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Chapter 48

Use of a DSS for Evaluating Land Management System Effects on Tepetate Lands in Central Mexico

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Abstract

Increases in population and subsequent increases in demand for agricultural production have resulted in agricultural systems that cause a severe decline in productivity of the soil resource in some areas of Mexico. The central region of Mexico contains areas in which the topsoil has been severely eroded. The exposed subsoil in these areas is characterized by bare and hard surfaces locally named Tepetates. Tepetates are volcanic soils that consist of a duripan exposed through erosion of the overlying soil. In completely exposed soils, the average annual rate of erosion is approximately 6 ton/ha which contributes to the detriment of water quality and loss of storage capacity in reservoirs in the area. Reclamation of tepetate lands for agriculture has been established as one alternative to help meet the demand for food production in that region of Mexico. The U.S. Department of Agriculture — Agricultural Research Service (USDA-ARS) in Tucson has developed a prototype decision support system (DSS) with a multiobjective framework. As a case study, the prototype DSS is applied in Texcoco, Mexico to evaluate crop productivity of maize in tepetate lands using straight row farming, contour row farming, narrow-base terraces, and bench terraces as management systems. The decision variables selected to evaluate the management systems are crop yield, total cost of terrace construction, sediment yield, and runoff. The weather generator CLIGEN is used to reproduce a 20-year record of daily precipitation and the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model to estimate sediment yield, crop yield, and runoff for the same time record. The application of the DSS in selecting conservation management systems in tepetate lands in Mexico provided an improved basis for decision making and revealed problems which will probably be common to many applications of multiobjective decision support technology in developing countries.

Introduction

Mexico is one of the countries most heavily affected by soil erosion. Soil erosion processes are the major cause of nonpoint pollution, and the effects of excessive sediment loading on receiving waters include the deterioration or destruction of aquatic habitat, loss of storage capacity in reservoirs, and accumulation of sediments that inhibit normal biological life. In addition, agricultural productivity in Mexico may be severely affected if soil erosion processes are not adequately controlled; Mexico's capacity to become food self-sufficient is at risk. Oropeza-Mota (1995) points out that soil degradation in Mexico is caused by several factors: (1) an increase in population has caused modification of land use to meet the demand for food production; (2) lack of research, promotion, and publication of simple and income-producing soil conservation management systems in rural environments; and (3) exploitation of natural resources at rates greater than self-recovery capacity.

In the Central Highlands of Mexico, many slopes are covered by duripans which locally are named Tepetates. The word tepetate comes from the Nahuatl language and means hard stratum. Ancient Mexicans used the word tepetate to characterize areas in which topsoil has been severely eroded and unconsolidated weathered rock exposed as a result of deforestation. Tepetate lands are composed of hardened volcanic materials. Their hardness and almost complete lack of nitrogen, phosphorous, and organic matter render them unproductive. Nevertheless, ancient Mexican civilizations cropped tepetate lands using bench terraces on sloping lands to reduce runoff and increase infiltration.

Today, the same technique is used to reclaim heavily eroded soils using heavy machinery. The main crops grown in this region are maize, beans, and squash. Soil conservation management systems are not practiced by farmers, thus soil productivity has diminished with time. Arias-Rojo (1992) reported that the average annual rate of erosion is approximately 6 ton/ha in bare runoff experimental plots, and tepetate lands are the main source of sediment carried by rivers nearby which contributes to the detriment of water quality and loss of storage capacity in reservoirs of the area. According to Zebrowski (1992), the total area covered by tepetate lands in Mexico is unknown. However, 27%, approximately, 30,700 km^2 of the Mexican volcanic axis is characterized by having tepetate lands. In some states of Mexico, for example the state of Tlaxcala, 54% of the area is covered by tepetate lands.

The Federal Government of Mexico established Proyecto Lago de Texcoco in 1973 to help solve some of the problems due to deforestation and changes in land use, and as one alternative to help meet the demand for food production in that region of Mexico. The program involved land reclamation and reforestation. Many benefits resulted from the program, such as incorporating tepetate lands to forest and agricultural activities, reducing soil loss rates, aquifer recharge, flood control, and a general improvement of the environment (Llerena-Villalpando and Sanchez-Bernal, 1992). Within the reclamation program, several studies have been carried out to determine the best management system in tepetate lands. Among management systems studied are contour row across the main slope, and narrow-base and bench terraces (Arias-Rojo, 1992; Pimentel-Bribiesca, 1992).

Purpose and Scope

The purpose of this paper is to provide a basis for identifying the best conservation management system alternatives in tepetate lands in Central Mexico that maximize crop productivity, enhance water quality, and minimize the rate of soil erosion at a minimum cost by applying the USDA-ARS Multiple Objective Decision Support System (Southwest Watershed Research Center, 1994). In addition, research data will be identified that is required for future applications of the DSS in Mexico.

Overview of the Prototype DSS

The USDA-ARS in Tucson, Arizona has developed a prototype DSS with a multiobjective framework. Multiobjective decision theory is one method of evaluating alternative management systems. The methodology involves ranking in order of importance or utility the objectives for different scenarios. The USDA-ARS DSS is a computer-based system which incorporates a decision model based on multiobjective decision making, a default database, a hydrologic/erosion/pesticide/nutrient/economic simulation model, and an interface shell. The DSS system runs on a workstation platform using the UNIX operating system under the X Window graphical interface environment. A full description of the DSS is given by Yakowitz et al. (1992 a, b) and Stone et al. (1995) and so only a brief description follows.

Decision Model

The decision model combines the use of scoring functions developed in Wymore (1988) with a modification of the decision tools described in Yakowitz et al. (1992a). Scoring functions are a means of scaling between 0 and 1 decision variables (i.e., runoff, sediment, nitrogen concentration, economic returns) which have different units and magnitudes. Four generic shapes of the scoring functions (Wymore, 1988) are shown in Figure 48.1. The decision variables are parameterized by either measured data or output from a modification of the GLEAMS (Davis et al., 1990) model discussed below. To make a decision with this methodology, several alternative management systems (i.e., no-till, ridge till) are selected to be compared against a conventional management system (i.e., continuous corn). The average annual, maximum, and minimum values of each decision variable of the conventional system are used to construct a scoring function chosen from the

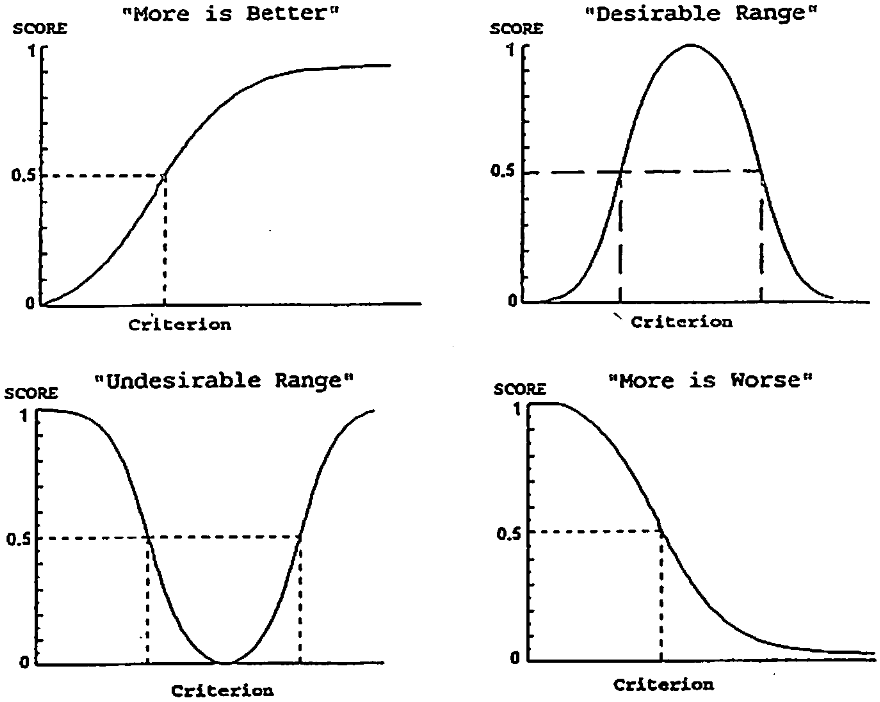

Figure 48.1 Generic scoring function types.

four generic scoring function types shown in Figure 48.1. The score for each individual decision variable for the conventional system is defined to be 0.5 and the combined score of all the decision variables is thus equal to 0.5. The average annual value of a decision variable for an alternative management system (i.e., contour row farming) is scored using the scoring function of that decision variable derived from the conventional system. For each alternative management system, the scores for all the decision variables are combined and the management system is ranked according to the combined score. The management system with the highest combined score is considered to be the best management system among those being evaluated.

Simulation Model

The primary purpose of the simulation model is to quantify the decision variables when values are not available through a database or expert opinion. The GLEAMS model was chosen for the prototype because it simulates many of the processes necessary for evaluating the effects of management systems on water quality. It is important to point out that the decision model described above is not dependent on whether field data or simulation data are used or in the particular model selected. GLEAMS has three major components: hydrology, erosion/sediment yield, and pesticides. The hydrology component uses daily climate data to compute the water balance in the root zone. The erosion component computes estimates of rill and interrill erosion on overland flow areas as well as channel erosion for each storm event. Sediment enrichment is computed for use in the estimation of adsorbed pesticide transport. The pesticide chemistry component simulates the

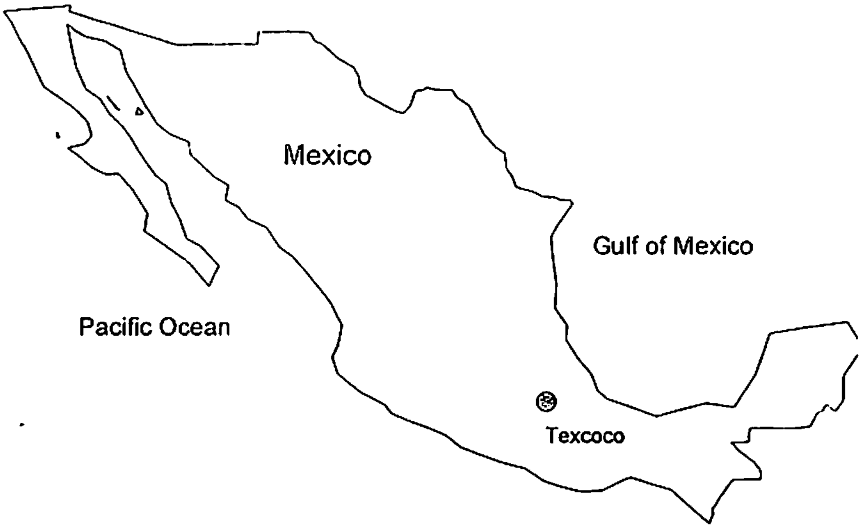

Figure 48.2 Location of experimental site.

movement of pesticides over the surface and through the root zone. A more detailed explanation of the simulation model is available in the WQDSS Reference Manual, version 1.1, (Southwest Watershed Research Station, 1994).

Application of the DSS in Central Mexico

Description of the Site

The study area is located approximately 5 km east of the City of Texcoco and 50 km northeast of Mexico City and is operated as a research facility by Colegio de Postgraduados (Figure 48.2). Mean annual precipitation on the area is about 640 mm with 84% occurring during the summer thunderstorm season of May to October. Mean maximum and minimum temperatures are 27 and 4°C, respectively. According to the FAO-UNESCO, the soil classification is Andisols and Inceptisols. The soils are not well drained and are composed of hardened volcanic materials. Soil may have fragments of duripan in some horizons within a depth of 50 cm. The pan is mostly impenetrable by plant roots. Soil texture is sandy loam with 66% sand, 22% clay, and 12% silt by weight.

Management Alternatives

Soil conservation management systems are not usually practiced by farmers, thus soil productivity has been diminished with time. As stated before, the government has established the program for reclamation of tepetate lands for agriculture as one alternative to help meet the demand for food production in this region. Within this program, farmers are encouraged to use contour row farming, narrow-base and bench terraces, as opposed to straight row farming which is the conventional management system in the region.

Experimental Design

In 1976 and 1977, Colegio de Postgraduados conducted experiments on ten runoff plots (Trueba-Carranza, 1978). For the purpose of this study, only six plots were considered. Plot treatments consisted of contour row farming and two types of terraces, bench and narrow-base. There were two replica plots for each treatment (Figure 48.3). Each plot was 95 by 74 m in size with the long axis perpendicular to the slope. A concrete channel perpendicular to the main slope was constructed for each plot to collect runoff and a flow meter was placed at the end of each channel to measure runoff from each plot. Maize (*Zea mays*) was the main crop grown in all plots. The planting day was July 5 of 1976 and the vegetative cycle of the maize was 120 days. The application rate of nitrogen was 137 kg/ha at the planting day in the form of ammonium nitrate. Crop yield production for each treatment, total sediment yield for the 2 years, and total costs of construction are listed in Table 48.1.

Later, a second experiment (1990 to 1993) was carried out by Colegio de Postgraduados to evaluate straight row farming parallel to the slope and contour row farming across the slope. The average annual crop yield production was 1.83 ton/ha for straight row farming parallel to the slope and 2.37 ton/ha for contour row farming across the slope. The average annual sediment yield for straight row farming was 1.0 ton/ha and 0.493 ton/ha for contour row farming.

Selection of Decision Variables

Four decision criteria were selected to evaluate agricultural management systems in tepetate lands in Central Mexico. The decision criteria were selected to reflect the farmers' and government's interests to increase crop productivity and reduce runoff and sediment yield at a minimum cost. The four criteria are

1. Crop yield
2. Total cost of terrace construction
3. Sediment yield
4. Runoff

Only 2 years (1976 and 1977) of data were available for the terrace management systems (bench and narrow-base) and 4 years (1990 to 1993) of straight row farming parallel to the slope (conventional) and 6 discontinuous years (1976 to 1977 and 1990 to 1993) of contour row farming across the slope. Thus, the GLEAMS model was used to estimate mean annual values for runoff, sediment yield, and crop yield for each of the management systems for a 20-year period. Climatological data were available at a nearby station for the period 1958 to 1984. Based on this record, two conditional probabilities were calculated: the probability of a wet day following a dry day, and the probability of a dry day following a wet day. The weather generator CLIGEN (Nicks and Lane, 1989) was used to estimate a 20-year time series of daily rainfall based on the calculated conditional probabilities, and mean monthly precipitation, monthly standard deviation, and coefficient of skewness of daily precipitation, monthly maximum and minimum temperatures, and solar radiation.

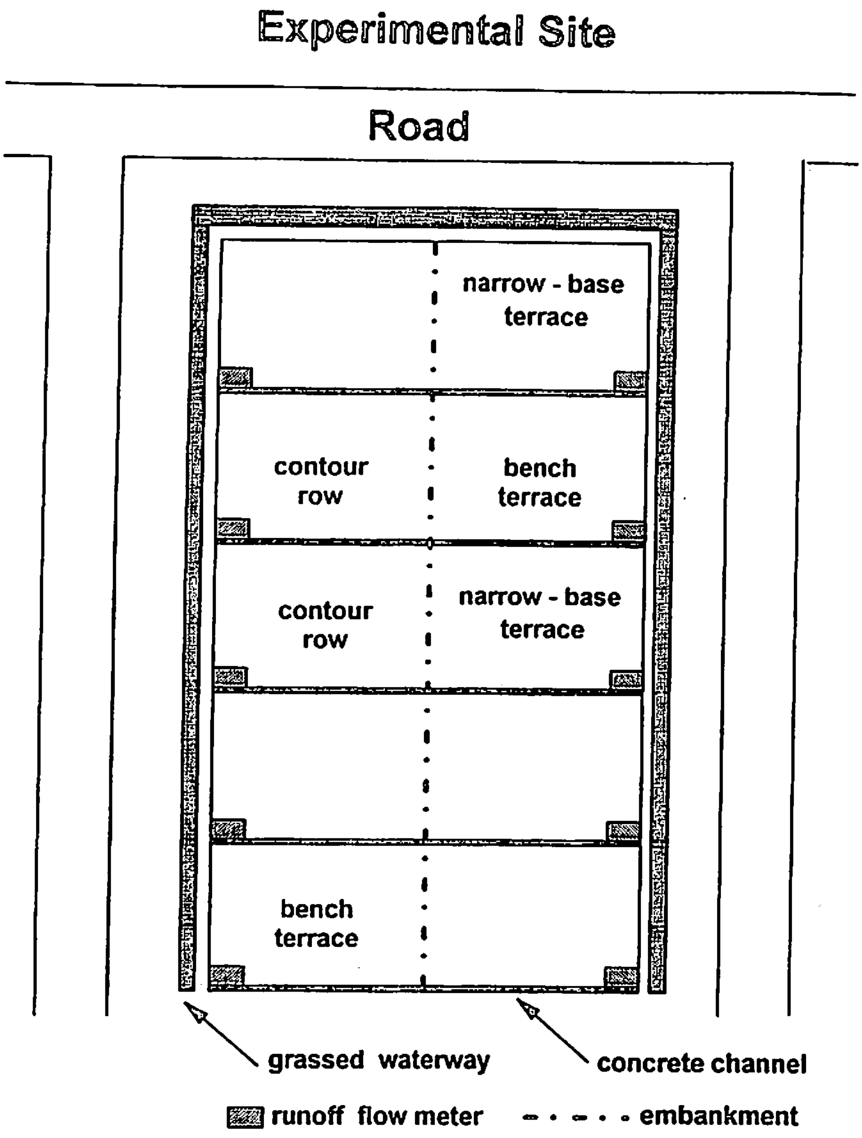

Figure 48.3 **Experimental site and distribution of management systems at Lomas de San Juan, Chapingo, Mexico.**

Table 48.1 **Maize Yield Production, Sediment Yield, and Total Costs of Construction**

	Maize yield		*Total sediment yield*		*Costs of*
Treatment	*1976 (ton/ha)*	*1977 (ton/ha)*	*1976 (ton/ha)*	*1977 (ton/ha)*	*construction (pesos)*
Contour row farming	2.90	2.12	0.356	0.433	75
Narrow-base terrace	2.72	1.90	0.292	0.339	2,195
Bench terrace	2.13	2.34	0.058	0.070	4,517

Trueba-Carranza, 1978.

Table 48.2 Results of the Calibration using the Straight Row Management System.

	Decision variables		
	Runoff (mm)	*Sediment yield (ton/ha)*	*Crop yield (ton/ha)*
Observed average annual values (4 years)	155	1.00	1.83
Average annual values based on a 20-year record	139	0.83	1.74

Table 48.3 Average Annual Values over the 20-Year Runs of the Simulations

	Decision variables			
Agricultural management systems	*Crop yield (ton/ha)*	*Terrace total cost (pesos)*	*Sediment yield (ton/ha)*	*Runoff (mm)*
Straight row parallel to the slope (conventional)	1.74	0.00	0.83	139.46
Contour row (alternative 1)	2.18	75.00	0.38	111.05
Narrow-base terrace (alternative 2)	2.23	2,195.00	0.30	59.54
Bench terrace (alternative 3)	2.20	4,517.00	0.080	18.33

Results

Simulation Model

The GLEAMS model was calibrated using the observed average annual values corresponding to the straight row management system parallel to the slope (conventional). Results of the calibration are shown in Table 48.2. The average annual values for each decision criterion determined by the model GLEAMS are presented in Table 48.3.

Decision Model

To obtain the scores, scoring functions were designed for each of the criteria. For example, for crop yield (ton/ha) a "more is better" scoring function (see Figure 48.1) was selected. This generic function is then customized in the DSS by including a lower threshold at 0.0 ton/ha, the minimum annual yield predicted by the conventional system simulation run and an upper threshold at 3.96 ton/ha, the maximum annual yield predicted by the conventional system. The average annual crop yield (1.74 ton/ha) from the conventional system determines the baseline value, for which this scoring function is 0.5. The slope of the function at the baseline value is a function of the threshold and baseline values. The baseline values can be determined using a standard or conventional system, federal regulation, or by expert opinion. All of the other alternative management systems are scored relative to the conventional management system for each criterion. A management system which performs better than the conventional system with

Table 48.4 Default Importance Decision Variable Order

Agricultural management systems	*Decision variable order* *Crop yield (ton/ha)*	*Sediment yield (ton/ha)*	*Runoff (mm)*	*Terrace total cost (pesos)*
Straight row parallel to the slope (conventional)	0.500	0.500	0.500	0.500
Contour row (alternative 1)	0.858	1.000	0.854	0.485
Narrow-base terrace (alternative 2)	0.884	1.000	0.995	0.139
Bench terrace (alternative 3)	0.870	1.000	1.000	0.006

regard to a specific criterion will score >0.5 for that criterion and one that performs worse will score <0.5. The default importance ordering of the criteria ranks highest that criterion which has the potential for the greatest change in score when a small change in the criteria near the conventional system is observed (Yakowitz et al., 1992b). Ranking the decision criteria by the normalized value of the slopes of the scoring functions at the baseline values resulted in a default importance order listed in Table 48.4.

Based on the established importance order of the decision criteria, best and worst composite scores are determined by the DSS for each of the alternatives by solving the linear programs given by Yakowitz et al. (1992b). The solutions to these linear programs are the most optimistic and pessimistic composite scores (weighted averages) consistent with the importance order given above. Figure 48.4 shows the range of composite scores from best to worst for each alternative for the default importance decision variable order.

Based on the default importance order and composite scores, all the alternatives score better than the conventional. The best alternative is the contour row since its composite average score is the highest among the other two alternatives. This scenario could reflect the government's perspective if it wants to encourage farmers to maximize crop productivity and reduce soil erosion through an established National Soil Conservation Program that may fully subsidize the cost of construction and maintenance of terraces.

The DSS allows the user to redefine an importance order for the decision variables. This is a realistic feature designed to accommodate a particular preference associated with a different user's perspective of the decision criteria. For example, a farmer with little capital may wish to place a higher importance on the terrace cost than other decision variables. A new importance decision variable order was selected in which the terrace cost and crop yield are the most important decision variables (terrace cost > crop yield > sediment yield > runoff). Figure 48.5 shows the range of composite scores from best to worst for each alternative for the new importance decision variable order. In this scenario, the average composite scores of both terrace management systems were lower than the conventional, but the contour row farming scored better than the conventional.

A farmer with more capital may wish to change the decision variable order to place a higher importance order on crop yield, terrace cost, and sediment yield, therefore the new decision order is as follows: crop yield > terrace cost > sediment yield > runoff. Figure 48.6 shows the range of composite scores from best to

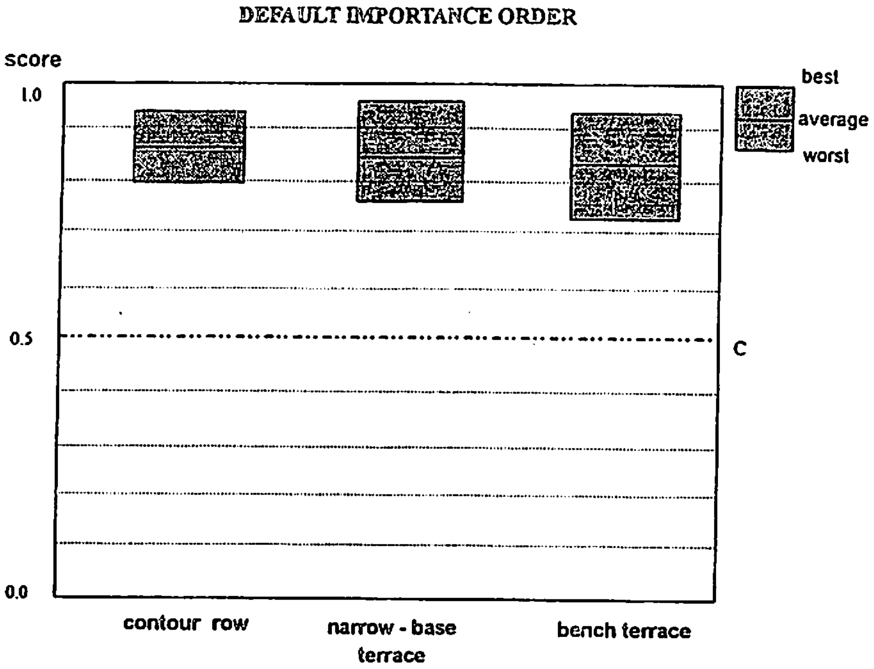

Figure 48.4 Range of scores for the four management systems and default importance order.

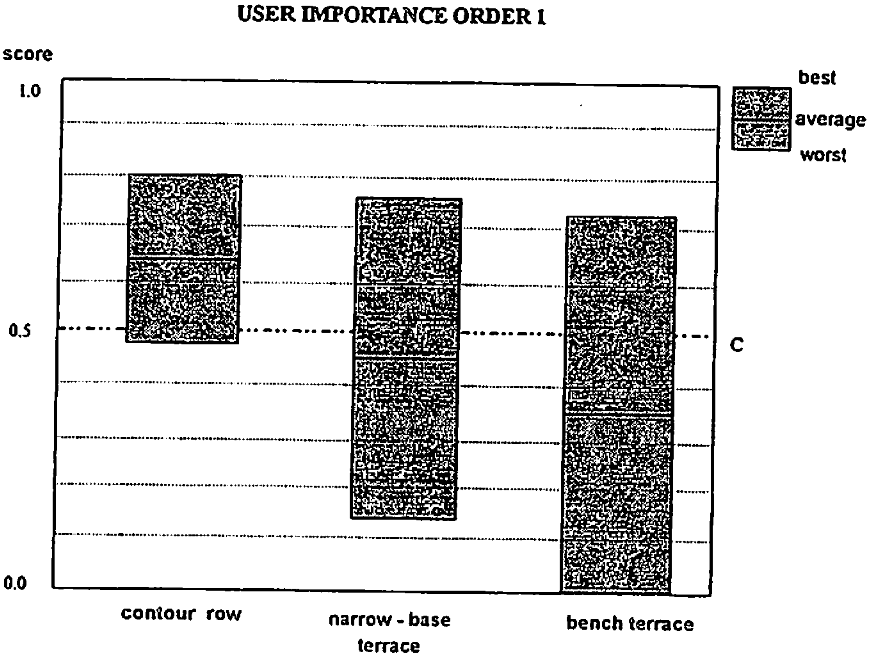

Figure 48.5 Range of scores for the four management systems and user importance order 1.

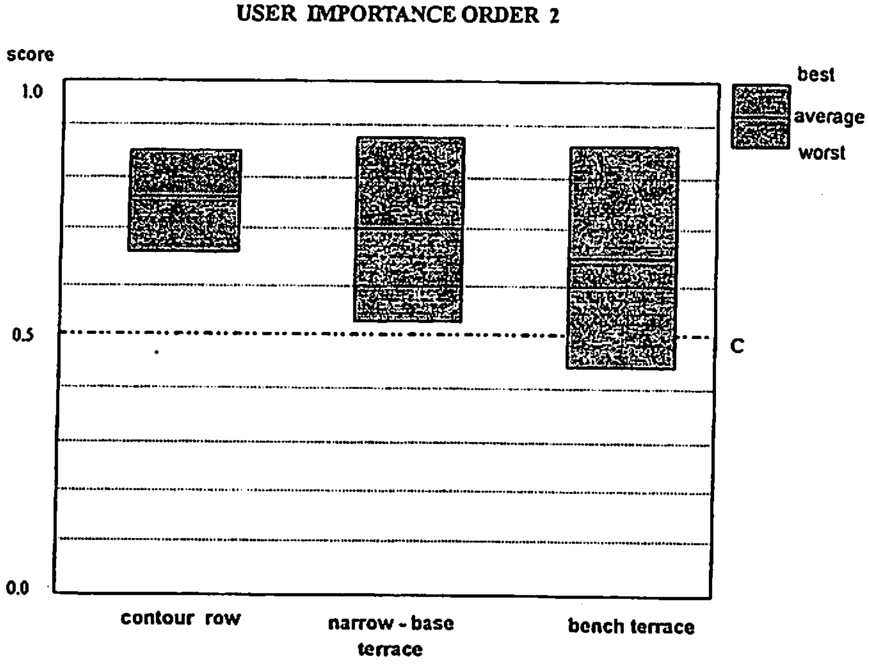

Figure 48.6 Range of scores for the four management systems and user importance order 2.

worst for each alternative for the new importance decision variable order. Notice that by shifting the order of importance of crop yield, the average composite scores of both terrace management systems performed better than the conventional.

Conclusions

The application of the DSS in selecting conservation management systems in tepetate lands in Mexico provided an improved basis for decision making. Of the three importance decision variable order sets: (1) default set, (2) terrace cost most important decision variable set, and (3) crop yield most important decision variable set, contour row farming scored higher than the conventional and terrace management systems. This result suggests that by implementing contour row farming in the region, maize yield production may not be as high as crop yields from terrace systems, however, the small difference in production may be offset by taking into account the low cost of contour row farming construction compare to the cost of terracing. Based on the information available, we were not able to assess offsite effects on water quality of surface and groundwater, recharge of local aquifers, and other conflicting societal issues. Under other scenarios, terraces might score better than the conventional and contour row farming. One potential application of the DSS is in planning the promotion of conservation technologies. Contour row farming does well in all importance orders constructed, and is the only system which does better than the conventional from the capital-constrained farmers' point of view. If an alternative were clearly better than all others when an importance order which reflects all of society is used, but that alternative is not dominant from the farmers' point of view, then a subsidy to adopt that system might be justified. In this case, the contour row system should be promoted: it scores higher than the conventional from all points of view and it is in the farmers' own interest.

Before any simulation model can be used routinely to analyze the physical processes and economics of water quality problems, a tremendous amount of data must be collected about the physical characteristics of the fields and the economics of the different practices. Without the proper parameters, the use of a simulation model is a potential case of information technology making misleading information more accessible. However, with the proper parameter information, simulation models can help quantify the decision variables when data are not available as a means of incorporating the "best science" in the decision-making process. For future applications of the DSS in Mexico, decision makers, scientists, local and federal agencies, and farmers will need to collaborate together in order to build a database that includes information on climate, watershed geometry, management system, soil characteristics, and economics.

The application of the DSS to tepetate lands has revealed problems which will probably be common to many applications of multiobjective decision support technology in developing countries. In general, less observed data are available which describe the effects of alternative management systems on the objectives of the decision maker. Extra efforts are required to extend the observed record to fill data gaps, that will require the use of probably simulation models. When these less-certain decision criteria are used to make a decision, in the absence of confidence limits, the results, particularly between closely ranked alternatives, should be interpreted jointly by scientists, farmers, and decision makers.

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