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Evaluating Agricultural Systems for Environmental Sustainability Using an Impact Matrix Approach

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Abstract: Sustainable agriculture is a complex problem that demands consideration of many interrelated factors, processes, and institutions. Unfortunately, current definitions of sustainability are expansive, and use as a guide for strategic planning or decision making is clouded by ambiguity and a plethora of definitions. Regardless of how sustainability is defined, agricultural producers are interested in developing and evaluating agricultural management systems that are both environmentally sound and economically profitable. There has been a proliferation of decision analysis and economic indicator tools developed to aid producers; however, the tools rarely are used due to excessive complexity or a failure to capture important criteria (e.g., economic, ecological/environmental and social factors) that better represent how producers define "sustainability." In this paper, we adapt the payoff matrix approach from the financial risk arena to develop a comparable framework for agroecosystem risk. The payoff matrix concept utilizes the probability function for management alternatives to represent multiple pieces of information; a matrix of these vectors allows for development of many types of decision rules (e.g., minimax regret or maximin strategies) that can represent alternative value systems. Instead of a payoff matrix, we create an "impact matrix" that contains a vector of plausible environmental indicators and outcomes for agricultural systems. The result of this research is a tool that allows indicators to be incorporated in an index that can be adapted to different situations, and thus used in a variety of contexts while remaining simple to understand.

Keywords: Decision rules; Impact matrix; Indices; Agriculture; Environment; Multicriteria.

1. INTRODUCTION

There are many efforts around the world to develop indices to track and understand ecosystems (see Rogers et al., 1997 for an extensive list of indices developed). Indices facilitate simultaneous comparison of two or more complex, multifaceted systems by reducing information about each system into a single number. Ideally, an index or an indicator is a means devised to reduce a large quantity of data down to its simplest form, retaining essential meaning for the questions that are being asked of the data. Paradoxically, while this reductionism enhances understandability, it works contrary to both the complex nature of the system and potentially disparate values that might be held by system users.

There has been an abundance of approaches for developing decision analysis and economic indicator tools, each searching for the "best" representation of processes or problems that often contain incommensurate and conflicting objectives. However, one goal has remained the same: research investigations have centered on whether and how to present a variety of multidimensional information in a single framework. This information can range from a single mathematical index to complex diagrams depicting many indices or indicators at one time. The search for an optimal way to represent multidimensional data has perhaps diverted scientists and decision makers away from other promising solutions. As Bakkes et al. [1994] states, indicators are specific to the process that they are a part of, therefore, there is no such thing as a universal set of indicators. Objectives and situations vary significantly over time and space.

An alternate way to proceed is to present the information in a framework that integrates a variety of decision rules. Concepts such as ecological, social, and economic condition can be incorporated into a single framework that permits many different types of decision rules to be used (rather than trying to adhere to a single decision rule). In this paper, we describe a flexible framework that will enhance researchers' ability to depict dimensionality in a greater number of situations. This framework is based on the payoff matrix concept used extensively in decision theory [e.g., Resnik, 1987]. An "impact matrix" is developed that uses similar concepts as the payoff matrix. The impact matrix provides a new tool that allows indicators to be incorporated in an index that can be adapted to different situations and thus used in a variety of ways, while remaining simple to understand. That is, the impact matrix allows flexibility in developing indices of complex, multifaceted systems so that many disparate value systems may be represented.

2. ENVIRONMENTAL INDICES

Constructing environmental or ecological indices is a popular topic that has been extensively addressed in many different research and policy arenas. Many of these studies have been conducted by international organizations such as the Organization for Economic Cooperation and Development (OECD), the World Bank, the European Union, the United Nations, the Food and Agriculture Organization, and World Health Organization [Rogers et al., 1997]. In particular, the OECD "Pressure-State-Response" framework is perhaps the most widely used international approach for developing indicators [OECD, 1993]. The framework is based on simplified relationships between the environment and the human activities. Pressures related to an ecosystem are exerted by human activities such as emissions or discharges of pollutants, state variables are indicators of the quality of the environment, and response variables indicate how society responds (e.g., enacting environmental policies and programs) to changes in pressures or states. A thorough discussion and explanation of the many environmental indices that have been developed and the methods and assumptions used to create them can be found in Bakkes et al. [1994], Ott [1978], and Rogers et al. [1997].

Traditionally, combining variables into indices or a single index requires an aggregator function, which implies weighting variables. However, designing universal aggregator functions is difficult because value judgments in assigning weights typically can not be avoided. Values are highly subjective and variable, and nearly impossible to aggregate across individuals [Hyatt and Hoag, 1997]. Heimlich [1995] presents three methods for addressing the problem of implicit weighting: 1) apply explicit weights; 2) do not weight (implies equality); and 3) do not aggregate. To show the impact of weighting choice on information displayed to the decision maker, let us consider the case of pressure variables within the context of the "Pressure-State-Response" framework. Pressure variables can often be measured by data with a specific unit because a single factor is the cause of the pressure. Nevertheless, a pressure variable can be converted into a dimensionless variable, called environmental pressure equivalents (EPeq), by relating it to a standard. This transformation allows the comparison of different pressure variables (e.g., can be summed, averaged, etc.) because they are normalized. The standard could be a prescribed target, such as greenhouse gas emissions from the Kyoto protocol, or any other desired outcome. An example of environmental pressure variables was developed by the Dutch government [Adriaanse, 1993]. In this case, target groups representing different human activities created pressure on a set of eight themes (representing state variables). Pressure equivalents were developed that measured the contribution of each target group to each theme, expressed in theme equivalent. Figure 1 shows an overview of pressures for the climate, acidification, eutrophication, and disturbance themes. Theme pressure equivalents were standardized by target values for the year 2000 in order to make them comparable. As seen in Figure 1, this presentation of the information implies no weighting. In Figure 2, we have mapped the themes weighted by targets for simplicity. The concept is to show progress toward several goals simultaneously without creating a single index. Figure 2 maps progress in 1985 and 1990 (as compared to 1980), and shows that improvements were made to three themes while disturbance has become worse.

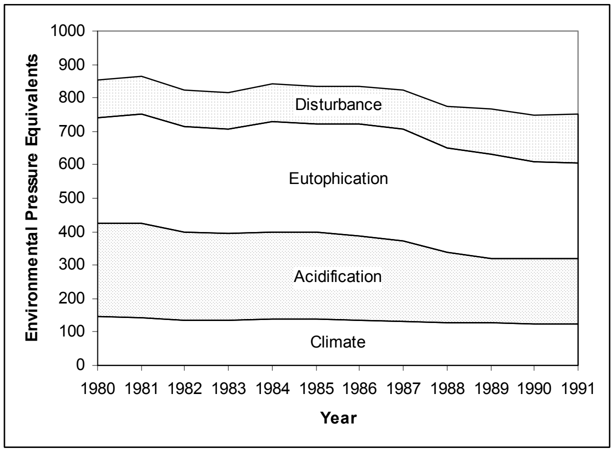

Figure 1. Environmental pressure on four Dutch themes, weighted by target value for 2000 [Adriaanse, 1993].

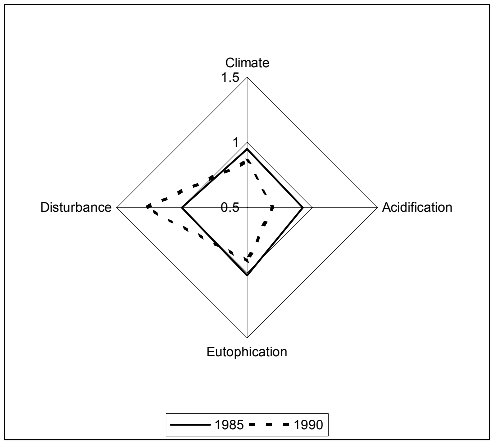

Figure 2. Amoeba diagram of Dutch data.

3. PAYOFF MATRIX

The payoff matrix is one of the most common tools used in decision theory when there is uncertainty involved in the outcomes. Each decision involves the analysis of *actions* that can be taken, potential *states* of the environment, and unique *outcomes* for each state-action combination. A decision maker has to consider the implications for all possible combinations. The potential outcomes can be arranged in a matrix called a payoff matrix, which enables a decision maker to use one of many decision rules. For example, suppose that a farmer is considering the purchase of new equipment or production facilities. The magnitude of the potential investment ranges from very large [e.g., a new irrigation system (A1)] to moderate [e.g., a new combine (A2) or farm shop building (A3)] to no new investment (A4). The type of investment the farmer selects is dependent on future economic conditions, i.e., will the price of grain the farmer sells be high [strong market (S1)], medium [fair market (S2)], or low [poor market (S3)]. Given the four decision alternatives and the three states of nature, which investment opportunity should the decision maker (farmer) choose? In order to answer this question, we need information on the profit associated with each combination of a decision alternative and a state of nature. For example, how much profit would the farmer experience if he/she decides to purchase a new combine (A2) and economic conditions are good (S1)? These types of decision situations can be organized into a payoff matrix. Entries in a payoff matrix can be stated in terms of profits, costs, or any other measure of output that may be appropriate for the particular situation. Table 1 below is the payoff matrix representation of the farm investment problem; table entries signify profits for each state-action combination.

Table 1. Payoff matrix for a hypothetical farm investment problem.

States/ Actions	S1	S2	S3	Maximax Criterion	Maximin Criterion	Minimax Regret Crit.
A1	500,000 (0)	150,000 (50,000)	-200,000 (200,000)	**500,000**	-200,000	200,000
A2	400,000 (100,000)	200,000 (0)	-150,000 (150,000)	400,000	-150,000	**150,000**
A3	200,000 (300,000)	100,000 (100,000)	-50,000 (50,000)	200,000	-50,000	300,000
A4	0 (500,000)	0 (200,000)	0 (0)	0	**0**	500,000

In the following sections we will review some common decision criterion, and demonstrate the criterion using the state-action profit information in Table 1.

3.1 Maximax Criterion

The maximax criterion is an optimistic approach. It suggests that the decision maker examine the maximum payoffs of alternatives and choose the alternative whose outcome is the best. This criterion appeals to the adventurous decision maker who is attracted by high payoffs. For the above example, the maximum among the maximum values is $500,000, so the decision is to purchase an irrigation system (A1). This value is found by first selecting the maximum (across the states) for each action, and then selecting the overall maximum from the "action maximums."

3.2 Maximin Criterion

The maximin criterion is a pessimistic approach. It suggests that the decision maker examine only the minimum payoffs of alternatives and choose the alternative whose outcome is the least bad. This criterion appeals to the cautious decision maker who seeks to ensure that in the event of an unfavorable outcome, there is at least a known minimum payoff. For the above example, the farmer would choose not to invest in new equipment or facilities (A4) because a payoff of $0 is the maximum among the minimum payoffs.

3.3 Minimax Regret Criterion

The minimax regret criterion examines the regret, opportunity cost or loss resulting when a particular situation occurs and the payoff of the selected alternative is smaller than the payoff that could have been attained with that particular situation. The regret corresponding to a particular payoff is defined as $R_{as} = X_s(\max) - X_{as}$ where $X_s(\max)$ is the maximum payoff attainable under the state S_s (the subscripts a and s refer to the action and state, respectively). The minimax regret criterion suggests that the decision maker look at the maximum regret of each strategy and select the one with the smallest value. This approach appeals to cautious decision makers who want to ensure that the selected alternative does well when compared to other alternatives regardless of what situation arises. This criterion transforms the payoff matrix into a regret matrix (shown in parentheses in Table 1). For the minimax regret criterion, the farmer would choose to purchase a new combine (A2) because the payoff of $150,000 is the minimum among the maximum regrets.

In summary, the farm investment example illustrates that use of several decision criteria often results in a mix of decisions. Hence, the appropriate criterion is dependent on the "risk" personality and philosophy of the decision maker.

4. IMPACT MATRIX FOR MULTIPLE ATTRIBUTES

We propose adapting the payoff matrix into an impact matrix for the purpose of calculating environmental indices. The concepts of state, actions and outcomes can be modified in many ways; decision rules for risk analysis can also be adapted and expanded with decision information from the indices literature. We will use a case study concerning the impact of agricultural production on the environment to illustrate the impact matrix concept. The approach used to develop indicators (within the impact matrix) is the Pressure-State-Response framework explained previously. For example purposes, consider four management practices applied to a field near Tifton, Georgia in the Southern Coastal Plain of the United States. The soils are Tifton sandy loam on 2-5% slopes, the drainage area is approximately 29 ha, and the conventional management practice is continuous corn [USDA-SCS, 1984, pg. 6-1]. The alternative practices under consideration are:

- Alternative 1: Continuous corn and a small grain winter cover crop.
- Alternative 2: A terrace system with grassed waterways, continuous corn and a small grain winter cover crop.
- Alternative 3: Fair pasture.

Fertilizer applied annually for the conventional practice (continuous corn) and Alternative practices #1 and #2 are 115 kg/ha nitrogen (N), and 30 kg/ha phosphorus (P). Alternative #3 requires only a single application each spring of 100 kg/ha N. The most significant "pressures" that the cropping systems "exert" on the environment are considered to be the following:

- SY: Sediment Yield (t/ha)
- RO: Runoff (mm)
- NLG: Nitrate Leaching to Groundwater (ppm)

The matrix in Table 2 represents the impact of the four management practices on the three environmental variables of interest.

Table 2. Matrix of environmental pressure variables.

	Conventional	Alternative 1	Alternative 2	Alternative 3
SY	4.72	3.83	0.79	0.09
RO	80.07	58.22	30.17	14.12
NLG	9.6	7.1	8.7	26.1

The information in Table 2 allows us to use any of the decision rules discussed in the previous section, plus additional new ones. Many of the payoff decision rules related to decisions under uncertainty find complementary concepts in the indices literature. To illustrate how the decision rules presented in the previous section can be adapted to the impact matrix concept, we need first to transform the three pressure variables into a pressure equivalent indicator. Pressure variable information (Table 2) is expressed in different units and therefore we can not make comparisons across rows (or columns). In order to solve this problem, each variable is expressed in terms of EPeq. The EPeq pressure value is unitless and can be used as a comparison tool across variables. A target value (or standard) is needed to calculate pressure values for each variable:

$$EPeq_{Variables} = \text{Impact (units)/Target (units)} \quad (1)$$

For expository purposes, different types of targets may be selected. For soil erosion, the target can be related to a sustainability criterion of 8 metric t/ha, as suggested by Adriaanse [1993]. This target is a proxy for the maximum level of sustainable soil erosion. For nitrate leaching to groundwater, a maximum concentration level (mcl) of 10 ppm (the U.S. standard for health safety) is used. There is no standard available for surface runoff, therefore the best possible outcome (i.e., the least amount of runoff) among the management practices is used as the runoff target.

- SY: 8 metric t/ha
- RO: 14.12 mm
- NLG: 10 ppm

The pressure value calculated for sediment yield using the conventional management practice is:

$$EPeq_{SY\ Conventional} = 4.72 / 8 = 0.59 \quad (2)$$

Converting all pressure variables into EPeq's results in an impact matrix as presented in Table 3.

Table 3. Impact matrix for selected agricultural management practices.

	Conventional	Alternative 1	Alternative 2	Alternative 3
SY	0.59	0.42	0.09	0.01
RO	5.64	4.12	2.14	1.0
NLG	0.96	0.71	0.87	2.61
Simple Average	2.40	1.75	**1.03**	1.21
Expected Value [1]	1.16	0.84	**0.44**	0.63
Maximax Value	0.59	0.42	0.09	**0.01**
Maximum Regret – SY	0.58	0.41	0.08	0
Maximum Regret – RO	4.64	3.12	1.14	0
Maximum Regret – NLG	0.25	0	0.16	1.90
Regret Index	5.47	3.53	**1.38**	1.90

[1] Assume that probabilities are the following: SY= 0.70, RO=0.10, and NLG=0.20.

The impact matrix in Table 3 applies the following decision rules: simple average, expected value, maximax, and minimax regret. For promoting environmental sustainability, Alternative #2 (terrace system) is the management practice of choice for the simple average, expected value, and minimax regret decision rules. Alternative #3 (fair pasture) is the management practice of choice for the maximax decision rule. In order to have a single index that allows us to evaluate all management practices, the regrets for each management practice are summed up to obtain a Regret Index; the last row of Table 3 presents the aggregation results. It should be noted that for the impact matrix approach, a variation of the original minimax regret rule was implemented. In standard minimax regret, the maximum regret is first calculated for each action (in this case management practice); the action having the minimum of the maximum regrets is then typically preferred as the optimal solution. In the impact matrix approach, as shown in Table 3, the regrets are summed to generate a Regret Index. This solution is a preferable method for analyzing environmental impacts since the opportunity cost of each pressure variable is now included in the final decision. The minimax regret index provides decision makers with one of many possible ways to aggregate impact matrix information into a single index. Most importantly, the aggregation rule is transparent, and can be explained in a way that accurately reflects decision maker preferences.

5. CONCLUSIONS

The objective in performing this study was to open the door for another way to present indices that might be more flexible and meaningful in certain situations. In this regard, we developed a flexible tool that allows the decision maker to analyze available information under different decision criterion and values. The decision rules used in the agricultural production example (Table 3) represent only some of the many options that the decision maker would have in a real-world situation. Most of the large variety of indices presented in Ott [1978] and Rogers et al. [1997] can be implemented using the information shown in the impact matrix example. Moreover, there are numerous ways in which the impact matrix concept can be extended. For example, it could be adapted to include changing (dynamic) actions over time, to treat the states as stochastic variables, and to use different types of weights so that multiple weighting decision methods can be compared simultaneously.

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