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Published online: 16 May 2017.

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SOIL & CROP SCIENCES | RESEARCH ARTICLE

Sustainability of wheat production in Southwest Iran: A fuzzy-GIS based evaluation by ANFIS

Ehsan Houshyar[1]*, Pete Smith[2], Mahmood Mahmoodi-Eshkaftaki[1] and Hossein Azadi[3]

Abstract: The sustainability of agricultural production is one of the most important issues in today's farming. A combination of analytical hierarchy process and fuzzy modeling was used with the combination of geographical information system (GIS) to develop a reference base that evaluates sustainability of winter wheat within the Fars province, Iran. Bio-physical (soil and climatic, agronomic, and machinery), and socio-economic factors (benefit-cost ratio, farmers' knowledge and experience) were taken into consideration in the assessments. Results showed that amongst bio-physical, soil salinity and annual precipitation were the main obstacles of the sustainable production. The total land suitability scores represent "medium" to "very high" levels of sustainability. The highest sustainability score was obtained from the socio-economic category, followed by machinery and agronomic categories. Over-fertilization and high water consumption were found as the main reasons of low agronomic sustainability. Almost all the sustainability scores were higher in the central region of the study area while the overall sustainability was "medium" in more than half of the area. The extension trainings, prevention laws and government provided credit to buy necessary farm machines are recommended to reduce fertilizer, pesticide and water consumption. The results also showed that larger farm sizes, coupled with suitable farm machinery, particularly on smaller farms are expected to enhance machinery sustainability scores. The study also concluded that ANFIS is as a capable tool to predict sustainability indices obtained from GIS. The developed ANFIS models could estimate sustainability indices with minimum errors to be amended by GIS.

ABOUT THE AUTHORS

Ehsan Houshyar's team specialises in agricultural sustainability, greenhouse gas emissions, bioenergy and energy use in agriculture.

Pete Smith's team specialises in environmental modelling with a particular focus on soils, agriculture, land use, sustainability, greenhouse gas emissions, climate change, food security, bioenergy and ecosystem services.

PUBLIC INTEREST STATEMENT

The sustainability of agricultural production is one of the most important issues in today's farming. We used computer modelling techniques to assess the environmental and socio-economic sustainability of winter wheat in the Fars province of Iran. Soil salinity and annual rainfall were found to be the main obstacles to sustainable production, with over-fertilization and high water consumption found to be the main reasons of low sustainability. Larger farm sizes, coupled with suitable farm machinery, particularly on smaller farms, would enhance machinery sustainability scores. We found that sustainability could be improved by extension training, stronger regulation and provision of government credit to purchase farm machinery which would enable a reduction in fertilizer, pesticide and water consumption.

1. Introduction

Sustainability in agriculture is critical since it guarantees continued food production for the growing population (Cahya, 2016; Pretty, Toulmin, & Williams, 2011). However, it can be a vague term which could be considered as almost too complex to measure. The vagueness has led to a multitude of definitions instead of a clear and comprehensive definition (Sabiha, Salim, Rahman, & Rola-Rubzen, 2016). Although the sustainability concept includes many dimensions, two main dimensions are generally considered for it as "bio-physical" and socio-economic (Larson et al., 2011; Pearson, Pearson, & Pearson, 2011). A comprehensive indicator should include all these dimensions, besides managing the embedded uncertainties. Adding further to this complex task, these functions can be analyzed and evaluated at a wide range of analytical scales, ranging from global to individual farms households (Borrelli, 2016). Given diverse farming conditions, a developed indicator for a given country may not be applicable to others. In other words, specific local indicators are necessary for different regions to represent the sustainability status (Hayati et al., 2010).

Wheat is a strategic crop in Iran, mainly used for flour and bread production. The average annual area of planted cereals is around 9,000,000 hectares (70%), of which wheat occupies 6,200,000 ha (69%) in 2015 (Ministry of agricultural-Jihad, 2016). Iran has predominantly relied upon the importation of wheat for decades (FAO, 2015). Although wheat is a staple crop in Iran, the sustainability of the crop has not yet been clearly evaluated in the country. Consequently, the main goal of this study is to determine the sustainability of wheat production considering both bio-physical (agronomic, machinery, soil and climate) and socio-economic (benefit- cost ratio, farmers' knowledge and experience) factors. To achieve the goal, a decision-making technique known as analytical hierarchy process (AHP) and fuzzy modeling are integrated in the Geographic Information System (GIS) to obtain appropriate scores indicating the sustainability status of the wheat production. In addition, an adaptive neuro-fuzzy inference system (ANFIS) is employed to infer sustainability indices from GIS.

1.1. Why using fuzzy logic, AHP and GIS?

Sustainability assessments may contain errors or uncertainties, based on the attributes and methods employed (An et al., 2017; Arodudu, Helming, Wiggering, & Voinov, 2017). In the non-stochastic method, for instance, the errors in measuring attributes and uncertainty about the relationship between attributes cannot be considered. Despite the better accounting for errors in measuring attributes in the stochastic method, it needs the probability distributions of attributes (Prato, 2009). Fuzzy logic is one of the most useful methods to manage these limitations, especially uncertainties in sustainability measurements (Lamastra, Balderacchi, Di Guardo, Monchiero, & Trevisa, 2016). This concept implies that the line between "yes" and "no" or "good" and "bad" is not very strict. The fuzzy technique, developed by Zadeh, Fu, Tanaka, and Shimura (1975), as a practical and flexible method, is mainly used in studies including ill-defined and vague components like sustainability assessments (Houshyar et al., 2014; Joolaie, Abedi Sarvestani, Taheri, Van Passel, & Azadi, 2016). Thus, a vague term such as sustainability can be more effectively dealt with by application of fuzzy modelling. Besides, GIS has increasingly been used in sustainability assessments due to certain capabilities as: (1) The sustainability criteria from several pillars with different weights, i.e. social, economic and environmental factors can be integrated into its software (Graymore, Wallis, & Richards, 2009; Leman, Ramli, & Khirotdin, 2016), (2) The specific data and detailed information regarding one or more locations can be visualized and overlaid in the GIS in such a way that geographical changes are easily understood by regional managers and decision makers (Hellwig et al., 2017), and (3) GIS also allows us to find out what is happening inside a specific area or areas within close proximity (Wang et al., 2013).

Sustainability includes not only the environmental aspects but also the economic and social aspects. The significance of each of the aspects regarding sustainability is not equal. In other words,

different aspects have different impacts/weights on sustainability. Accordingly, the weight of each factor considered in this study is determined using the AHP technique. AHP is a decision-aided method to handle multi-criteria decision-making which de-composes a complex multi-factor problem into a hierarchy structure, while each level is composed of specific elements (Craheix, Angevin, Doré, & de Tourdonnet, 2016; Pandey & Kumar, 2017). Indeed, the capability of AHP is used to determine the suitable weights of factors considered in this study. GIS is mainly applied to combine and visualize different special data in which the power of fuzzy logic is employed to manage the uncertainties in the sustainability evaluations.

1.2. Why using ANFIS?

The integration of different maps in GIS can show the border of the sustainable area in a given region. However, it is a time-consuming process especially when other methods like fuzzy and AHP are applied in GIS (Ma & Cheng, 2016). Accordingly, ANFIS is employed to examine whether or not the sustainability indices which are determined by GIS can be estimated.

ANFIS is a powerful tool to predict one or more outputs according to one or more inputs in a learning procedure. The basic principles of ANFIS is not described in details here, but the details can be found in Bektas Ekici and Aksoy (2011). In brief, ANFIS uses a combination of the best features of fuzzy logic systems and neural networks. This system consists of if-then rules and uses neural network learning algorithms in a training process. Five layers are used in a typical ANFIS system to predict outputs. The first layer contains fuzzy membership functions. Each node of this layer stores the parameters to define a bell-shaped membership function. The mathematical multiplication is employed in the second layer which is known as "firing strengths of the rules". Each node of this layer acts as the connective operation "AND" within the rule antecedent to determine the corresponding firing strength. The normalization of the firing strengths is done by the nodes of the third layer. The output of layer four is the linear combination of the inputs multiplied by the normalized firing strengths. The node of this layer is adaptive with output. Layer contains the final output which is the weighted average of all rule outputs (Bektas Ekici & Aksoy, 2011). The main advantage of this system is that it can overcome the drawbacks of fuzzy logic (to determine correct membership functions and rules in a time-consuming procedure) and neural networks (difficulties in determination of proper size and optimal structure of the neural net, and in manipulating parameters for learning and convergence). Thus, ANFIS is employed to estimate sustainability indices of agronomic, machinery and socio-economic factors. In other words, it simplifies the procedure of using GIS, AHP and fuzzy logic to obtain sustainability indices.

2. Methodology

The sustainability of irrigated wheat production was measured in the farming year 2015 in the central region of the Fars province, Southwest Iran. This region was chosen since it contains the best-irrigated wheat production area in the country with the highest average yield of 5–6 ton/ha (Ministry of agricultural-Jihad, 2016).

Using a simple random sampling method without replacement, 350 farmers were selected for the study from a total of 3,935. The required sample size was calculated by Equation (1) (Amidi, 2005):

$$n = (N \times Z^2 \times p \times q)/(N \times d^2 + Z^2 \times p \times q) \tag{1}$$

where, n is the required sample size, N is the number of holdings in target population, Z is the reliability coefficient (1.96 which represents the 95% reliability), p is equal to 0.5, q is equal to 0.5, d is the precision ($\bar{x} - \bar{X}$) which is equal to 0.05 in this study.

The necessary data was gathered through face-to-face interviews using several questionnaires (open and close ended). The questions related to the agronomy, machinery and socio-economic factors (see Section 2.1.1) were embedded within the questionnaires. The validity of the questionnaires was assessed by a panel of agricultural experts affiliated with either universities or agricultural

organizations. The reliability of the questionnaires was assessed using Cronbach's alpha coefficient. Revising the questionnaires, all of the final coefficients were estimated above 0.81 which confirmed the *highly reliable* questions of the questionnaires.

2.1. Sustainability assessment using AHP, GIS and fuzzy modeling

2.1.1. The AHP and GIS
The sustainability of wheat production was determined considering five main criteria, i.e. soil, climate, agronomy, machinery and socio-economic factors. Each criterion contained several factors (Figure 1) as follows:

(a) Soil factors: (1) salinity (ds/m), (2) alkalinity (%) and (3) depth (m),

(b) Climatic factors: (1) mean annual precipitation (mm/year) and (2) mean temperature of the growing cycle (°C),

(c) Agronomic factors: (1) fertilizers (kg/ha), (2) agrochemicals (kg/ha), (3) water (m^3/ha) and (4) yield (kg/ha),

(d) Machinery factors: (1) fuel consumption in farm operations (L/ha), (2) total waiting time for farm operations (day) and (3) farm size (ha),

(e) Socio-economic factors: (1) farmers' knowledge, (2) farming experience (year) and (3) benefit to cost (B/C) ratio.

To analyze soil suitability, a basic soil map (1:25,000) containing 356 sampling points from the Fars Agricultural Organization, covering 1,453 km^2 (145,300 ha), was used. This detailed soil map was essential to provide valid sustainability indices. The climatic data were obtained from four meteorological stations in the region. The other data used in the study was gathered from the farmers via face-to-face interviews. To evaluate farmers' knowledge, a questionnaire containing 10 questions related to agricultural sustainability was designed. The farmers were asked to answer the questions using a five-point Likert scale (ranging from "very low" "low", "medium", "high" and "very high"), respectively (Likert, 1961). Therefore, the knowledge score ranged between 5 and 50. As Figure 1 shows, the criteria and sub-criteria are put into a hierarchical structure. A layer was developed in GIS for each factor. The soil criteria, for instance, included three layers, i.e. salinity, alkalinity and depth. The geospatial data related to each factor was converted to grids (25 × 25 m^2) by interpolation. The new grid layers were then fuzzified based on the experts' knowledge as described in the next section. Afterwards, the fuzzified layers were integrated to reach the final criteria maps.

A primary sustainability index was obtained from each factor which led to the 15 sustainability indices from all the factors (sub-criteria). Next, five secondary sustainability indices were obtained from the five main criteria. The main land suitability index was assessed by combination of the soil and climatic suitability indices. Finally, the total sustainability index was developed by combination of the land suitability index and agronomic, machinery and socio-economic indices, that represents the total sustainability of wheat production. To find the suitable weights the AHP technique was used by asking 26 agricultural experts affiliated with either universities or agricultural organizations to make the pairwise comparisons between the criteria and sub-criteria. Almost all experts that were available in the region participated in the study without sampling. The experts' knowledge can be considered as a valuable source of knowledge to support environmental monitoring (Giordano & Liersch, 2012). Experts are those who are best placed to assess ecological changes and contribute relevant information and actions to solve environmental problems (Azadi, Shahvali, van den Berg, & Faghih, 2007; Hambly & Angura, 1996). The comparisons were done using a standard scale developed by Saaty (1994): 1 = equal importance; 3 = moderate importance; 5 = strong importance; 7 = very strong importance; 9 = extreme importance, and 2, 4, 6, and 8 as intermediate values to reflect compromise.
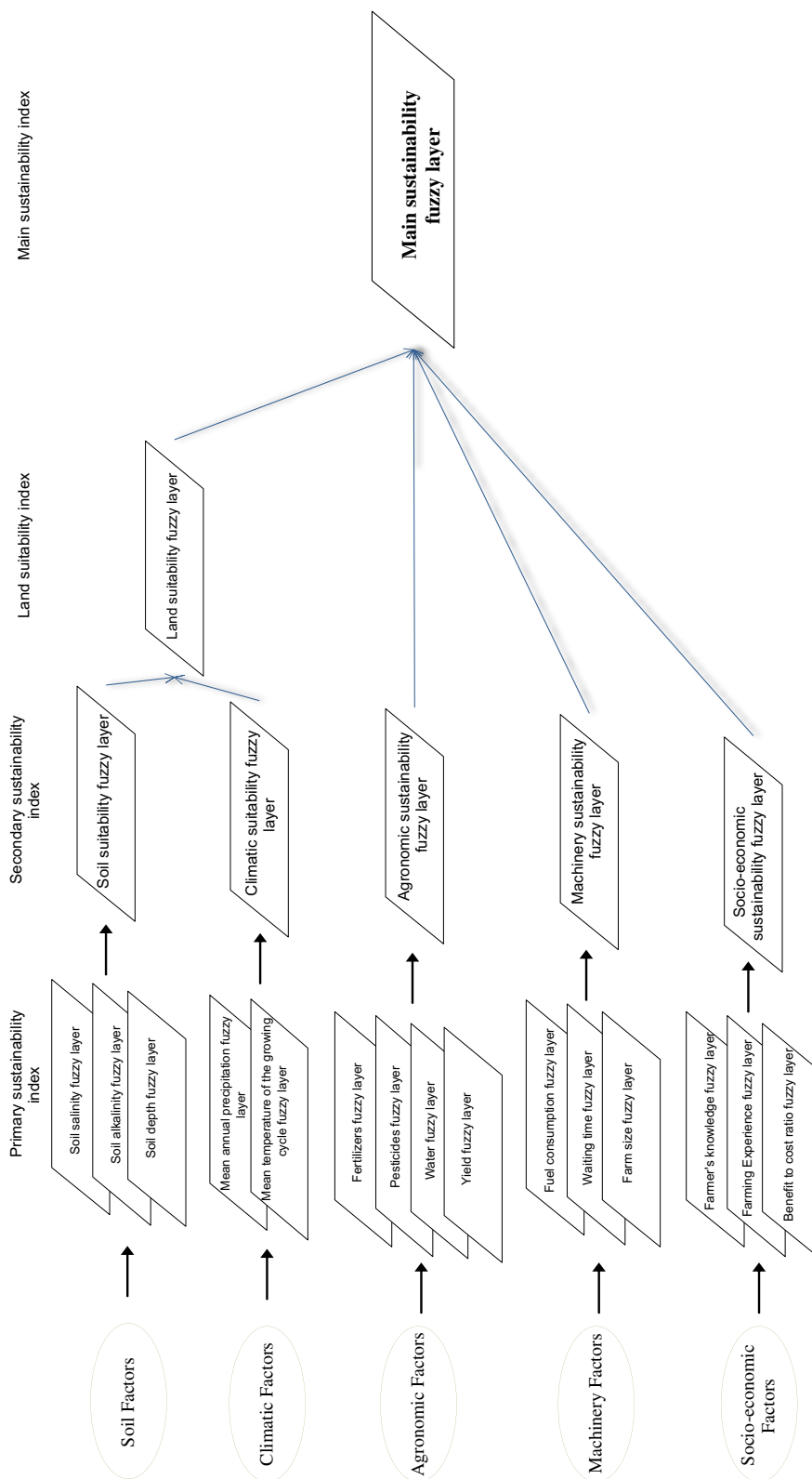
Figure 1. The schematic diagram of modeling procedure used in wheat sustainability evaluation.

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	Factor	Unit	Most suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Currently not suitable (N1)	Not suitable (N2)
Table 1. The ranges of suitability classes for wheat production							
Soil factors	Salinity	ds/m	0–4	4–6	6–8	8–12	>12
	Alkalinity	%	0–15	15–20	20–25	–	>25
	Depth	cm	75–>100	50–75	25–5	–	<20
Climatic factors	Total annual precipitation	mm/year	>1,500	1,200–1,500	700–1,200	–	<700
	Mean temperature of the growing cycle	°C	18–32	16–18	14–16	–	<14
				32–35	35–40		>40

To avoid inconsistent pair-wise comparisons, the inconsistency index was evaluated, which should be lower than 0.1 (Diaz-Balteiro, González-Pachón, & Romero, 2017; Saaty, 1980). Gathering pair-wise comparisons, the weight of each factor was calculated by Criterium Decision Plus (version 3. 0, Info Harvest Inc., USA). Applying the weights to the layers, each grid layer was calculated as $grid_i \times weight_i$ and the final layer as $(\sum(grid_i \times weight_i))$ (Çetinkaya, Özceylan, Erbaş, & Kabak, 2016). The equation for the final machinery layer, for instance, is:

$$\sum(grid_i \times weight_i) = (grid_{Fuel} \times weight_{Fuel}) + (grid_{Waiting\,Time} \times weight_{Waitinf\,Time}) + (grid_{Farm\,Size} \times weight_{Farm\,Size})$$

(2)

2.1.2. Fuzzy modeling in the GIS

To fuzzify the layers in GIS, the fuzzy modeling toolbar in ArcGIS 10 was used. Linear fuzzy modeling was applied by using experts' knowledge. To do so, the agricultural experts were asked to define minimum and maximum values of each factor to define the linear fuzzy function, assuming that the sustainability index of the farm size lower than 3 ha is 0, and higher than 10 ha is 1. Thus, the corresponding fuzzy function is:

$$\mu(SI_i) = \begin{matrix} 0 \\ \frac{FS-3}{7} \\ 1 \end{matrix} \begin{cases} IF & FS \leq 3 \\ IF & 3 \leq FS \leq 10 \\ IF & FS \geq 10 \end{cases}$$

The function also shows that the sustainability of 6.5 and 8 ha is 0.5 and 0.714, respectively. By this fuzzification, all the values are between zero and one. Applying the similar procedure, the fuzzy functions of all the factors were defined. To fuzzify soil and climatic factors, the FAO standard (Sys, Ranst, Debaveye, & Beernaert, 1993) was used (Table 1). This standard defines five classes of suitability, i.e. most suitable (S1), moderately suitable (S2), marginally suitable (S3), currently not suitable (N1) and not suitable (N2). The experts defined the linear fuzzy functions and controlled the outputs based on the given standard. It is expected that the most "suitable" condition would lead to the most "sustainable" production. The standard given by International Union for Conservation of Nature and Natural Resources (IUCN, 2001) was employed in which the domain of sustainability can be considered as:

- 0 to 0.2: very low (unsustainable),
- 0.2 to 0.4: low (almost unsustainable),
- 0.4 to 0.6: medium (moderately sustainable),
- 0.6 to 0.8: high (almost sustainable),
- 0.8 to 1: very high (sustainable).

After fuzzification, the result of the GIS was controlled by the experts for their final confirmation (Zhang, Su, Wu, & Liang, 2015). Some factors like farmers' knowledge and experience are totally subjective and needed experts' control, which is called "expert validation". In other words, these factors cannot be tested against real data to find what experience or knowledge is sustainable or unsustainable. Some other factors like fertilizer or water consumption can be tested in the field to determine the most sustainable consumption. Nonetheless, performing this task is not feasible in most agricultural studies and experts' validation is needed (Sattler, Stachow, & Berger, 2012). Accordingly, in the current study, all the outputs were controlled by the experts for the final revision and confirmation. At last, a total consensus of 96% was obtained from the experts' final check.

2.2. Sustainability forecasting using ANFIS

The main purpose of developing an ANFIS model is the prediction of sustainability indices obtained from GIS analyses. In GIS, one sustainability index was obtained from each criterion and a final index was obtained in the second step. Accordingly, five primary ANFIS models for prediction of primary sustainability indices of five criteria (i.e. soil, climate, agronomy, machinery) and socio-economic factors (benefit- cost ratio, farmers' knowledge and experience) were developed (Figure 2). The ANFIS models were developed and trained to predict sustainability index based on the given inputs. The input of each ANFIS model is the factors described in Section 2.1. For instance, the inputs of agronomic ANFIS model is: (1) fertilizers (kg/ha), (2) agrochemicals (kg/ha), (3) water (m³/ha) and (4) yield (kg/ha), and the output is agronomic sustainability index which is calculated in the GIS.

An ANFIS model was designed for prediction of final sustainability index (Figure 2). The input of this model is the five sustainability indices from previous primary models. The total data from the farmers were divided into three parts: 70% for training, 15% for validation and 15% for the final test. The best model was chosen based on the result of the testing step. The performance of the best ANFIS models was examined using statistical parameters: root mean square error (RMSE) and correlation coefficient (R).

3. Results

3.1. The suitability of land for wheat production

The land suitability map (Figure 3), from the aggregation of final soil and climatic suitability maps shows that suitability scores are between 0.476 and 0.854; "medium" to "very high" sustainability levels. The scores in about 50% of the study area are 0.71 to 0.8, which indicate the "high" suitability of land for wheat production. It is noticeable that although the suitability of land affects the sustainability of wheat production, farmers have little control over these bio-physical factors.

The detailed reclassified soil and climatic maps from GIS are shown in Figures A1 and A2 in Appendix A. The soil salinity, alkalinity and depth maps reveal that around 70 to 99% of the area is highly suitable (0.91 to 1) for wheat production, whereas the most limiting factor is the soil salinity, mainly in the southwest and southeast areas. There are almost no limitations caused by soil alkalinity and depth. According to the experts' pair-wise comparisons, the three soil factors were aggregated with an equal weight to reach the soil suitability map. This map displays that the suitability scores of around 75% of the study area is between 0.81 and 1 that can be considered as "high sustainable".

The mean temperature map (Figure A2 in Appendix A) indicates that the suitability scores in around 90% of the area are between 0.61 and 0.9; "high" to "very high" sustainability level. However, the area is not in a suitable condition from the view point of precipitation since the suitability score in about 60% of the area is lower than 0.5. The highest and lowest precipitations are 528 and 226 mm/year (Table 2) in northwest and northeast areas, respectively. The low precipitation in the majority of the area suggests that the area is under the risk of water deficiency although suitable soil and mean temperature are available for wheat production. Currently, near to 90% of the farms use furrow irrigation systems using a well for each 3–6 ha. The application of modern irrigation systems
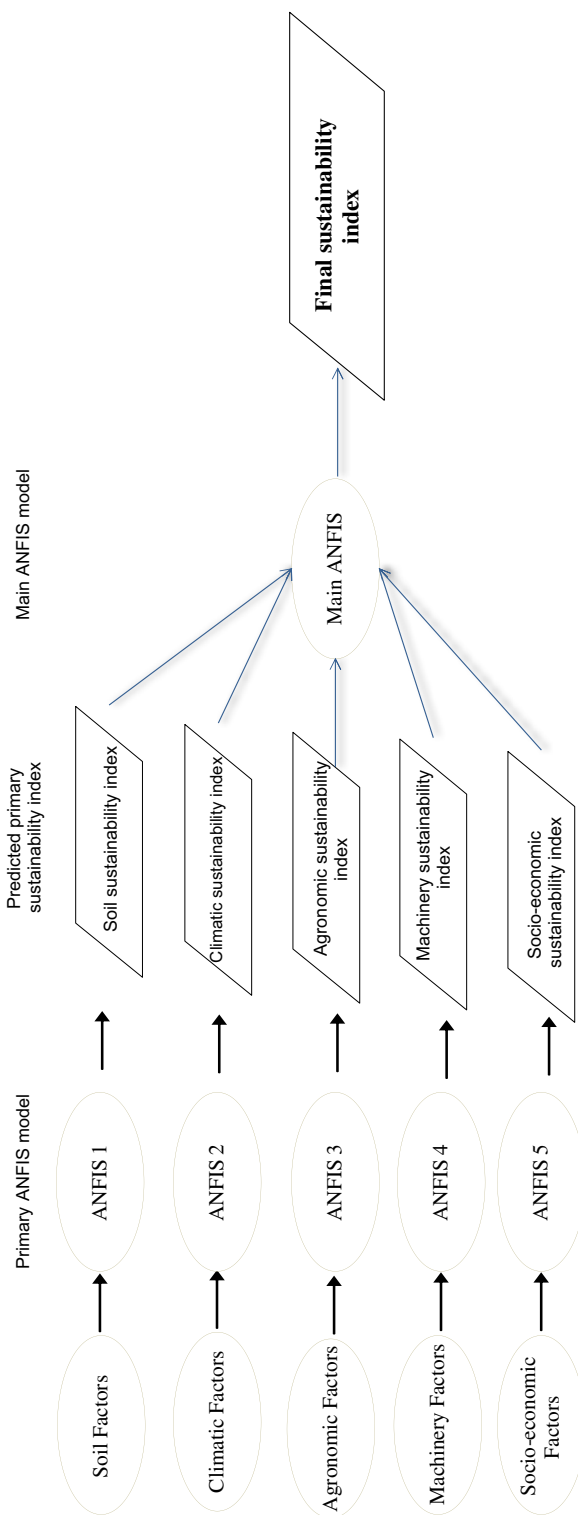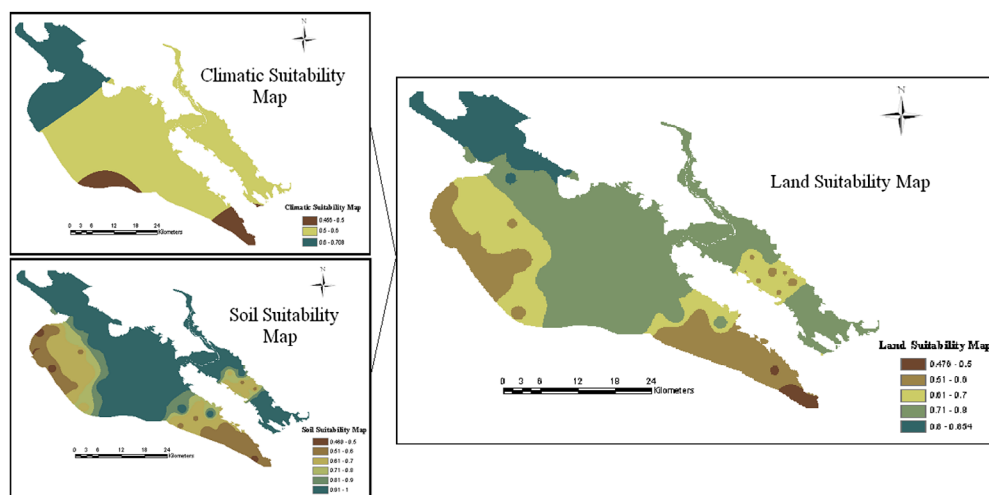
Figure 2. ANFIS models to predict sustainability index: Right shows the structure of scenario 1 and left shows the structure of scenario 2.

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Figure 3. The land suitability maps.

coupled to timely irrigation could substantially reduce water consumption and consequently enhance sustainability. The climatic suitability map shows that about 75% of the area is "moderately suitable" (0.51 to 0.6). It is clear that this map receives a negative impact from the precipitation map, because all the suitability scores in the mean temperature map are higher than 0.501.

3.2. Agronomic sustainability

The detailed agronomic sustainability map is shown in Figure A3 in Appendix A. The fertilizer sustainability map reveals that all the scores are between "very low" and "low" domains of sustainability (0 to 0.333). The farmers over-fertilize the crop since they use 250 to 450 kg/ha, mostly without considering soil samples to find the optimum amount of fertilizer to use. Due to the high price of soil sampling and laboratory analyses, 90% of soil sampling has been conducted every three or five years, usually with the financial support from the government. The data from the last year of soil samples show that the majority of farms need 150 to 270 kg/ha fertilizers, especially urea. It means that about 100 to 200 kg/ha extra fertilizer have currently been applied on the farms. Unfortunately, farmers tend to use large quantities of fertilizer, especially nitrogen, which is a harmful element to the environment and reduces the sustainability of production. Similar finding has also been reported with regard to production of some other crops, such as corn in Iran (Houshyar, Azadi, Almassi, Sheikh Davoodi, & Witlox, 2012).

Table 2. Inputs for and output of wheat farming		Min	Max	Average
Soil factors	Salinity	0	14	3
	Alkalinity	0	25	6
	Depth	60	135	126
Climatic factors	Mean temperature (°C)	12	17	14
	Precipitation (mm/year)	226	528	368
Machinery factors	Fuel (L/ha)	90	132	112
	Waiting time (day)	0	4	2
	Farm size (ha)	2	15	8
Socio-economic factors	Farmer's knowledge (from 50)	20	50	32.5
	Farming experience (year)	5	25	15
	Benefit to cost ratio (*B/C* ratio)	2.63	5.58	4.45
Agronomic factors	Fertilizers (kg/ha)	250	400	338
	Agrochemicals (kg/ha)	0.3	6	3
	Water (m³/ha)	5,000	9,100	7,103
	Yield (ton/ha)	2.14	7.8	4.35

Figure 4. The total sustainability map.
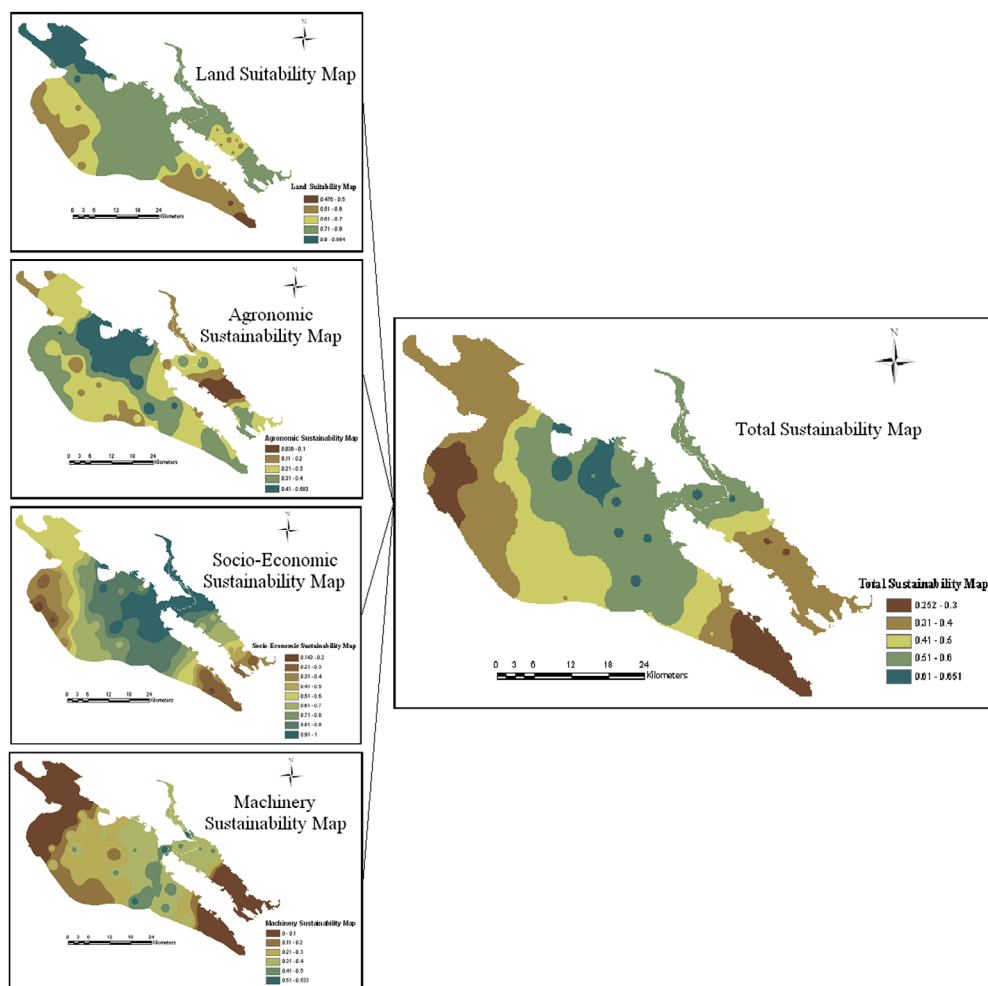
The agrochemicals map (Figure A3 in Appendix A) shows that farmers in the southwest, southeast and central regions use less agrochemicals and their sustainability scores are higher than 0.6. Less agrochemicals are applied in southwest and southeast farms, generally due to lower weed loads. However, more agrochemical machinery applicators are used in the central region, which seemingly leads to their efficient agrochemical use and lower waste, despite higher weed loads. The sustainability scores lower than 0.4 (low sustainability) indicate that agrochemicals are used extra in around 30% of the area. The detailed analysis showed that farmers use large amount of agrochemicals, mainly because they do not use suitable, precise farm machinery or equipment to apply agrochemicals properly. Furthermore, some farmers in the area are sufficiently wealthy to buy and waste large amount of agrochemicals carelessly.

The water sustainability map shows that water is used in "very low" domains of sustainability (0–0.2) in around 85% of the area. Currently, furrow irrigation systems are used in 90% of farms. Although farmers are eager to use modern irrigation systems, the financial situation inhibits them from applying modern, efficient irrigation systems like sprinklers. As discussed, the area is at risk of water deficiency based on the precipitation map. Accordingly, governmental financial incentives are necessary to help farmers apply modern irrigation systems.

The highest sustainability indices are found in central and northwest areas in terms of yield sustainability. This is reasonable since southwest and southeast areas contain lower indices, due mainly to soil suitability limitations (salinity and alkalinity). The average yield is 2 ton/ha lower than in China

(Zhen, Zoebisch, Chen, & Feng, 2006) and 1–3.5 ton/ha higher than India, Pakistan and Bangladesh (Ahmad, Chaudhry, & Iqbal, 2002; Rasul & Thapa, 2004; Yadav, Dwivedi, & Pandey, 2000), while the maximum yield is higher than these countries. A study in China showed that irrigation water, farm yard manure application, and total labor are the main factors that determine the yield of wheat (Zhen et al., 2006), whereas farm yard manure is often used for summer crops; tomato, cucumber and corn in Iran.

The final agronomic sustainability map indicates that the highest sustainability indices come from central areas; 0.41 to 0.583 which is a "medium" sustainability level (Figure 4). The score of 0.583, for instance, belongs to a typical farmer with fertilizers, agrochemicals, water and yield sustainability scores of 0.33, 0.96, 0.08 and 0.98, respectively.

3.3. Machinery and socio-economic sustainability

Figure A4 shows that wheat production is higher than the "medium" sustainability level with regard to farm size and waiting time factors. These two maps indicate that waiting time to finish farm operations is higher in smaller farms because most small-scale farmers hire farm machines, whereas larger farmers own the necessary farm machines and equipment (Rasouli, Sadighi, & Minaei, 2009). Nonetheless, the higher waiting time in eastern areas show that farm machines for the wheat production is currently inadequate, despite having larger farms. The sustainability of fuel consumption is "very low" almost all over the area, which suggests that farm machines may not be suitable. Currently, two main types of tractor are used for the primary (plowing and disking) and planting operations, i.e. 110–170 and 45–75 hp tractors, respectively. The data show that about 70% of the existing tractors are used with unsuitable equipment, which leads to higher fuel consumption. Moreover, high power tractors in smaller farms consumed higher fuel due to the short length of farms and more passes of the fields (Almassi, Kiani, & Lovimi, 2008).

The sustainability scores of factors: planting experience, agricultural knowledge and benefit to cost ratio are "high" to "very high" since all the scores are higher than 0.61 in around 80% of the area (Figure A5 in Appendix A). The average *B/C* ratio (Table 2) is similar to Indian farmers (Yadav et al., 2000). Comparing the planting experience and agricultural knowledge shows that highly experienced farmers in the northwest and southeast areas do not have a high level of agricultural knowledge. This highlights the necessity of extension programs to improve farmers' knowledge in these areas, while Shi and Gill (2005) found that the limited availability of information and low level of farmers' knowledge are barriers to the adoption of ecological agricultural practices. The lowest and highest *B/C* ratios are 2.63 and 5.58, respectively, whereas the lowest scores are obtained from the east and southwest areas. Nonetheless, the socio-economic sustainability is higher than agronomic and machinery sustainability, because all the scores are above "medium" (0.5) in around 85% of the area (Figure A5 in Appendix A).

3.4. The overall sustainability of wheat production

The combination of land suitability, agronomic, machinery and socio-economic sustainability maps is shown in Figure 4. The total scores are between 0.262 and 0.651 which shows a range of "low" to "high" sustainability levels, respectively, but the scores in the majority of area are 0.3 to 0.6. Despite relatively higher land and socio-economic sustainability scores, particularly in the central areas, the final map has some negative impacts from low agronomic and machinery sustainability levels. As a result, the scores in the majority of this area reach only 0.4 to 0.6; the "medium" domain of sustainability. Since soil and climatic characteristics are not under farmers' control, the socio-economic, and especially agronomic and machinery factors, need more attention to improve wheat production sustainability.

3.5. The evaluation of ANFIS models for prediction of sustainability indices

To achieve the best prediction results, several modifications were made via trial and error in the ANFIS models. MATLAB's ANFIS editor provides several fuzzy membership functions (MFs) including triangular, trapezoidal, generalized bell (Gbell) etc. Except in the case of socio-economic ANFIS

Figure 5. The structure of ANFIS model for prediction of machinery sustainability index.
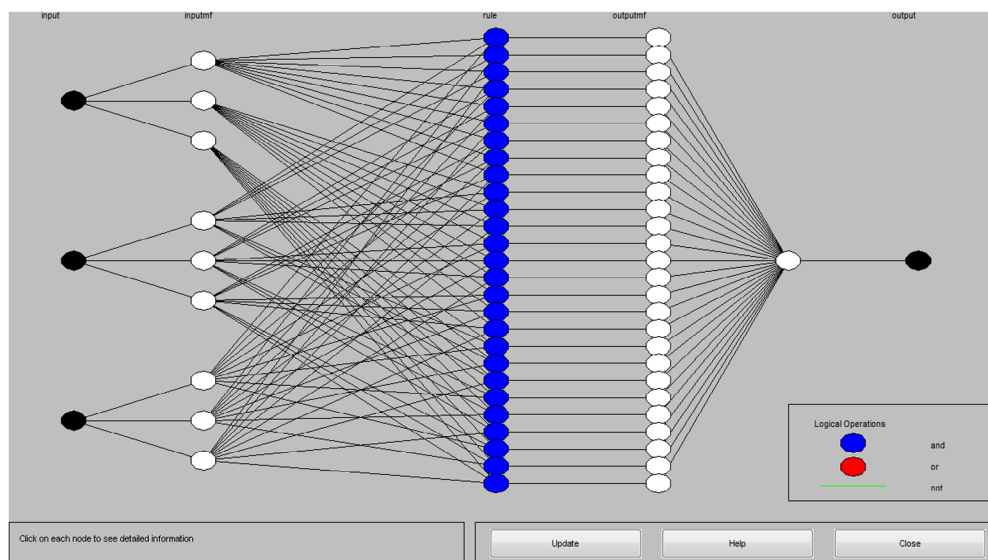
model, Gbell performs better than other MFs (Table 3). Yet, one of the most challenging modifications in an ANFIS model is the number of MFs for inputs and outputs. As described in Section 2.1.2, the sustainability index was considered in five domains based on IUCN's standard. However, four MFs were defined for the sustainability index in ANFIS model 6. With three MFs for inputs in ANFIS 1 to 5, best predictions which had least RMSE were obtained. The output was considered linear in all models. The learning algorithm was hybrid in all the models. This learning algorithm of ANFIS is composed of the use of a back-propagation learning algorithm and the least squares method together.

These modifications determine the final structure of an ANFIS model. The structure of ANFIS 3 has been shown in Figure 5 as an example which indicates that this model includes three inputs where each input have three MFs. A total of 27 rules are embedded in this model. The optimum number of epochs are 40 for all the models except in the model for the prediction of the main sustainability index which needs 60 epochs to reach the best predictions. Table 3 reveals that the lowest accuracy comes from ANFIS 1 for the prediction of soil sustainability index of $R^2 = 0.886$. The best forecast is obtained from machinery and main the ANFIS models of $R^2 = 0.956$ and 0.972, respectively. The graph of correlation between predicted and actual values of these two ANFIS models are shown in

ANFIS model	Type of MF	Number of MF	Epochs	Learning method	R^2	RMSE
Soil sustainability index (ANFIS 1)	Gbell	3, 3, 3	40	Hybrid	0.886	0.125
Climatic sustainability index (ANFIS 2)	Gbell	3, 3	40	Hybrid	0.899	0.114
Machinery sustainability index (ANFIS 3)	Gbell	3, 3, 3	40	Hybrid	0.956	0.056
Socio-economic sustainability index (ANFIS 4)	trimf	3, 3, 3	40	Hybrid	0.922	0.089
Agronomic sustainability index (ANFIS 5)	Gbell	3, 3, 3, 3	40	Hybrid	0.913	0.095
Total sustainability index (main ANFIS)	Gbell	4, 4, 4, 4, 4	60	Hybrid	0.972	0.043

Table 3. The characteristics of best examined ANFIS structures

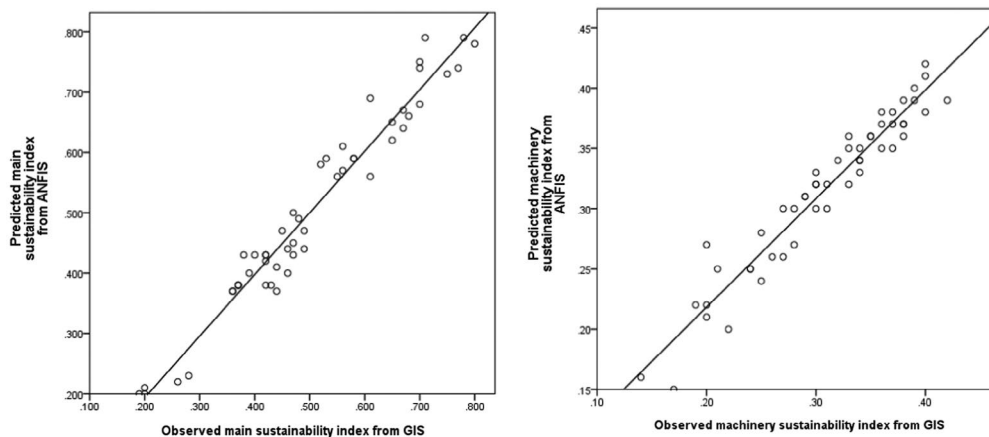**Figure 6. Machinery and main sustainability estimation performance of ANFIS models.**

Figure 6. Highly accurate, successful predictions are possible, especially for the main sustainability index and this shows that ANFIS can overcome the difficulties in working with GIS.

4. Discussion and conclusion

This study shows that AHP and fuzzy models can effectively be integrated with GIS to form a suitable hybrid tool for the sustainability assessment. The GIS provides suitable maps, which are very useful for farmers and regional managers for monitoring the changes in sustainability. It is important since almost no technical information is required to use the outputs from the GIS. All the proposed tools including fuzzy models, the AHP and GIS are cost effective in generating and visualizing information about the sustainability interactions (Graymore et al., 2009), which is a crucial factor to be considered, especially in developing countries.

The proposed methodology contains some advantages and drawbacks. One of the main advantages is that the sustainability is measured at a regional scale, which is an appropriate scale for progressing sustainability, creating a link between national and local policies (Buckingham & Theobald, 2003; Coelho et al., 2006). In addition, the methodology provided the results at the farm level, where improvements can be implemented by farmers. Application of fuzzy logic in GIS can be a superior tool to manage uncertainty embedded in measuring sustainability The fuzzy modeling allows for the use of all the available sources of knowledge; implicit and explicit, quantitative and qualitative. It is an important feature, since interactions between human activities and natural systems can be complex, implicit and qualitative, which may not fully be understood (Page, 2011). Nonetheless, improving rule-based fuzzy modeling in GIS is strongly recommended, since it enhances the flexibility and robustness of the tool in sustainability assessments.

Despite several advantages, the methodology also contains several weaknesses. Some parts of study are based on subjective experts' knowledge (Mackay, Landsberg, Whitten, & Bond, 2017). Although 96% consensus was obtained in this study, subjectivity is implicit because each expert interprets according to his or her personal values, which could result in some biases in modeling (Ormerod, 2014). It should be noted that using experts' knowledge can be very useful, particularly in broad studies with time and financial limitations. Another drawback is that the results, especially subjective results, are not validated against data from the field. In other words, due mainly to extent of the study area, sustainability indices were validated based on the experts' knowledge.

The result showed that the area cannot be considered totally sustainable from viewpoints of soil salinity and precipitation. Nonetheless, 75% of the area was designated as "moderate" and "high" suitability, respectively, with regard to all the three soil and climatic factors. The agronomic sustainability maps showed that fertilizers and water sustainability were in the lowest conditions involving "very low" to "low" sustainability levels. The extension trainings, are essential to prevent

unnecessarily high chemical fertilizer and pesticide application. Governmental financial aid in the form of low interest rate loans are important to help farmers employ modern irrigation systems, leveling farms and efficient water transfer from wells to farms, that respectively decrease and increase water use and sustainability scores. The machinery sustainability scores could be improved by increasing size of farms and using suitable machines, especially in smaller farms, although finding the most suitable farm machines (optimum size) for different farm sizes is recommended for future studies. All the socio-economic sustainability scores were higher than 0.61 ("high" to "very high") in around 80% of the area, which shows that the socio-economic factors were in a higher sustainability condition compared to some bio-physical factors (i.e. agronomic and machinery). The combination of the two sustainability dimensions—bio-physical and socio-economic—displayed "medium" sustainability in the majority of the area. To enhance the overall sustainability score, a focus on the agronomic and machinery factors is essential. Main suggestions to improve wheat production sustainability are:

(1) The agronomic sustainability indices are not high due to low indices, particularly from water and fertilizers maps. Subsequently, it seems that the most important focus should be on these two factors, to enhance agronomic sustainability level.

(2) Extension trainings, coupled with regulations restricting pesticide use would help prevent farmers from applying agrochemicals unnecessarily. It is also recommended that some suitable alternative crop protection methods, like mechanical and biological methods and integrated pest management (IPM), should be examined and introduced to the area, which may, in turn, reduce pesticide use.

(3) Determining the effect of farm yard manure on wheat yield in the region is also suggested for future studies. The local agricultural research institutes should represent some alternative winter crops since wheat is continuously planted in winter on 90% of farms. It is essential to increase soil and crop biodiversity, which in turn will enhance wheat sustainability (Brussaard, de Ruiter, & Brown, 2007). Furthermore, suitable seed could improve wheat yield, although its affect is not examined in this study.

(4) Farm size needs to be increased and suitable machinery should be used, especially in smaller farms, to enhance machinery sustainability indices. Investigating the most suitable farm machines and equipment for different farm sizes should feature in future studies.

(5) ANFIS as an alternative method is suggested to provide information on the sustainability of wheat production. The results confirm that ANFIS can be used as a superior alternative tool for sustainability predictions. However, the main obstacle is that this kind of models needs to be trained and validated by a set of data on the ground. Accordingly, it is suggested that the models are run again using a new set of data every several years.

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References

Ahmad, M., Chaudhry, G. M., & Iqbal M. (2002). Wheat productivity, efficiency, and sustainability: A stochastic production frontier analysis. *The Pakistan Development Review, 41*, 643–663.

Almassi, M., Kiani, S., & Lovimi, N. (2008). *Principles of agricultural mechanization* (4th ed). Tehran: Jungle publication. (In Persian).

Amidi, A. (2005). *Sampling methods, volume one*. Tehran: Payamnoor University Publication. (In Persian).

An, D., Xi, B., Ren, J., Wang, Y., Jia, X., He, C., & Li, Z. (2017). Sustainability assessment of groundwater remediation technologies based on multi-criteria decision making method. *Resources, Conservation and Recycling, 119*, 36–46. https://doi.org/10.1016/j.resconrec.2016.08.002

Arodudu, O., Helming, K., Wiggering, H., & Voinov, A. (2017). Towards a more holistic sustainability assessment framework for agro-bioenergy systems-A review. *Environmental Impact Assessment Review, 62*, 61–75. https://doi.org/10.1016/j.eiar.2016.07.008

Azadi, H., Shahvali, M., van den Berg, J. V. D., & Faghih, N. (2007). Sustainable rangeland management using a multi-fuzzy model: How to deal with heterogeneous experts' knowledge. *Journal of Environmental Management, 83*, 236–249. https://doi.org/10.1016/j.jenvman.2006.03.012

Bektas Ekici, B., & Aksoy, U. T. (2011). Prediction of building energy needs in early stage of design by using ANFIS. *Expert Systems with Applications, 38*, 5352–5358. https://doi.org/10.1016/j.eswa.2010.10.021

Borrelli, I. P. (2016). Territorial sustainability and multifunctional agriculture: A case study. *Agriculture and Agricultural Science Procedia, 8*, 467–474. https://doi.org/10.1016/j.aaspro.2016.02.046

Brussaard, L., de Ruiter, P. C., & Brown, G. G. (2007). Soil biodiversity for agricultural sustainability. *Agriculture, Ecosystems and Environment, 121*, 233–244. https://doi.org/10.1016/j.agee.2006.12.013

Buckingham, S., & Theobald, K. (2003). *Local environmental sustainability*. England: Woodhead Publishing Limited and CRC Press.

Cahya, D. (2016). Analysis of urban agriculture sustainability in metropolitan Jakarta (Case study: Urban agriculture in Duri Kosambi). *Procedia - Social and Behavioral Sciences, 227*, 95–100. https://doi.org/10.1016/j.sbspro.2016.06.048

Çetinkaya, C., Özceylan, E., Erbaş, M., & Kabak, M. (2016). GIS-based fuzzy MCDA approach for siting refugee camp: A case study for southeastern Turkey. *International Journal of Disaster Risk Reduction, 18*, 218–231. https://doi.org/10.1016/j.ijdrr.2016.07.004

Coelho P., Mascarenhas, A., Vaz, P., Beja, I., Dores, A., & Ramos, T. B. (2006). *A methodological framework for indicators of sustainable development at the regional scale: The case of a Portuguese region (Algarve)*. In 12th Annual International Sustainable Development Research Conference 2006, Hong Kong.

Craheix, D., Angevin, F., Doré, T., & de Tourdonnet, S. (2016). Using a multicriteria assessment model to evaluate the sustainability of conservation agriculture at the cropping system level in France. *European Journal of Agronomy, 76*, 75–86. https://doi.org/10.1016/j.eja.2016.02.002

Diaz-Balteiro, L., González-Pachón, J., & Romero, C. (2017). Measuring systems sustainability with multi-criteria methods: A critical review. *European Journal of Operational Research, 258*, 607–616. https://doi.org/10.1016/j.ejor.2016.08.075

FAO. (2015). *National report, Islamic Republic of Iran*.

Giordano, R., & Liersch, S. (2012). A fuzzy GIS-based system to integrate local and technical knowledge in soil salinity monitoring. *Environmental Modelling & Software, 36*, 49–63. doi.org/10.1016/j.envsoft.2011.09.004

Graymore, L. M. M., Wallis, A. M., & Richards, A. J. (2009). An index of regional sustainability: A GIS-based multiple criteria analysis decision support system for progressing sustainability. *Ecological Complexity, 6*, 453–462. https://doi.org/10.1016/j.ecocom.2009.08.006

Hambly, H., & Angura, T. O. (1996). *Grassroots indicators for desertification*. Ottawa: IDRC.

Hayati, D., Ranjbar, Z., & Karami, E. (2011). Measuring agricultural sustainability. *Sustainable Agriculture Reviews, 5*, 73–100. https://doi.org/10.1007/978-90-481-9513-8

Hellwig, N., Graefe, U., Tatti, D., Sartori, G., Anschlag, K., Beylich, A., … Broll, G. (2017). Upscaling the spatial distribution of enchytraeids and humus forms in a high mountain environment on the basis of GIS and fuzzy logic. *European Journal of Soil Biology, 79*, 1–13. https://doi.org/10.1016/j.ejsobi.2017.01.001

Houshyar, E., Azadi, H., Almassi, M., Sheikh Davoodi, M. J., & Witlox, F. (2012). Sustainable and efficient energy consumption of corn production in Southwest Iran: Combination of multi-fuzzy and DEA modeling. *Energy, 44*, 672–681. https://doi.org/10.1016/j.energy.2012.05.025

Houshyar, E., SheikhDavoodi, M. J., Almassi, M., Bahrami, H., Azadi, H., Omidi, M., … Witlox, F. (2014). Silage corn production in conventional and conservation tillage systems. Part I: Sustainability analysis using combination of GIS/AHP and multi-fuzzy modeling. *Ecological Indicators, 39*, 102–114. https://doi.org/10.1016/j.ecolind.2013.12.002

IUCN (2001). *IUCN resource kit for sustainability assessment* (p. 95). Gland: Author.

Joolaie, R., Abedi Sarvestani, A., Taheri, F., Van Passel, S., & Azadi, H. (2016). Sustainable cropping pattern in North Iran: Application of fuzzy goal programming. *Environment, Development and Sustainability*. doi:10.1007/s10668-016-9849-9

Lamastra, L., Balderacchi, M., Di Guardo, A., Monchiero, M., & Trevisa, M. (2016). A novel fuzzy expert system to assess the sustainability of the viticulture at the wine-estate scale. *Science of The Total Environment, 572*, 724–733 https://doi.org/10.1016/j.scitotenv.2016.07.043

Larson, D. L., Phillips-Mao, L., Quiram, G., Sharpe, L., Stark, R., Sugita, S., & Weiler, A. (2011). A framework for sustainable invasive species management: Environmental, social, and economic objectives. *Journal of Environmental Management, 92*, 14–22. https://doi.org/10.1016/j.jenvman.2010.08.025

Leman, N., Ramli, M. F., & Khirotdin, R. P. K. (2016). GIS-based integrated evaluation of environmentally sensitive areas (ESAs) for land use planning in Langkawi, Malaysia. *Ecological Indicators, 61*, 293–308. https://doi.org/10.1016/j.ecolind.2015.09.029

Likert, R. (1961). *New patterns of management* (p. 279). New York, NY: McGraw Hill.

Ma, J., & Cheng, J. C. P. (2016). Estimation of the building energy use intensity in the urban scale by integrating GIS and big data technology. *Applied Energy, 183*, 182–192. https://doi.org/10.1016/j.apenergy.2016.08.079

Mackay, J. P., Landsberg, M. J., Whitten, A. E., & Bond, C. S. (2017). Whaddaya know: A guide to uncertainty and subjectivity in structural biology. *Trends in Biochemical Sciences, 42*, 155–167. https://doi.org/10.1016/j.tibs.2016.11.002

Ministry of agricultural-Jihad. (2016). *Annual agricultural statistics, department of agronomy*. Ministry of agricultural-Jihad of Iran. Retrieved from www.maj.ir

Ormerod, R. J. (2014). Critical rationalism in practice: Strategies to manage subjectivity in OR investigations. *European Journal of Operational Research, 235*, 784–797. https://doi.org/10.1016/j.ejor.2013.12.018

Page, G. (2011). Modelling sustainability: what are the factors that influence sustainability of organic fruit production systems in New Zealand? *Organic Agriculture, 1*, 55–64. https://doi.org/10.1007/s13165-011-0005-4

Pandey, A., & Kumar, A. (2017). Commentary on "Evaluating the criteria for human resource for science and technology (HRST) based on an integrated fuzzy AHP and fuzzy DEMATEL approach". *Applied Soft Computing, 51*, 351–352. https://doi.org/10.1016/j.asoc.2016.12.008

Pearson, L. J., Pearson, L., & Pearson, C. J. (2011). Sustainable urban agriculture: Stock take and opportunities. *International Journal of Agricultural Sustainability, 8*, 7–19.

Prato, T. (2009). Fuzzy adaptive management of social and ecological carrying capacities for protected areas. *Journal of Environmental Management, 90*, 2551–2557. https://doi.org/10.1016/j.jenvman.2009.01.015

Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability, 9*, 5–24. https://doi.org/10.3763/ijas.2010.0583

Rasouli, F., Sadighi, H., & Minaei, S. (2009). Factors affecting agricultural mechanization: A case study on sunflower seed farms in Iran. *Journal of Agricultural Science and Technology, 11*, 39–48.

Rasul, G., & Thapa, G. B. (2004). Sustainability of ecological and conventional agricultural systems in Bangladesh: An assessment based on environmental, economic and social perspectives. *Agricultural Systems, 79*, 327–351. https://doi.org/10.1016/S0308-521X(03)00090-8

Saaty, T. L. (1980). *The analytical hierarchy processes*. New York, NY: McGraw Hill.

Saaty, T. L. (1994). How to make a decision: The analytic hierarchy process. *Interfaces, 24*, 19–43. https://doi.org/10.1287/inte.24.6.19

Sabiha, Noor-E, Salim, R., Rahman, S., & Rola-Rubzen, M. F. (2016). Measuring environmental sustainability in agriculture: A composite environmental impact index

approach. *Journal of Environmental Management, 166*, 84–93. https://doi.org/10.1016/j.jenvman.2015.10.003

Sattler, C., Stachow, U., & Berger, G. (2012). Expert knowledge-based assessment of farming practices for different biotic indicators using fuzzy logic. *Journal of Environmental Management, 95*, 132–143. https://doi.org/10.1016/j.jenvman.2011.10.004

Shi, T., & Gill, R. (2005). Developing effective policies for the sustainable development of ecological agriculture in China: the case study of Jinshan County with a systems dynamics model. *Ecological Economics, 53*, 223–246. https://doi.org/10.1016/j.ecolecon.2004.08.006

Sys, I. C., Ranst, E. V., Debaveye, I. J., & Beernaert, F. (1993). *Land evaluation, Part III, crop requirements* (p. 199). Brussels: Agricultural Publications.

Wang, H., Guo, W., Wang, J., Huang, W., Gu, X., Dong, Y., & Xu, X. (2013). Exploring the feasibility of winter wheat freeze injury by integrating grey system model with RS and GIS. *Journal of Integrative Agriculture, 12*, 1162–1172. https://doi.org/10.1016/S2095-3119(13)60445-1

Yadav, R. L., Dwivedi, B. S., & Pandey, P. S. (2000). Rice-wheat cropping system: Assessment of sustainability under green manuring and chemical fertilizer inputs. *Field Crops Research, 65*, 15–30. https://doi.org/10.1016/S0378-4290(99)00066-0

Zadeh, L. A., Fu, K. S., Tanaka, K., & Shimura, M. (1975). *Fuzzy sets and their applications to cognitive and decision processes*. New York, NY: Academic Press.

Zhang, J., Su, Y., Wu, J., & Liang, H. (2015). GIS based land suitability assessment for tobacco production using AHP and fuzzy set in Shandong province of China. *Computers and Electronics in Agriculture, 114*, 202–211. https://doi.org/10.1016/j.compag.2015.04.004

Zhen, L., Zoebisch, M. A., Chen, G., & Feng, Z. (2006). Sustainability of farmers' soil fertility management practices: A case study in the North China Plain. *Journal of Environmental Management, 79*, 409–419. https://doi.org/10.1016/j.jenvman.2005.08.009

Appendix A

Figure A1. The sustainability maps of soil factors.
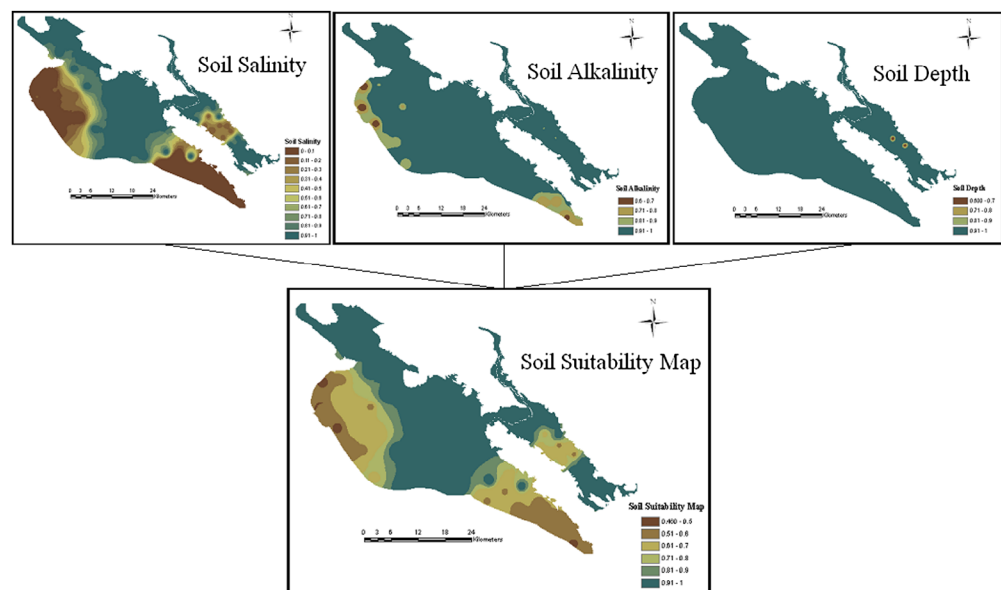
Figure A2. The sustainability maps of climatic factors.
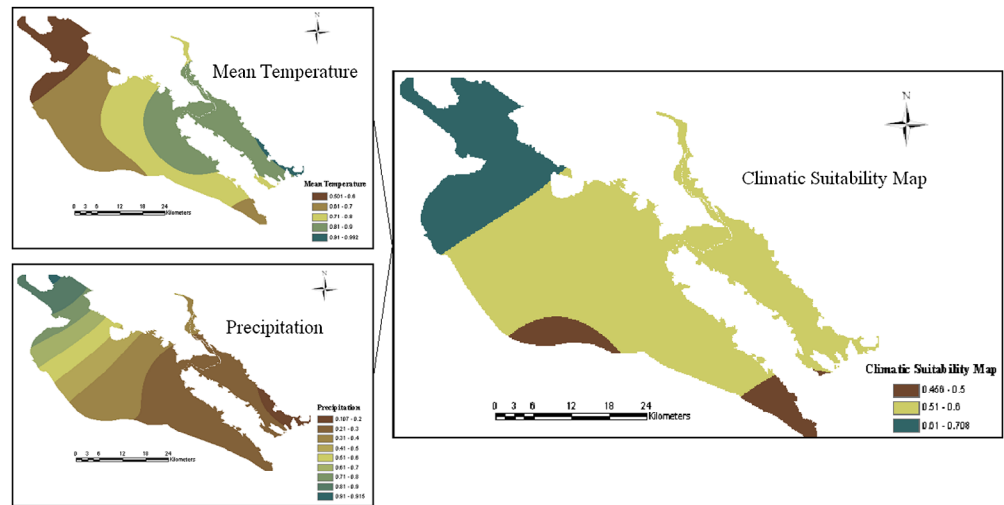

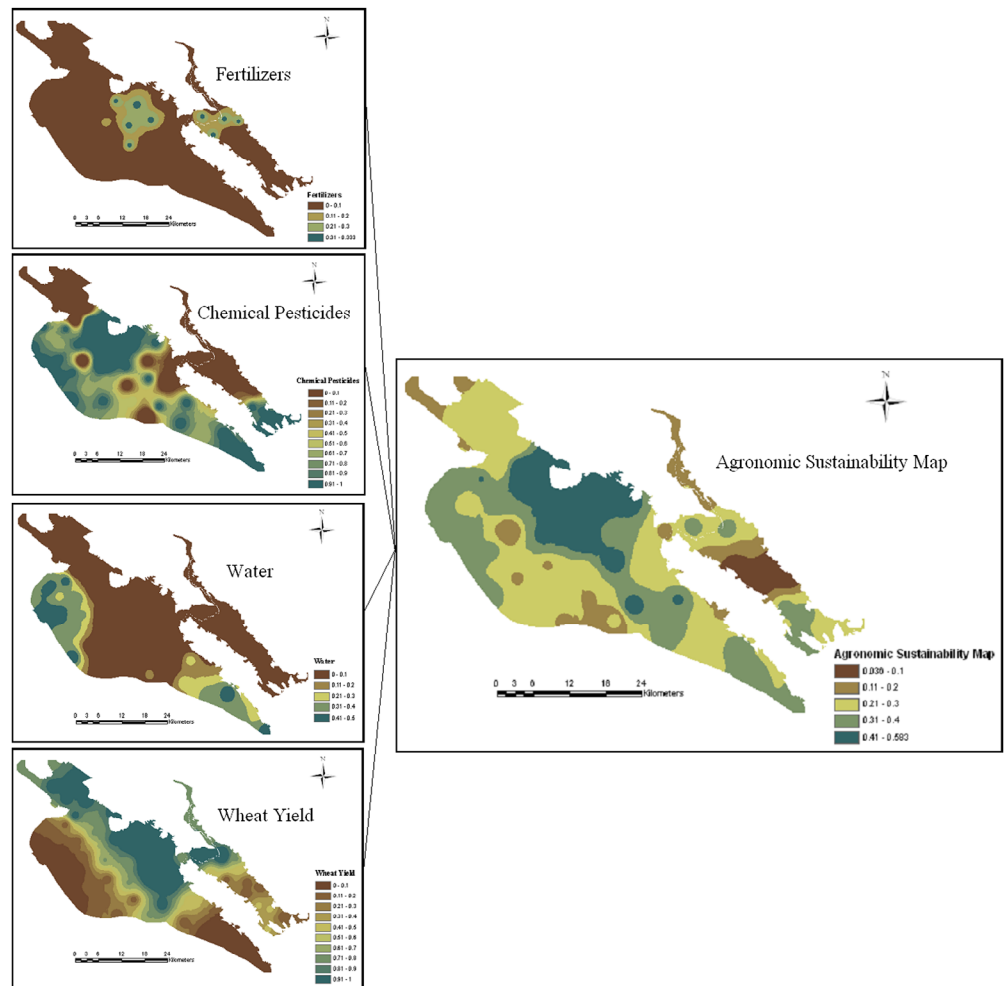**Figure A3. The sustainability maps of agronomic factors.**

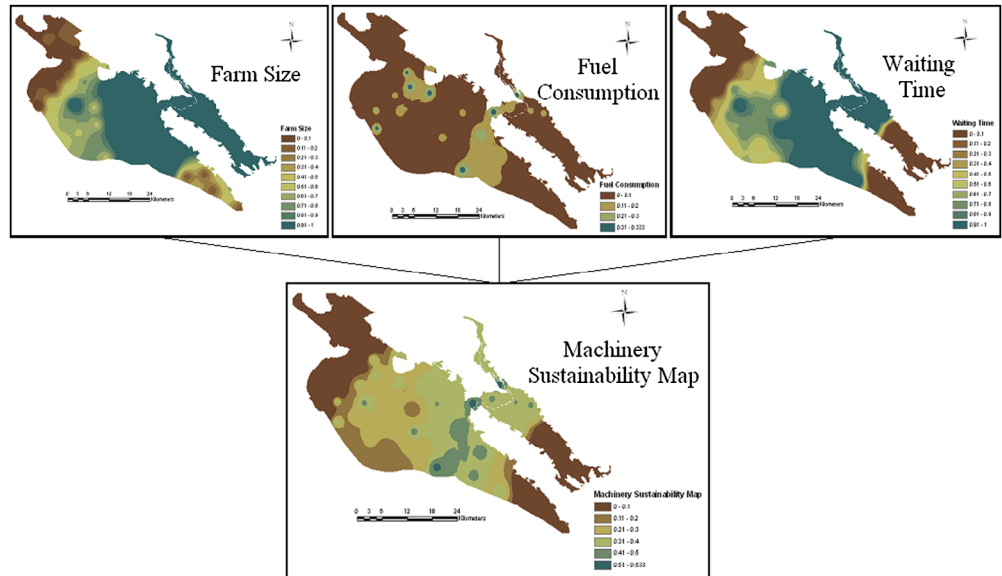**Figure A4. The sustainability maps of machinery factors.**

Figure A5. The sustainability maps of socio-economic factors.