Assessing the sustainability of agricultural production systems using fuzzy logic

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Abstract

First stage for attaining to sustainability in a system is the measurement of current state of sustainability. Indicators are widely used as tools for measurement of sustainability. In this study, a comprehensive index was proposed to measure sustainability in agricultural production systems. This index takes advantage of fuzzy logic to combine all six indexes which were selected as the representative of three dimensions of sustainability. A set of models and sub-models based on the fuzzy inference system were employed to define the index. A case study conducted in two large production farms of maize and wheat, in Iran, proved the feasibility and usability of the model.

Keywords: comprehensive index, fuzzy logic, sustainability analysis

Introduction

Concerns about the negative effects of economic development on the people, community and environment have found expression in the concept of sustainable development (Mebratu, 1998). Concept of sustainable development puts emphasis on the link among the key components of sustainability, namely the economic, social and environmental dimensions (OECD, 1998). As one of the most important economical activities, agriculture is widely considered in sustainable discussions (OECD, 1998).

The need for a practical tool to assess sustainability is crucial to policy-makers if they are looking for secure future development. There are several models and approaches presented for partial or universal assessment of sustainability (e.g., Pearce, et al., 1990; Castoldi and Bechini, 2010; Lindner, et al., 2010; Sattler, et al., 2010). The term 'sustainable development' is not clearly defined, and instead a multitude of definitions is available (WCDE, 1987). Sustainability is difficult to define or measure, because it is an inherently vague and complex concept. Fuzzy logic, due to its ability to emulate skilled humans and its systematic approach to handle ill defined situations where traditional mathematics is ineffective, seems to be a powerful technical tool for sustainability assessment. In the last decade, the use of fuzzy approach was offered and extended as a valuable tool for sustainability measurement (e.g., Prato, 2000; Phillis and Andriantiatsaholiniaina, 2001; Cornelissen, 2003; Mendoza and Prabhu, 2003). Fuzzy logic provides the ability of translating sophisticated statement from natural language into a mathematical formalism. This ability is very applicable for the use of experts, politicians, scientists, farmers, and other specialists' knowledge (Bojadziev and Bojadziev, 2007). It seems no publications are available that discuss in the topic of development of such comprehensive models for agricultural farms in Iran's condition. On the other hand, totally, there is the lack of practical fuzzy inference models for sustainability comprehensive assessment of agricultural activities. In this study, a model was developed on the base of fuzzy inference system to combine the selected indexes in all common areas of sustainability.

Material and Methods

Fuzzy models

Fuzzy inference

Fuzzy inference system is a scientific tool permitting simulation of a system without a detailed mathematical description. There are two common types of inference method, including Mamdani and Sugeno. Mamdani is the most commonly seen fuzzy methodology that basically contains below stages:

1. Fuzzification
2. Application of the rule base to fuzzy data
3. Inference of fuzzy results
4. Defuzzification

In the stage of fuzzification, real values are transformed to fuzzy form using membership functions. Rule bases are sets of IF-THEN linguistic rules, which describe a logical evolution of system according to the linguistic values of its principal characters. Combination process of input memberships is used to inference from the IF-part to the THEN-part of one rule. This process is usually done by employing AND, OR or compensatory operators. To aggregate THEN-parts of several rules, several aggregation methods are available (Vaníček, et al., 2009). However, Max and Sum are mostly utilized in fuzzy inferences systems. Obtained final fuzzy values from aggregation process are transformed to real data in defuzzification stage. Defuzzification may be done using several methods such as center of gravity, center of maximum, center of area, mean of maximum and so on (Bojadziev and Bojadziev, 2007).

Model development

Development of a rule based fuzzy model established upon experts' knowledge is down in several stages. In this study, a five steps cycle schemed in Figure1, was followed to complete the final model. This cycle may be repeated even more than one hundred times to provide a reliable final model and in each cycle, one or more factors may be modified. After each cycle outputs of model from real and simulated input data compared whit experts' viewpoints. As model outputs fulfill the experts' desire, this cycling will be stopped.

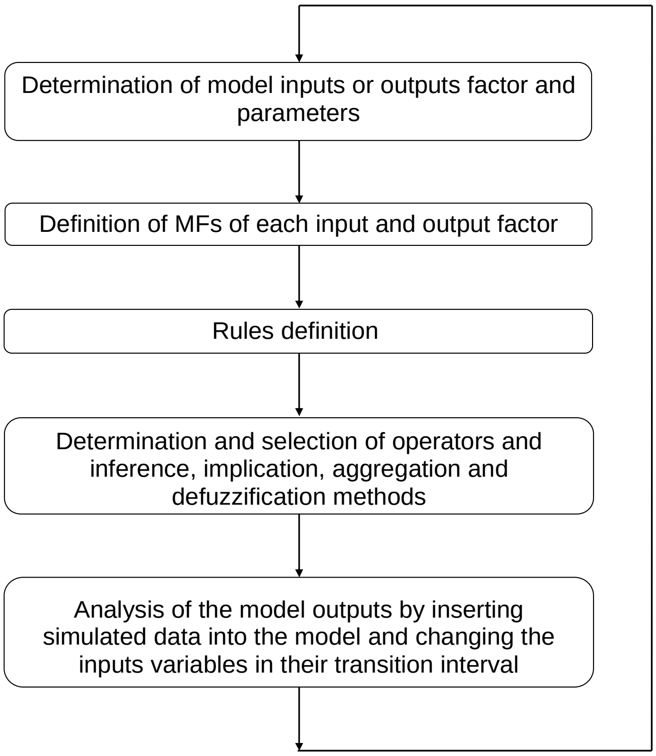

Figure 1. The scheme for the development of fuzzy inference model based on experts' knowledge

Selection and calculation of criteria and indicators

In general, standards for sustainable management can be viewed in the term of a set of criteria and indicators, which can serve as tools not only to promote sustainable management, but also as a base for monitoring the condition and progress toward sustainability (OECD, 2000a; 2000b). In this study, six indicators were chosen to suit the circumstances of the region situations regarding sustainability purposes. Furthermore, for evaluation of some indicators, a set of fuzzy sub-models was developed. In adopting indexes, it was tried to each index be the best proxy of its indicator and simple for calculation. The selection of indexes was based on literature review and expert questioning. To construct the model, we used homogenous experts. Since, handling of heterogeneous experts knowledge is more difficult, most studies have been done based on homogeneous experts' knowledge. Nevertheless, heterogeneous experts were discussed in some studies (Vrana, et al., 2012; Azadi, et al., 2007).

At the following, selected indicators, their importance and calculations are briefly discussed.

Energy indicator

Energy is one of the basic indicators of sustainability and is broadly used to evaluate the degree of sustainability in agricultural systems. Assessment of energy flow and its indicators is widely used to analyze sustainability-related issues. In fact, efficient use of energy is one of the most important elements in sustainable agriculture (Van Cauwenbergh, et al., 2004; Meng, et al., 2010).

In the developed model, the Output-Input Energy Ratio (SI_{ER}) was used as energy index. Input and output energy are expressed in the term of MJ-ha^{-1} and are calculated based on a mixed of data collected from the farms and energy equivalents. Output energy is obtained by multiplying all farm removed yield by its coefficient of energy. The energy equivalents for different inputs and outputs used in energy budget calculation are shown in Table 1.

Pesticide risk indicator

Pesticides are listed as the first most common pollutants of groundwater (Spalding and Exner, 1993). Pesticides pollute soil, ground and surface waters and have adverse effects on non-target organisms. In addition, application of pesticides can impress unwanted effects on pesticide applicator or third party (Campbell and Cooke, 1995). To assess ill-effects of pesticides, quantity of pesticides entered to the surface or ground waters is usually considered (Pimentel, et al*.,* 1992; Pretty, et al*.,* 2000; Pimentel, 2005). In this study, a fuzzy model was schemed to include all aspects of pesticides hazards. Output of model is named Pesticides Risk Index (SI_{PR}), which presents the risks of pesticides application in the farm.

Nitrate risk indicator

Usually, farm crops do not absorb all applied fertiliser. The excess fertiliser flows into groundwater, rivers and lakes, which causes serious environmental problems (EPA, 1997). N fertiliser releasing into environment depends on various local factors such as fertiliser type, application amount, application time, soil condition, etc (Eva, et al., 2008). Several models and equations are available for assessment of fertiliser consumption risks (EEA, 2005). However, these models generally demand too input data, which need to be collected from farm lands using advanced technologies and equipments. For a more usable and universal estimation of N fertiliser risk, in this study, a fuzzy sub-model using most prevalent environmental factors regarding nitrogen consumption was developed.

Table 1. Energy equivalent of farms Input and output

Input/output (unit)	Energy equivalent (MJ*unit^{-1})	
	Maize	Wheat
Human labor(h)	2.2	2.2
Machinery(kg) (Average)	132.6	130.8
Fertilisers (kg)	-	-
Nitrogen (N)	78.4	78.4
Phosphate (P_2O_5)	17.4	17.4
Potassium (K_2O)	13.7	13.7
Others (Average)	8.8	8.8
Manure(t)	303.0	-
Pesticides(kg or l) (Average)	202.9	166.1
Irrigation (indirect)	-	-
Electricity for irrigation (kWh)	12.0	12.0
Diesel (l)	47.8	47.8
Gasoline(l)	46.3	46.3
Seed (kg)	14.0	13.0
Total energy input	-	-
Total energy output	14.0	13.0

Sources for Energy equivalent: Kitani 1998; Pimentel and Pimentel 1979; Pimentel 1980.

Air pollution indicator

Numerous estimation methodologies have been developed and proposed to estimate emission of pollutants in different sectors (e.g., Li, 2000; De Vries, et al*.,* 2004; Havlikova and Kroeze, 2006). These models chiefly require complete details and consistent monitoring to evaluate air pollution caused by agricultural practices. Required inputs for these models are not easily available. Furthermore, these models are not directly applicable for integrated assessment (Ignaciuk, et al*.,* 2002). Therefore, to present the air pollution risk of agricultural practices, we defined the Air Pollutant Index (SI_{AP}), and developed a fuzzy model to estimate it. In this model, we only considered air pollution of direct energy inputs to farms.

Economic indicator

Economy is the most impressive factor in all production systems and widely considered in sustainability projects. Without a satisfactory economic income, a production system cannot sustain for a long term and will stop very soon. For an acceptable analysis, the Benefit/Cost Ratio was used as the index of economic conditions (SI_{BCR}). This is a dimensionless index, which could be easily used in the model.

Social indicator

To present the social effects of production, employment of labor in the system was used as social indicator. This criterion, which expresses job creation in the system, is one of the best criteria for sustainability analysis of mechanized farms. Total annual work times of labors in the farms were used to express labor employment (Leiva and Morris, 2001). Table 2 summarized all input parameters and factors of the models.

Case study

For examining the applicability and feasibility of presented model, it was tested in a case study. The region of study is located in southwest of Iran, in northeast of Khuzestan province. Data were collected from two large mechanized farms of wheat and maize. Wheat was cultivated in a farm with extension of 500 ha during November 2008 – May 2009, and maize was cultivated in a farm with the extension of 220 ha, during July – October 2009. These crops have similar characteristics and usages, and can be substitute by each other according to need. The both farms had the similar states, and similar management practices were implemented in both of them. The farms reflected typical large mechanized farming systems in the study region.

Table 2: An overview on the model parameters

Sustainability dimension	Sustainability criteria	Selected indexes	Inputs for computing every index	Unit per hectare
Environmental	Energy	Energy ratio (SI_{ER})	Total energy input to agroecosystem	MJ
			Total output energy from agroecosystem	MJ
	Nitrate pollution	Nitrate risk index (SI_{NR})	Amount of nitrate consumption	kg
			Number of application	N
			Type of fertiliser	Linguistic variable
	Pesticide pollution	Pesticide risk index (SI_{PR})	Amount of pesticide consumption	kg or l
			Toxicity of pesticide	ppm
			Half-life of pesticide	d
			Consumption management	Linguistic variable
	Air pollution	Air pollution index(SI_{AP})	Amount of electrical power consumption	kWh
			Amount of diesel fuel consumption	l
			Amount of gasoline fuel consumption	l
			Pollution degree of every power sours	Dimensionless
Economical	Economical income	Benefit-cost ratio (SI_{BCR})	Total farm annual cost	$
			Total farm annual benefit	$
Social	Labor employment	Labor employment index (SI_{LE})	Annual work time of labors in farm	h

Conclusions and discussions

Discuss on the model

With increasing the number of input factors, the number of fuzzy rules increases exponentially and consequently it becomes more difficult to express the input parameters relationships in the form of fuzzy rules. Hence, we developed the model in the several layers using several intermediate fuzzy inputs and outputs. At first, three sub-models, SI_{PR}, SI_{NR} and SI_{AP} were defined. Afterward in the main model, sustainability indicators were combined using two rule bases. The first rule base combines environmental indexes (SI_{ER}, SI_{PR}, SI_{NR} and SI_{AP}), and the second rule base combines output of the first rule base with labor employment index (SI_{LE}) and benefit to cost ratio (SI_{BCR}). Models, their inputs, rule bases and selected mathematical parameters are presented in Table 3.

Among the fuzzy operators, in most cases, gamma operator provided best results. This is probably due to the interrelationships of the models input parameters. However, other types of operators were also employed. We tested both method of Center of Gravity and Mean of Maximum. Significant difference between two methods was not observed. On the other hand, observed differences were compensated by changes in the functions and rules. We finally used the Center of Gravity method for defuzzification in all models. Center of Gravity method is the most

Table 3: Models inputs and their mathematical factors

Model name	Input parameters (number of linguistic variables)	Number of rules	Defuzzification method	Implication method	Aggregation method
SI_{PR} model	Pesticide consumption rate (2), Pesticide toxicity (4), Pesticide half-life (3), Consumption management (5)	120	Center of Gravity	Min	Max
SI_{NR} model	Nitrate consumption rate (4), Application number (5), Fertiliser type (7)	120	Center of Gravity	Gamma	Max
SI_{AP} model	Power source quantity (3), Air pollution risk of power source (5)	15	Center of Gravity	Min	Max
Main model (rule 1)	Energy Ratio Index (4), Pesticide Risk Index (3), Nitrate Risk Index (3), Air Pollution Index (3)	108	Center of Gravity	Gamma	Max
Main model (rule 2)	Benefit to Cost Ratio(3), Labure Employment Index (3), Environmental index(3)	27	Center of Gravity	Gamma	Max

widely used defuzzification technique in similar studies (e.g. Phillis and Andriantiatsaholiniaina, 2001; Azadi, et al*.,* 2007; Sattler, et al*.,* 2010). For aggregation, the Max method was employed since this method was used almost in all knowledge based models (e.g. Ocampo-Duque et al., 2000; Sattler, et al., 2010; Rajaram and Das, 2010).

Models rule bases were made using experts' views and other related information. Expert's knowledge is the most common technique for determining rules. The experts are asked to summarize their knowledge about the system in the form of cause and effect relationship (Mazloumzadeh, et al., 2008). At first, a prototype was made and several cycles of feedbacks were exerted, so that models outputs satisfied the expectations of experts and model provided a continuous and reasonable range of data. For this purpose, several sets of inputs were entered into the model, and outputs were evaluated.

For each model input, membership functions were developed and related linguistic variables were defined. Definition of functions was based on the inherent property of parameters, past literature and/or scientific knowledge (e.g., Leiva and Morris, 2001; Phillis and Andriantiatsaholiniania, 2001; Cornelissen, 2003; Mendoza and Prabhu, 2003; Sattler, et al*.,* 2010). We found triangular functions best for the model parameters. However, trapezoidal and shoulder functions also were used in the models. These types of functions are simple to understand and compute. Linear functions also can be made using minimum information and are compatible with the most natural phenomena (Pedrycz, 1994; Heske and Heske, 1996).

Illustrative Sample

For example, fuzzy membership function of Benefit/Cost Ratio Index and its related rules are illustrated following:

Figure 2 shows fuzzy membership function diagram of SI_{BCR}. In this diagram, horizontal axis expresses SI_{BCR} value and vertical axis expresses membership grad for every SI_{BCR} value. Structure of this membership function is on the base of two main critical values, which were modified and simulated in the form soft thresholds.

According to this membership function for economic index, three general rules can be defined as following;

If SI_{BCR} is smaller than 1, the system obviously is not sustainable.

If SI_{BCR} is between 1 and 1.18, the system may be sustainable, if other factors have acceptable situation (in the country which study carried out bank rate is 18% that can be considered as the lowest profit rate).

And, if SI_{BCR} is greater than 1.18, the higher SI_{BCR} index do not has visible role in increment of sustainability of farm. In other word, two similar farms with different SI_{BCR} indexes have relatively similar sustainability indexes.

These factors and other similar questions cannot be easily modeled using common assessment models. Nevertheless, fuzzy models satisfactory handle these problems. Related rules can be expressed as Table 4.

Table 4. Applied rules in the main model (rule block 2)

If SI_{BCR} is	And environmental indexes are	And social index is	Then SI is
Low	Low	Low	Low
Low	Low	Medium	Low
Low	Low	High	Low
Low	Medium	Low	Low
Low	Medium	Medium	Low
Low	Medium	High	Low
Low	High	Low	Low
Low	High	Medium	Low
Low	High	High	Low
Medium	Low	Low	Medium-low
Medium	Low	Medium	Medium-low
Medium	Low	High	Medium
Medium	Medium	Low	Medium
Medium	Medium	Medium	Medium
Medium	Medium	High	Medium
Medium	High	Low	Medium
Medium	High	Medium	Medium-high
Medium	High	High	Medium-high
High	Low	Low	Medium-low
High	Low	Medium	Medium
High	Low	High	Medium
High	Medium	Low	Medium
High	Medium	Medium	Medium
High	Medium	High	Medium-high
High	High	Low	Medium-high
High	High	Medium	Medium-high
High	High	High	High

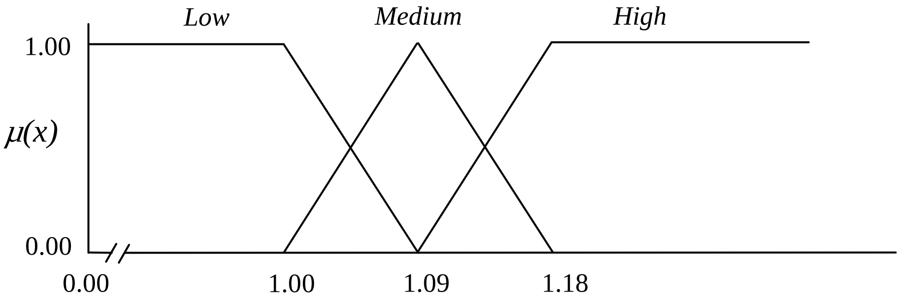

Figure 2. Membership function of SI_{BCR}

Case study results

Input data of Nitrate Risk Index, Pesticide Risk Index and Air Pollution Index are shown in Table 5, 6 and 7, respectively. These data were collected from agricultural farms during the growing seasons of crops. Input and output values of the fuzzy model are shown in Table 8. Output values of every sub-model for different types of inputs in each farm were aggregated and used as index value for SI_{NR}, SI_{PR} and SI_{AP}. Each output of the sub-models is a dimensionless value ranging between 0 and 1. The greater number shows the greater risk regarding the issue. Comparing the obtained indexes values for two farms shows that wheat production has the better condition in all indexes except labor employment index. Labor force was used as the operator for the machines and equipments also for scattering the irrigation water in the farms. Because of the greater use of machinery power and greater consumption of water in maize production, labor force employment in the maize farm was higher, and consequently SI_{LE} was more suitable.

The final output, which is obtained after defuzzification in the model, shows the overall sustainability of agricultural production practice. This value is a dimensionless number varying between 0 and 1. The closer the index is to one, the higher is sustainability of production practice. The level 'one' is considered as maximum sustainability. Overall sustainability index in studied farms showed that current wheat production system is more sustainable than maize production.

Table 5. Input data in SI_{NR} model

Parameters	Wheat		Maize		
	Type 1	Type 2	Type 1	Type 2	Type 3
N fertiliser consumption	91.65	5.17	203.86	35.79	0.59
Number of application	3	1	4	1	1
N fertiliser type	Very high-hazard	Very high-hazard	Very high-hazard	Very high-hazard	Low-hazard

Table 6. Input data in SI_{PR} model

Parameters	Maize			Wheat				
	2-4-D	Alacoholor	Atrazine	2-4-D	Clodinafop propargyl	MCPA	Dicloroprop	Mecoprop
Pesticide Consumption (Kg or l*ha-1)	0.64	2.13	0.07	0.68	0.08	0.18	0.35	0.15
Toxicity of Pesticide (ppm)	64.00	4.20	4.50	64.00	0.40	117.00	100-200	124.00
Half-life of Pesticide(d)	46.00	21.00	60.00	46.00	0.8>	10-30	10.00	7-21
Consumption management	Low-hazard	Low-hazard	Low-hazard	Low-hazard	Very high-hazard	Low-hazard	Low-hazard	Low-hazard

Table 7. Input data in SI_{AP} model

Parameters	Wheat			Maize		
	Electricity	Diesel	Gasoline	Electricity	Diesel	Gasoline
Consumption amount	5208.02	72.41	2.31	14275.75	124.72	0.00
Weight degree	0.029	0.429	0.55	0.029	0.429	0.55

Table 8. Inputs and outputs of the main model

Index	Wheat	Maize
Energy Ratio	1.31	0.80
Pesticide Risk	0.10	0.28
N Fertiliser Risk	0.26	0.60
Air Pollution Rick	0.84	1.69
Benefit/Cost Ratio	1.48	1.07
Labor Employment	6.11	13.85
Sustainability	0.46	0.29

Conclusions and suggestions

It is widely accepted that an integrated assessment of system sustainability should embrace all of its aspects. This integrated analysis demands precise, detailed and consistent information about production system. Therefore, prevalent approaches designed for this purpose will be complex or/and incomplete. Fuzzy approach appears to be well suited to provide a comprehensive model without detailed information. In this study for a comprehensive assessment of sustainability in agricultural farms, a model was developed based on the fuzzy inference system. The analysis results of the developed model proved that the model is satisfactory usable regarding inherent complexity of sustainability in agricultural sector. The inputs data of the model can be simply gathered from the agricultural fields during the growing seasons and from other available sources. As a consequence, use of the model is simple in condition that precise monitoring cannot be employed. The other advantage of this fuzzy-logic-based model is its possibilities to work with linguistic and uncertain data, which is highly beneficial when precise information is not available.

For some ranges of input data, responses of experts and therefore outputs from the model were largely linear. Hence, it seems that for more limited assessments, which a comprehensive model is not needed, other simple models can be efficiency employed.

The proposed model has been developed for Iran's conditions and provides maximum efficiency in the study region and in similar production systems. For use of the model in other conditions, it should be improved considering new conditions and sustainability purposes in new region. Modification of the model asks precise choice of new indexes or new factors also needs various information about quantity and quality of new parameters and their interrelationship, so that a good definition of functions and rules can be provided. This type of information is not easily available. Thus, more studies are needed to be carried out in this context. For the development of similar models, we suggest model be divided as far as possible to sub-models and development of models be done in several stages. This makes easier the comprehension of the model for experts. Integrated analysis of sustainability, in the case study using comprehensive index, was revealed that wheat production system was more sustainable in comparison with maize production, and it can be suggested as a more sustainable production.

Acknowledgements

We express our tanks to all experts who help us in the development of the model also express our appreciation from the Shahid Rajai Agro-Industry, Iran, for its support of this research.

References

Azadi, H., Shahvali, M., van den Berg, J., Faghih, N., (2007) Sustainable rangeland management using a multi-fuzzy model: how to deal with heterogeneous experts' knowledge. Journal of Environmental Management, 83(2), 236–249.

Bojadziev, G., Bojadziev, M., (2007) Fuzzy Logic for Business, Finance, and Management. Advances in Fuzzy Systems - Applications and Theory, 23.

Campbell, LH., Cooke, AS., (1995) The Indirect Effect of Pesticides on Birds. Peterborough: Joint Nature Conservation Committee.

Castoldi, N., Bechinl, L., (2010) Integrated sustainability assessment of cropping systems with agro-ecological and economic indicators in northern Italy. European Journal of Agronomy, 32(1), 59–72.

Cornelissen, AMG., (2003) The two faces of sustainability: fuzzy evaluation of sustainable development. Ph.D. Thesis. Wageningen: Wageningen University.

De Vries, W., Kros, H., Velthof, GL., Römkens, PFAM., Gies, E., Voogd, JCH., (2004) A decision support system for the integrated evaluation of agricultural management on environmental quality. Proceedings of the 13th Clean Air and Environmental Protection, London, September.

EEA. EMEP/CORINAIR Emission Inventory Guidebook, (2005) Technical report No. 30. 3. ed. Copenhagen: European Environmental Agency.

Eva, H., Milan, M., Eva, C., (2008) The nutrients balance of crop rotation as an indicator of sustainable farming on arable land. Journal of Central European Agriculture, 9 (3), 431–438.

Havlikova, M., Kroeze, C., (2006) Evaluation of methods for quantifying agricultural emissions of air, water and soil pollutants. Science of the Total Environment, 372(1), 133–147.

Heske, T., Heske, JN., (1996) Fuzzy Logic for Real World Design. San Diego: Anna Books.

Ignaciuk, A., Kroeze, C., van Ierland, EC., (2002) Models and databases to analyze interactions between emissions of air pollutants in Europe, World Resour Rev., 14, 25–53.

Kitani, O., (1998) Energy and environment in agricultural engineering research. International Engineering Conference, Bangkok. Bangkok: Thai Society of Agricultural Engineering.

Leiva, FR., Morris, J., (2001) Mechanization and Sustainability in Arable Farming in England. Journal of Agricultural Engineering Research, 79(10), 81-90.

Li, C., (2000) Modeling trace gas emissions from agricultural ecosystems. Nutrient Cycling in Agroecosystems, 58(1–3), 259–276.

Lindner, M., Suominen, T., Palosuo, T., Garcia-Gonzalo, J., Verweij, P., Zudin, S., Päivinen, R., (2010) ToSIA—A tool for sustainability impact assessment of forest-wood-chains. Ecological Modeling, 221(10), 2197–2205.

Liu, K.F.R., (2007) Evaluating environmental sustainability: an integration of multiple criteria decision-making and fuzzy logic. Environmental Management, 39(5), 721–736.

Mazloumzadeha, SM., Shamsia, M., Nezamabadi-pourb, H., (2008) Evaluation of general-purpose lifters for the date harvest industry based on a fuzzy inference system. Computer and Electronic in Agriculture, 60(1), 60–66.

Mebratu, D., (1998) Sustainability and sustainable development: historical and conceptual review. Environmental Impact Assessment Review, 18, 493-520.

Mendoza, GA., Prabhu, R., (2003) Fuzzy methods for assessing criteria and indicators of sustainable forest management. Ecological Indicators, 3(4), 227–236.

Meng, W., Hao, C., Li, H., Ju, M., (2010) EMERGY analysis for sustainability evaluation of the Baiyangdian wetland ecosystem in China. Frontiers of Environmental Science and Engineering in China, 4(2), 203–212.

Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J., Schuhmacher, M., (2006) Assessing water quality in rivers with fuzzy inference systems: A case study. Environment International, 32(6), 733–742.

OECD, (1998) The TDS Activity on Territorial Data and Indicators: Brief Overview. Territorial Development Service. Paris: Organization for Economic Co-operation and Development.

OECD, (2000a) Towards Sustainable Development. Indicators to Measure Progress. Paris: Organization for Economic Co-operation and Development.

OECD, (2000b) Frameworks to Measure Sustainable Development: An OECD Expert Panel. Paris: Organization for Economic Co-operation and Development.

Pearce, D., Barbier, E., Markandya, A., (1990) Sustainable Development: Economics and Environment in the Third World. London: Earthscan Publications.

Pedrycz, W., (1994) Why triangular membership functions. Fuzzy Sets Systems, 64(1), 21–30.

Phillis, YA., Andriantiatsaholiniania, L., (2001) Sustainability: An ill defined concept and its assessment using fuzzy logic. Ecological Economic, 39(3), 435-456.

Pimentel, D., (1980) Handbook of Energy Utilization in Agriculture. Boca Raton: CRC Press.

Pimentel, D., (2005) Environmental and economic costs of the application of pesticides primarily in the United States. Environment, Development and Sustainability, 7(2), 229-252.

Pimentel, D., Pimentel, M., (1979). Food, Energy and Society. Resource and Environmental Science Series. London: Edward Arnold Publ.

Pimentel, D., Stachow, U., Takacs, DA., Brubaker, HW., Dumas, AR., Meaney, JJ., O'neil, JAS., Onsi, DE., Corzilius, DB., (1992) Conserving Biological Diversity in Agricultural/Forestry Systems. BioScience, 42(5), 354-362.

Prato, T., (2000) A fuzzy logic approach for evaluating ecosystem sustainability. Ecological Modeling, 130(2–3), 157–166.

Pretty, J., Brett, C., Gee, D., Hine, R., Mason, CF., Morison, JIL., Raven, H., Rayment, M., van der Bijl, G., (2000) An assessment of the total external costs of UK agriculture. Agricultural Systems, 65(2), 113–136.

Rajaram, T., Das, A., (2010) Modeling of interactions among sustainability components of an agro-ecosystem using local knowledge through cognitive mapping and fuzzy inference system. Expert Systems with Applications, 37(2),1734–1744.

Sattler, C., Nagel, UJ., Werner, A., Zander, P., (2010) Integrated assessment of agricultural production practices to enhance sustainable development in agricultural landscapes. Ecological Indicators, 10(1), 49–61.

United States Environmental Protection Agency (EPA), (1997) [Online]. Available at: http://www.epa.gov/OWOW/NPS/facts [Accessed 21 March 2013]

Van Cauwenbergh, N., Biala, K., Bielders, C., Brouckaert, V., Franchois, L., Garcia Cidad, V., Hermy, M., Mathijs, E., Muys, B., Reijnders, J., Sauvenier, X., Valckx, J., Vanclooster, M., Van Der Veken, B., Wauters, E., Peeters, A., (2007) SAFE – a hierarchical framework for assessing the sustainability of agricultural systems. Agriculture Ecosystem and Environment, 120(2–4), 229–242.

Vaníček, J., Vrana, I., Aly, S., (2009) Fuzzy Aggregation and Averaging for Group Decision Making. Knowledge-Based System, 22(1), 79–84.

Vrana, I., Vaníček, J., Kovář, P., Brožek, J., Aly, S., (2012) A Fuzzy Group Agreement-Based Approach For Multiexpert Decision Making in Environmental issues. Environmental Modelling and Software, 36, 99–110.