



NORTH-HOLLAND

Targeting Farms to Improve Water Quality

Philip Heilman,

Diana S. Yakowitz,

and

Leonard J. Lane

Southwest Watershed Research Center

USDA-ARS

2000 E. Allen Rd.

Tucson, AZ USA 85719

ABSTRACT

Voluntary programs to improve the quality of surface and subsurface water affected by agriculture should target the farms that have an economic incentive to adopt management systems with water quality benefits. We propose a method that can identify such opportunities within a region by linking a field scale simulation model, a multiobjective decision model, and a pair of farm-scale constrained optimization models. The simulation model estimates the effect of alternative management systems on the quantities of pollutants leaving individual fields and on economic returns. The multiobjective decision model uses site specific economic and technical information to score and rank the alternative management systems. An optimization model is solved to select the set of management systems which are most economically advantageous to the farmer. A second, similar optimization model is solved to select the set of management systems of interest to society considering offsite water quality issues. Farms which have economic incentives to adopt management systems with water quality benefits can be identified and targeted by extension agents or policy makers. © Elsevier Science Inc., 1997

INTRODUCTION

A goal of the United States Department of Agriculture (USDA) is to improve water quality through the voluntary adoption of farm management systems that are less polluting [1]. Fortunately, in many regions, opportuni-

ties exist to increase farm income while reducing pollutant loads from agriculture. For example, in some locations it may be possible to reduce the amount of nitrogen applied without lowering yields but still reduce the potential for surface and groundwater pollution. Another opportunity in some areas is to reduce or eliminate tillage, which reduces costs. By reducing tillage, more crop residues are maintained on the soil surface to promote infiltration and decrease erosion. On the other hand, reduced tillage may require more herbicides to control weeds, and the potential exists for leaching more agricultural chemicals into the groundwater. New technology, such as machinery that can plant through heavy residue or build ridges on steeply sloped fields more easily, is speeding the adoption of conservation tillage. Nationally, farmers are adopting reduced tillage practices, but the proportion of cultivated land using conservation tillage (defined as leaving at least 30% residue cover) was still only 35% in 1995, up from 25% in 1989 [2].

Although opportunities to increase farm income by changing farm management systems exist, such changes are not undertaken lightly. In some cases, new management systems are inappropriate for the soil and climate, or require expensive machinery and skills which farmers do not have. Among the reasons farmers may be unwilling or unable to adopt new management systems [3] are excessive labor requirements and the lack or inconsistency of information. In other cases, the management systems may work, but the rate of adoption is slow. If opportunities exist to increase income and improve water quality, and farmers are capable of adopting those systems, it is in society's interest to encourage and facilitate that change.

We propose a method for 1) identifying those farms within a region that have economic incentives to adopt management systems with water quality benefits and 2) quantifying those economic incentives. The basic issue is to determine if current management systems can be improved economically or environmentally and what are the required tradeoffs. Of course, "improvement," depends on the interest group to which one belongs. Farmers' interests will differ from those of the people affected offsite. However, by quantifying the economic and environmental effects of different management systems as well as the values put on those effects, any common ground that exists can be found.

Specifically, the proposed method links a Multiple Objective Decision Support System (MODSS) to two optimization models. The Southwest Watershed Research Center of the Agricultural Research Service (ARS) developed the MODSS to rank farm management systems for individual fields based on farm income, water quality stressors and considering the preferences of decision makers [4-7]. Since the decision making unit is typically a whole farm rather than a single field, the optimization models

ensure that potential management systems are feasible, given the whole farm constraints. A flexible model structure, symmetric quadratic [8, 9], allows consideration of aversion to both income and input availability risk. Together, these tools can calculate the economic incentives farmers have, or would need, to adopt management systems which improve water quality.

PROBLEM: A TARGETING METHOD IS NEEDED

Traditionally, agricultural conservation programs have been based on the need to reduce erosion. The primary tools have been the Universal Soil Loss Equation, which calculates a long-run annual average erosion rate, and the concept of soil loss tolerance, which defines an acceptable upper limit of soil erosion. Increasingly, however, the public recognizes that offsite pollution from agriculture can affect water quality and that efforts are needed to control the sediment, nutrients, and pesticides leaving farm fields. Simultaneously, budgets for conservation programs are tightening. The result is an increased need to target conservation efforts to those regions, and to those farms within regions that can have the greatest impact in maintaining or improving water quality.

The importance of targeting farms for water quality have been recognized. The Committee on Long-Range Soil and Water Conservation of the National Research Council [10] stated:

“The highest priority for programs to change farming systems would be where soil and water quality degradation and the potential to improve producer’s management are greatest. . . . The need to improve targeting however, is urgent, and new approaches are needed to identify the regions and enterprises that should receive the greatest attention. The information available for guiding targeting efforts will, most likely, always be less than ideal. It is urgent that means be found to move ahead with the information that is available now. . . . even crude targeting will help reduce the costs and increase the effectiveness of current programs to improve soil and water quality.”

There are two primary difficulties in developing a method to target farms for water quality. First, although the idea of identifying which farms present the greatest potential to improve soil and water quality problems is appealing, improving both soil and water quality often involves multiple, conflicting objectives. A number of agrichemicals can affect either groundwater or surface water, and there is always the issue of farm income. Reducing water quality problems from agriculture is a multiple objective problem.

Second, as noted above, available information is rarely adequate. Many complicated factors should be considered: weather, changing technologies, site specific effects of soil and topography, proximity to water bodies, and differing interests of the parties involved, which may change over time. An inherent problem in controlling water quality problems from agriculture, as a nonpoint source of water pollution is that agriculture is spread over a large area, making it difficult and expensive to measure the amounts of pollutants leaving farms and even harder to trace their movement to affected water bodies.

DESCRIPTION OF THE METHOD

According to economic theory, water pollution is an "externality." The welfare of water users is affected by the decisions polluters make, but the water users are not compensated for any loss of welfare resulting from pollutants in their water. The interests of the water users are outside, or "external" to the interests of the polluters. A simple theoretical model can show this concept clearly. Assume a firm which produces one output, y , and one pollutant z , as a function of one input, x , so $y = f(x)$, and $z = g(x)$. Further assume that functions f and g are differentiable, p is the price of output y , c is the cost of input x , and that the marginal damage is known to be a constant d . Then society's objective function can be written

$$\text{Max}_x \pi = pf(x) - cx - dg(x),$$

with the first order condition for an optimal solution being

$$\frac{d\pi}{dx} = pf_x - c - dg_x = 0 \quad \text{or} \quad pf_x = c + dg_x.$$

Society would use input x up to the point where its marginal value product equals the input cost plus the marginal damage associated with the use of that quantity of the input. This is not to say that there would be no pollution damage if society were to select the management system. Pollution damage would be treated just as any other production cost, in this case, that of assimilating waste.

The externality arises because the firm, in contrast to society, does not consider the marginal damage of the pollutant in its objective function

$$\text{Max}_x \pi = pf(x) - cx.$$

So the firm's decision rule is

$$\frac{d\pi}{dx} = pf_x - c = 0 \quad \text{or} \quad pf_x = c.$$

Thus, the firm would use more of x than society would, resulting in more off-site damage than is socially optimal (in addition to raising a host of equity issues). One approach to removing the externality is to impose a Pigouvian tax, t , equal to the marginal damage rate, d , times the marginal production of pollution (g_x). However, as a practical matter, even for large point-source polluters such as industrial plants, marginal off-site damage is usually unknown. The problem is usually addressed by specifying a desired use for the water body ("fishable and swimmable"), estimating the level of water quality consistent with that use, and then trying to reduce discharges to achieve that level of water quality. Water quality damage from an individual field is so small that the benefits from understanding all of the relationships contributing to off-site damage are unlikely to outweigh the cost of collecting all of that information, even if the overall damage from agriculture is significant. A practical approach to improving water quality from agriculture will require further simplifications.

Our approach is to focus on how the management system the farmer uses affects the quantities of pollutants leaving individual fields. The damage associated with various quantities of agrichemicals leaving the farmer's fields is assessed by experts who create score functions for individual pollutants. The multiobjective nature of water quality problems is handled by the MODSS, which scores the social desirability of each management system, resolving all of the information on the different objectives down to a single overall indicator of utility or social desirability.

Given a single score for each management system, it is possible to use the same theoretical framework which considers the problem as two distinct optimization problems, one highlighting society's interest and the other the farmer's. Farm scale optimization models are used to examine the problem from both points of view. The first model ("the farmer's model") is solved for an objective function that maximizes the farmer's net returns, considering risk aversion. In the second model ("society's model"), the objective function is solved for the maximum feasible area-weighted score.

Since each management system on each field has both an expected return and an associated score, the area weighted score associated with the farmer's model and the economic returns for society's model can be calculated. The difference between the economic returns from the farmer's preferred set of management systems and from society's is the economic incentive needed to

make the farmer indifferent to a choice between the most profitable set of management systems and the most socially desirable set of management systems. Targeting can then be done based on the results (Table 1). Given the uncertainties in weather, model parameterization, market conditions, and the scoring of management alternatives, the results should be interpreted as indicators, but they should be sufficiently accurate for targeting purposes.

Obviously, if the farmer's model indicates that a given management system is the most profitable, but it is rarely used, a more detailed examination of the constraints in the model might be warranted. Or perhaps there is a noneconomic reason that a particular group of farmers do not use that management system. If a given management system is the most profitable, some farms should be using it, and there should also be a move towards adopting it more widely.

To summarize, the steps required are

1. Define the regional water quality problems affected by agriculture, the alternative management systems that could help solve those problems, and the representative farms.
2. Quantify the effects of alternative management systems on the pollutant loads.
3. Rank the management systems using the MODSS from both the farmer's and society's points of view.
4. Solve farm scale optimization models from the farmer's and then society's points of view, subject to whole farm feasibility.

TABLE 1
APPROACH TO ENCOURAGE ADOPTION OF MANAGEMENT SYSTEMS TO IMPROVE
WATER QUALITY BASED ON CURRENT MANAGEMENT SYSTEM RELATIVE
TO ALTERNATIVE MANAGEMENT SYSTEMS

Current Management System(s)		
	Not Most Economically Desirable	Most Economically Desirable
Not Most Socially Desirable	Promote a preferred alternative or Regulate/ Incentives	Regulate/ Incentives
Most Socially Desirable	Regulate/ Incentives	Do Nothing

5. Determine the economic incentive needed to make a farmer indifferent between the preferred set of management systems and the set of socially preferred management systems and target farms.

To make the method more concrete, each step will be explained in the context of an example of a single representative farm.

DEFINE THE PROBLEM

For targeting purposes, farms are lumped into representative farms in a region. A hypothetical farm, representative of farms in the Deep Loess region of western Iowa with class "D" slopes (9–14%) and Ida Monona soils, is assumed to consist of 600 acres in 5 fields. The representative farm consists of two 75 acre fields that are not terraced and are assumed to have characteristics exactly like Watershed 1 of the Deep Loess Research Station (DLRS) of the USDA-ARS, located near Treynor, Iowa. Three 150 acre fields are terraced and are assumed to have characteristics exactly like Watershed 4 of the DLRS. These experimental watersheds have been studied for over 30 years to understand the processes controlling soil detachment and sediment yield, nutrient cycling, and crop productivity [11]. Two other nearby watersheds also provide useful information about weather, soils, and the responses of the watershed to changes in management systems, although not all of the pollutant loadings have been measured: there are no pesticide data, and measurements of pollutant loadings do not exist for a number of management systems.

Loess (wind blown silt) soils are susceptible to detachment and transport into surface water. As loess soils are often many meters thick, lost soil does not reduce productivity as much as it might at other sites, but productivity can be reduced when organic matter is lost and gully formation can restrict the use of machinery. Much of this land is considered "Highly Erodible," and farmers must have an acceptable conservation plan on file with the Natural Resources Conservation Service to qualify for government programs through "Conservation Compliance" provisions. In addition to erosion and sediment yield as resource problems, elevated levels of nitrate have been found in the groundwater in the area, and there is general concern in the Midwest about the herbicide atrazine.

A set of 24 management systems were defined which would be expected to have water quality benefits, consisting of variations in tillage practices, nitrogen application rates and methods, and herbicide use. Table 2 lists the combinations of management practices which are considered. Each of the management systems produced by combinations of these practices will have a complex set of effects on the crop yield, production cost, and the

TABLE 2
MANAGEMENT PRACTICES CONSIDERED IN THE EXAMPLE

Tillage System	Nitrogen Application Method
Mulch Till ("MT") [C] No Till ("NT")	Anhydrous PReplant ("ANR") [C] Anhydrous PPostplant ("ANO") Liquid ("LIQ")
Nitrogen Application Rates	Herbicide
140 kg/ha ("148") 168 kg/ha ("168") [C]	Atrazine ("ATR") [C] Dicamba (Banvel—"BAN")

(C = Conventional, or current practice)

quantities of pollutants generated. The tillage practice within a management system will have the greatest effect on the quantities of pollutants leaving a field since controlling residue levels affects infiltration and soil detachment. With little residue on the surface, runoff is higher, and the quantity of agricultural chemicals moved with the water and adsorbed to sediment is greater.

The tillage system definitions used here are those of the Conservation Tillage Information Center. Mulch till implies that the farmer tries to leave at least 30% residue cover by using a shallow disk or field cultivator. No till implies even more residue, as there is no cultivation, and typically a burndown herbicide (Glyphosate) is needed to kill the weeds before planting.

The timing and depth of incorporation as well as the quantity of nitrogen applied affect the amount of nitrogen moved from the field. Anhydrous ammonia can be injected as a gas into the soil either pre- or postplant. Postplant anhydrous application is the most likely to provide nitrogen just when and where the corn plant needs it, although it requires time during a more critical period. Liquid nitrogen can be mixed with herbicides and sprayed on the ground surface, so it can be spread quickly and cheaply and is often contracted out. Two levels of nutrient application are considered. 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. A number of herbicides are used in a corn bean rotation in this area. The two alternatives considered here are atrazine, which is generally cheap and effective and as an alternative, dicamba.

For research purposes, Watershed 1 has historically been kept in continuous corn, deep disking, and dry application of 170 kg/ha nitrogen. Deep disking causes too much erosion to qualify for the Conservation Compliance

program. The management system closest to this, a corn bean rotation with mulch till, 168 kg of nitrogen applied as anhydrous ammonia, preplant with atrazine as the herbicide will be considered the conventional management system.

QUANTIFY THE EFFECTS OF ALTERNATIVE MANAGEMENT SYSTEMS

The field scale simulation model provides an estimate of the quantities of agricultural pollutants delivered to the edge of the field and to the bottom of the root zone. The model does not simulate the fate and transport of the pollutants after leaving the field to the point where damage is caused to surface waters downstream or to groundwater. Initializing models is time consuming, although tools are under development that make this task easier using existing databases [12, 13].

The simulation model used is a modified version of the Groundwater Loading Effects of Agricultural Management Systems, or GLEAMS, model [14]. Modifications of the model include the addition of the nitrogen leaching component for CREAMS [15] and the EPIC crop growth component [16]. A modified version of the economic accounting program based on the Cost and Returns Estimator, or CARE program [17], is used to compute the returns of the management systems based on the simulated yields as well as the labor requirement for each month. The 24 management systems for each field were entered into the program using the input file builder which is included in the MODSS. The model was calibrated to match runoff, base-flow as a proxy for percolation, sediment yield and corn yields for the period 1972–1991, and then adjusted for a corn soybean rotation and the amount of residue left by the model management systems as described in [18]. The price of corn was assumed to be \$2.20/bu. and \$5.60/bu. for soybeans, the average of local prices for market years 1991–1993. The resulting annual average economic returns were similar to standard budgets used by the Southwest Iowa Farm Business Association [19].

RANK MANAGEMENT SYSTEMS USING MODSS

In order to compare noncommensurable decision criteria such as net income or the average annual amounts of sediment leaving the field, a score or value function is used to convert the predicted data from the simulation model (or input by the user) to values on a 0 to 1 unitless scale, with 1 being the best score possible. The decision variables for the conventional or

baseline practice score 0.5 by definition. Initially, the importance order of the criteria is determined by a default method in the MODSS but can be modified by the user subsequently [6].

Assuming an additive value function and an importance order of the decision criteria, **best** and **worst composite scores** for each alternative are determined by the solutions of two simple linear programs according to [7].

Suppose there are m criteria which are ordered in importance. Let $Sc(i, j)$ be the score of alternative j evaluated with respect to criterion i in the importance order. If $w(i)$ indicates the unknown weight factor associated with criterion i , the highest(lowest) or best(worst) additive composite score for alternative j consistent with the importance order is found by solving the following linear program for the weights $w(i)$, $i = 1, \dots, m$.

BEST (WORST) COMPOSITE SCORE

$$\text{maximize}(\text{minimize}) \sum_{i=1}^m w(i) Sc(i, j)$$

$$\text{s.t.} \sum_{i=1}^m w(i) = 1$$

$$w(1) \geq w(2) \geq \dots \geq w(m) \geq 0.$$

In both cases (maximizing or minimizing) the first constraint normalizes the sum of the weights to 1, the second requires that the solution be consistent with the importance order and restricts the weights to be positive. Thus, the decision maker is not asked to determine an exact weight factor for each criterion. The solution of the two programs indicated above yields the full range of possible composite scores given the importance order. That is, any weight vector that is consistent with the importance order will produce a composite score that falls between the best and worst composite scores. Closed form solutions for the above programs are given in [7].

These two composite scores are then averaged to determine the preference ranking of the alternatives. A highlight of the method is that it does not involve setting specific weights to determine the composite scores, but rather considers all possible weights consistent with the importance order of

the criteria. The solutions to these linear programs are the most optimistic and the most pessimistic composite scores (weighted averages) which are consistent with the importance order. The method produces a complete ranking of the alternatives.

To compare representative farms within a region, the score functions need to be calculated for one of the representative farms in the region and then applied to the other representative farms. Or, if that is not possible, the region could be subdivided. For the example of the representative farm from the deep loess region, a group of experts (including one farmer) familiar with the water quality problems of western Iowa met and agreed that the default score functions were reasonable and that an appropriate importance order was [20].

1. Net returns
2. Atrazine in Runoff; Atrazine in Sediment
3. Sediment Yield
4. Nitrogen in Runoff; Nitrate Nitrogen in Percolation
5. Soil Detachment
- 6+. All other pesticides in surface or groundwater.

Because decision variables which are not highly ranked do not have a strong influence on the overall ranking, the problem was simplified by not considering any pesticides other than atrazine in surface water. One of the strengths of the MODSS is that interest groups can interactively change the ordering to see the effect the order has on the overall ranking, to work towards agreement on criterion ranking.

The result of scoring the alternatives for Watershed 1 can be seen in Figure 1, which reduces all of the previously considered information to a single point for each management system. The score of each management system is shown relative to the four management practices to highlight the effects of each practice on the overall score. The average score for all management systems using a particular practice is shown by the horizontal bar. Management systems which include both mulch till and atrazine earned consistently low scores because of the importance given to atrazine in runoff and sediment and the amounts of atrazine estimated to leave the field with those practices. Management systems with mulch till and atrazine were not markedly worse than the others on the terraced field because the terracing limited the amount of atrazine leaving the field. Each management practice can have conflicting impacts on desirable objectives. Only by quantifying the effect of each change can one determine whether or not, on the whole, adopting a management subsystem would be an improvement. The highest score overall on both watersheds was for the no till, anhydrous ammonia applied postplant, 168 kg/ha of nitrogen and atrazine management system.

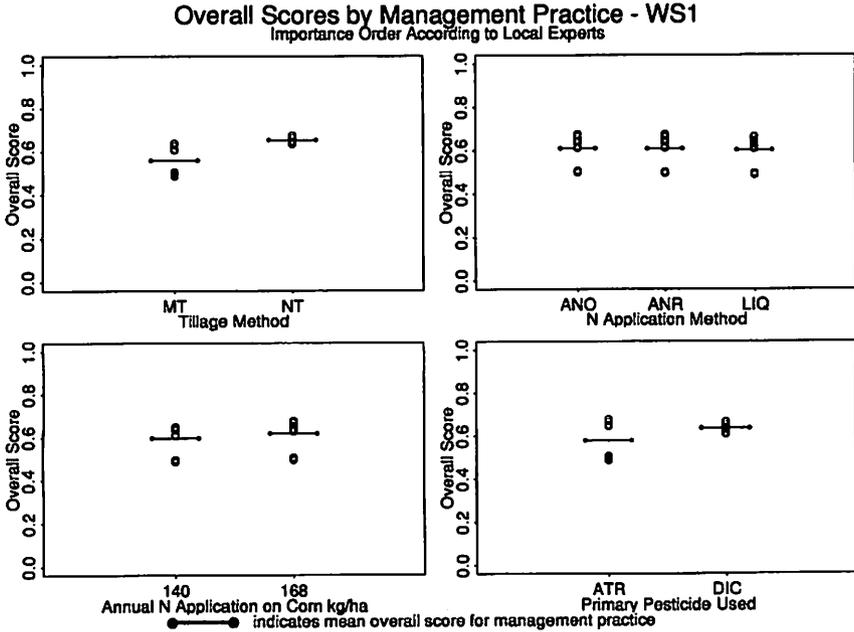


FIG. 1. Scores for the 24 management systems on the unterraced field.

WHOLE FARM ANALYSIS

It is possible to use the MODSS directly with farmers for individual fields. However, since the MODSS has been developed at the field scale using annual average values of each of the decision variables, there are two farm scale issues that should also be considered. First, a risk averse farmer would be averse to the overall variation in income from all of the fields in the farm, not from individual fields. Second, it may not be physically possible for a farmer to implement the most highly ranked management systems on all of his fields because a resource, such as the farmer's labor, is limited during critical periods. Both of these issues can be addressed by using a constrained optimization model.

Utility theory suggests that risky alternatives can be compared by calculating a certainty equivalent for each alternative by subtracting a risk premium from the expected returns. If the change in wealth from using a different management system is small relative to a farmer's overall wealth, a constant Arrow-Pratt [21] risk aversion coefficient ($\phi = -u''/u'$) can be assumed. A constant risk aversion coefficient implies a negative exponential

form of the utility function [22]

$$u(r) = 1 - e^{-\phi r}.$$

For a vector of activities (management system alternatives) with normally distributed returns, r , a variance covariance matrix of the returns Σ_r , and a negative exponential utility function, Freund [23] was able to show that maximizing expected utility $E(u^*)$, is equivalent to maximizing

$$\text{Max}_x E(u^*) = E(r)'x - \frac{\phi}{2} x' \Sigma_r x.$$

This is generally called the mean variance formulation. In 1979, Paris [8] was able to show that this formulation could be extended to consider variation in the limiting supplies of inputs (right-hand sides), which he called the generalized mean variance formulation

$$\text{Max}_{x,y} Z = E(r)'x - \frac{\phi}{2} x' \Sigma_r x - \frac{\phi}{2} y' \Sigma_b y$$

s.t.

$$Ax - \phi \Sigma_b y \leq E(b)$$

$$x \geq 0, \quad y \geq 0$$

where there is an additional term comprising a penalty for risk from variation in the right-hand sides, as y is a vector of shadow prices associated with the constraints and Σ_b is the variance-covariance matrix of the $E(b)$ vector of right-hand sides. It is assumed that the production technology embodied in the A matrix of technical constraints is linear and nonstochastic, and further, that there is no interaction between input supplies and variable returns. A symmetric quadratic model has been used to analyze the changes in incentives for soil conservation facing farmers from potential changes in farm programs in [24]. Musser et al. [25] and Thompson [26] have concluded that risk aversion in mathematical programming models needs to be considered carefully, as risk may be confounded with missing constraints, or omission of risk with extraneous activities in the optimal solution, either of which would affect the economic interpretation of the model results.

The primal formulation of the symmetric quadratic problem (from the farmer's perspective) is

$$\text{Max}_{\mathbf{x}, \mathbf{y}} z_F = E(\mathbf{r})' \mathbf{x} - \frac{\phi}{2} \mathbf{x}' \Sigma_{\mathbf{r}} \mathbf{x} - \frac{\phi}{2} \mathbf{y}' \Sigma_{\mathbf{b}} \mathbf{y}$$

s.t.

$$\text{for all } m, \sum_f \sum_i x_{fi} * \text{LaborNeed}_{fmi} \leq \text{AvailLabor}_m$$

$$\text{for all } f, \sum_i x_{fi} \leq \text{FieldArea}_f$$

$$\text{for all } m, \sum_f \sum_i x_{fi} * \text{FieldDayNeed}_{fmi} - \phi \Sigma_{\mathbf{b}} \mathbf{y}' \leq E(\text{AvailFieldDay}_m)$$

$$\text{for all } p, f, \sum_i x_{fi} * \text{Pollution}_{pfi} \leq x_{fi} * \text{PollutantLimit}_{pf}$$

$$\mathbf{x}, \mathbf{y} \geq \mathbf{0},$$

where

Indices

i	index for management systems
f	index for fields
m	index for months
p	index for pollutants

Parameters

z_F	Scalar value of risk adjusted utility for farmer of representative farm
$E(\mathbf{r})$	Vector of expected net returns per hectare by management system and field
ϕ	Scalar risk aversion coefficient
$\Sigma_{\mathbf{r}}$	Variance-covariance matrix of net returns
$\Sigma_{\mathbf{b}}$	Variance-covariance matrix of right hand sides (with nonzero values associated only with expected available field days)
LaborNeed_{fmi}	Labor needed for each field, month and management system
$\text{FieldDayNeed}_{fmi}$	Field days needed for each field, month and management system
Pollution_{pfi}	Production of each pollutant from each management system on each field

FieldArea _{<i>f</i>}	Area in each field
AvailLabor _{<i>m</i>}	Labor available by month
AvailFieldDay _{<i>m</i>}	Number of days machinery can operate in field by month
PollutantLimit _{<i>pf</i>}	Maximum acceptable quantity of each pollutant from each field

Variables

x_{fi}	Vector of proportions of each field be put into each management system
y_b	Vector of dual variables associated with constraints (the only nonzero values are associated with field day constraints).

In this case, the only right-hand side values which were considered variable were monthly "available field days," which refers to the number of days in which the temperature and soil water permit the operation of farm equipment on a field. Labor and field day constraints are especially critical after the soil has warmed and dried enough to permit operations and before crops have matured to the point where field operations would damage the crop. In a questionnaire distributed to farmers in West Pottawattamie County, Iowa with "D" slopes and Ida-Monona soils, 22 farmers of the 62 responding to the questionnaire reported that having fields too wet to work was one of their biggest constraints. Field day availability and monthly variances were calculated from data provided from central Iowa in [27]. None of the other constraints were considered stochastic. By varying the amounts of pollutants allowed to leave a field, abatement cost curves could be generated, although because the simulation model is only for the field scale, drinking water standards would not generally apply without further assumptions about the fate and transport of the pollutants to a drinking water source.

The validation of the farmer's optimization model was an attempt to predict the management systems currently in place for those farmers that responded to the questionnaire. Farms were grouped by size, and individual farms were modeled by varying the number of hours worked per week in May and June, the size of the machinery (number of rows), and the size of the farm. In order to encourage responses to the questionnaire, the requirements to specify each farm's resources were limited. The optimization model was used to simulate the average proportion of each management system used on each of four farm sizes.

In general, the optimization model overpredicted the use of the management system found most profitable [28], although in some cases that appeared to be due to assumptions made in the simulation of the alterna-

tives. For example, no till was predicted to be the tillage practice used exclusively. Many farmers are still in the process of switching and may not be convinced that chemical weed control is as effective as mechanical control as was assumed for the simulation. The optimization model provided reasonable predictions of nitrogen application methods, though the quantities of nitrogen applied by farmers were lower than predicted by the model. Atrazine use was also overpredicted. Although there was a consensus that the next best alternative cost \$8/acre more than atrazine, a new regulation did not allow for the use of atrazine within 66 feet of a watercourse, and some farmers reported that atrazine was not as effective at weed suppression as it had been in the past.

For the set of management systems considered on the representative farm, consideration of risk aversion did not have a major influence on the management systems in the optimal solution although the utility was reduced. Because all of the management systems were substantially similar, using the same crop rotation and tillage practices which leave a large amount of residue, differences in the mean and variances of the returns tended to be small, and the management systems with high mean returns tended to also have low variances. Aversion to variation in the right-hand sides had little effect on the utility, even though the field day availability was binding. If more elements of the \mathbf{b} vector of right-hand sides were considered variable and were binding in the optimal solution, aversion to variation in the limiting supplies would have had a greater effect.

The optimization model representing society's perspective does not consider risk aversion and is a simple LP formulation with the objective function

$$\text{Max } z_s = \mathbf{x}'\mathbf{s}$$

and the same constraints as the farmer's model except for the field day constraint which becomes

$$\text{for all } m, \sum_f \sum_i x_{fi} * \text{FieldDayNeed}_{fmi} \leq \text{AvailFieldDay}_m.$$

The code for both models in the GAMS language [29] is available in [30].

TARGET FARMS

The solution for the representative farm assumes that the farmer works 60 hours a week, uses 6-row equipment and has a risk aversion coefficient of

$\phi = 0.00001$. The optimal solution to the farmer's model is 242 hectares planted in no till, preplant anhydrous ammonia at 168 kg/ha, and using atrazine on both terraced and unterraced fields, with an additional 0.3 hectares of no till, liquid nitrogen at 168 kg/ha with atrazine. The area weighted net return is \$76/hectare, and the area weighted score is 0.68. The solution to the model from society's point of view is almost exactly the same, except there were an additional 0.3 hectares of the liquid nitrogen applied on a terraced field, rather than preplant anhydrous ammonia. If the farm were larger, the farmer worked fewer hours or had 4-row equipment instead of 6-row equipment, more liquid application of nitrogen would have entered the solution.

Given the results of the simulation model, the default scoring functions, the importance order defined by local experts and the formulation of the optimization models, farms like the representative farm have the correct economic incentives to adopt the management systems preferred by society. Figure 2 highlights the potential for improvement from the conventional management system. The background is a scatterplot of the net returns and scores for the 24 management systems on the two types of fields. The area

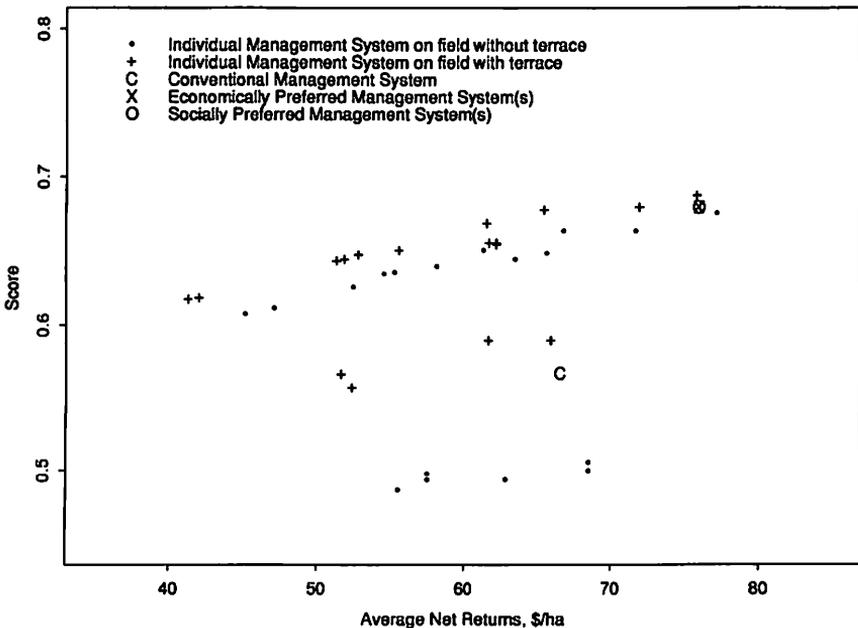


FIG. 2. Score/economic return possibilities using experts' importance order.

weighted return and score for the mulch till, preplant anhydrous ammonia at 168 kg/ha with atrazine on all fields, was considered the conventional management system and is marked with a "C". The average score and net return for the result of the optimization models from the farmer's ("X") and society's ("O") points of view overlapping on the upper right of Figure 2.

The potential for improvement from society's point of view can be seen by the vertical distance between a farmer's existing management practices and those with the highest score. Because farms on highly erodible land need a conservation plan on file with the Natural Resources Conservation Service which specifies the crop rotation and tillage system for the conservation compliance program, it should be possible to target individual farms for the promotion of the management practices that would greatly increase their score. Farms similar to the representative farm that are using mulch till on unterraced fields should be targeted for the promotion of no till.

Another factor to consider when targeting farms is that the farmers, their families, and neighbors are the ones most likely to be affected by a number of agricultural pollutants, especially those pollutants moving toward groundwater. A group of farmers from the deep loess region was asked to specify an importance order for the MODSS. The farmers agreed with the expert's ranking, except that the importance of nitrogen moving toward the groundwater was ranked second, instead of atrazine in surface water, and atrazine ranked fourth where the experts had ranked nitrogen [20]. The scores from the MODSS for each alternative were used in the same optimization models with the farmers' importance order yielding the results shown in Figure 3. The solution which maximized the area weighted score ("O") included the nitrogen application rate of 140 rather than 168 kg/ha on the terraced fields, since terraces promote infiltration. Farmers could expect to earn \$10/ha more by applying the management systems which maximize income, which is the size of the incentive they would need. However, as the farmers are the ones affected by the pollution, it is not in their interest to risk the environmental damage, and no economic incentive is needed.

SUMMARY AND CONCLUSIONS

To have the greatest improvement in water quality from agriculture, the farms and regions causing the greatest problems and with the most potential for improvement should be targeted for conservation efforts. This paper proposes a method to target farms for water quality which highlights the potential to improve the producer's management systems. The approach is simple. The following questions are answered: what are the resource problems? what are the alternative management systems that address those

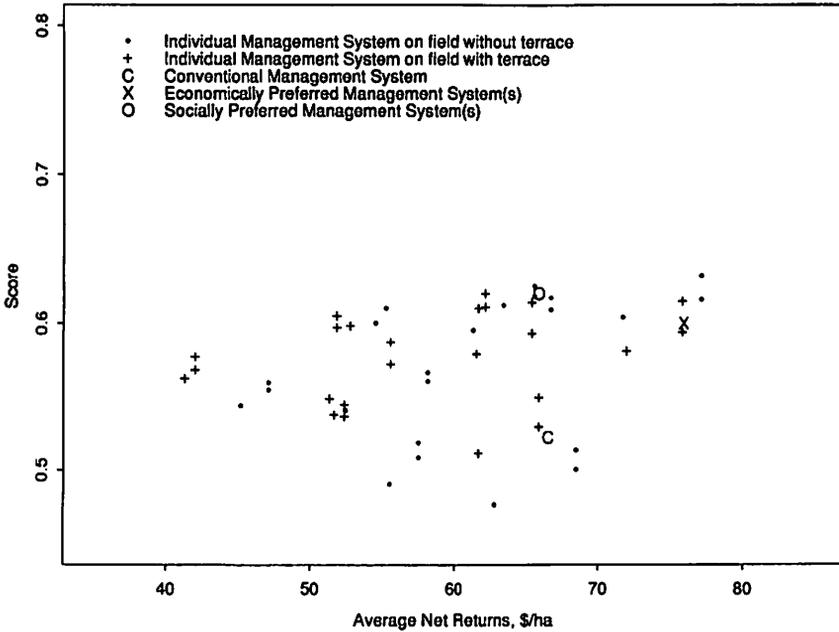


FIG. 3. Score/economic return possibilities using farmers' importance order.

problems? what effect do the management alternatives have on the problems? how desirable, overall, is each alternative? and, do farmers have the economic incentives to adopt the management systems that will lead to the greatest overall improvement? The answers to those questions are quantified, although given the imperfect state of our knowledge, technological change, etc., the recommendations could change over time.

Given data on the effects of alternative management systems on the resource problems, the MODSS provides a practical way of considering offsite water quality effects. If data exist that relate pollutant loading to offsite damage, those data could be used to define scoring functions and the importance orderings for the MODSS. In the more likely event that such data are not available and the magnitude of the offsite damage does not warrant the expense of detailed study, expert opinion can be used with existing information about offsite water quality effects in the MODSS to score and rank the alternatives.

The use of a constrained optimization model as a complement to the MODSS allows consideration of the whole farm issues of feasibility and risk aversion. The symmetric quadratic model with the associated generalized

mean variance economic interpretation is proposed as the most general formulation to mimic a risk averse farmer selecting management systems. Whether the added complexity of the asymmetric quadratic over a simple linear programming formulation, or of the symmetric quadratic over the asymmetric is justified will depend on the specifics of the problem. A symmetric quadratic model should be considered if some of the management systems are riskier than others and some of the right-hand sides are highly variable and are expected to be binding in the optimal solution.

The proposed method also provides information not only on which farms to target, but on how to encourage the adoption of alternative management systems. If, for most of the representative farms in a region, farmers have economic incentives to adopt the preferred management systems, or if a major fraction of the increase in score is also in the farmer's interest, then a voluntary approach to encouraging the adoption of alternative management systems is appropriate. On the other hand, major offsite resource problems in an area would be reflected in the scoring functions and importance order and result in a significant potential increase in score over those determined from the farmer's economic point of view. Such a situation would require subsidies or regulation.

There are two primary advantages of the proposed method to targeting for conservation efforts. First, a quantitative framework is provided to allow the incorporation of technical information about management system alternatives, the values assigned to conflicting objectives, and whole farm constraints. Improvements to our understanding of any of the individual parts can be incorporated, but targeting can be done now based on existing information supplemented by a simulation model and expert opinion. The second advantage is that the method highlights the economic incentives farmers face to adopt conservation management systems. It is possible to identify how much of an incentive is needed for farmers to adopt a given management system. The method proposed here for targeting farms can and should be further refined. Nevertheless, it provides a reasonable approach which does not require an inordinate amount of input data to target farms to improve water quality.

We would like to thank Larry Kramer of the Deep Loess Research Station in Treynor, Iowa for providing data used to model the alternative management systems, Marco Buske of the Extension Service for help in defining alternative management systems, and Lyle Peterson of the Natural Resources Conservation Service for much practical advice on farming systems and conservation measures and for help administering the questionnaires. They all showed exemplary patience.

REFERENCES

- 1 A. D. Ward, C. A. Onstad, P. V. Patterson, M. R. Burkart, B. L. Schmidt, J. W. Porterfield, and A. J. Weber, President's water quality initiative—a market emphasis. ASAE Paper No. 91-2167, St. Joseph, MI. (1991).
- 2 Conservation Tillage Information Center, National Survey Report, various years.
- 3 P. Nowak. Why farmers adopt production technology, *Journal of Soil and Water Conservation* 47:14-16 (1992).
- 4 L. J. Lane, J. C. Ascough, and T. Hakonson, Multiobjective decision theory—decision support systems with embedded simulation models. In *ASCE, Irrigation and Drainage Division, Proceedings*, Honolulu, HI, July 22-26, 1991.
- 5 D. S. Yakowitz, L. J. Lane, J. J. Stone, P. Heilman, and R. K. Reddy. A decision support system for water quality modeling. In: *Proceedings of Water Resources Planning & Management*, Water Forum '92 ASCE, Baltimore, MD, August 2-6, pp. 188-193 (1992).
- 6 D. S. Yakowitz, J. J. Stone, L. J. Lane, P. Heilman, J. Masterson II, J. Abolt, and B. Imam, A decision support system for evaluating the effects of alternative farm management practices on water quality and economics, *Water Science and Technology* 28(3-5):47-54 (1993).
- 7 D. S. Yakowitz, L. J. Lane, and F. Szidarovsky. Multiattribute decision making: dominance with respect to an importance order of attributes, *Appl. Math. Comp.* 54:167-181 (1993).
- 8 Q. Paris, Revenue and cost uncertainty, generalized mean-variance and the linear complementarity problem, *American Journal of Agricultural Economics* 61(2):268-275 (1979).
- 9 Q. Paris, Revenue and cost uncertainty, generalized mean-variance and the linear complementarity problem: reply, *American Journal of Agricultural Economics* 71(3):810-812 (1989).
- 10 *National Research Council, Soil and Water Quality: An Agenda for Agriculture*, National Academy Press, Washington, D.C., 1993, p. 128.
- 11 Deep Loess Research Station (USDA-ARS), Treynor, Iowa, unpublished data, 1992.
- 12 C. E. C. Drungil, W. F. Geter, and K. J. Wickey, A GIS data inference for water quality modeling. ASAE Paper No. 932565, Chicago, IL, 1993.
- 13 M. Hernandez, P. Heilman, L. J. Lane, J. J. Stone, J. A. Abolt, and J. E. Masterson II, A prototype shell for running field scale natural resource simulation models, In: *ASAE Proceedings of Application of Advanced Information Technologies: Effective Management of Natural Resources*, Spokane, WA, June 18-19, pp. 124-149, 1993.
- 14 F. M. Davis, R. A. Leonard, and W. G. Knisel. GLEAMS User Manual, Lab Note SEWRL-030190FMD USDA-ARS and University of Georgia, Tifton, Georgia, 1990.
- 15 W. G. Knisel (Ed.). CREAMS: a field-scale model for Chemicals, Runoff, and

- Erosion from Agricultural Management Systems. Conservation Research Report No. 26, U.S. Department of Agriculture, Science and Education Administration, 1980.
- 16 J. R. Williams, C. A. Jones, J. R. Kiniry, and D. A. Spanel, The EPIC crop growth model. *Transactions of ASAE* 32:497-577 (1989).
 - 17 Midwest Agricultural Research Associates, User Manual Cost and Return Estimator, USDA-Soil Conservation Service, Contract no. 54-6526-7-268, 1988.
 - 18 P. Heilman, A Decision Support System for Selecting Economic Incentives to Control Nonpoint Source Pollution from Agricultural Lands, Ph.D. Thesis, University of Arizona, Tucson, AZ, 1995, Appendix C.
 - 19 L. McAlexander, Southwest Iowa Farm Business Association, personal communication, 1994.
 - 20 P. Heilman, A Decision Support System for Selecting Economic Incentives to Control Nonpoint Source Pollution from Agricultural Lands, Ph.D. Thesis, Univ. of Arizona, Tucson, AZ, 1995, p. 92.
 - 21 E. Silberberg, *The Structure of Economics: A Mathematical Analysis*, Second Ed., McGraw Hill, New York, NY, 1990.
 - 22 P. Heilman, A Decision Support System for Selecting Economic Incentives to Control Nonpoint Source Pollution from Agricultural Lands, Ph.D. Thesis, Univ. of Arizona, Tucson, AZ, 1995, Appendix A.
 - 23 R. Freund, The introduction of risk into a programming model, *Econometrica* 24:253-263 (1956).
 - 24 W. T. McSweeney, and R. Kramer, The integration of farm programs for achieving soil conservation and nonpoint pollution control objectives, *Land Economics*, 62:159-173 (1986).
 - 25 W. Musser, B. McCarl, and G. Smith, An investigation of the relationship between constraint omission and risk aversion in firm risk programming models, *Southern Journal of Agricultural Economics* December: 147-165 (1986).
 - 26 G. Thompson, Activity specification and input risk aversion in risk programming models: In: *Proceedings, Western Agricultural Economists Meeting*, 165-179, (1989).
 - 27 A. S. Babeir, T. S. Colvin, and S. J. Marley, Predicting field tractability with a simulation model, *Transactions of the ASAE*, Vol. 29(6):1520-1525 (1986).
 - 28 P. Heilman, A Decision Support System for Selecting Economic Incentives to Control Nonpoint Source Pollution from Agricultural Lands, Ph.D. Thesis, Univ. of Arizona, Tucson, AZ, 1995, p. 102.
 - 29 A. Brooke, D. Kendrick, and A. Meeraus, *GAMS: A User's Guide*, The Scientific Press, South San Francisco, CA, 1992.
 - 30 P. Heilman, A Decision Support System for Selecting Economic Incentives to Control Nonpoint Source Pollution from Agricultural Lands, Ph.D. Thesis, University of Arizona, Tucson, AZ, 1995, Appendix E.