy MCDA approaches facilitated the integration of expert knowledge into the model of land suitability evaluation. Third, weighting of the factors was made according to their relative importance taking the crop requirement for sorghum under local conditions into consideration. Fourth, in place of deriving land suitability classes as Boolean classification (i.e. S1, S2, S3 and N1), the Fuzzy MCDA outcomes in continuous classification and this is a more realistic in nature.

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