

**Compromise Solution  
for Economic-Environmental Decisions  
in Agriculture**

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**Abstract**

Least cost production versus the environmental on- and off-site erosion damage of agriculture is evaluated in a policy context for a major Corn Belt watershed. Compromise programming, previously utilized in firm-level multi-criteria decision making problems, is applied to a regional agricultural production model with environmental policy goal trade-offs. The crop sector model allocates land, water, labor, capital, and commodity-program base acres to crop production. Production options include four conservation practices, three tillage methods, and several crop rotations. Crop yield and fertilizer levels are dependent upon erosion. Cropping options selected allow for both wind and water erosion.

The vector of objectives include three minimization functions: current production cost, future value of productivity loss, and sediment damage. Vector optimization technique was used to generate the payoff matrix containing efficient but simultaneously unobtainable solutions. Given the ideal but infeasible solution vector we generated efficient solutions in the compromise subset corresponding to the  $L_1$ ,  $L_2$ , and  $L_\infty$  metrics. Trade-off relations were developed using the noninferior set estimation technique.

## Compromise Solution for Economic-Environmental Decisions in Agriculture

### Introduction

Concern over the inter-relationship among agriculture, natural resources, and the environment is increasing. Over-exploitation of land resources for current private profit and the absence of conservation measures consistent with public and long-term interest, is hastening this process. A major issue for regional agricultural policy analysts is how to better manage the natural resource base. Among prominent resource-management issues are the impacts of commodity and conservation programs for soil erosion, nonpoint chemical and sediment pollution, and health risks from chemical residues in food.

Soil erosion as an on- and off-farm problem received extensive attention in the 1985 Food Security Act (FSA). The on-farm impact of erosion is soil productivity loss. A report relating corn yields to medium-textured top-soil depth in southern Iowa has shown that reducing depth from 12 to 10 inches reduces corn yield by 6 percent (Webb and Bear, 1972, cited in Langdale and Shrader, 1982). Soil productivity losses influence inter-generational comparative advantage, production patterns, and cropland value. In short, the costs of erosion-induced productivity loss are internal to the farm and usual resource-use efficiency criteria.

The major off-farm impact of erosion is sediment pollution of water bodies. U.S. cropland-induced sediment damage has been estimated at \$3.5 billion (Clark et al., 1985). Sediment damage is clearly a negative externality. In some regions these externalities are internalized through state regulations, penalties, and taxes. As a result of such environmental regulations, minimization of sediment damage may enter a producer's multi-criteria decision framework. The decision maker (DM) has to find an optimal solution given the multi-criteria decision (MCD) problem in an integrated (economic/environmental) situation. The environmental objectives of reducing erosion-induced sediment damage and of reducing productivity loss generally conflict with the least cost production criteria.

The purpose of this analysis is to show that the Vector Optimizing Compromise Program (VOCP) can be applied to large-scale integrated multi-objective models in regional agriculture to generate a compromise solution set. These solutions will provide information on efficient economic-environmental trade-offs. The case study used to illustrate the modeling approach also has the merit of indicating how

productivity loss coefficients can be developed for use in more extended evaluations of MCD problems relating to agriculture.

## **2. The Model**

The model developed for analysis of resource use efficiency in agriculture and on- and off-farm soil erosion impacts (productivity loss and sediment damage) is sketched in Figure 1. The model utilizes an integrated systems approach (Hafkamp, 1984) comprising three inter-linked process modules--those of crop production, productivity loss, and sediment damage -- as well as a decision-making module. The operational version of the model incorporates an equilibrium optimization framework and generates a simultaneous solution consistent with the economic and environmental goals.

### **2.1. Productivity Loss Valuation**

Productivity loss in this compromise programming exercise is defined as the impact of one year's soil loss on the future income stream. The model selects a set of management practices that minimizes the loss in the net present value (NPV) of the future streams of income due to productivity impacts of top-soil loss. Each year, the agent evaluates future income paths for alternative management practices and makes a choice. Valuing productivity loss from soil erosion involves several issues: soil loss and its impact on yield, the measures taken to offset the yield loss, the value of future yields, and societal viewpoints on discounting.

The NPV of profits may not attach the proper social value to productivity loss (AAEA, 1986). Market failure may occur when inadequate information or inconsistent incentives exist for decision makers. The discount rate required to evaluate NPV weighs the welfare of current and future generations. Given observed societal concern for future generations (AAEA, 1986), a near zero discount rate was used.

Soil loss accounted for water induced sheet and rill erosion (Wischmeier and Smith, 1978) and wind erosion (Woodruff and Siddoway, 1965). The Erosion Productivity Impact Calculator (EPIC) (Putman and Dyke, 1987) was used to estimate soil losses for alternative management practices. Gully erosion was not measured, and no distinction was made between soil erosion and actual soil movement from fields (Johnson, 1988). Estimates of soil-loss impacts on yields were developed with the EPIC-EPIS (Erosion Productivity

Impact Simulator) (Putman et al., 1987) system prepared for the 1985 Resources Conservation Act (RCA) appraisal. These estimates were available by soil type, region, management practice, and crop rotation.

Given the base yield (yield for the year 1980 calibrated using 1979-81 average yields from published statistics), equation (1) estimates the base yield adjusted for erosion:

$$EY_t = Y_0 \times (1 + \Omega) \quad (1)$$

where  $EY_t$  is the base yield adjusted for erosion between  $t$  and  $t_0$ ;  $Y_0$  is the base yield; and  $\Omega$  is the erosion-yield impact coefficient. With the EPIC yield-loss impact as a constant percent, the actual forgone loss in future yield is greater with higher technological growth. Therefore, future yields,  $TY_t$ , for a given technological growth,  $\tau$ , were first estimated assuming no erosion (equation 2). The rates of technological growth assumed in this study were the moderate trends used in the 1985 RCA appraisal (U.S. Department of Agriculture, 1989). It was also assumed that each rotation was repeated indefinitely in the future:

$$TY_t = Y_0 \times [(1 + \tau) * (t - t_0)] \quad (2)$$

Then, for the same set of rotations, future yields were calculated allowing for both erosion and technological growth impacts:

$$ETY_t = Y_0 \times (1 + \Omega) \times [(1 + \tau) * (t - t_0)] \quad (3)$$

The difference between  $TY_t$  and  $ETY_t$  is the yield loss ( $L_t$ ), as shown in equation (4):

$$L_t = -(Y_0 * \Omega) \times [(1 + \tau) * (t - t_0)] \quad (4)$$

Of the data regarding additional crop production costs possibly incurred to offset the yield loss due to erosion, only those accounting for increased fertilizer cost are available. The EPIC system estimates the cost of replacing major nutrients lost due to erosion. The annual losses of these chemicals per ton of soil eroded are assumed constant over time. Equation (5) estimates the erosion adjusted fertilizer requirement:

$$NF_i = BF_i \times [ (1 + \beta_i) * (t - t_0) ] \quad (5)$$

where  $i$  stands for fertilizer type (nitrogen, phosphorous, and lime). Note that,  $BF_i$  is the base fertilizer requirement,  $NF_i$  is the erosion adjusted fertilizer requirement, and  $\beta_i$  is the fertilizer-erosion impact coefficient. Cost associated with the increased fertilizer requirement ( $NF_i - BF_i$ ) is also included in the NPV.

Two issues are especially important in valuing productivity loss. The first and foremost is price. Historical and current price data reflect government policies, export markets, climate, and other factors. For this analysis, observed 1980 commodity and input prices were used. All prices were assumed constant over time; and assuming price separability, the mathematical representation for NPV of productivity loss is:

$$NPV(L_t) = P_Y \sum_{t=1}^T L_t e^{-\delta t} + \sum_{i=1}^3 R_i (NF_i - BF_i) \quad (6)$$

where  $\delta$  is the discount rate,  $P_Y$  is the commodity price, and  $R_i$  is the price of  $i^{\text{th}}$  fertilizer. This separability greatly facilitates solution of the model. A steady-state solution for (6) is obtained by assuming a terminal time  $T = 100$  years.

The model cropping activities are rotations of one to six years. The coefficients  $P_Y$ ,  $L_t$ ,  $NF_i$ , and  $BF_i$  represent the vector of crops (corn, wheat, soybeans, and hay) for the six different rotations. The loss calculation is made for each crop. Then the totals by crop for each rotation are summed and discounted at an annual rate. A second issue in valuing productivity loss is the use of appropriate discount rate. The trade-off here is to either use a higher discount rate from a private perspective or use a lower discount rate from a social perspective. For the present analysis, we abstract from this difficult conceptual problem and use a discount rate of 1 percent.

The productivity loss function developed here is simpler than those used in other studies of erosion. Computational capacity and data availability prohibit the development of a more complex criterion function for productivity loss. McConnell (1983) assumed that farmers maximize the NPV of stream of profits plus the market value of their farm at the end of the planning horizon by choosing a constant set of management practices. Walker (1982) assumed that farmers maximized NPV by choosing the appropriate time to switch

from conventional to conservation tillage. Burt (1981) assumed that farmers chose crop mixes over time to determine the optimal soil loss from a private perspective. Frohberg (1977) allowed switching of management practices at three discrete intervals in a 40 year planning horizon to achieve optimal soil loss from a social perspective.

## **2.2. Crop Production**

The area modeled is Water Resources Sub Area number 703 (U.S. Water Resources Council, 1970). This watershed (Producing Area [PA] 41) comprises most of central and eastern Iowa, and western parts of Illinois and Wisconsin. Most of the data for the model are from the Agricultural Resource Interregional Modeling System (ARIMS) (English et al., 1989). The criterion function representing the production sector is a linear function that minimizes the cost of production for a given level of output. Commodity output is held constant at levels dictated by historical patterns to generate a trade-off relation between production and environmental goals.

Producers are assumed to have the following resources available for production: land, machinery, operator labor, and commodity base acres. Producers take commodity prices and government program parameters as fixed and for the given output level select the most efficient set of production technologies. Production options available to the producer are crops grown by land class, rotation, tillage, and conservation practices<sup>1</sup>. Conventional fall plow, conservation tillage, and zero tillage options are the alternative tillage options. Operator labor can be supplemented with hired labor at increased wages. Basic cost estimates, input use, and yield information for PA41 are from the ARIMS. Additional data are from published state level agricultural statistics and from the Resource Use and Supply Economics Information System (RUSE) (Putman and Rosenberry, 1988).

## **2.3. Sediment Damage**

The sediment sector includes the following three components: sediment delivery ratio (SDR), sediment transport ratio (STR), and cost per ton of sediment. The SDR is the ratio of average annual sediment yield

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<sup>1</sup>In addition to the straight row cropping, conservation practices included are strip cropping, contouring, and terracing.

per unit area to the average annual potential soil loss per unit area (Khanbilvardi and Rogowski, 1984). The SDR estimates the proportion of gross soil eroded by runoff (sheet and rill erosion) entering a water body. The SDR is a function of drainage density and soil texture. The primary sources of data for the SDR are the 1982 National Resources Inventory (NRI) and the 1975 Water Resources Council Second National Water Assessment (English and Alexander, 1988; Wade and Heady, 1977). The STR is adopted from Fowler et al. (1983) and it reflects the aggregate transport efficiency of each stream reach which has inflow from upstream regions and outflows to other regions. For the watershed under study, the SDR and STR coefficients are 0.505 and 0.4, respectively.

There is no single realistic estimate of the cost of sediment damage. Clark et al. (1985) provide a national estimate of the cost of off-farm sediment damage. Ribaud (1986) has disaggregated these estimates by USDA production region. The cost coefficient was taken from these two studies and they suggest only orders of magnitude. Actual costs may vary from one-tenth to 10 times the estimated level (Clark et al., 1985).

#### **2.4. Decision Making**

The vector optimization program (VOP) can be used to optimize more than one objective subject to a set of linear/nonlinear constraints. For VOP problems a unique optimum solution is normally not defined. Common VOP techniques include goal program, constraint program, and multi-criterion simplex programs all generating a set of efficient solution,  $S^*$ . The elements of  $S^*$  are feasible if no other feasible solution can achieve the same or better performance for all the criteria and strictly better for at least one criterion (Romero and Rehman, 1984). There are two major drawbacks in applying these methods for large-scale integrated models. First, a large number of extreme efficient points is generated, making it difficult for the DM to choose the best solution from  $S^*$ . Second, the algorithms generating  $S^*$  are typically expensive.

An alternative method overcoming these difficulties is the Vector Optimizing Compromise Program (VOCP). VOCP is a method for choosing a unique optimum from  $S^*$ . The general idea of this method is to avoid the problem of identifying preferences. Instead, by accepting plausible choice assumptions, it is



possible to bound that portion of the efficient set which is tangent with the underlying iso-utility function (Zeleny, 1973). The VOCP problem is defined as

$$\max/\min_{X \in F} Z(X) = G(Z_1(X), Z_2(X), \dots, Z_m(X)) \quad (7)$$

where  $Z(X)$  is an  $m \times 1$  vector of objective functions,  $X$  is an  $n$ -dimensional vector, and  $F$  is a feasible set.

The first step in the VOCP algorithm is to establish the "ideal" solution, i.e., the optimal solution vector,  $Z^*(X^*)$  obtained by optimizing each objective separately. Of course, if there were a single feasible solution vector  $X^*$ , then this vector would be the unique optimum. Unfortunately, the ideal solution set is not feasible. It can, however, serve as a standard against which to evaluate the compromise solutions. The idea is to choose feasible solutions closest to the ideal as the best compromise. The compromise program approximates DM's preferences by geometric measure of distance from the ideal solution vector.

The second step is to set up a payoff matrix as illustrated in Table 1. The diagonal entries of Table 1 are ideal values. The element  $Z_{ij}$ , read across Table 1 is the value of the objective function  $j$  when the  $i^{\text{th}}$  objective is optimized. The third step is to obtain the deviation,  $d_j(X)$ , between the  $j^{\text{th}}$  objective value and its ideal and to normalize it for consistent results when the objectives are measured in different units (Zeleny, 1982). The normalization factor is the inverse of absolute deviation between the ideal ( $Z_j^*$ ) and anti-ideal solution ( $Z_j^{**}$ ). For a maximizing criteria,

$$d_j(X) = \frac{[Z_j^* - Z_{ij}(X)]}{|Z_j^* - Z_j^{**}|}, \quad i, j = 1, 2, \dots, m \quad (8)$$

and for a minimization criteria,

$$d_j(X) = \frac{[Z_{ij}(X) - Z_j^*]}{|Z_j^* - Z_j^{**}|}, \quad i, j = 1, 2, \dots, m \quad (9)$$

where  $d_j(X)$  is the normalized distance between the  $j^{\text{th}}$  objective value and its ideal.  $Z_j^{**}$  is the anti-ideal point, i.e. the smallest (largest) value for  $Z_j(X)$  in the pay-off matrix when in fact  $Z_j(X)$  is a maximization (minimization) criteria.

The final step in generating the compromise set,  $S^c$ , is to select a particular distance measure. The one used here is the family of  $L_\Theta$  metrics:

$$L_\Theta(\alpha, m) = \left[ \sum_{j=1}^m (\alpha_j d_j(X))^\Theta \right]^{\frac{1}{\Theta}} \quad (10)$$

where the value of  $\alpha_j$  reflects the importance of the  $j^{\text{th}}$  objective, which is set here to unity implying that all objectives are equally important. The value of the parameter  $\Theta$  reflects the importance attached to the deviation of each objective from its ideal value. Given that  $\alpha_j = 1$  for all  $j = 1, 2, \dots, m$ , then  $S^c$  is simply the set of compromise solutions determined by solving for all  $\Theta$  in the range 1 to  $\infty$ . Generally, for a compromise set  $S^c$ , three points corresponding to  $\Theta = 1, 2$ , and  $\infty$  are calculated.

If  $\Theta = 1$ , then the  $m \times 1$  VOP has the following form:

$$\min_{X \in F} L_1(1, m) = \sum_{j=1}^m d_j(X) \quad (11)$$

The value  $\Theta = 1$  implies that all deviations are equally significant. Geometrically, this metric measures the longest distance and hence an upper bound for  $S^c$ .

If  $\Theta = \infty$ , the problem has the following form:

$$\min_{X \in F} L_\infty(1, m) = \max_{\text{all } j} d_j(X), \text{ s. t. } d_j(X) \leq d_\infty \quad (12)$$

where  $d_\infty$  is defined as  $\max [d_j(X)]$  for all  $j$ . Note that as  $\Theta$  increases, the larger deviations are given more weight. Thus, the  $L_\infty$  minimizes maximum deviation and yields a lower bound for  $S^c$ . Observe that the  $L_1$  and  $L_\infty$  optimization problems are linear. This is not the case for  $L_2$  metric ( $\Theta = 2$ ).

If  $\Theta = 2$ , then the  $m \times 1$  VOP has the following nonlinear form:

$$\min_{X \in F} L_2(1, m) = \left[ \sum_{j=1}^m [d_j(X)]^2 \right]^{\frac{1}{2}} \quad (13)$$

Note that the  $L_2$  metric minimizes the sum of squared deviations (quadratic distance function). Hence, the optimization problem is a nonlinear quadratic programming (QP) problem. If the constraints are linear, the

problem can be solved by any descent algorithm. One has to simply represent the nonlinear objective function in  $R^m$  space by

$$f(X) = k + c'X + \frac{1}{2}X'QX \quad (14)$$

where  $k$  is a constant scalar,  $c' = [c_1, c_2, \dots, c_m]$ , and  $Q = [m \times m]$  matrix.

Interestingly, the family of  $L_\Theta$  metrics will always produce a nondominated point for all  $\Theta$  in the range of 1 to  $\infty$ . The  $L_1$  and  $L_\infty$  metric problems are linear. Hence, given standard regularity assumptions, it can be shown that a unique global optimum exists. The  $L_2$  metric is a nonlinear problem, however. It will not be possible to find a global optimum for a nonlinear problem unless it is known that any local optimum is also a global optimum. Because the  $L_2$  metric objective function is a quadratic function, which is smooth and convex everywhere, the local optimum is also a global optimum.

The  $L_\Theta$  metrics are geometric measures of distance between two points  $X$  and  $Y$  with coordinates  $(x_1, x_2, \dots, x_m)$  and  $(y_1, y_2, \dots, y_m)$ . This approach has intuitive appeal since it does not require articulation of subjective preferences. Once  $S^c$  is generated by defining different values for  $\Theta$ , there is no a priori justification for choosing a particular solution. At this stage the choice is referred to the DM.

### 3. Empirical Example and Results

The model used is a large-scale regional, integrated multi-objective model that simultaneously minimizes: (1) productivity loss; (2) cost of production; and (3) sediment damage. Thus, the objective function vector is a  $[3 \times 1]$  vector. The fertilizer cost component of productivity loss is included directly in the objective function. Transfer rows and separate activities are used to account for yield losses. The model was solved using a Stanford Optimization Laboratory's Fortran based routine MINOS, Version 5.0 (Saunders and Murtagh, 1983).

Productivity loss was calculated according to the procedure outlined in Section 2.1. Tables 2 and 3 show the net present value of productivity loss for each rotation, three tillage systems and two soil groups. The soil group with a fine texture had no productivity loss. Fine-textured soil corresponds to land capability classes I, IIwa and IIIwa (land group 1) for which EPIC indicates no yield reduction due to erosion and also

there is no fertilizer impact. The largest net present values of productivity loss per acre were associated with rotation corn-corn-corn-soybeans, corn-soybeans-corn-soybeans, and continuous corn. In general, large differences existed among these net present values, even within the same tillage system.

The feasible solutions generated by optimizing the objectives individually are shown in the payoff matrix in Table 4. Reading across columns in Table 4 gives the values of the three objectives when only one, indicated by the row heading, was minimized. The value of the minimized objective in each row is an ideal solution. For example, ideal production cost is \$1,897 million. The values of productivity loss and sediment damage under production cost minimization turn out to be anti-ideal solutions. Thus, these two objectives are in conflict with the goal of resource-use efficiency.

Because the ideal solution vector (diagonal vector) is not feasible, the DM has to select a particular optimization criteria. Of course, there is a trade-off between objectives. Since the ideal vector is not feasible, we resort to a geometric measure of distance to find a feasible compromise solution vector that has minimum deviation from the ideal vector. The compromise solutions for the  $L_1$ ,  $L_2$ , and  $L_\infty$  metrics are shown in Table 5. Note that the  $L_2$  solution is bounded by  $L_1$  and  $L_\infty$ , as expected (Cohon, 1978). As mentioned earlier, there is no a priori justification for choosing between the solutions associated with the different metrics. If program benefits from participation in soil conservation measures are substantial, then the DM might choose  $L_1$  solution. If not,  $L_\infty$  solution would be a reasonable choice. If the penalties for causing nonpoint sediment pollution are severe, then  $L_2$  would be plausible.

Total amounts of soil eroded, sediment deposit, and productivity loss are shown in Table 6 for the different optimization criteria and distance metrics. Clearly, the solutions obtained for distance metrics are consistent with the environmental goal and are also consistent with productivity maintenance criteria. To illustrate how compromise solutions are also consistent with resource-use efficiency criteria, we have generated trade-off relations among the three objectives by considering two at a time.

### 3.1. Trade-Off Relations

The ideal coordinate (ideal solution) of any two objectives is considered to form the bounds of a transformation curve measuring the relationship between those two objectives. The slope of this curve

indicates the trade-offs between the two objectives. These trade-offs can be regarded as shadow values of production cost in terms of productivity loss or of sediment damage (Romero et al., 1987). Computationally, the establishment of the transformation curve is equivalent to generating a set of pareto optimal solutions. In this study, we utilize the noninferior set estimation (NISE) method as the most suitable VOP technique for generating the trade-off curve. The NISE method developed by Cohon, Church, and Sheer (1979) permits exact generation of the efficient set when only two objectives are considered. In this method, the weights assigned to the objectives are established by the slopes of the segment connecting the extreme efficient points. Note that the NISE method is a variant of the goal programming method (Cohon, 1978).

Trade-off curves for production costs and productivity loss, and production cost and sediment damage are shown in Figures 2 and 3, respectively. The slopes of the straight lines connecting the extreme efficient points represent the magnitude of trade-off (shadow value) between production cost-productivity loss and between production cost-sediment damage. For instance, the slope of segment ab in Figure 2 indicates that a one-million-dollar reduction in productivity loss would increase the cost of production by 0.05 million dollars. Similarly in Figure 3, the segment lm, with a slope coefficient of 0.03, indicates that a one-million-dollar reduction in sediment cost would increase the cost of production by 0.03 million dollars. Given this efficiency locus, then, the DM by his subjective judgment chooses a point preferred by him. A large number of efficient points, however, are in that locus; and hence one has to either reduce the size of the efficient set by some subjective judgment or establish a compromise set. The compromise set is established by plotting the  $L_1$  and  $L_\infty$  solutions because we know that these two metrics form the boundary for the compromise set. Note that segments sc and sn in Figures 2 and 3 represent the respective compromise sets. Obviously, this set is smaller and relatively closer to the ideal set.

#### **4. Conclusions**

##### **4.1. Limitations**

As a mathematical programming model, the VOCP suffers from restrictions typical of such models (Hazell and Norton, 1986). The model is set up to satisfy fixed demand vector such that it could allow us to generate the required trade-offs. However, care is taken to see that these demands are consistent with

historical patterns prevailing in that region so that the solutions represent a competitive equilibrium. On the physical side of the model the representation of the sediment system is an elementary approximation that may introduce irregularities into the process of policy analysis and formulation. For instance, the procedure for estimating sediment impacts and cost are at best crude. These are only approximations of sediment damage coefficients; and thus, like all other coefficients and assumptions of this model, may seriously modify the results if in error. They do indicate, however, the need for information and inter-disciplinary research on nonpoint pollution.

In spite of the detailed representation, the model is still highly aggregated over variables of interest in soil and water quality policies. Braden et al. (1989) examine a smaller watershed (1200 acres) to illustrate the problems inherent in assuming fixed delivery ratios for sediment. Conservation practices used on adjoining fields not only slow the erosion process but also reduce or at least do not increase transport of sediment from the field in question. Therefore, the cost of obtaining a given sediment standard is overstated by assuming fixed sediment delivery and transport ratios. With larger areas being modeled, getting site specific data is a highly limiting factor.

#### **4.2. Concluding Comments**

A methodology for evaluating trade-off frontiers among the alternative policy goals of least-cost food production, minimization of productivity loss, and minimization of sediment damage has been presented. An empirical application to an important Corn Belt watershed validates the model's performance. The framework allows identification of efficient ranges for the three goals and illustrates the ranges in which impediments become binding.

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Table 1. Illustrative payoff matrix for VOCP

Objective	$z_1$	$z_2, \dots, z_m$
$z_1$	$z_{11}^*$	$z_{12}, \dots, z_{1m}$
$z_2$	$z_{21}$	$z_{22}^*, \dots, z_{2m}$
	$\vdots$	$\vdots$
$z_m$	$z_{m1}$	$z_{m2}, \dots, z_{mm}^*$

\*Denotes ideal points

Table 2. Net present value of productivity loss from medium soil by fertilizer and yield impact (\$/acre)

Crop Rotation <sup>1</sup>	Conventional Till			Conservation Till			Zero/No Till		
	Fertl	Yield	Total	Fertl	Yield	Total	Fertl	Yield	Total
CCCC	1.00	31.98	32.98	0.94	15.19	16.13	0.52	7.20	7.72
CHHH	0.02	1.00	1.02	0.03	0.47	0.50	0.01	0.22	0.23
CBCB	2.02	24.54	26.56	0.81	11.66	12.47	1.01	5.52	6.53
WHHH	0.05	0.07	0.12	0.01	0.03	0.04	0.03	0.02	0.05
BHWH	0.21	0.90	1.11	0.06	0.43	0.49	0.11	0.20	0.31
CBHH	0.28	3.51	3.79	0.11	1.67	1.78	0.14	0.79	0.93
CBWB	1.87	10.60	12.47	0.49	4.92	5.41	0.92	2.38	3.30
CBWH	1.00	5.69	6.69	0.26	2.69	2.95	0.49	1.28	1.77
CCBW	1.53	8.68	10.21	0.41	4.12	4.53	0.75	1.95	2.70
CCCB	3.02	37.51	40.53	1.16	17.82	18.98	1.51	8.45	9.96
CWHH	0.43	3.13	3.56	0.11	1.48	1.59	0.21	0.70	0.91
CBWW	1.92	8.15	10.07	0.52	3.87	4.39	0.94	1.83	2.77

<sup>1</sup>C: corn; B: soybeans; W: wheat; H: hay

Table 3. Net present value of productivity loss from coarse soil by fertilizer and yield impact (\$/acre)

Crop Rotation <sup>1</sup>	Conventional Till			Conservation Till			Zero/No Till		
	Fertl	Yield	Total	Fertl	Yield	Total	Fertl	Yield	Total
CCCC	3.76	10.82	14.58	2.01	5.14	7.15	1.88	2.43	4.31
CHHH	0.10	0.78	0.88	0.04	0.37	0.41	0.05	0.18	0.23
CBCB	3.22	8.90	12.12	4.03	4.23	8.26	1.61	2.00	3.61
WHHH	0.05	0.36	0.41	0.10	0.17	0.27	0.03	0.08	0.11
BHWH	0.22	0.87	1.09	0.43	0.41	0.84	0.11	0.20	0.31
CBHH	0.44	1.86	2.30	0.55	0.88	1.43	0.22	0.42	0.64
CBWB	1.97	4.85	6.82	3.69	2.31	6.00	1.02	1.09	2.11
CBWH	1.01	3.18	4.19	1.93	1.51	3.44	0.54	0.72	1.26
CCBW	1.62	3.75	5.37	3.02	1.78	4.80	0.85	0.85	1.70
CCCB	4.66	13.12	17.78	6.03	6.23	12.26	2.33	2.95	5.28
CWHH	0.43	1.92	2.35	0.81	0.91	1.72	0.24	0.43	0.67
CBWW	2.07	4.78	6.85	3.75	2.27	6.02	1.09	1.08	2.17

<sup>1</sup>C: corn; B: soybeans; W: wheat; H: hay

Table 4. Payoff matrix for the example VOCP (million \$)

Objective	Pdty. Loss	Prod. Cost	Sed. Cost
Min. Pdty. Loss	102.6 <sup>*</sup>	2080.9 <sup>**</sup>	271.6
Min. Prod. Cost	434.2 <sup>**</sup>	1897.3 <sup>*</sup>	895.7 <sup>**</sup>
Min. Sed. Cost	118.5	2064.0	252.2 <sup>*</sup>

\*ideal solution

\*\*anti-ideal solution

Table 5. Compromise solution matrix for the VOCP (million \$)

Distance Metric	Pdty. Loss	Prod. Cost	Sed. Cost
$L_1$ Metric	109.2	1938.8	267.2
$L_2$ Metric	154.3	1931.9	313.3
$L_\infty$ Metric	157.6	1927.7	359.0

Table 6. Soil erosion, sediment pollution and productivity loss

Criteria	Amt. of Soil Eroded		Sediment Pollution		Productivity Loss	
	Mil. Tons	Tons/Ac.	Mil. Tons	Tons/Ac.	Mil. \$	\$/Ac.
Pdty. Loss	78.72	3.54	36.21	1.63	102.58	4.62
Prod. Cost	259.63	11.68	119.43	5.37	434.16	19.56
Sed. Cost	73.09	3.31	33.62	1.51	118.54	5.36
L <sub>1</sub> Metric	77.43	3.51	35.62	1.61	109.21	4.95
L <sub>2</sub> Metric	90.80	4.10	41.77	1.88	154.30	6.96
L <sub>∞</sub> Metric	104.05	4.71	47.86	2.17	157.60	7.13

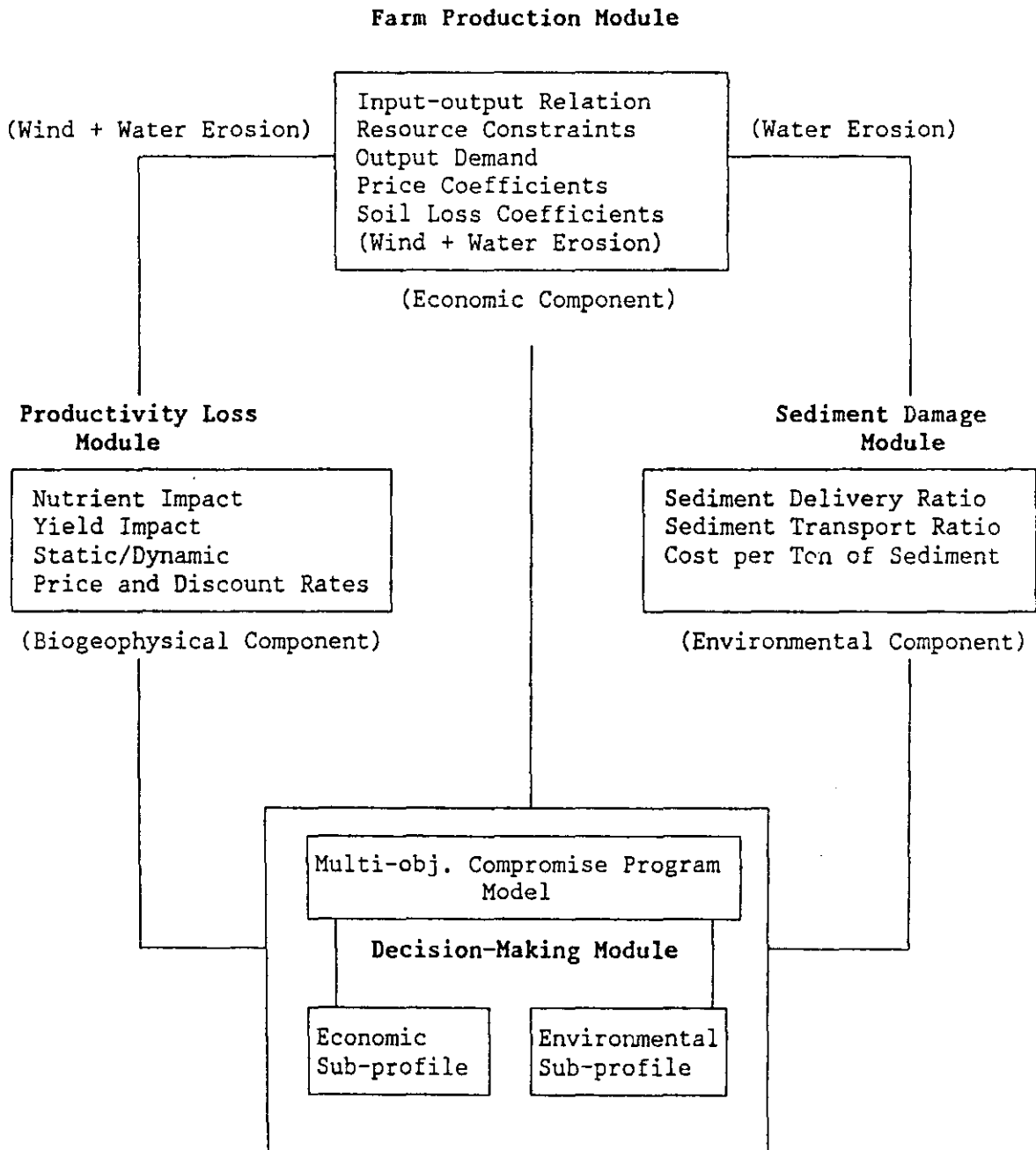


Figure 1. Integrated Modeling Framework

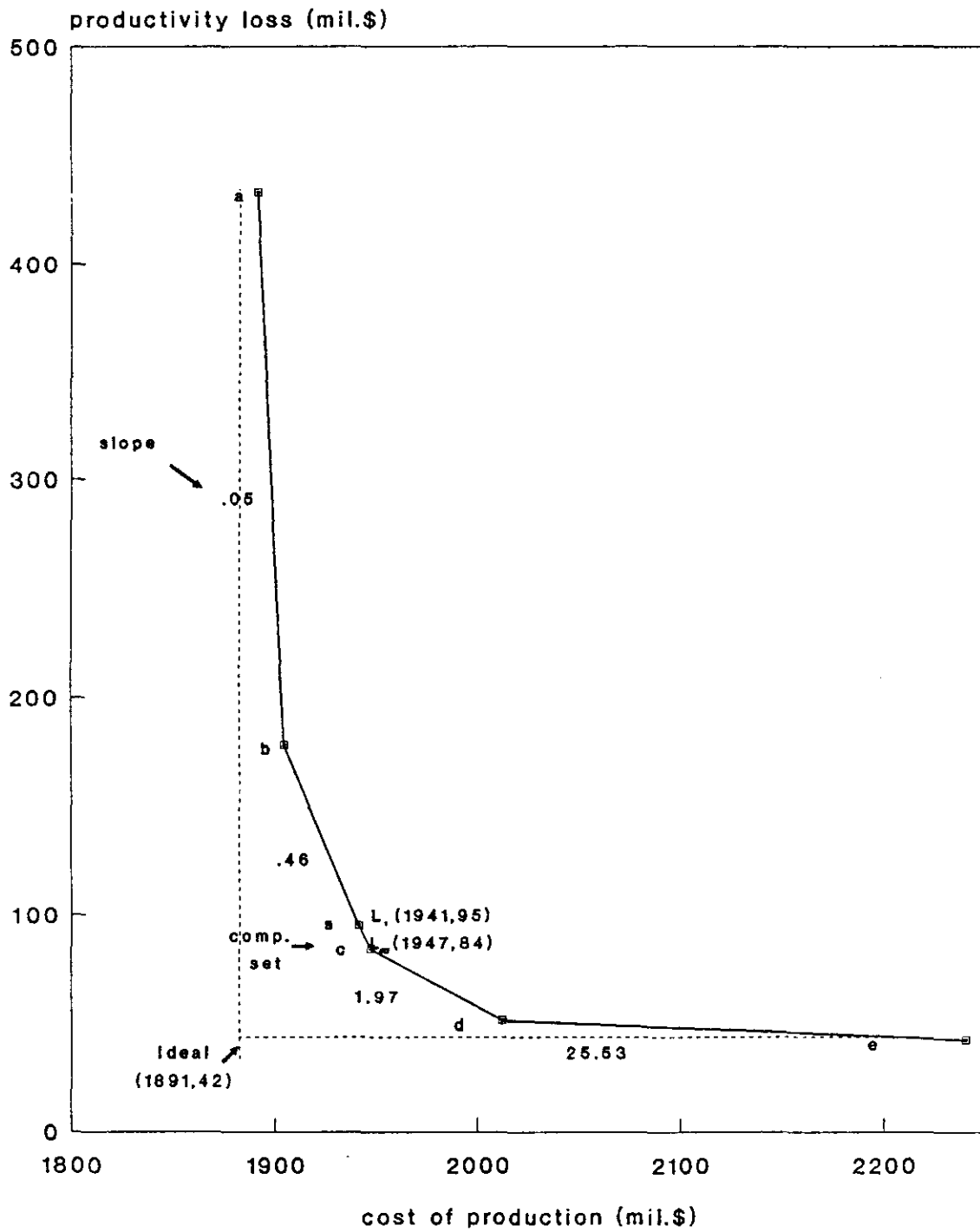


Figure 2. Trade-off Between Production Cost and Productivity Loss

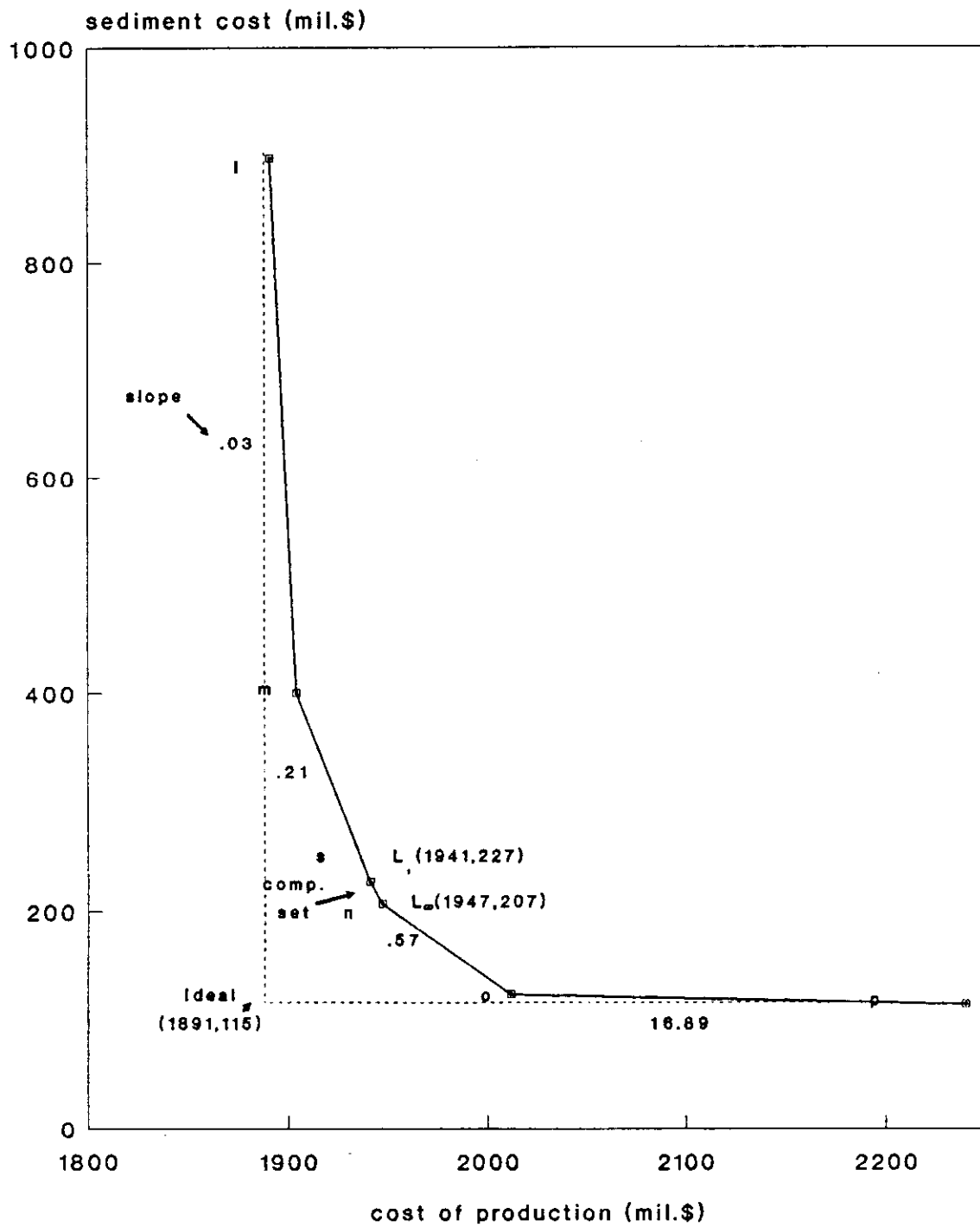


Figure 3. Trade-off Between Production Cost and Sediment Damage