EVALUATING ALTERNATIVE FARMING SYSTEMS: A FUZZY MADM APPROACH

by

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INTRODUCTION

Agricultural economists are increasingly called upon to collaborate with biological and physical scientists in developing an integrated, or systems, approach to solving real world problems. Constrained optimization techniques can provide only asymmetric treatment of the decision maker's goals. Approaches based on the generation of trade-off surfaces between two or more goals (Haimes, Larson and Wismer 1971; Prato and Fulcher, 1995) have limited practical ability to handle a large number of goals or to provide the prescriptive information needed in decision support. The most common approach economists use to integrate economic and environmental goals is to place a monetary value on environmental outcomes and incorporate these outcomes into standard, single objective economic decision models (Lutz and Munasinghe, 1994; Cropper and Oates, 1992).

A related problem is the difficulty of generating the increasingly "precise" and unambiguous information needed for complex, equations-based models of reality. This problem stems from the fundamental assumption of bivalent (Boolean) logic built into our mathematics and our models. An alternative logic, known as multivalent or "fuzzy" logic, can be used in a multiple attribute decision making (MADM) framework. In this paper, we outline a fuzzy MADM approach to decision making which builds on previous research (Dunn, Keller, and Marks, 1997; Marks et al., 1995; Dunn et al., 1995) and is used to evaluate ten Missouri crop-livestock farming systems on the basis of eleven economic, environmental, and social criteria. These decision criteria, and associated preference information, were elicited from Missouri farmers. Additional hypothetical farming systems and farmers with different preferences were used to test the sensitivity of the model to preference information.

FUZZY SETS AND LINGUISTIC VARIABLES

Fuzzy logic is an inference system based on the concept of multivalence (Klir and Yuan, 1995; Bardossy and Duckstein, 1995). In contrast to bivalent logic, in which a statement is either true or false, multivalent logic allows for a statement to have degrees of truth. Fuzzy sets are the building blocks in fuzzy logic. A fuzzy set, A, is described by the set of ordered pairs (Zimmermann, p.11):

$$A = \{ (x, \mu_A(x)) \mid x \in X)\}$$

where x is an object in the collection of objects X, and $\mu_A(x)$ indicates the degree of membership of x in A. The mapping μ_A is called the membership function for the fuzzy set A. For every object in X, the membership function for A returns a value from zero to one ($0 \leq \mu_A \leq 1$). Thus, an object can be completely ($\mu_A = 1$), partially ($0 \leq \mu_A \leq 1$), or not at all ($\mu_A = 0$) a member of a fuzzy set.

A linguistic variable is a variable with a range that consists of linguistic terms. Each term is modeled as a fuzzy set. For example, a linguistic variable representing the attribute "age of person" might be named AGE as in figure 1. The base variable, X, is usually a physical or numerical variable on which the fuzzy terms of the linguistic variable are defined. The age of a person is measured in number of years. One would expect a typical person in the Western hemisphere to live anywhere from 0 to 90 years. Hence, the range over which the linguistic variable, AGE, is defined is [0, 90]. The terms set for the linguistic variable AGE has three terms: Young, Middle Age, and Old. The example AGE is measured over a natural scale, however, variables may also be defined over an artificial interval or ordinal scale. Variables measuring qualitative concepts are constructed on artificial interval scales.

DECISION CONTEXT: FARMING SYSTEMS, ATTRIBUTES, AND PREFRENCES

The fuzzy MADM model was used to evaluate the combined economic, environmental, and social performance of ten actual farming systems and several hypothetical systems. The differences between the farming systems were calculated on the basis of representative soil and productivity characteristics for a 640-acre farm in North Central Missouri (Godsey, 1996). Ten realistic farming systems alternatives (FSAs) were constructed based on varying proportions of a corn-soybean crop component and a cow-calf livestock component. The livestock component was further varied to reflect high, medium, and low grazing intensity management.

The relevant decision criteria, or attributes, selected for this research reflect both the work of scientists in the area of sustainable agriculture and the opinions of actual farmers from the area of the representative farm. The final set of eleven attributes represent the economic, environmental, and social dimensions of farming. The economic attributes are profit, risk, return on assets, and cash flow. The environmental attributes are soil erosion, soil quality, pesticide runoff, and landscape aesthetics. The social attributes are health and safety, community impact, and lifestyle.

The set of attributes includes both qualitative and quantitative concepts. One advantage of using a fuzzy MADM approach is that it can handle problems characterized by a combination of qualitative and quantitative variables. Six quantitative indicators were used to generate measurements for each of the quantitative attributes - - profit, risk, return on assets, cash flow, soil erosion, and pesticide runoff (Godsey, 1996). The five qualitative attributes are measured using rating scales. These attributes are soil quality, landscape aesthetics, health and safety, lifestyle, and community impact. Each alternative is rated on an interval scale from zero to twenty for each of the attributes. At either end of the scale are opposing adjectives, for example, the range of landscape aesthetics is determined by the terms “unattractive” and “attractive”. For additional details on the representative farm, attributes, and indicators, see Godsey (1996).

Table 1 is the decision matrix that concisely summarizes the multiple attribute decision problem. There are FSAs representing the different mixes of the livestock and cropping components, and the eleven attributes representing the decision criteria of the decision maker. Each cell in the decision matrix provides a rating for an alternative farming system, represented in that row, with respect to an attribute represented in that column. From the decision matrix one can see that the cropping and mixed operation systems are dominated by the total livestock systems. In the results section, therefore, only the ranks of the alternatives which are non-dominated are reported.

A hierarchical weighting method (HWM) was developed to express the relative importance of the eleven attributes in terms of the preferences of the decision maker. The HWM first elicits the degree of importance that the decision maker attaches to the three dimensions of sustainability, and then elicits the preferences for the specific attributes. The decision maker can trade off among the economic, environmental, and social dimensions, and can then trade off among the different attributes within each dimension. Direct tradeoffs are not allowed among all eleven attributes. In a direct interview format, farmers were asked to allocate counters (pebbles) to different cards, representing the attributes or dimensions, in relation to their degree of importance. Table 2 summarizes the normalized weights elicited from a crop farmer, a livestock farmer, and a farmer with a mixed crop-livestock operation.

While the fuzzy MADM model is demonstrated in an actual decision context in Missouri, the model was extensively tested to determine how explicit farmer weights affect the final ranking of each FSA. In order to isolate the effect of different preferences in the model, several hypothetical decision makers and hypothetical farming systems were formulated. Three "types" of farmers' preferences were formulated. The first type of farmer is the baseline or equal weights farmer who weights all eleven attributes equally. The baseline farmer provides a standard against which all other results can be compared, and allows the unweighted ratings in the decision matrix to determine the final rank of each decision alternative. The second type of farmer is only interested in one dimension of farming, resulting in the "green", "greedy", and "social" farmers. The greedy farmer is only interested in the economic aspects of farming while the other farmers are interested in the environmental or social aspects only. The third type of farmer is the myopic farmer who is only interested in a single aspect of farming, that is, just one attribute in the decision matrix. For example, the "profit oriented" farmer is only interested in the profitability of his or her farm operation. There are eleven myopic farmers in total, with six of these included for illustrative purposes in table 2. Several hypothetical FSAs were devised to test how preference information is handled by the fuzzy MADM model. The results for these systems, which reflect extremes in each of the dimensions of sustainability, are reported in the results section.

CONSTRUCTION OF THE FUZZY MADM MODEL

The fuzzy MADM decision support method consists of four rulebases where inferences can be made about the performance of each FSA. Because of the hierarchical nature of the concept of sustainability, a rulebase was constructed to reflect each of the three dimensions of sustainability as well as the overall sustainability. The economic, environmental, and social rulebases consist of a series of rules where deductions are made about the economic, environmental, and social performance of each FSA. The overall sustainability rulebase consists of a series of rules where deductions are made about the overall performance of each FSA.

Linguistic Variables

Each rule in the rulebase is a fuzzy proposition constructed on linguistic variables. Fifteen linguistic variables were constructed in this research. For details on the construction of the linguistic variables, see Marks (1998). All terms are represented by symmetric or non-symmetric Gaussian functions, except the first and last terms which are represented by half-Gaussian functions. A 50 percent overlap on the real line was assumed for several of the artificial variables. The symmetric Gaussian function depends on two parameters σ and c (MathWorks 1998, p. 3-34), and is given by

$$f(x;\sigma,c) = e^{\frac{-(x-c)^2}{2\sigma^2}}$$

where c is the mean value and sigma is the variance around the mean. Gaussian functions have the advantage of being smooth and non-zero for all values of x. This functional form was found to work well when combined with the gamma operator.

Fuzzy Rules

Each fuzzy rule consists of an IF-THEN statement that links the input variables to an output variable. The four examples below illustrate how the rules were written in each of the four rulebases:

Fuzzy Rule from Economic Dimension:

IF PROFIT is Low AND CASH FLOW is Good AND RISK is Low AND RETURNS is High THEN ECONOMIC PERFORMANCE is High.

Fuzzy Rule from Environmental Dimension:

IF SOIL EROSION is Low AND LANDSCAPE is Attractive AND PESTICIDE RUNOFF is Low AND SOIL QUALITY is Good THEN ENVIRONMENTAL PERFORMANCE is High.

Fuzzy Rule from Social Dimension:

IF COMMUNITY IMPACT is Neutral AND HEALTH & SAFETY is Neutral AND LIFESTYLE is Supportive THEN SOCIAL PERFORMANCE is Medium.

Fuzzy Rule from Overall Sustainability:

IF ECONOMIC PERFORMANCE is High AND ENVIRONMENTAL PERFORMANCE is High AND SOCIAL PERFORMANCE is Medium THEN OVERALL PERFORMANCE is High.

Gamma Operator

The previous rules were constructed using multiple antecedents clauses which are linked by the aggregation operator "and". Zimmermann's (1987) gamma aggregation operator was selected for the fuzzy MADM model because it is parameterized, adaptable, compensatory, does not exhibit undesirable aggregation behavior when $0 < \text{gamma} < 1$, and, perhaps most importantly, it allows the explicit incorporation of preferences in the model. The gamma operator is a weighted combination of the noncompensatory "and" and the fully compensatory “or” operators. The greater the tendency towards compensation (larger gamma), the more the “or” component of the combination takes over. The less the tendency towards compensation (smaller gamma) the more the “and” component takes over. The gamma operator is defined as follows:

$$\mu_\theta = (\prod_{i=1}^{m} \mu_i^{\delta_i})^{1-\gamma} . (1 - \prod_{i=1}^{m} (1-\mu_i)^{\delta_i})^{\gamma}$$

where $0 \le \mu_i \le 1$, $0 \le \gamma \le 1$, and $\Sigma\delta_i = m$. The δ_i are the individual weights attached to each attribute i. The μ_i are the membership values that the set of ratings for each alternative take in each term set.

The value of γ (gamma) determines the degree of compensation in the model, or the degree of compensation between attributes. A drawback of the gamma operator is the lack of theoretical guidance for selecting the level of gamma (Zimmermann 1987; Zysno 1982). However, in the fuzzy MADM model this consideration proved unimportant as changes in gamma, when these changes are consistent throughout the model, do not affect the relative rank of the alternatives.

MODEL RESULTS

The fuzzy MADM model was first used to rank the representative farming systems on the basis of the actual preference information provided by Missouri farmers. The final output of the fuzzy MADM model is a numeric value associated with the combined output set for each farming system. This number is a defuzzified centroid value, defined as the value for which the area under the graph of the output set is divided into two equal subareas (Klir and Yuan 1995, p. 336). Differences among the final rankings for pairs of alternatives were evaluated in terms of Howard’s degree of discrimination (see Howard, 1991).

Results for Representative Farm and Actual Farmers

As indicated earlier, seven of the ten actual FSAs derived from the model farm were dominated. Only the three all-livestock operations were in the nondominated set. Results for the crop, livestock, and mixed operation farmers were identical despite slight differences in the explicit weights of these farmers. The high management level (HML) system is ranked first, with the medium management (MML) system ranked second, and the low management level (LML) system ranked third. The results reflect the closeness of the alternatives and the closeness of the weights of the three farmers. For example, the livestock farmer has almost identical weights to the equal weights farmer for each attribute in the environmental dimension. Likewise, the crop farmer is not that different from the livestock farmer. In general, the rank order of the alternatives reflected their relative ratings in the decision matrix. In this sense, one can argue that intra-attribute preferences are preserved.

Sensitivity Analysis – Myopic Farmers

The fuzzy MADM model was tested for its sensitivity to the preferences of the myopic farmers and the baseline farmer. Results indicate that economic, social, and environmental performance are either a strictly decreasing function of each variable in the model or a non-increasing function, depending on whether the variable being tested is modeled symmetrically or non-symmetrically. All the social variables were modeled as symmetric linguistic variables, while some of the economic and environmental variables were non-symmetric. This result is consistent with expectations – one would expect the utility of both types of decision maker to decrease as the performance of an alternatives is progressively worsened.

The absolute value of the centroid for economic, environmental, and social performance is strictly greater for the baseline farmer than for the myopic farmers. This relationship holds for all levels of each variable, which is consistent with expectations. A myopic farmer will place greater weight on the level of the variable being varied. His or her disutility from unit decreases in the variable of interest is therefore greater than the baseline farmer, and he or she is not fully compensated by the utility derived from the performance on the other variables. *A priori* one would expect the rate of decrease in the centroid value for economic, environmental, and social performance to be greater for the myopic farmers than the baseline farmer. That is, one would expect the absolute difference between pairs of centroid values to be greater for the myopic farmers than the baseline farmer. One would also expect the cumulative difference to be greater. Results indicate that the cumulative decrease is greater for the myopic farmers than the baseline farmer. The baseline farmer's discriminates less between pairs of alternatives than the myopic farmers, because myopic farmers are more sensitive to changes in the performance of each variable.

Sensitivity Analysis – Single Dimension Farmers

The model was tested using three hypothetical farming system alternatives -- "profitable", "organic", and "commune" – that each have HIGH overall performance in one dimension of farming and LOW performance in the other two dimensions. For example, the profitable FSA has excellent economic performance but low environmental and social performance. The centroid value for the baseline farmer for each system is the same (0.616, 0.614, and 0.608 respectively). Hence, the baseline farmer is indifferent between all three FSAs and ranks them equally with a degree of discrimination between pairs around one percent. The greedy farmer prefers the profitable farm to the organic and commune farms, with a relatively higher degree of discrimination (nine percent). Likewise, the green farmer prefers the organic farm, while the social farmer prefers the commune farm. Their respective degrees of discrimination are also around nine percent.

In conclusion, the sensitivity results show that weights of different types of farmers are correctly reflected in the fuzzy MADM model. Different attribute and dimension weights are fully reflected in the ranks of the alternatives.

CONCLUSIONS

This paper has made a significant contribution to the problem of modeling decisions among complex decision alternatives characterized by multiple, conflicting objectives. Multiple attribute decision making has not been extensively applied in the field of agricultural economics. The few applications that exist have tended to focus on formulating the alternatives rather than the development of the ranking algorithm itself (Foltz et al., 1995). Alternatively, other applications have been characterized by relatively simple decision problems, such as three alternatives judged on three attributes (Yakowitz et al., 1993).

There are several advantages to using fuzzy MADM in the context of agricultural sustainability: 1) through the use of linguistic variables data collection requirements can be minimized; 2) qualitative concepts can be mathematically modeled; 3) informational uncertainty arising from vagueness, imprecision, and ambiguity can be modeled with the use of fuzzy sets; 4) the fuzzy MADM model can fully rank discrete farming systems; 5) decision maker weights can be incorporated into the model through the operator; 6) the model preserves interattribute and intra-attribute preferences; 7) information is provided not only on total utility but also in terms of the economic, environmental, and social performance of the system; 8) the fuzzy MADM model is not subject to the rank reversal problem of other MADM methods, namely, the analytic hierarchy process; and, 9) the problem of converting non-commensurate data to a common numerical scale is solved by the use of the linguistic variables.

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Table 1 The Decision Matrix

Farming Systems	Profit ($)	Risk (%)	Return on Assets (%)	Cash Flow ($)	Soil Erosion (tons/ acre)	Pesticide Runoff	Soil Quality	Landscape Aesthetics	Health & Safety	Lifestyle	Community Impact
All Crop	7,595	43	2.81	1,719	8.9	2,980	5	6	2.5	6.5	2.5
1/3 HML	7,282	40	2.77	1,485	4.7	1,986	7	7	4.5	7.5	4.5
1/3 MML	7,338	38	2.96	1,327	4.7	1,986	6.5	7	4.5	8.5	5.5
1/3 LML	6,902	38	2.70	1,273	4.7	1,986	6	7	3.5	8.5	5.5
2/3 HML	7,726	31	2.85	1,295	4	993	13	14	12.5	12.5	12
2/3 MML	9,874	26	3.23	918	4	993	12	11	10.5	11.5	11
2/3 LML	6,726	33	2.67	810	4	993	10	8.5	9.5	11.5	9.5
HML	22,086	1	5.29	698	0	0	17	18.5	18.5	17.5	20
MML	25,286	1	5.97	352	0	0	16	15.5	16.5	16.5	18
LML	20,493	1	4.96	198	0	0	13	13.5	16.5	15.5	16

Source: Godsey (1996, p.106).
Legend: HML = high grazing intensity; MML = medium grazing intensity; and LML = low grazing intensity.

Table 2 Normalized Weights by Farmer (Actual and Hypothetical)

	Economic	Environ-mental	Social	Profit	Risk	Return on Assets	Cash Flow	Landscape Aesthetics	Pesticide Runoff	Soil Erosion	Soil Quality	Community Impact	Lifestyle	Health & Safety
Crop Farmer	0.50	0.33	0.17	0.40	0.13	0.17	0.30	0.25	0.10	0.40	0.25	0.20	0.40	0.40
Livestock Farmer	0.40	0.40	0.20	0.33	0.08	0.33	0.25	0.21	0.25	0.29	0.25	0.25	0.33	0.42
Mixed Farmer	0.33	0.5	0.17	0.05	0.30	0.50	0.15	0.10	0.30	0.33	0.27	0.00	0.40	0.60
Baseline	0.33	0.33	0.34	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.33	0.33	0.33
Greedy	0.90	0.05	0.05	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.33	0.33	0.34
Green	0.05	0.90	0.05	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.33	0.33	0.34
Social	0.05	0.05	0.90	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.33	0.33	0.34
Profit Oriented	0.33	0.33	0.34	0.85	0.05	0.05	0.05	0.25	0.25	0.25	0.25	0.33	0.33	0.34
Risk Averse	0.33	0.33	0.34	0.05	0.85	0.05	0.05	0.25	0.25	0.25	0.25	0.33	0.33	0.34
Landscape Obsessed	0.33	0.33	0.34	0.25	0.25	0.25	0.25	0.85	0.05	0.05	0.05	0.33	0.33	0.34
Chemical Conscious	0.33	0.33	0.34	0.25	0.25	0.25	0.25	0.05	0.85	0.05	0.05	0.33	0.33	0.34
Community Oriented	0.33	0.33	0.34	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.90	0.05	0.05
Lifestyle Obsessed	0.33	0.33	0.34	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.05	0.90	0.05

Figure 1: Linguistic Variable AGE