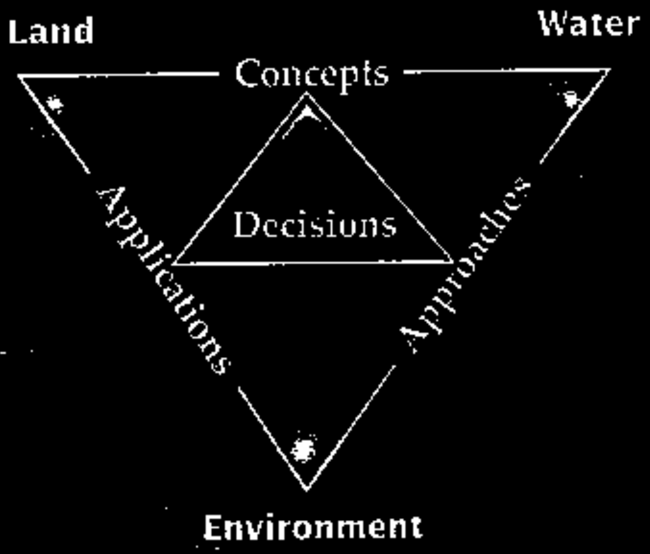
Multiple Objective Decision Making for Land, Water, and Environmental Management

Proceedings of the First International Conference on Multiple Objective Decision Support Systems (MODSS) for Land, Water, and Environmental Management: Concepts, Approaches, and Applications



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Chapter 44

Quantifying Economic Incentives Needed for Control of Nonpoint Source Pollution in Agriculture

PHILIP HEILMAN, LEONARD J. LANE, AND DIANA S. YAKOWITZ

Multiobjective decision support systems (MODSS) can be a powerful tool to improve natural resource management in agriculture. When the decision is the selection of a land management system from the point of view of all of society, a problem may arise. Some of the objectives will reflect the interests of land managers and others by those affected off-site. An important issue is how to encourage the adoption of improved management systems if they are in society's overall interest, but not in the land manager's interest, as happens with nonpoint source water pollution. Further economic analysis is needed to encourage the adoption of improved management systems, as a complement to MODSS. A farm scale optimization model can be used to estimate the expected cost to a farmer of adopting management systems which will abate the production of agricultural pollutants. An example from the deep loess hills of western Iowa illustrates this approach.

Introduction

A common problem in environmental management is to select a land management system that provides the landowner with an adequate stream of income, maintain long-term productivity, and does not cause negative off-site environmental impacts. MODSS — such as the USDA-ARS Southwest Watershed Research

Center's Multiobjective Decision Support System for Water Quality (Stone et al., 1995) — can be used to rank management systems based on all three primary objectives. However, if an alternative management system is identified to be preferable to the existing system, a pertinent issue is how to encourage the adoption of the preferred management system. If the preferred management system can increase income, sustainability, or reduce the environmental damage directly affecting the landowner, then it is in the landowner's interest to adopt the preferred management system.

On the other hand, the environmental damage may occur off-site and not directly affect the landowner, as happens with externalities such as nonpoint source pollution. In those situations, the landowner does not face the economic incentives needed to encourage the adoption of the preferred management system. This paper describes a method to quantify the cost to a landowner of abating the production of individual pollutants at the farm scale. Management systems highly ranked in a DSS will be implemented only if they are feasible, that is if their resource requirements, such as seasonal labor, do not exceed the quantities available to the farmer.

A method for estimating the economic incentives facing farmers consists of defining a representative farm, consisting of a number of fields, and a set of alternative management systems deemed likely to resolve the major negative off-site effects from each of the fields. Available data relating the effect of potential alternative management systems on the criteria of interest are collected, or if not available, simulated. The current and alternative management systems are then scored in a MODSS. If no alternatives are found which improve upon the current management systems, then no significant improvement is likely and resources can be devoted to other areas where there is a greater potential for improvement. If alternative management systems are identified that are preferred to the current management systems, a farm-scale optimization model is used to analyze the tradeoffs between farm income and the production of individual pollutants.

An understanding of the economic incentives facing farmers to adopt alternative management systems should facilitate the development of more appropriate policies to promote the voluntary adoption of preferred management systems. It may be possible to identify and promote alternative management systems, such as no till tillage, that can improve economic returns to the farmer as well as having positive off-site benefits. The overall benefits of an alternative management system may only be realized at a significant cost to the farmer, for example, by eliminating the use of a particularly cost effective pesticide. Alternative management systems that are ranked highest by MODSS will most likely be adopted if farmers have the economic incentive to adopt those systems. If society's preferred management systems are not the same as the farmer's, economic incentives could be implemented either as charges on management systems or estimated emission levels assuming the "polluter pays" principle is applied.

This paper will step through a multiobjective analysis of a set of alternative management systems for a representative farm in the deep loess hills region of western Iowa. The analysis consists of (1) simulating the effects of the alternative management systems on a number of criteria; (2) using a MODSS to rank the management systems; (3) and using a farm-scale optimization model to estimate abatement cost curves for sediment, nitrogen, and atrazine. Conclusions will be drawn about the need for economic analysis to complement the application of

MODSS, when off-site damage (externalities) exist. Additional details for all stages of the analysis are available in Heilman (1995).

Problem Definition

The Deep Loess Research Station (DLRS) near Treynor, Iowa has been collecting data on the effects of conservation management systems on erosion, runoff, sediment, and water quality from loess soils since 1964. Loess, wind-borne silt, has been deposited on the eastern side of the Missouri River in western Iowa to depths of 5 to 25 m. The soils on the research station, primarily Monona-Ida Series, are moderately permeable with 6 to 18% slopes. The four experimental watersheds are in two sets of pairs located 4 km apart. Observed data on rainfall, storm runoff, baseflow, and sediment yield are available from 1964 to the present, with some nitrogen and phosphorus movement data beginning in 1969 (Saxton et al., 1977; Hjelmfelt, undated).

A farm, representative of the deep loess hills region, consisting of 243 ha in 5 fields was defined. The fields have characteristics of two of the watersheds of the DLRS, Watersheds 1 and 4. Two 30-ha fields are not terraced and are assumed to be exactly like Watershed 1 of the DLRS, which is an unterraced field with a predominant slope of 12%. Three 61-ha fields are terraced and are assumed to be exactly like Watershed 4 of the DLRS. The terraces on Watershed 4 are "double-spaced" or separated by twice the distance in the Soil Conservation Service's specifications for terraces, but as no observed data exist for terraced fields which meet the specifications, Watershed 4 will be considered representative of a terraced field in the deep loess hills region.

A set of alternative management systems was defined that would reduce sediment, nutrient, and pesticide losses when compared to the management system in place on Watershed 1. The management system on Watershed 1 is continuous corn with deep disking, preplant anhydrous ammonia applied at a rate of roughly 168 kg/ha, and atrazine used as an herbicide. The timings and quantities of inputs used with each operation are specified in Heilman (1995), and the rotation, tillage systems, nitrogen application methods and rates, and pesticide subsystems used are described as follows.

All alternatives use a corn-soybean rotation, which is the standard rotation in the area. Two tillage systems will be considered: mulch till, which allows some tillage, as long as there is 30% residue cover at planting (here assumed to be a shallow disking) and no till, which does not allow tillage and has higher residue levels. Three possible nitrogen application methods will be considered: liquid nitrogen and a pre- or postplant application of anhydrous ammonia. It is assumed that liquid nitrogen will be custom applied, so the farmer will have more labor available in May for other activities.

Two different nitrogen application rates are considered, 140 kg/ha (125 lb/acre) and 168 kg/ha (150 lb/acre). Only the corn crop in each rotation receives nitrogen, which is split into two applications. Each corn crop gets 28 kg/ha of nitrogen at planting as starter fertilizer, and the remainder in one of the three methods mentioned above. Preplant nitrogen application ensures that the farmer will not have to devote time to fertilizing between planting and when operations can no longer be performed on a crop. However, the nitrogen is available to be leached below the root zone during the period when large rainfall events are possible and before the crop roots have developed sufficiently to utilize the nitrogen. Postplant application provides nitrogen only later in the season when the growing plants need it, but requires another operation at a time when the farmer would prefer to concentrate on weed control.

Effective weed control often requires a number of different herbicides depending on the timing and type of weed infestations. Only atrazine will be considered as a decision variable, although a number of different herbicides will be simulated. Atrazine is a commonly used herbicide because it is inexpensive and effective. Unfortunately, atrazine is also persistent, particularly once it reaches surface waters. Current measures to control atrazine in Iowa include limits on the amount that can be applied in any given year and a prohibition against using it within 66 ft of waterways.

In total, 24 alternative management systems will be considered on each of the two types of fields. Each management system consists of a combination from each of: two tillage systems, mulch till and no till; three nitrogen application methods, liquid and pre- and postplant anhydrous ammonia; two nitrogen application rates, 140 and 168 kg/ha; and either atrazine or another herbicide.

Simulation Model

Since Watersheds 1 and 4 of the DLRS did not use any of the alternative management systems, a simulation model was used to estimate the effects of the alternative management systems on a number of measures reflecting different objectives. The model was parameterized and run using the Multiple Objective Decision Support System for Water Quality (WQDSS), developed by the Southwest Watershed Research Center of the USDA-ARS. The WQDSS was developed to run under the Unix operating system and implemented using the X Window System and the Motif Libraries[a] in order to provide a graphical user interface. Components of the WQDSS include databases, input file builders, simulation models, a decision model, and a system driver. The user interface to the system driver and the input file builders which facilitate running the simulation model by using the databases to parameterize the simulation model (Hernandez et al.,1993).

The simulation model is a modification of the Groundwater Loading Effects of Agricultural Management Systems (or GLEAMS) model (Leonard et al., 1987; Davis et al., 1990). Modifications to the model include the addition of a nitrogen leaching component from CREAMS (Knisel, 1980) and the EPIC crop growth component (Williams et al., 1989). A budget generator based on the Cost And Returns Estimator (or CARE) (Midwest Agricultural Associates, 1988), is used to compute the net returns and estimate the amount of time needed for each operation. The simulation model is capable of estimating the sediment yield, nutrient and pesticide loading in runoff and adsorbed to sediment to the edge of the field and the nutrient and pesticide leached below the root zone, as well as net returns for many management systems in rainfed agriculture. A more detailed

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explanation of the modifications made to the simulation model, hereafter referred to as HGLEAMS, is available in the WQDSS Reference Manual, version 1.1 (Southwest Watershed Research Center, 1994). Erosion (overland detachment) was estimated by the West Pottawattamie County Field Office of the Natural Resources Conservation Service using the Universal Soil Loss Equation (Wischmeier and Smith, 1978).

The model was parameterized using the WQDSS default databases. The most sensitive parameters were modified based on the observed effects of deep disking and ridge till on runoff, sediment yield, baseflow, and corn yield and a method to estimate the runoff curve number based on crop residue presented in Rawls et al. (1980).

Ranking Alternative Management Systems with the WQDSS

The decision theory used in the WQDSS is based on Wymore (1988), Lane et al. (1991), and Yakowitz et al. (1992, 1993a, 1993b). The WQDSS uses score functions for each decision variable and an importance order to calculate an overall score for each management system which is then used to rank the management systems. Ideally, the score functions and importance order would be based on site specific information relating the average annual movement of pollutants from the edge of the field and bottom of the rootzone to off-site damages. For this study, the default scoring functions were used without modification. An importance order from society's point of view was determined by a group of experts familiar with local agriculturally related environmental problems on August 29, 1994.* The importance order determined by the experts is presented in Table 44.1 (both of the atrazine and both nitrogen objectives were given equal importance). The loess soils are so deep that erosion does not significantly reduce yields (Spomer and Alberts, 1984).

Table 44.1 Ranking of Objectives

Rank	*Experts' importance order*
1	Net returns
2	Atrazine in runoff
	Atrazine in sediment
3	Sediment
4	Nitrogen in runoff
	Nitrate nitrogen in percolation
5	Soil erosion
6	Other pesticides

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* Marco Buske of the Iowa State University West Pottawattamie County Extension Service; Michael Dea, farmer and chairman of the West Pottawattamie Soil Conservation District; Larry Kramer of the Deep Loess Research Station; Lyle Peterson, Soil Conservation Service; and Roger Webster of Treynor Ag Supply. We appreciate the efforts of all who contributed to this research.

Ranking of the alternative systems is done relative to the "conventional" system that is currently in place. In this example, all management systems were judged relative to a mulch till, preplant anhydrous ammonia, 168 kg/ha N application with atrazine, as that is the management system closest to the one currently in place on Watershed 1. The default scoring functions of the DSS were used along with the importance order listed in Table 44.1, although no other pesticides other than atrazine were considered. On the nonterraced field, no till generally scored higher than mulch till, the 168 kg/ha N scored higher than the 140 kg/ha and the management system without atrazine scored higher than the one with atrazine, while there were no major differences in the scores for the method of nitrogen application (Figure 44.1). The management systems that scored the worst were the combinations of mulch till with atrazine, because of the relatively high amounts of atrazine in runoff. On the terraced field, the results were similar. The management systems with no till tended to score higher than the mulch till systems, the systems with higher levels of nitrogen application scored higher than those with low levels and those which did not use atrazine scored higher than those that did use atrazine (Figure 44.2). The method of nitrogen application did not have much effect on the scores. The management systems using both mulch till and atrazine also had the lowest scores.

Optimization Model

After one or several management systems that score higher than the conventional management system are identified, there is still the problem of inducing the farmer to adopt an improved system. In areas where society would most prefer to see a significant change in management systems, such as situations with large off-site damage from pollution, the farmer probably has little incentive to adopt the management system society would prefer. Efficient economic incentives to control nonpoint source pollution can be fashioned as subsidies/charges on polluting inputs or pollution generated, or as controls on the quantities of polluting inputs or pollution generated (Griffin and Bromley, 1982).

A farm is a system of interconnected activities. Changing one activity on the farm may require other activities to change as well. Because the WQDSS works on a single management unit (at the field scale), and the farm decision-making unit is the whole farm, situations may arise where the management system recommended could be used on an individual field, but not on all similar fields on the farm. For example, labor or machinery availability during a critical period, marketing limits, or government program limits may preclude the adoption of that management system on all of the fields of the farm.

To quantify the cost to the farmer of reducing pollution, a model of how the farmer would react to limits placed on the quantities of pollutants leaving the farm can be estimated using an optimization model. In effect, the optimization model is used to simulate a farmer selecting alternative management systems in order to maximize returns subject to risk aversion and whole farm feasibility. One of the benefits of building a farm scale optimization model is that additional constraints can be imposed on the allowable levels of pollutants leaving the farm's fields. By varying the amounts of the pollutants allowed to leave the fields, an abatement cost curve to the farmer for the pollutant can be estimated. Although

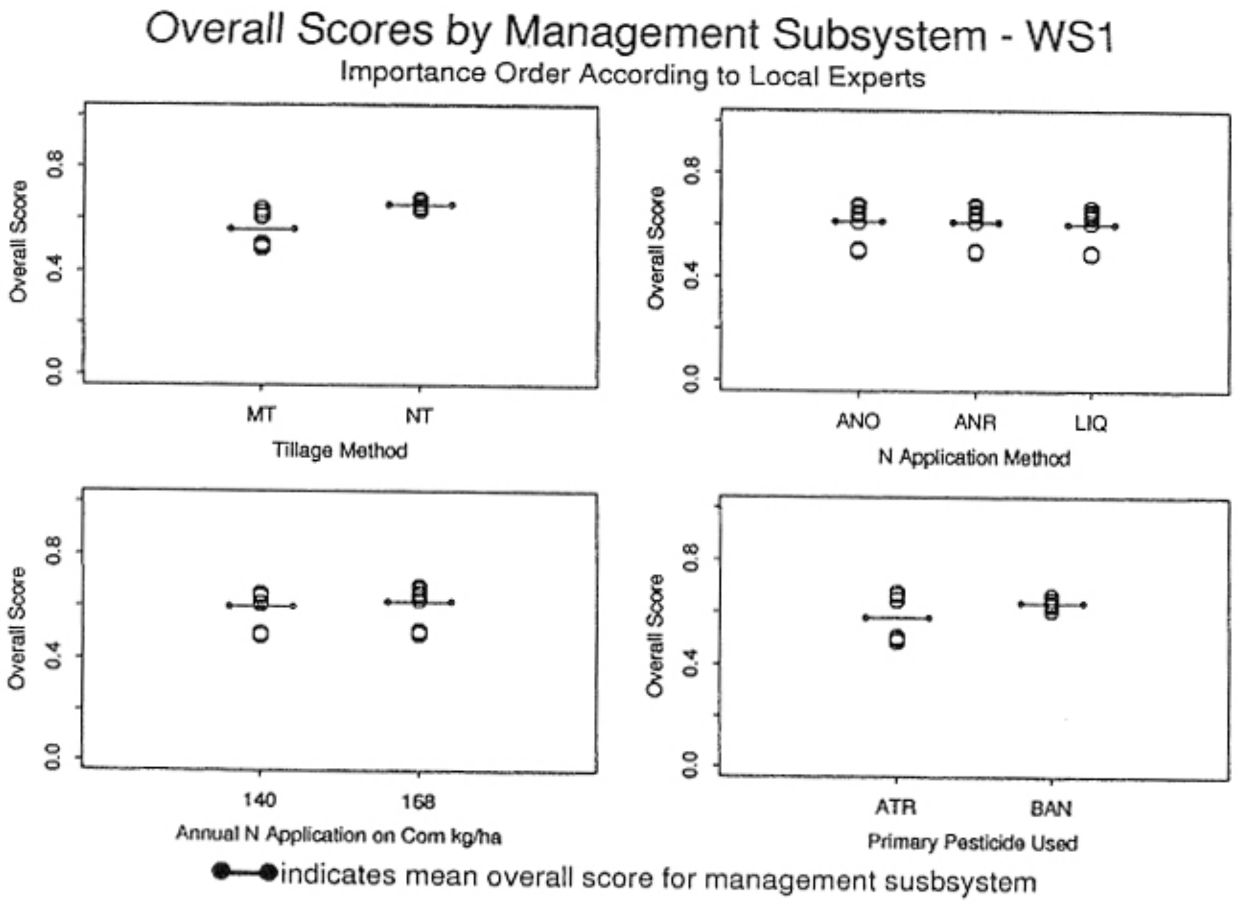

Figure 44.1 Overall score by management subsystem: mulch or no till; postplant, preplant anhydrous, or liquid N application; 140 or 168 kg/ha N application; and atrazine or glyphosate on Watershed 1 (nonterraced).

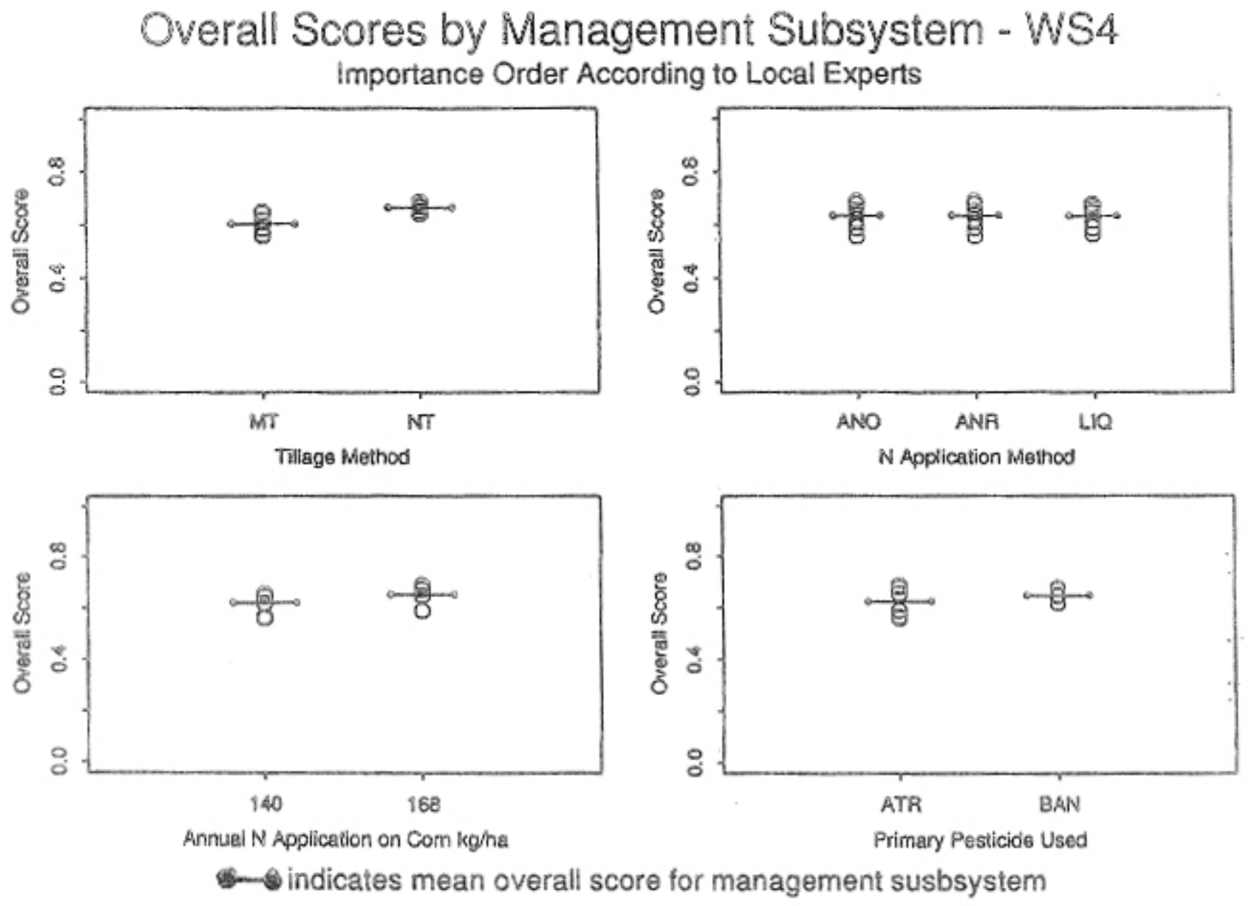

Figure 44.2 Overall score by management subsystem: mulch or no till; postplant, preplant anhydrous, or liquid N application; 140 or 168 kg/ha N application; and atrazine or glyphosate on Watershed 4 (terraced).

the cost of controlling a number of different pollutants could be analyzed, only the three most important will be analyzed here: sediment, nitrogen in percolation, and atrazine in runoff.

The structure of the optimization model used, the generalized mean variance approach, was first proposed by Paris (1979, 1989) to consider aversion to risk in both income and fluctuations in the availability of limiting input supplies. Farmers have to contend with variations in the availability of inputs, for example, when the amount of time available for field work is limited by the weather, or when labor supplies are uncertain. In a mathematical programming framework, such variations correspond to uncertain right-hand sides of constraint equations which ensure that the use of that input is less than or equal to its expected supply.

Using the results of the hydrologic simulation model and the budget generator, a model was built using the GAMS algebraic modeling language (Brooke et al., 1988) that contained constraints limiting the labor to available labor, field area, and time available when the fields are workable. From a base solution, additional constraints were added to limit the quantities of pollutants leaving individual fields to estimate abatement cost curves. Such constraints could be implemented in programs such as the USDA's Conservation Compliance Program which limits eligibility to government programs to those farms following acceptable conservation plans.

As a validation test, the optimization model was used to predict the management systems currently in place. A survey was conducted of farms with predominantly 12% slopes on Ida-Monona soils, in the West Pottawattamie Soil Conservation District to determine what management systems farmers were actually using. The optimization model's predictions were based on farm-size class, the size equipment (the number of rows) that farmers used, and the amount of time farmers reported working in May and June. The predictions made by the optimization model generally matched those reported by farmers, although the model overpredicted the proportion of farms using no till and atrazine (Heilman, 1995).

The farmer was assumed to use 6-row equipment, work an average of 60 hr/week during the months of May and June, and to be moderately risk averse. By changing tillage systems and nitrogen application methods, both labor and field day availability could be modified to maintain feasibility. The base solution without environmental constraints was to use no till, preplant nitrogen at 168 kg/ha and atrazine on almost the whole farm, with only 0.3 ha getting liquid nitrogen. If the farmer wanted to work less, or had 4-row equipment rather than 6-row, liquid nitrogen would have been used on a greater portion of the representative farm.

Sediment Abatement Costs

Although the deep loess hills region is prone to high rates of erosion, most of the soil is redeposited in the grassed waterways and at the base of the slope before leaving the field. For the observed management system on the unterraced Watershed 1, deep disking with continuous corn, the average annual sediment losses were only 14 t/ha from 1973 to 1991 (Deep Loess Research Station, 1992). As would be expected, sediment yields are very low. The most profitable tillage system is no till, which reduces detachment and transport, and in addition, most of the representative farm is terraced (Figure 44.3). Constraining sediment yield to less than 2 t/ha would force the farmer to abandon cultivation on some fields, particularly those that are not terraced.

The implications for conservation agencies are clear: the adoption of no till on similar farms should be encouraged, as both the farmer and offsite water users enjoy benefits. In this case, there is no tradeoff between net returns and sediment yield. Net returns with no till are higher, sediment yield is reduced and no till requires less time than the shallow disking associated with the mulch till system.

Nitrate in Percolation Abatement Costs

Farmers in the area are concerned about nitrogen affecting groundwater quality (Heilman, 1995). The amount of nitrogen leaving the field in surface water or percolation is affected by the natural rate of mineralization of the organic matter in the soils. The Ida Monona soils are high in organic matter, and will lose some nitrogen, no matter what management system is used.

Since the simulation model did not generate percolation at the same rate observed for baseflow at the DLRS, the units in Figure 44.4 are in parts per million concentration, rather than in units of mass. This conservative estimate overstates the concentration of nitrate nitrogen leaving the root zone. A potential problem is that the Maximum Contaminant Level (MCL) for nitrate is set at 10 ppm. The MCL is intended to be used in drinking water on an annual basis and should not be applicable to water leaving the root zone, assuming natural processes continue to reduce nitrate concentrations. The abatement cost curve is generally smooth, as greater proportions of the farm receive both postplant applications of nitrogen and lower rates of nitrogen application, first on the terraced fields and then on the unterraced.

Atrazine in Runoff Abatement Costs

As with most pesticides, it is possible to completely eliminate emissions of atrazine by replacing that pesticide with another, or some other means of reducing damage from the pest. In response to the survey mentioned earlier, the farmers reported that it cost \$20/ha for the best replacement for atrazine. Because atrazine is only used every other year on the corn crop, the average annual cost to eliminate atrazine is \$10/ha. If atrazine cannot be used at all, it would have a significant impact on farm returns (net of labor and land charges), which were reported to be on the order of \$90/ha for 1,400 fields across Iowa in the years 1992 and 1993 (Soil Conservation Service, 1993).

All management systems considered used a corn-soybean rotation, the no till management systems earn more than the mulch till systems while reducing runoff, and the nitrogen application methods and rates had little effect on the quantities of runoff generated. Consequently, the only management choice that could affect the quantity of atrazine leaving the field is the quantity of atrazine applied (Figure 44.5) and the abatement costs are almost linear.

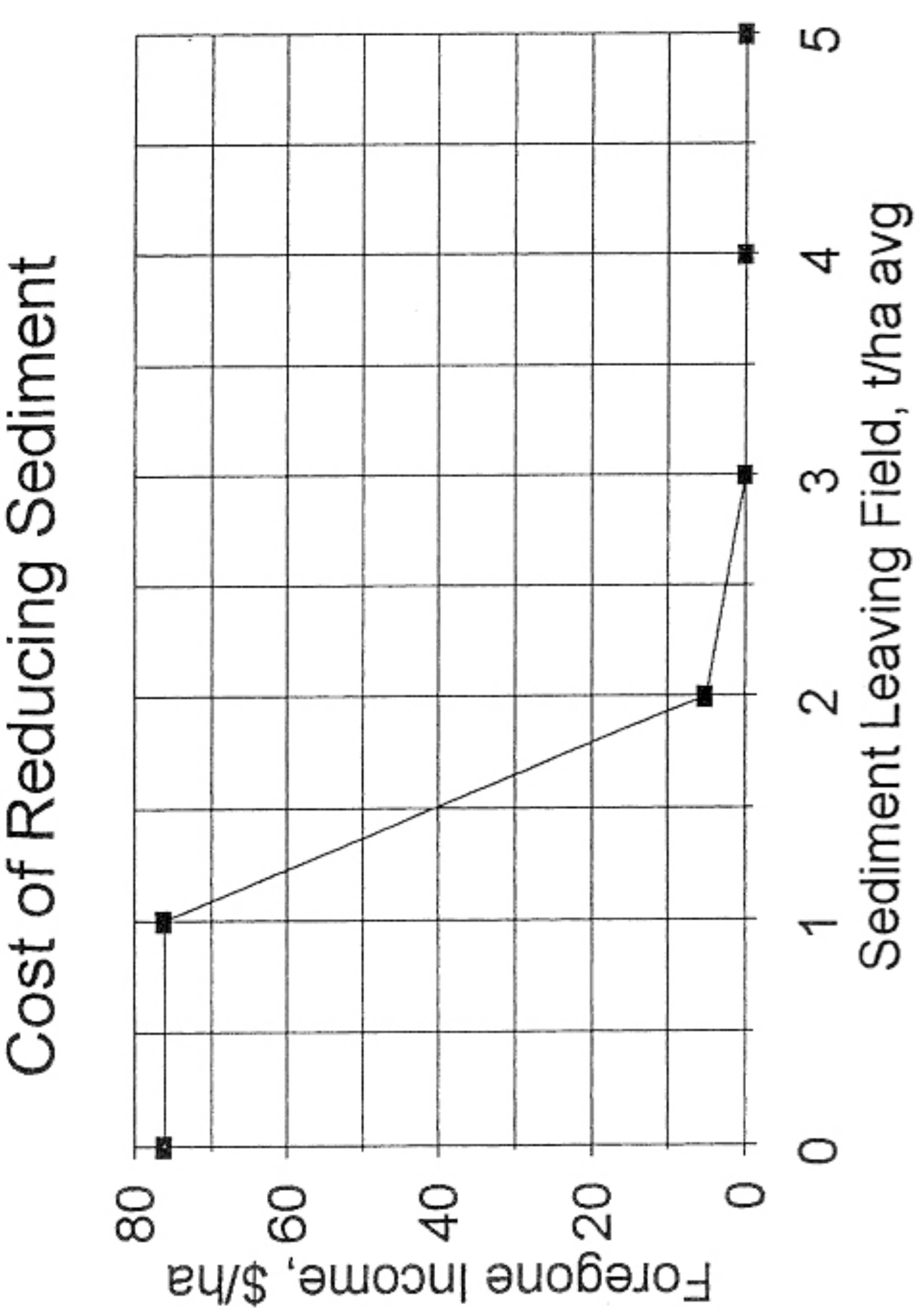

Figure 44.3 Abatement cost curve for sediment leaving the edge of the field.

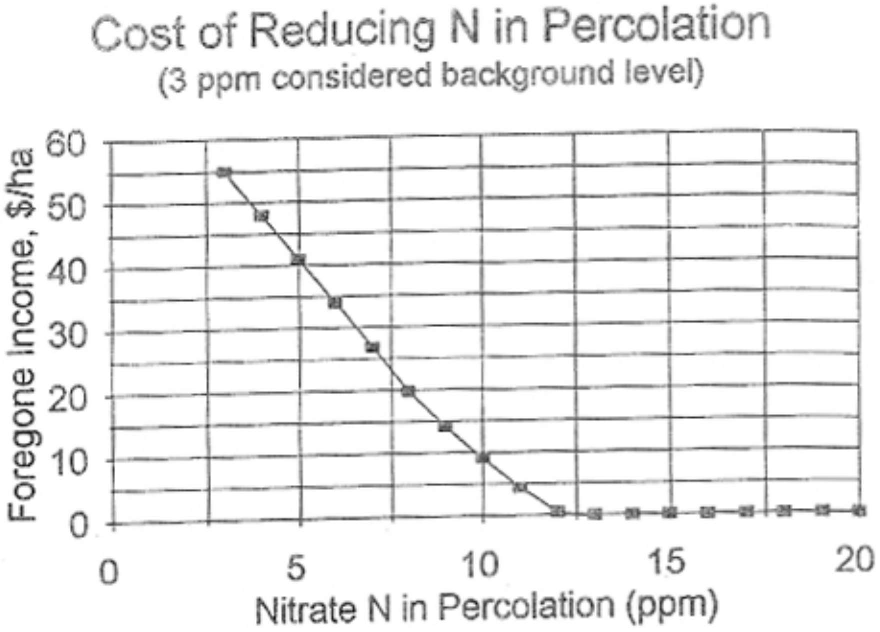

Figure 44.4 Abatement cost curve for nitrate N leaving the bottom of the root zone.

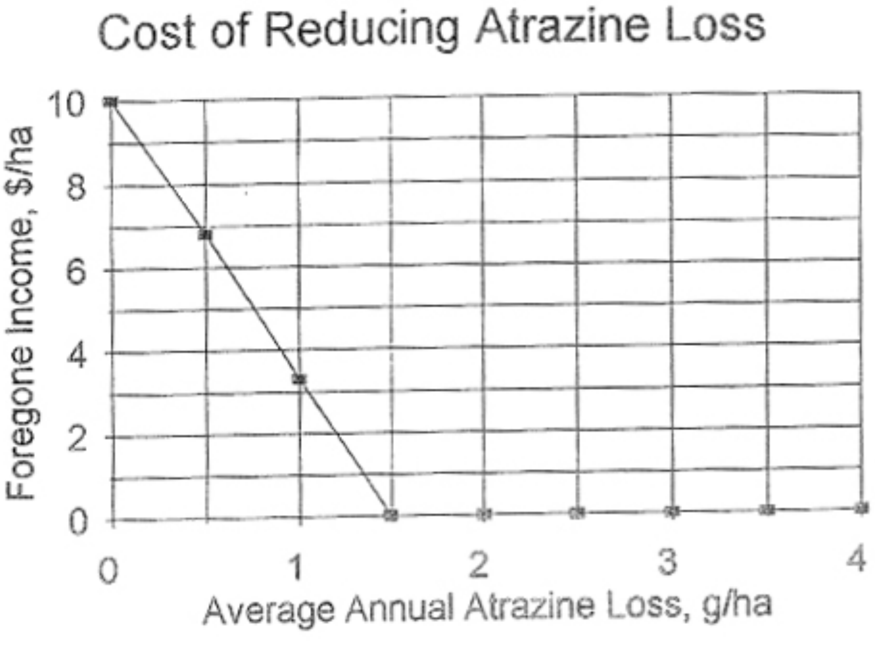

Figure 44.5 Abatement cost curve for atrazine leaving the edge of the field.

Summary and Conclusions

A policy to target farms to encourage the adoption of preferred management systems can be devised, using the information on farms in the deep loess hills region from the simulation model, the decision component of the WQDSS, and the optimization model. Specifically, no till tillage should be promoted to those farms which are not currently using no till, particularly those with small equipment. Management systems with high application rates of nitrogen were highly ranked by the decision component, even though there is a potential problem in exceeding the MCL for nitrate in percolation. Testing of nitrate concentrations under fields cropped in corn and soybean rotations could provide further information about the desirability of restricting nitrogen applications. If farms are using no till, then runoff is reduced, so that even if atrazine is ranked highly as a decision variable, management systems that include atrazine will be highly ranked and also selected in the optimization model. Farms that use mulch till should be the first to reduce atrazine use.

The benefits from using an optimization model as a complement to a MODSS for water quality include the ability to look at farm-scale issues, such as whole farm feasibility and risk aversion, as well as the ability to estimate abatement cost curves by varying constraints on pollutants emitted. However, care must be used in interpreting abatement cost curves. The simulation model estimates the quantities of pollutants leaving the field, rather than the amount of pollution in a given body of water.

Attempts to improve environmental management of nonpoint source pollution by using MODSS may require additional analysis to assess the economic incentives facing the landowners. Voluntary adoption of the preferred management systems will more likely occur if the management systems which lead to both an improved score and increased income for the farmer can be identified and promoted. If the most desirable management systems can only be adopted at some cost to the farmer, the magnitude of the economic incentives needed to make the farmer indifferent between the current system and the preferred system can be estimated and the potential benefits and costs of implementing a system of economic incentives can be examined.

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