Multigoal Linear Programming Analysis of Trade-Offs Between Production Efficiency and Soil Loss Control in U.S. Agriculture

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A MULTIGOAL LINEAR PROGRAMMING ANALYSIS OF TRADE-OFFS BETWEEN PRODUCTION EFFICIENCY AND SOIL LOSS CONTROL IN U.S. AGRICULTURE

by

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INTRODUCTION

Topsoil exposed to rainfall when crops are produced on sloping land creates a major environmental problem in the United States. Runoff and the resulting soil erosion carries sediment and agricultural chemicals into public waterways. Besides polluting the waterways, the process also reduces soil productivity. Even with conservation efforts, including the creation of soil conservation [30] and land use laws regulating soil and water conservation, erosion of agricultural topsoil remains a problem and will likely require new and integrated policies set by national agencies.

Soil Loss and Sedimentation From Agriculture

It was estimated that four billion tons of soil wash into the nation's waterways each year and that 75 percent of this total comes from agricultural and forestlands [2]. The amount has increased since 1972 as "fence-to-fence row" farming was practiced in response to high prices and exports and land retirement programs were relaxed. One effect of this soil loss from agricultural land is declining productivity. Taylor estimates that the three billion tons of soil eroded annually from agricultural and forestlands contain an average of 0.10 percent nitrogen, 0.15 percent phosphorous, and 1.5 percent potassium. These estimates imply an annual erosion loss of 50 million tons of plant nutrients. Erosion also affects surface soil structure, reducing both the water infiltration rate and the water-holding capacity of the soil.

Sedimentation, or the deposition of eroded soil in waterways, is considered to be the nation's largest single water pollution problem. Sedimentation restricts barge transportation and reduces the storage capacity of man-made reservoirs. Also, sedimentation increases water treatment costs for cities and industries and reduces the value of waterways as wildlife habitats and recreational areas.

Damages due to sedimentation have been greatly reduced by improving agricultural conservation practices in the past three decades. Improved cropland management practices can provide more effective control of soil erosion. The practices include land treatment practices, tillage practices, and the selection of appropriate crop sequences for rotation. Land treatment practices refer to contouring, strip cropping, and terracing. Tillage practices encompass time, method, and the intensity of tillage and crop residue management.

Recent developments in agricultural land use and impacts on erosion and sedimentation

Technological developments and price-cost relationships in U.S. agriculture have caused a gradual change in crop rotations during the last 30 years. Many farmers find continuous row cropping with one or two crops highly profitable under current technology. Commercial nitrogen fertilizers and pesticides have helped eliminate sod crops and small grains from rotations. This substitution of one technology for another increases erosion rates on sloping lands unless adequate land treatment or tillage practices are employed.

Soil conservation practices including reduced tillage and terracing can protect the topsoil from erosion under continuous row cropping. However, because the costs incurred by society in coping with sedimentation of public waterways are not incorporated into farm production decisions, farmers do not adequately protect their soil from erosion. The resulting decline in the productivity of U.S. agricultural lands has been partially masked by higher yielding crop varieties, large applications of fertilizer, and improved chemical pest control practices. But some of these offsetting factors may not be so effective or available in the future because of the potential problems resulting from high energy prices.

Increasing export demands

The spurt in exports during the early 1970s encouraged a greater acreage of row crops. Erosion increased accordingly. The greater row crop acreage was encouraged through the market as land retirement programs were abandoned and as high prices encouraged marginal lands to be brought into production. These potentials for soil erosion will remain unless less favorable prices and government programs now at hand can cause a reversal of recent trends.

The Soil Conservation Service estimates that more than half of the land coming into production recently has been idle or in forage crops since the 1930s and that about 60 million tons of topsoil were lost from these previously idle acres in 1974 [28]. More importantly, the increasing acreage of corn and soybeans means many more acres of land are subject to potentially severe erosion losses (Table 1).

Table 1. Change in harvested acreages of principal crops in the United States

Crop	1969	1974	Change
		(million acres)	
Increasing crops:			
Wheat, all	47.1	65.5	18.4
Corn, all	63.1	76.7	13.6
Soybeans	41.3	52.5	11.2
Others[a]	77.6	80.8	3.2
Total	229.1	275.5	46.4
Decreasing crops:			
Oats	18.0	13.3	-4.7
Barley	9.6	8.3	-1.3
Others[b]	23.9	22.1	-1.8
Total	51.5	43.7	-7.8

SOURCE: USDA [31].

[a] Cotton, hay, rice, sugarcane, peanuts, popcorn, dry beans, and tobacco.

[b] Flaxseed, rye, sugar beets, sorghum (all), potatoes, sweet potatoes, and dry peas.

Scarcity of energy and fertilizer inputs

The days of inexpensive energy for agricultural production are limited. As recently expressed by Secretary of Agriculture Bergland, U.S. agriculture has developed a system heavily dependent upon petroleum and petroleum products (fertilizer, pesticides, etc.) [1]. Since oil supplies will be exhausted in the near future, the U.S. agricultural system is in jeopardy. Bergland also has warned that phosphate rock may last only for another 20 to 30 years at the present rate of use. Scarcity of such resources will assume greater importance if the productivity of U.S. agriculture continues to be depleted by excessive erosion of the topsoil.

Objectives of This Study

Greater export demands, resource scarcity, and growing environmental problems make high rates of soil erosion of greater public concern. Thus, society's pressure to improve the quality of the environment and to conserve the land will likely intensify in the coming years. Pressure for action by the Federal and state governments rather than relying on individual voluntary action is increasing. In formulating and implementing programs to reduce sediment yields from cropland, important conflicts need to be considered. Thus, there is need for quantitative information concerning the formulation of public programs to cope with the problem and the potential impact of such programs on agriculture.

This study has two major purposes. The first is to generate trade-off information between (a) the cost of producing the nation's food supplies and (b) the maintenance of a productive land base and a high level of environmental quality. Previous studies [21, 22] have linked agricultural production and soil loss by means of interregional linear programming models. These models have evaluated the potential impact of restricting soil loss from cropland at both the regional and national levels under the single objective of minimizing the total cost of producing and transporting food to the consumer. However, environmental quality has become a goal that must be treated appropriately along with economic efficiency. Thus, selection of programs for U.S. agriculture with a single goal in the objective function may produce a solution which is not an optimal or efficient one in an overall sense.

To accomplish the first purpose, the study uses a two-goal objective function in which each goal is weighted to represent alternative social

preferences. The relative weights or values for the goals are altered to obtain "pairs" which define a trade-off curve between food producing efficiency and soil conservation. Six alternative "pairs" or trade-off points on the curve are analyzed and compared. The six solutions analyzed in this study are referred to as Solutions 1 through 6. The first of these, Solution 1, extends ongoing trends to the year 1985 and places no weight (value) on the soil erosion goal. For the remaining alternatives, a set of nonzero weights (values) is attached to both goals. The weights or values attached to the soil erosion goal imply an implicit value or cost to society for soil loss as a nonpoint source of pollution and can be interpreted as a tax imposed or subsidy (tax credit) paid to the farmer for farm conservation investments.

The study analyzes and compares each "pair" in terms of reductions in soil loss, contributions to environmental quality, the cost involved in reducing the soil loss, and the implications of the conservation policies on the agricultural production systems. Each solution point on the trade-off curve represents an alternative to society and policy makers and indicates the amount of sacrifice in one objective required to achieve higher levels of the other objective. Information on trade-offs is a prerequisite to the selection of optimal programs for U.S. agriculture in which the environmental problems are included. Since the eventual valuation of the soil loss in terms of tax credit or subsidy to farmers seems apparent, it is better for society to confront explicitly the choice of values and their implications for U.S. agriculture and the society.[1]

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[1] There are two conservation bills before Congress. These bills support the idea of tax credit or subsidy to farmers for their conservation investments. The cost of the activities by one of the bills is about $1 billion annually by 1983 [29].

The second major purpose of this study is to evaluate and analyze the alternatives in terms of their impacts on conservation and farming practices, land and other resources used in agriculture, soil loss levels, production patterns and farm incomes at the national and regional level. Further, associated with these "pairs," the study attempts to determine the shifts in regional comparative advantage, indicating which regions might be affected differently by the national impact. The resulting farming practices, land and resource use, and crop and livestock production patterns can indicate possible shifts in cost of production and income.

II. THE MODEL

This section summarizes the method used and the construction of the multigoal linear programming model on which the analysis is based. The model has four parts: (a) the land and water resources available to agriculture, (b) crop and livestock activities for the transformation of these resources into agricultural commodities, (c) the commodity transportation network, and (d) the domestic and foreign demands for agricultural products. The model is solved for each alternative with the objective of meeting the demands for agricultural products in a manner to minimize simultaneously both (a) the cost of producing and transporting the nation's agricultural products and (b) soil losses form U.S cropland.

Method

Most linear programming studies of U.S. agriculture have optimized an objective function related to a single goal of economic efficiency.

If other social and environmental goals are not included, regardless of the fact that these goals are of positive importance to society, incomplete answers may result. As Hurwicz pointed out:

> ...The mechanism designed under the influence of programming (linear and nonlinear programming) theory dealt to a large extent with one-objective-function problems and thus failed to face the crucial issue of goal conflict. [14].

To simultaneously evaluate conflicting goals such as economic efficiency and environmental quality in agricultural production, requires a programming model that accounts for both goals. Hence, a single goal optimization model is replaced by the vector maximization problem.

Vector Maximization Problem

A vector maximization problem arises when two or more real-valued objective functions are to be maximized (or minimized) over a set of feasible solutions. In the vector maximization problem optimality is replaced by the concept of efficiency. Given $f_1(x)$, $f_2(x)$, ..., $f_p(x)$ and $g_1(x)$, $g_2(x)$, ..., $g_m(x)$, which are real-valued functions on x in R^n, the formulation of the vector maximization problem may be stated as

Maximize a vector-valued function

$$F(x) = [f_1(x), f_2(x), \ldots, f_p(x)]^T \tag{1}$$

subject to

$$g_i(x) \geq 0 \qquad i = 1, 2, \ldots, m \tag{2}$$

$$x_j \geq 0 \qquad j = 1, 2, \ldots, n \tag{3}$$

where each component in F(x) is concave with respect to a convex set $X \varepsilon R^n$ and each $g_i(x)$ is also concave. The region defined by the constraint set in (2) and (3) is known as the feasible region in decision space (Figure 1). The problem identifies an efficient set of points, or an efficient vector x* within which the solution to the vector maximization problem lies. The efficient set is a subset of the feasible region in objective space and efficient vectors must lie on the boundary of the feasible region.

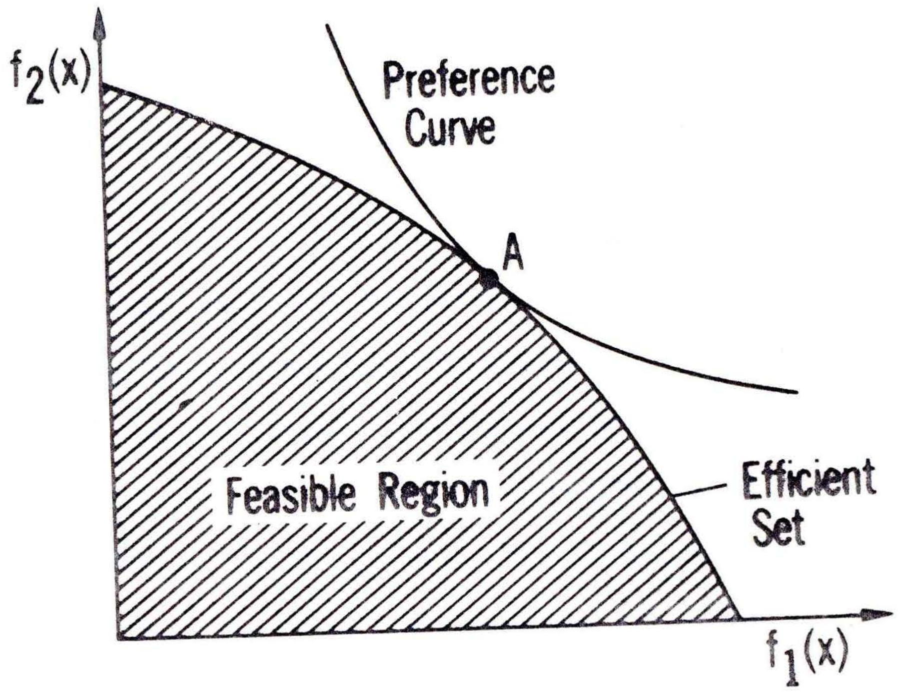

Figure 1. Efficient set and best-compromise solution, A, for a two-objective function problem.

The vector x* is efficient if there is no other feasible vector x** such that

$f_i(x^{**}) \geq f_i(x^*)$ for all i = 1, 2, ..., p

$f_i(x^{**}) > f_i(x^*)$ for some i

That is, x* is at least as good as x** over all criteria and better than x** for at least one component. The set of efficient vectors x* has different names in the literature: Koopmans' efficient set [16], Pareto-optimal set [24], noninferior set [36], and transformation set [9].

Efficient set represents the physical possibilities available to society. It provides information about the sacrifice of one goal that may be required to acheive higher levels of another goal. The preference curve presents society as ordering combinations of net benefits for the two goals. The preference curve generally is convex to the origin (Figure 1) and at any point on it, society is indifferent to the combination of the goals.

The optimal solution, characteristics of single-objective problem, can be obtained for a vector maximixation problem only by introducing the preference curve of society or the policymaker into the solution process. The optimal alternative will be at the tangency of the highest attainable preference curve with the feasible set. That is, the optimum is on the boundary of the feasible set. The optimal solution point A in Figure 1 can be classified as the "best-compromise" solution [3].

Solution Techniques for a Vector Maximization Problem

In recent years a great deal of effort has been devoted to the development of solution techniques suitable for solving vector maximum problems [15, 26, 27]. Price classifies these techniques as: (a) prior weighting of objectives, (b) exploration of the solution space, and (c) goal programming [25].

Prior weighting of objectives

This method employs the Kuhn-Tucker conditions identifying the efficient set of solutions of X* [17]. The Kuhn-Tucker condition says that a vector maximum for several concave functions $f_1(x)$ ..., fp(x) can be transformed into a "scalar" maximum by choosing appropriate constants w_i's, for scalarization as stated in (4):

$$F(x) \quad \sum_{i=1}^{p} w_i f_i(x) \qquad (4)$$

Maximizing this linear combination of the individual objectives will generate an efficient solution. Zeleny [37] specified the conditions for efficient solutions as requiring a nonempty polyhedron $X \epsilon R^n$ defined by $X = \left| x/x \epsilon R^n;\ Ax \leq b \right|$ and given $w_i \geq 0$ [37]. A solution x* to (4) is efficient if and only if there exists a multiplier $\mu \leq 0$, such that

$$Ax^* \leq b \qquad (5)$$

$$\mu A + wF(x) = 0 \qquad (6)$$

$$\mu(Ax^* - b) = 0 \qquad (7)$$

These conditions are necessary for an efficient solution. The convexity condition on the objective functions and the contraints ensures that efficient points will not be dominated by a combination of other points.

Cohon and Marks defined a constraint method that follows directly from the Kuhn-Tucker conditions in (6) [8]. The constraint method attempts to maximize one of the components of F(x), say $f_r(x)$, and allows all other components to vary. Rewriting (6) we have

$$w_r f_r(x) + \sum_{\substack{j=1 \\ j \neq r}}^{p} w_j f_j(x) + \mu A = 0 \qquad (6.a)$$

and since the relative values of the w_i's are of significance, the rth objective can be selected as the numeraire objective, i.e., $w_r = 1$. Hence, (6.a) becomes

$$f_r(x) + \sum_{\substack{j=1 \\ j \neq r}}^{p} w_j f_j(x) + \mu A = 0 \qquad (6.b)$$

The condition in (6.b) implies that the efficient set of solutions can be derived by solving the problem:

$$\text{Max } f_r(x) \qquad (8)$$

$$\text{Subject to } x \epsilon X$$

$$f_j(x) \geq \beta_j \qquad \text{all } j \neq r \text{ and } j = 1.2, \ldots, p \qquad (9)$$

where β_j is a lower bound on objective j. Using selected values for β_j for all j the efficient set can be derived.

Exploration of the solution space

The exploration of solution space method is described separately by Benayoun et al. [4] and Geoffrion et al. [13]. The method, as described by Benayoun, is a sequential exploration of the solution space with the decision maker. The first step in the Benayoun process requires the computation of an optimum solution for each individual objective function. Then a "compromise solution" is obtained by minimizing the weighted sum of deviations from each individual optimum. The decision maker analyzes this compromise solution and compares it with his "ideal solution." If this compromise solution is only partially satisfactory he then specifies how much he would relax the value of each objective function to obtain a new solution. The procedure is repeated until the decision maker accepts a solution.

Exploration of the solution space as described by Geoffrion et al. [13] is based on the Frank-Wolfe algorithm [35]. An initial solution to the following problem is obtained:

$$\text{Max } U\,[f_1(x),\ f_2(x)\ \ldots,\ f_p(x)] \tag{10}$$

$$\text{subject to } x \varepsilon X$$

where the utility function (U) of (10) is not known but is assumed to be a quasi-concave, nondecreasing original utility function of the decision maker. The decision maker reacts to this solution by assigning weights to the ith objective function at the kth solution point. These weights w_i^k are defined as

$$w_i^k = \frac{\left(\frac{\partial U}{\partial f_i}\right)^k}{\left(\frac{\partial U}{\partial f_1}\right)^k}, \qquad i = 1, \ldots, p \tag{11}$$

The weights in (11) are then used to compare the solution x* by solving

$$\text{Max } \sum_{i=1}^{p} w_i^k F_i(x^k)x \tag{12}$$

$$\text{Subject to } x \varepsilon X \tag{13}$$

This is known as the "direction-finding problem." The second step in this method involves determining an optimal solution t_k of the step-size problem

$$\text{Max } U[f_1(x_k + td_k^*),\ \ldots,\ fp(x_k + td_k^*)] \tag{14}$$

where

$$d_k = (x^* - x_k) \text{ and } 0 \leq t \leq 1$$

The first step (the direction-finding problem) determines the "best" direction d_k (based on a local linear approximation to the decision maker's utility function) in which to move away from x_k. At the second step, the analyst derives the values of the various functions for $0 \leq t \leq 1$, and shows these to the decision maker. The decision maker determines the amount (t) of movement in this direction which maximizes his utility in the region of the restriction of the overall problem. This defines a new operating point x_{k+1}, and the procedure is then repeated [13].

Goal programming

Goal programming was first developed by Charnes and Cooper [7]. This method minimizes the weighted absolute deviations from selected targets for each objective. Lee [18] formulates the general goal programming model as

$$\text{Min } \sum_{k=1}^{p} (d_k^+ + d_k^-) \tag{15}$$

$$\text{Subject to } x \varepsilon X$$

$$f_k(x) - d_k^+ + d_k^- = b_k \qquad k = 1, 2, 3, \ldots p \tag{16}$$

$$x_k,\ d_k^+,\ d_k^- \geq 0$$

where d^+, d^- represent deviations from the kth goal and b_k represents the level of the kth goal that the decision maker wishes to attain. A major problem in goal programming is the original ranking of conflicting goals. The decision maker determines the relative importance of each goal by assigning priorities as in (17),

$$\text{Min} \sum_{k=1}^{p} P_k(d_k^+ + d_k^-) \tag{17}$$

where P_k reflects the importance assigned to deviations from the previously selected levels of the various objective functions.

Evaluation of the techniques

Each of the methods described will give acceptable solutions to the multigoal problem. The prior weighting and constraint methods are the derivation of the efficient set. A best-compromise solution within the set is then determined by the policy maker's subjective preferences. As Cohon and Marks [8] pointed out, for fewer than three goals, prior weighting and the constraint methods are especially practical for public policy problems because it is possible to explicitly display the trade-offs between conflicting goals as in Figure 1. However, these methods have their limitations. The prior weighting method requires the scalarization of F(x) using subjective criteria supplied by the decision maker. The analyst using the constraint method has to choose the levels β_j and may very well select a combination of β_j's for which no solution exists. Finally, when there are more than three goals, the number of solutions required to obtain the efficient set increases exponentially with the number of goals.

Exploration of the solution space and goal programming is attractive since they allow interaction with the decision maker's judgement on each solution. However, for these methods, solution will be unsuccessful if the decision maker is not completely consistent in his judgement at each point. These techniques are generally efficient in handling the

problems in the private sector where priorities and targets are clear and well-defined and where fewer individuals are involved in the decision-making process.

Formulation of the study using the prior weighting technique

This study employs the prior weighting technique for the following reasons: (a) this technique is computationally easier for large models because it reduces the multiple-goal problem to an equivalent scalar-valued objective problem soluable by linear programming packages and (b) this study concentrates on deriving the efficient set (the trade-off function between the goals). To find the best-compromise solution, society needs information about the trade-offs between alternatives implied by the trade-off function. The prior weighting technique provides this information without requiring society's preference function.

For this study, the goals of (a) minimizing production and transformation costs and (b) soil erosion are combined in a single objective function with the assignment of explicit weights to each goal (see pages 31 and 32 for a description of each goal). The a priori specification of a vector of weights, w, indicating the relative importance of each objective, yields a composite linear objective function. The efficient set of solutions can be generated repeatedly optimizing this function as the weights are parametrically varied.

The general description of the multigoal problem with p goals can be specified as follows:

$$\text{Min } F = Cx \tag{18}$$

$$\text{Subject to } Ax \leq b \qquad (19)$$
$$x \geq 0$$

where F is a p x 1 vector, C is a p x n matrix and x is an n x 1 vector. A is an m x n matrix, and b is an m x 1 vector. Since this study analyzes two goals, the problem in (18) is

$$\text{Min } F = [F_1(x), F_2(x)]^T = Cx \qquad (20)$$

where C is now a 2 x n matrix. The constraint set defined in (19) on R^n is assumed to be a strictly convex set and the objective function in (20) on R^2 is strictly concave. The constraint set on R^n maps into the possible region defined by F on R^2.

The generation of the efficient set to (20) can be obtained by transforming the vector-valued objective function in (20) into a scalar-valued function in the following manner:

$$\text{Min} \sum_{i=1}^{2} w_i f_i(x) \qquad (21)$$

where the w_i's are the relative weights assigned to each objective (all $w_i \geq 0$). Systematically varying the w_i's in (21) will yield a trade-off curve between the goals.

The choice of weights in (21) indicating the relative importance of the objectives implies relative prices. Thus, the technique can be used for objective functions defined in different units, such as production costs in dollars and pollution measured in soil erosion. As Candler [6] indicates, one of the goals can be given a weight of 1. Then, the other goal weights have significance relative to this "numerarie" goal. This study defines the cost goal as the "numerarie" goal. Hence, the weights

assigned the soil loss goal can be interpreted as the pollution cost of a ton of eroded soil to society. By systematically varying the weights assigned the soil loss goal, the study traces out the efficient set of solutions for the problem.

The schematic in Figure 2 illustrates the framework for a hypothetical multi-goal model with two producing areas aggregated to form one market region. The schematic also shows how the objective function interacts with the rest of the model via the goal accounting restraints [5].

The objective function in the schematic includes two nonzero entries, one for each of the two goal functions. The entries w_1 and w_2 refer respectively to the weights the study attaches to the soil loss goal and the cost of production and transportation goal. The multi-goal programming illustrated in the schematic yields an efficient set of solutions to the problem for any level of w_1 and w_2, the relative weights assigned to each goal.

Six solutions were made in this study and each corresponds to a different pair of weights. Each efficient solution or "pair" on the trade-off curve (presented in the next section) is obtained by assigning a hypothetical set of relative weights (or values) to the conflicting goals described above. End points on the curve are derived by minimizing only the cost of production or minimizing only soil erosion, respectively. Since the study assumes the cost of production goal as "numerarie," each intermediate "pair" is obtained by assigning these alternative weights to the soil erosion goal. The set of alternative weights employed in this study is zero, \$2.50, \$5.00, \$10.00, and \$20.00 for the soil erosion goal and 1 for the cost of production goal (1 per \$1.00 of cost).

	Relationship	Crop Production in PA 1	Crop Production in PA 2	Livestock Production in MR 1	Cost Goal	Soil Loss Goal
Objective Function					w_1^a	w_2
Cost Accounting Restraint	0 =	VC^b	VC	VC	-1	
Soil Loss Accounting Restraint	0 =	SL^c	SL			-1
Resource Restraints in PA 2	$\geq$	B_{11}^d				
Resource Restraints in PA 2	$\geq$		B_{21}			
Commodity Demands in MR 1	$\leq$	C_{11}^d	C_{21}			

[a] w - weights assigned to the goal activities.

[b] VC - variable costs of production.

[c] SL - soil loss in tons/acre.

[d] B_{ij}, C_{ij} - interaction coefficients for PA_i in MR_j.

Figure 2. Illustrative framework for a hypothetical multi-goal model with two producing areas (PA) aggregated to form one market region (MR)

Regional Delineation and Specification of the Model

The study uses an interregional linear programming model for the U.S. agricultural sector and it is one of the series being developed under ISU-RANN (Iowa State University-Research Applied to National Needs). The model is defined with a set of regions consistent with the natural resources, the production possibilities, and the interregional interaction of U.S. agriculture. The major resource restraints are the regional availability of cropland by quality class, water, and nitrogen. The model incorporates regional demand restraints for crop and livestock commodities. The activities are defined on a regional basis to stimulate crop and livestock production possibilities, fertilizer and water purchases and to provide for the transfer of resources and commodities to meet the demands. The model is solved such that the overall cost of the agricultural bill (cost of producing and transporting farm commodities) and soil losses from cropland are minimized, satisfying the resource and demand restrictions.

Regions of the Model

The model is based on four different sets of regions. They are, respectively: (1) the data collection regions within which the data base for the model is collected, (2) producing areas within which the production activities of the model are determined, (3) the market regions within which the demands for agricultural products are defined, and (4) the reporting regions for aggregating the results.

The data collection regions, Figure 3, are built on county approximations of the major land resource areas which are used by the Soil

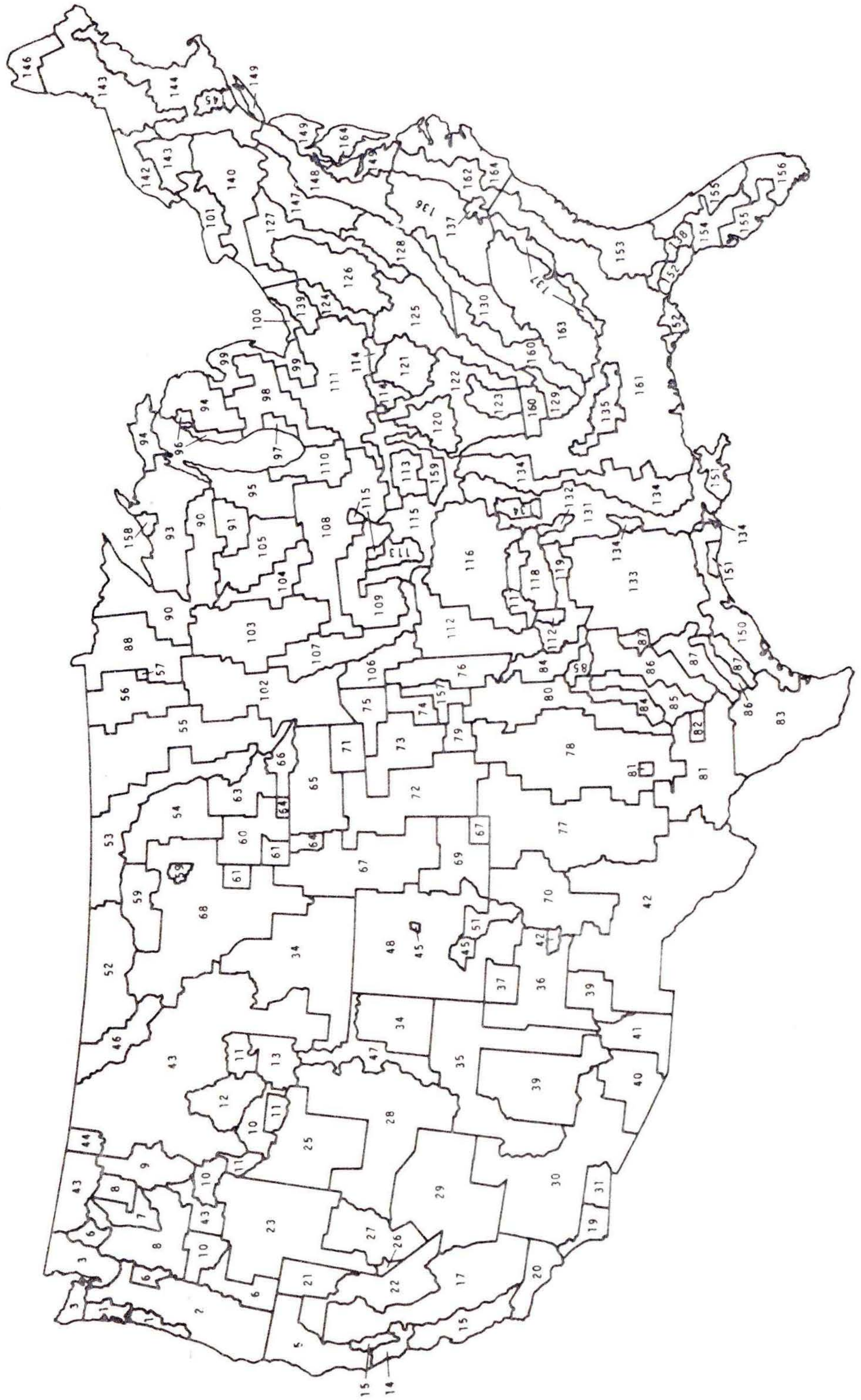

Figure 3. The SCS data collection areas

Conservation Service, United States Department of Agriculture. The regions delineate the land of the United States into 156 areas based on dominant soil type and management characteristics. Appropriate sets of weights are used to transfer data from data collection regions into the producing regions.

The producing areas, Figure 4, are the 105 regions which are derived from the Water Resource Council's 99 aggregated subareas consistent with the agricultural patterns found in the aggregated subareas. The crop production sector and the land base of the model are defined within these regions. The water supplies are defined in producing areas 48 to 105 in the Western United States. Continuous producing areas are aggregated into the 28 market regions shown in Figure 5. The market regions in the model function as both a demand and a transportation center. The metropolitan centers identified in each market region are the links in the transportation sector of the model. Livestock production is defined at the market region level.

Finally, the set of reporting regions shown in Figure 6 is formed for the purpose of reporting the findings.

Major Sectors of the Model

The following subsections outline the data sources used and the interregional interactions involved in the model.

The land sector

The land base of the model was built from the Conservation Needs Inventory (CNI) [11]. The inventory reports acres of land by use and by

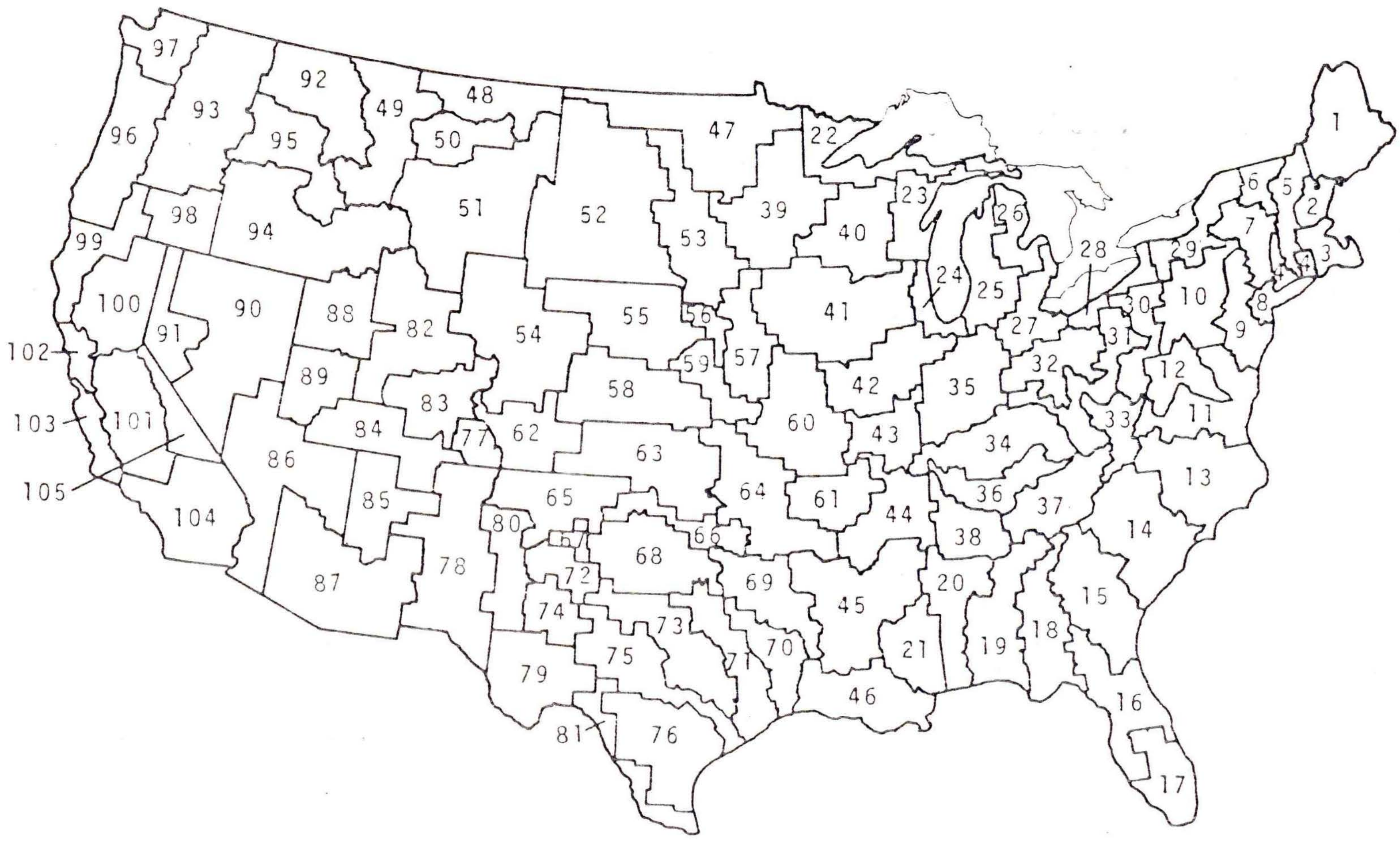

Figure 4. The 105 producing areas

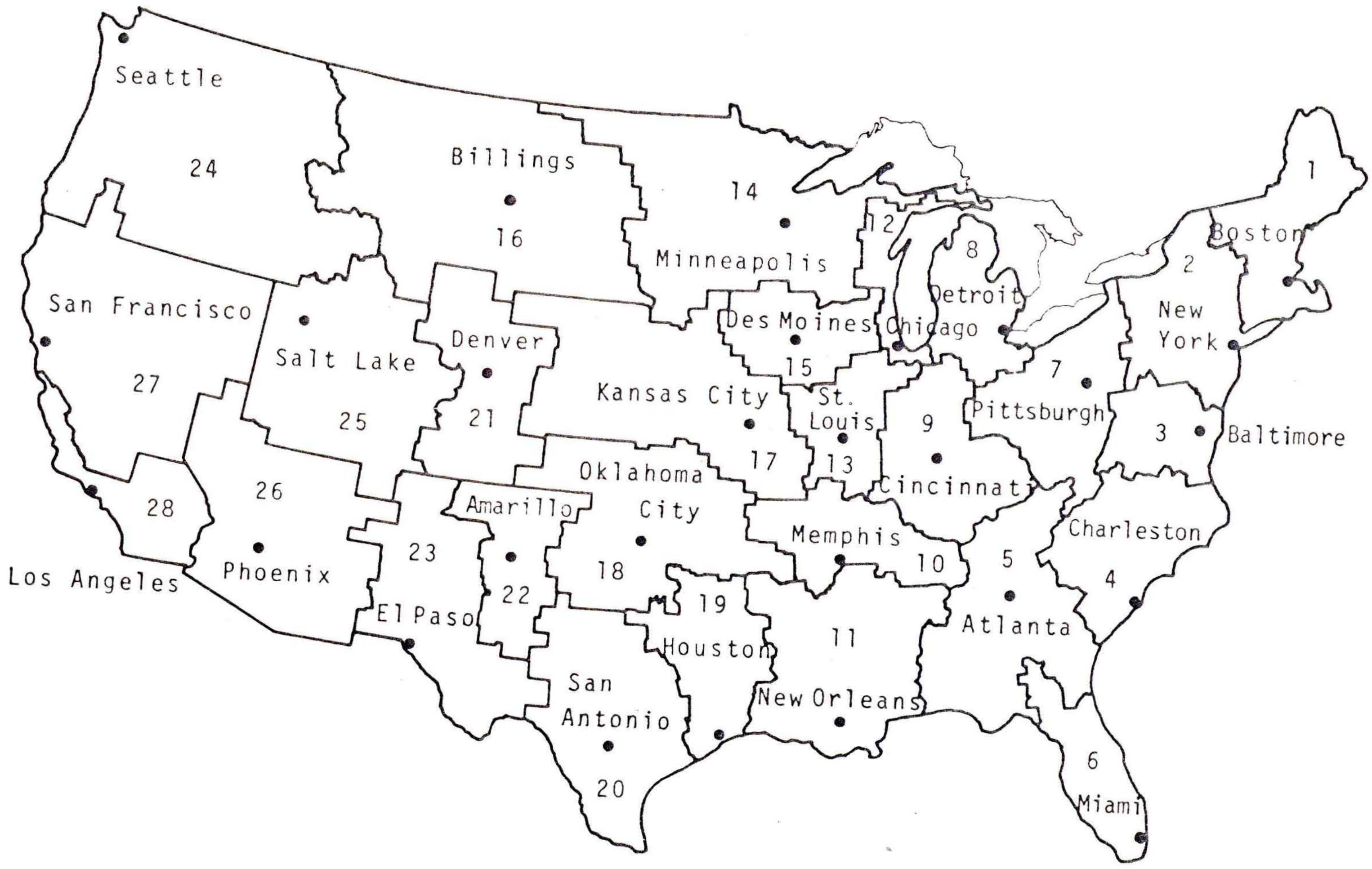

Figure 5. The 28 market regions

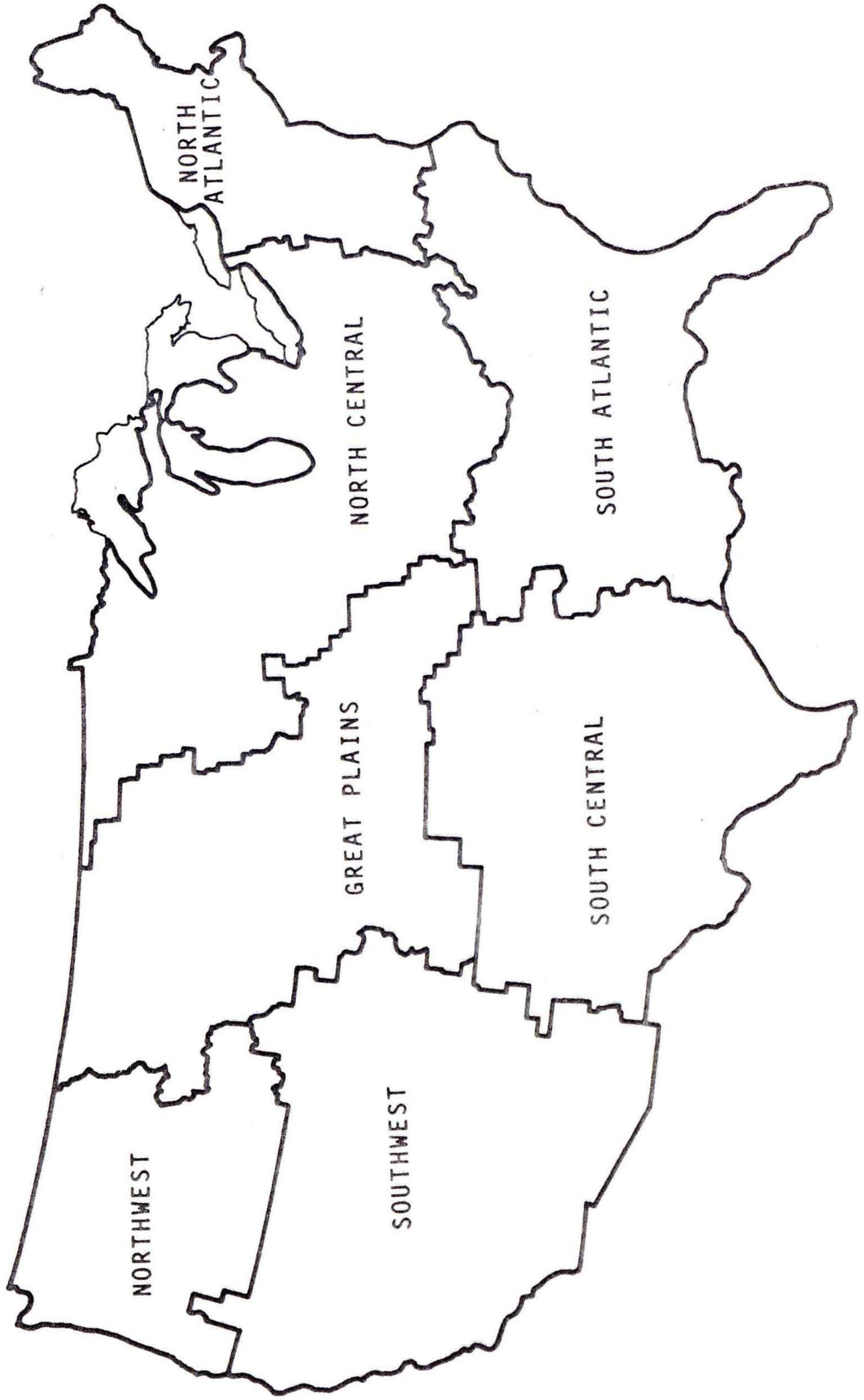

Figure 6. The 7 reporting regions.

agricultural capability class. There are eight major capability classes in the CNI. Classes II through VIII are further subdivided to reflect the most severe hazard which prevents the land from being available for unrestricted use. The subclasses reflect susceptibility to erosion (e), subsoil exposure (s), drainage problems (w), and climatic conditions preventing normal crop production (c).

The land defined in 29 capability class-subclasses in the CNI is aggregated from the county level to the 105 producing areas for each of the dryland and irrigated uses. These 29 class-subclasses are then aggregated to give the five land quality classes of the land base in this model (Table 2).

Table 2. Five land quality classes aggregated from the Conservation Needs Inventory

Land Class	Inventory Class-Subclasses
1	I, IIwa, IIIwa
2	rest of II, III, IV, all of V
3	IIIe
4	IVe
5	VI, VII, VIII

The crop production sector

The endogenous crop production sector includes alternative production activities for barley, corn, corn silage, cotton, legume and nonlegume hays, grain sorghum, sorghum silage, soybeans, sugar beets, oats, and wheat in rotational combinations. These production activities specify different crop sequences and tillage and conservation practices for irrigated and dryland cropping methods on each land class in producing areas.

These crop activities produce the commodities needed to meet livestock and consumer demands when the nitrogen, land, and water resources defined in the model are used.

The crop sequences used in the model are taken from the rotations indicated in the Soil Conservation Service Questionnaire [20] for the Land Resource Areas. Each rotation is then combined with one of four conservation practices: straight row cropping, contouring, strip cropping, or terracing. Each crop management system is completed by adding one of three tillage practices: conventional tillage with residue removed, conventional tillage with residue left, or reduced tillage.

Because of space limitations the large data sets representing crop yields and costs on each land class for each crop and cultural practice are not listed here. Their basis is explained elsewhere [20] and the tapes containing them are available at the Center for Agricultural and Rural Development, Iowa State University.

The soil loss sector

Gross soil loss represents the average number of tons of soil leaving the field per year. The soil loss calculation for each crop production activity is made through the use of the Universal Soil Loss Equation [34]. This equation provides a procedure for computing the expected average annual soil loss from alternative land practices on a particular acre of land:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

where A is the predicted soil loss in tons per acre per year,

R is the average rainfall erosion index per year,

K is the soil erodibility factor,

L is the slope length factor in feet,

S is the slope gradient factor,

C is the cropping management factor which relates to a particular crop rotation and tillage practice, and

P is the erosion control practice factor which relates to the conservation practice.

This soil loss equation can be used to predict soil losses under alternative production techniques on various types of soils. For further detail, see Wischmeier and Smith [34] and the Soil Conservation Service (SCS) sources [21]. For the agricultural land in the West, a soil loss equation has not been developed. An alternative procedure is developed for the estimation of soil loss in this region [23]. The conservation practices which can be used for each land class in each region have been defined by the Soil Conservation Service [20, 23]. These practices are defined only for soils which will support them.

The livestock sector

Dairy, hogs, beef cows, and beef feeding activities are defined at the market regional level. These activities simulate production possibilities in each market region and create an intermediate demand for the feed commodities. Livestock rations are formulated to permit endogenous substitutions between roughages, grains, and roughages and grains. Hence, the model endogenously selects a least-cost ration for livestock in each consuming region. The nitrogen in the manure produced by this sector can be utilized as a fertilizer by the crop production activities. For detailed information about the livestock sector, see [20].

Water sector

The water sector defines water availability in the Western United States in producing regions 48 to 105. This sector also included activities for the transfer of water between producing regions. Further information about this sector can be obtained elsewhere [10].

The demand sector

The demand sector requires the production of the endogenous commodities to be consistent with projected levels of demand for food and fiber, net exports, exogenous livestock food requirements, and industrial and nonfood uses [20]. Domestic demands are based on the OBERS 1985 projections [32, 33].

Export demands are based on the OBERS E' (high) Export Levels which reflect substantial changes in international trade conditions during 1971-74 [33].[1] However, corn, soybeans, and wheat exports are increased by 7, 48, and 3 percent, respectively, over the OBERS E' (high) projections, reflecting experience of the last few years. Additional details about the demand sector can be found elsewhere [33].

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[1] The OBERS E' (high) Export levels were a set of projections completed for the National Water Assessment study conducted by the Center for Agricultural and Rural Development for the Water Resources Council. They were low relative to export levels which have been experienced in recent years.

The transportation sector

The transportation routes are defined between each pair of contiguous regions. These routes are measured by the distance between the metropolitan centers in each market region. Over each route, two activities are defined for each commodity, one for shipment in each direction [20].

Time horizon and uncertainty

Evaluation of policy impact alternatives within the limitations of the model requires that a sufficient time horizon be specified to allow for the implied adjustments to materialize. For this reason, the analysis uses 1985 as the year of projection.

The study assumes "normal weather" for 1985. Demand conditions used have already been explained. The supply and demand conditions are projected in a deterministic manner. The weather (and hence, total supplies) and exports (and hence, total demands) have stochastic characteristics related to climatic variables in both the United States and the world. Hence, the outcome in 1985 may not be the same as the "average conditions" assumed for the study. The degree of uncertainty surrounding prices and yields may prevent farmers in adjusting to the extent that the following normative analysis supposes. The analysis is normative in the sense that it does not predict what farmers will do; instead, it determines what production and resource use patterns if the conditions assumed prevail and if the objective function is optimized relative to the restraints of the model.

III. ANALYSIS OF RESULTS

Six linear programming solutions, each based on a different level of cost attached to a soil loss goal, were completed for this analysis.[1] The number of solutions is minimal for an analysis of this type but is believed to be adequate to give important insight into the impact and trade-offs between the conflicting goals.

The programming solutions generate quantitative trade-off information between cost efficiency in producing food and soil loss control. Policy-makers can determine a point along the curve which corresponds to society's preference information. Also, to accomplish the decline in gross soil loss specified by each "pair" on the curve, each solution reflects changes in land use patterns, resource use levels, farming and conservation practices, agricultural income, and food prices at the farm level. The data are presented at national and regional levels. Initially, comparison is made of alternative "pairs" on the trade-off curve and the impacts of weights (values) for soil erosion goal on cost of production in U.S. agriculture and on per acre soil loss from cropland. Then, in following sections, comparisons are made of the production pattern, resource use, and farm income under the alternative solutions.

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[1] Solution 6 (minimum soil loss solution) provides the end point of the trade-off function in Figure 2. However, its results are not applicable to the real world because production costs do not enter into the optimization. For this reason the results of Solution 6 are not presented.

The Trade-off Curve

The trade-off function between (a) the cost of production and transportation and (b) soil erosion from cropland in Figure 7 is obtained by solving the model using a series of a priori weights for the soil loss goal in the model. The numbered points correspond to the six solutions.

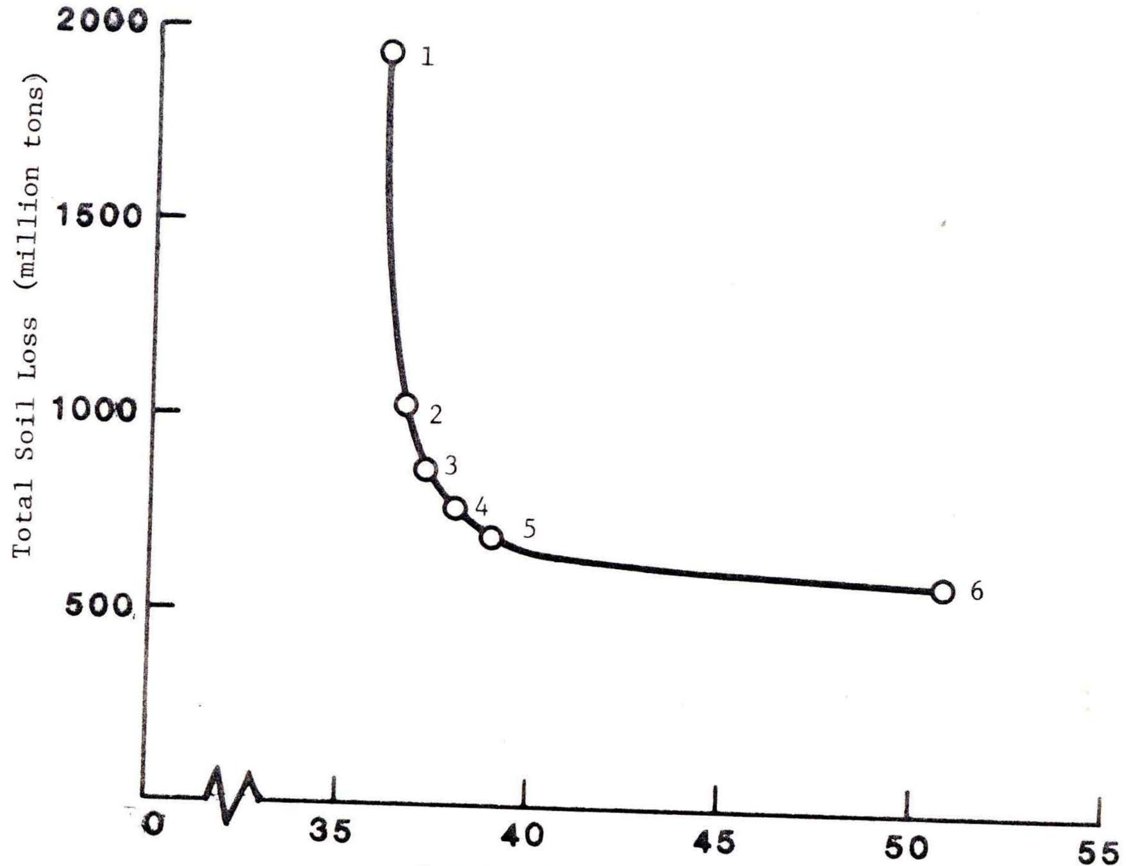

Figure 7. Trade-off frontier between goals for cost of production and soil conservation in an efficient agriculture for the United States

Points on the trade-off curve in Figure 7 represent efficient points between the two goals, i.e., minimum levels of soil erosion and cost of production and transportation, given the resources, the technology, and the demands for agricultural products specified in the model.

Solution 1, (upper point in Figure 7) is derived under the assumption of a zero weight for the soil erosion goal, i.e., only the cost of production and transportation goal is minimized. Solutions 2, 3, 4 and 5 (points in Figure 7) are derived by assigning the following respective weights to the soil erosion goal: $2.50, $5.00, $10,00, and $20.00. The unit of activity for the soil erosion goal is one ton so the assignment of these weights or values is equivalent to assigning a cost per ton of soil eroded. To obtain Solution 6 in Figure 7, the soil erosion goal is minimized, i.e., the cost of production goal is given zero weight in the solution.

As indicated by the shape of the trade-off curve, starting from point 1, substantial improvements can be made in the conservation or environmental goal without great sacrifice in production costs for U.S. agriculture. The curve then "bends sharply" between points 2 and 5, indicating that beyond point 5 large sacrifices are made in the cost of production for small improvement in the conservational goal.

The situation portrayed in Solution 1 is one where farmers would adopt the most profitable cropping plans based on continuous row cropping and commercial fertilizer as a cheaper source of nitrogen than legumes. When continuous row cropping is used with straight-row farming, protection against erosion on sloping fields is minimal. Interregionally, production patterns develop according to regional comparative advantage regardless of soil erosion hazard. For example, cotton and soybeans are produced in

the South Atlantic region even though the land is highly susceptible to erosion. When society attaches a value to soil eroded from the fields (even a relative small amount as in Solution 2), it is not profitable to continue to use erosive farming practices on sloping land because net returns decline; the eroding soil has a cost attached to it. Some of the most erosive land is taken out of row crop production in regions where problems are severe. Erosion hazards in some regions are overcome by proper tillage practices and rotations including hay crops or, in highly erosive cases, by terracing. Even though it is more costly, terracing becomes profitable because it permits row cropping while arresting erosion. Conservation depends to a lesser degree on a large acreage of relatively less profitable forage crops.

However, beyond point 5, small reductions in total U.S. soil loss entail large increases in production costs as it becomes costly to implement terracing and other conservation practices on the extremely marginal lands which were not cropped in previous solutions. Additionally, production costs increase rapidly because of interregional adjustments in crop production patterns. For example, cotton and soybean production shifts away from the South Atlantic region to regions in the West having higher production costs. Thus, the shape of the trade-off curve in Figure 7 beyond Solution 5 implies that society would have to make a sizable sacrifice in one goal in order to minimize the other goal.

If a high level of environmental quality is preferred, then minimizing only the soil loss goal greatly increases costs of production. Conversely, if society is only interested in economic efficiency in U.S.

agriculture, then minimizing only cost of production results in high rates of soil erosion from U.S. cropland. The intermediate solutions indicate a "corner" on the trade-off curve between the goals. Although information on the preference function is not available to reach the optimal solution, the decision maker could notice quite easily, for example, that without other data it might be more sensible to choose Solutions 2 or 3 over other solutions in which there are large decreases in the amount of soil eroded in return for some small increases in cost of production.

As Meisel [19] has pointed out, with the information provided on the trade-off curve, the decision maker need not justify his choice in terms of a relative weighting of the two goals but only in terms of localized trade-off between alternative solutions.

Alternative solutions on the efficiency frontier provide an optimal land use pattern for U.S. agriculture for each of the 105 producing regions. The solutions also provide information on optimal resource use, expenditures for inputs, cropland utilization, crop and livestock production, total soil loss, farming practices and conservation measures to achieve the soil erosion goal. Finally, each solution provides information concerning the cost of achieving this optimal organization of U.S. agriculture in terms of food prices at the farm level.

National Changes in Production Pattern, Resource Use, and Income

This study of the valuation of soil eroded from agriculture implies many changes for agriculture and for the nation. These implications are derived from the changes in land and resource use and costs of production

needed to reduce soil losses and still meet the same demands for agricultural products.

Soil loss

When the soil loss goal has zero value (Solution 1), about 2 billion tons or 5.56 tons per acre of soil are eroded from U.S. cropland (Table 3). The annual average rate of soil erosion declines from 5.56 tons per acre to 1.67 tons per acre as the weight for the soil loss goal is increased from zero to $20.00 per ton. This decline in erosion is achieved partly by changing farming practices and partly by interregional adjustments in crop production patterns. The largest reductions in soil erosion occur in the South Atlantic, Great Plains, and South Central Regions. In these three regions total soil erosion declines 74, 72, and 68 percent, respectively, in Solution 5 compared to Solution 1. Total soil erosion for U.S. agriculture is reduced 64 percent in Solution 5 as compared to Solution 1.

Table 3. Per acre soil erosion on cultivated lands in major regions under alternative solutions in 1985

Regions	Solutions 1	2	3	4	5
	(tons per acre)				
United States	5.56	3.05	2.50	2.20	1.98
North Atlantic	5.65	2.76	2.65	2.32	1.91
South Atlantic	12.58	6.61	5.62	4.05	3.31
North Central	4.80	3.07	2.79	2.67	2.39
South Central	4.77	2.76	1.64	1.59	1.51
Great Plains	4.68	1.76	1.29	1.27	1.29
North West	3.56	1.79	1.53	1.04	.99
South West	1.29	.96	.85	.81	.74

Imposing the relatively small cost per ton of soil eroded in Solution 2 greatly reduced erosion in most regions as cropping practices change and marginal land highly susceptible to erosion is taken out of production. Compared to Solution 1, the reductions in average annual soil loss per acre in Solution 2 range from 42 percent in the South Central region to 63 percent in the Great Plains.

Conservation and tillage practices

Annual soil losses decline steadily as higher costs are assigned to the soil erosion goal (Solutions 3, 4, and 5). On the cropland least susceptible to soil erosion, terracing substitutes for strip cropping (Figure 8 and Table 4). Along with shifts in conservation practices there is a significant shift in tillage practices as conventional tillage methods are replaced by reduced tillage methods (Figure 9 and Table 6). As shown in Figures 8 and 9, substantial changes in farming practices occur between Solutions 1 and 2. However, the changes are not as striking from Solution 3 through Solution 5 because most of the adjustments that are practical for agriculture have already occurred between Solutions 1 and 2. This declining rate of change in farming practices explains, in part, the corner curve in Figure 7.

Changes in cropland utilization and production patterns

Soil erosion can be reduced by using appropriate combinations of crop rotations and conservation practices consistent with the cost assigned to the soil erosion goal. As the value assigned to a ton of

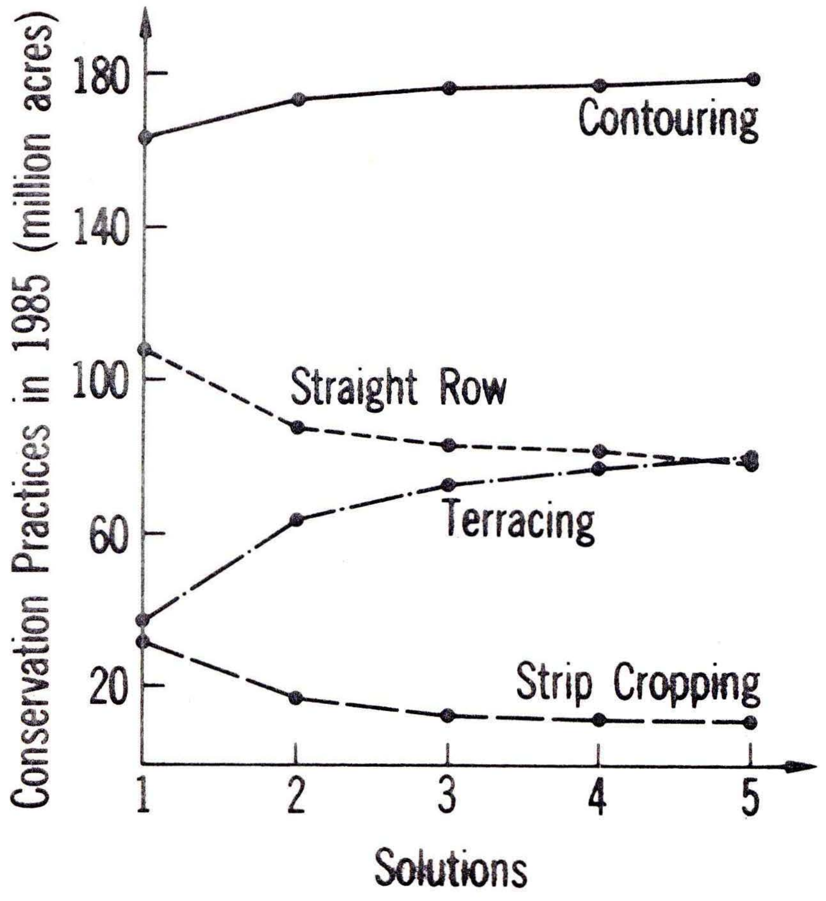

Figure 8. Changes in acres of conservation practices under alternative solutions in the United States

Table 4. Percentage changes of acres by conservation practices under alternative solutions in 1985 in the United States

Conservation practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Straight Row	33	25	23	24	23
Contour Farming	47	51	52	51	51
Strip Cropping	9	5	4	3	3
Terracing	11	19	21	22	23

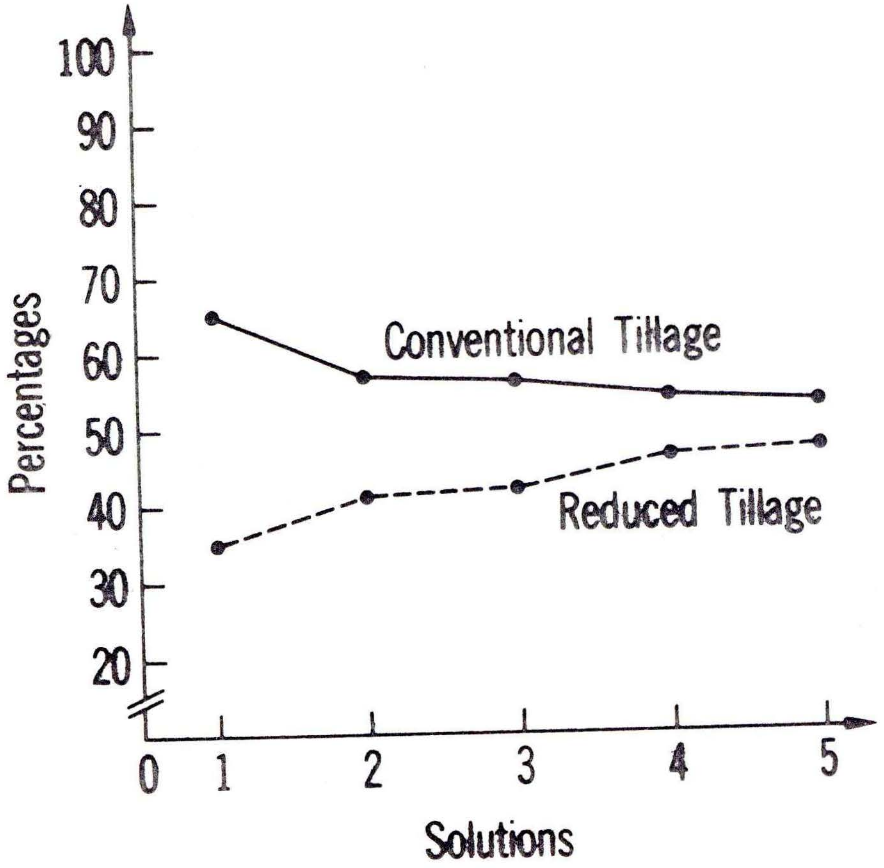

Figure 9. Changes in proportions of two tillage practices under alternative solutions in 1985 in the United States

eroded soil increases, cropland utilization and cropping patterns change. The highly erosive croplands are either terraced or idled if their productivity is too low to cover the cost of terracing. Cropping sequences change from continuous row cropping to rotations including sod and small grain crops as the cost assigned to the soil loss goal increases.

Table 5 displays total U.S. acres for the major commodity groups in the model. The total acreage of row crops steadily declines from Solution 1 to 4, then increases slightly in the last solution. The total acres of corn grain first declines (Solution 2) and then increases. The decrease

Table 5. National acreage of different crops under alternative solutions in 1985 in the United States

Commodities	Solutions 1	2	3	4	5
			(000 acres)		
Row Crops (total)	219,749	205,657	201,685	199,823	202,311
Corn Grain	59,057	58,099	59,423	63,305	65,859
Sorghum Grain	16,416	16,881	16,271	12,297	12,846
Sorghum and Corn Silage	32,200	22,922	19,859	17,617	16,587
Soybean	104,881	101,002	100,351	99,981	100,147
Cotton	7,195	6,753	6,481	6,701	6,872
Small Grains (total)	72,675	73,530	75,140	75,944	75,333
Barley	8,624	9,162	10,303	11,380	12,524
Oats	4,238	4,702	5,426	5,951	6,966
Wheat	59,813	59,666	59,411	58,613	55,843
All Hay	38,098	50,679	58,359	61,934	65,070

in corn acres is due to the elimination of the highly erosive lands from the cropland base reflecting the national trend in utilization of cropland (Table 14). But, as the cost per ton of soil eroded increases above $2.50, it becomes profitable to terrace this erosive land and intensively row crop it. Terraces are effective because they reduce the slope length, thus allowing more intensive row cropping on sloping fields. In the study, terracing is allowed only on soils which are deep enough to allow it. The amount of land put under terracing is small after Solution 3 and not extremely large after Solution 2.

The decline in erosion rates occurs as small grains and especially hay crops are substituted for sorghum grain, silage, soybean, and cotton crops. In particular, the raising of corn and sorghum silage for livestock consumption is greatly reduced because of the inadequate protection afforded the soil surface by such crops. Soybeans and cotton, along with the silage crops, are the most erosive crops. Hence, when it is profitable the model substitutes alternative crops. Silage production is greatly reduced and is offset by an increase in hay acreage to insure adequate feed supplies for livestock. The result of this substitution is reduced erosion.

Changes in tillage practices accompanying the shifts in land use patterns are shown in Table 6. The proportion of acres under conventional tillage decreases while the proportion under reduced tillage substantially increases.

Changes in yields of the crops result in changes in acres grown to meet the fixed demands for agricultural products specified in the model

(Table 7). For example, as the concentration of corn production on the most productive lands declines, average yields fall. Hence, more acres are needed to meet a given demand. Alternatively, cotton yields rise following interregional shifts in production, so fewer acres are needed. Increasing wheat yields is the result of growing this crop in rotation with row crops on some of the more productive land as a soil conservation measure.

Table 6 . Percentage of acres by tillage practices under alternative solutions in 1985 in the United States

Tillage practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Conventional Residue Removed	18	14	13	14	14
Conventional Residue Left	47	44	43	40	39
Reduced Tillage	35	42	44	46	47

Table 7. Average crop yields under alternative solutions in 1985 in the United States

Crops	Unit	Solutions 1	2	3	4	5
Corn grain	Bu.	109.13	110.04	106.47	104.15	99.33
Sorghum grain	Bu.	51.22	54.39	53.80	57.13	55.27
Barley	Bu.	55.80	56.66	54.69	54.04	47.14
Oats	Bu.	64.94	63.22	56.46	58.08	63.25
Wheat	Bu.	33.12	33.51	33.93	34.31	35.90
Corn silage	Tons	14.80	16.37	14.93	15.02	15.37
Sorghum silage	Tons	13.91	14.44	15.75	12.32	10.86
Legume hay	Tons	4.08	4.04	3.96	4.03	4.01
Nonlegume hay	Tons	1.86	2.03	2.08	2.11	2.22
Soybean	Bu.	33.31	33.87	33.73	33.43	33.20
Cotton	Bales	1.53	1.63	1.69	1.64	1.60

Changes in feed consumption pattern

Table 8 shows the changes in feed consumption patterns under alternative solutions. These changes are the result of the shifting production patterns described previously. There is a substantial substitution of hay and small grains for silage in the livestock rations.

Table 8. Feed consumed by all classes of livestock under alternative solutions in 1985 in the United States

Commodity groups	Solutions 1	2	3	4	5
			(000 tons)		
Corn and Sorghum grain	88,832	89,553	86,499	89,102	87,873
Barley, Oats and Wheat	7,935	9,747	11,461	13,181	13,921
Corn and Sorghum Silage	457,047	345,089	295,205	239,215	218,679
All Hays	277,646	315,507	337,073	350,447	358,410
Oilmeals	21,475	19,766	18,923	17,956	17,531

Changes in resource use

Resource use and production costs in agriculture are altered as the higher costs are assigned to the soil erosion goal, causing changes in cropping practices and regional production patterns. The data in Tables 9 and 10 show the use of fertilizer and pesticides by commodity groups in each solution. The use of fertilizer increases for every commodity group except corn and sorghum silage, which is consistent with their declining acreages. In general, the increase in fertilizer use exceeds the increases in acreages of commodity groups. For example, acreage increases for corn and sorghum grains, small grains, and hays are 4, 3, and 70 percent, respectively, in Solution 5 compared to Solution 1. However, the rates of increases in nitrogen use for the same commodity group are 11, 15, and 122, respectively.

Table 9. Nitrogen use in crop production under alternative solutions in 1985

Commodity groups	Solutions 1	2	3	4	5
			(000 tons)		
Corn and Sorghum Grain	4,154.4	4,084.8	4,290.1	4,437.4	4,613.3
Corn and Sorghum Silage	1,233.6	917.2	793.3	711.8	698.1
Soybeans	314.5	317.1	320.6	428.4	430.0
Cotton	305.9	321.9	364.7	325.2	347.0
Barley, Oats and Wheat	1,940.1	2,052.0	2,155.1	2,234.8	2,240.2
Hays	619.3	880.0	1,024.6	1,166.3	1,379.4

Table 10. Changes in pesticide use under alternative solutions in 1985 in the United States

Commodity groups	Solutions 1	2	3	4	5
			(000 dollars)[a]		
Corn and Sorghum Grains	645.681	647,323	650,964	715,089	767,822
Corn and Sorghum Silage	31,332	24,138	26,490	27,398	26,043
Soybeans	558,648	839,465	895,339	996,209	1,063,017
Cotton	131,968	163,470	210,284	244,339	251,371
Barley, Oats and Wheat	107,615	131,456	172,016	172,343	150,842
Hays	33,134	84,630	82,949	99,660	126,343

[a] Expenditures are in terms of 1972 dollars.

For U.S. agriculture as a whole, the use of nitrogen increases steadily as agriculture provides increasing protection for land and water resources. The largest portion of the increase in nitrogen occurs because of lower corn yields caused by acreage shifts to less productive regions. To compensate for these reduced yields, more nitrogen fertilizer is needed.

Total and per acre expenditures on pesticides increase as agriculture adjusts its practices to provide more protection for the soil. Pesticide application rates almost double when Solution 5 is compared to Solution 1. Part of the reason for the increase is the shift from conventional to reduced tillage methods. Pesticide application increases because reduced tillage does not control insect and weed problems as well as conventional tillage.

The increasing use of pesticides and ferilizer represents another trade-off with the goal of reducing soil erosion. U.S. agriculture is already dependent on high-priced energy for food production and the results of this study imply that the conservation of agricultural land could increase that dependency. Also, the environmental impact of the increased usage of pesticides, particularly insecticides, must be considered.

Changes in return to land

Table 11 shows the percentage change in the return to land under alternative solutions. The return to a particular acre of land is found by subtracting variable production costs from the total value of the crop raised on that acre. The return to land for the United States decreases in Solution 2 and then increases sharply as succeeding solutions are compared to Solution 1 (Table 11). The decrease in net returns to land in Solution 2 compared to Solution 1 can be attributed to sharply increasing variable production costs following the large adjustments in cropping practices shown in Figures 4 and 5. Increasing net returns to land for Solutions 3 through 5 are due to commodity supply prices rising faster than variable production costs.

Table 11. Percentage change in land shadow prices under alternative solutions in 1985

	Solutions				
Regions	1	2	3	4	5
United States	100	96	109	162	268
North Atlantic	100	97	104	148	240
South Atlantic	100	75	79	114	188
North Central	100	103	122	184	301
South Central	100	85	91	121	199
Great Plains	100	98	112	177	307
North West	100	107	114	182	297
South West	100	103	118	176	311

Changes in supply prices of the agricultural commodities

Assigning a pollution cost to soil erosion implies a major impact on commodity prices for the consumer. Changes in conservation and tillage practices to control soil erosion from cropland raises the cost of producing crops (Table 12). The results of the study indicate that the supply prices increase as the desired level of environmental quality rises. Crops such as soybeans have the largest supply price increase because of their highly erosive nature. When Solution 5 is compared to Solution 1, soybean prices increase 180 percent.

Table 12. Indication of relative farm level supply prices (shadow prices) for some agricultural commodities under alternative solutions in 1985 in the United States

Commodities	Solutions 1	2	3	4	5
Corn	100	104	115	144	198
Wheat	100	106	114	145	205
Soybean	100	113	134	184	280
Hay	100	102	107	129	172
Cotton	100	92	104	115	136
Silage	100	102	109	132	185
Pork	100	105	113	133	174
Beef	100	101	107	123	155
Milk	100	102	106	116	137

Higher livestock values reflect the higher production costs for the crops. Swine prices increase more than the other livestock classes because of their high consumption of corn grain. With the ruminants, more substitution among feed inputs occurs, thus limiting increases in the expense of feeding them.

Changes in gross farm income

Assigning a cost to soil erosion affects national gross farm income[1] in various degrees under alternative solutions (Table 13). The changes in gross farm income also show cost to society in each solution for the conservation policy. As evidenced in Table 13, compared to Solution 1, total costs to consumers for this policy increases moderately in Solutions 2 and 3 and substantially in Solutions 4 and 5 reflecting the ongoing trend in shadow prices under alternative solutions. The

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[1] Gross farm income is the value of all endogenous commodities produced in the model. The shadow prices determine the value of each crop.

4 percent increase in gross farm income between Solutions 1 and 2 results in a per acre soil loss reduction of 46 percent. The gross farm income increases 12 percent between Solutions 1 and 3 and the reduction in per acre soil loss is about 55 percent in Solution 3 compared to Solution 1. However, in Solutions 4 and 5 the income effect of a conservation policy is much larger compared to Solution 1. The cost to society increases by about 36 and 81 percent in Solutions 4 and 5 while per acre soil loss decreases by 60 and 64 percent, respectively compared to Solution 1. The results indicate that the cost to the consumer increases substantially in Solutions 4 and 5 for marginal improvements in the conservation goal.

Table 13. Percentage changes in the national and regional value of agricultural production under alternative solutions in 1985

Regions	Solutions 1	2	3	4	5
United States	100	104	112	136	181
North Atlantic	100	98	103	126	171
South Atlantic	100	112	117	140	176
North Central	100	105	116	150	207
South Central	100	104	105	122	162
Great Plains	100	100	116	132	170
North West	100	103	111	143	193
South West	100	102	110	134	175

Regionally, the increases in the value of production in the North Central region, especially in Solutions 4 and 5, are significant. This gain in income is due to the increases in production of soybeans and small grains and the expansion of hog and cattle production in the last two solutions.

Regional Changes in Production Pattern, Resource Use and Income

Assigning a non-zero value to the soil loss goal in the model establishes an efficient regional land use pattern that minimizes national soil losses at minimum cost to farmers and to society. As can be seen from Table 14, regions with fewer erosion problems gain a comparative advantage relative to those regions having severe erosion problems.

Table 14. Percentage of cropland utilized by regions under alternative solutions in 1985

Regions	Solutions 1	2	3	4	5
			(percentage)		
United States	94	93	94	94	95
North Atlantic	98	94	93	95	95
South Atlantic	96	94	94	89	89
North Central	96	96	97	97	98
South Central	95	95	92	93	94
Great Plains	90	88	93	93	94
North West	91	86	86	87	96
South West	92	87	88	95	96

The cropping of available land is reduced in the South Atlantic region as the cost assigned to the soil loss goal increases under alternative solutions. The Great Plains and North Central regions, however, gain a comparative advantage as the assigned cost rises.

The cropping of available farmland in the United States declines in Solution 2 compared to Solution 1, then rises in Solutions 3, 4, and 5 (Table 14). In Solution 2, the assigned cost of $2.50 per ton of soil eroded from the field makes it profitable for U.S. agriculture to greatly increase the use of reduced tillage and terracing relative to Solution 1 (Figures 8 and 9). Average crop yields increase because the greater use of these management practices more than offsets any crop yield declines caused by regional shifts of production to areas of lesser productivity (these shifts will be described in the following sections). After Solution 2, however, the interregional adjustments outweigh any gains resulting from improved management practices, and average yields decline. This interaction between management practices and interregional adjustments is the explanation for the varying rates of cropland use in the United States (Table 14).

The North Central Region

Soil erosion in the North Central Region declines about 50 percent while the use of available cropland increases by about 2 percent when Solution 5 is compared to Solution 1 (Tables 3 and 14). The reduced soil erosion is the result of changing cropping patterns and more terracing.

Conservation and tillage practices

As shown in Tables 15 and 16, conservation and tillage practices change under alternative solutions. Straight-row cropping declines even though it is the least-cost method of cropping because the practice offers little protection against erosion when used on sloping fields. To protect the soil as the assigned cost to soil erosion rises, the model requires a substantial shift to terracing on those lands especially subject to erosion (land classes III and IV). Strip cropping decreases as the cost rises because it becomes profitable to use terracing to provide more protection for the topsoil.

Table 15. Percentage of acres by conservation practices under alternative solutions in 1985, the North Central region

Conservation practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Straight Row	25	22	21	21	21
Contour Farming	62	62	62	62	62
Strip Cropping	11	6	5	4	2
Terracing	2	10	12	13	15

Table 16. Percentage of acres by tillage practices under alternative solutions in 1985, the North Central region.

Tillage practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Conventional Residue Removed	4	2	2	2	--
Conventional Residue Left	23	23	23	23	24
Reduced Tillage	73	75	75	75	76

Changes in production patterns

Soil erosion declines in the North Central region as the increasing cost of eroded soil favors the use of land management practices that control soil erosion. Small grain and hay crops partly substitute for the row crops (Table 17). The acres of corn and sorghum grain and silage decline as the acres of hay, oats, and barley increase when higher values are assigned to the soil loss goal. This substitution of crops in the North Central region occurs because the small grain and hay crops are grown as a soil conservation measure in rotation with the row crops, corn, and soybeans.

Table 17. North Central acreage of different crops under alternative solutions in 1985, the North Central region

Commodities	Solutions 1	2	3	4	5
	(000 acres)				
Row Crops	107,980	104,980	104,852	102,967	101,783
Corn Grain	47,117	44,412	41,969	40,217	41,017
Sorghum Grain	414	394	309	169	92
Sorghum and Corn Silage	2,176	1,661	1,667	1,669	194
Soybeans	58,273	59,463	60,815	60,917	60,480
Small Grains	22,861	25,392	27,215	29,489	9,278
Barley	2,374	2,548	3,235	4,788	9,278
Oats	751	922	1,212	1,533	3,135
Wheat	19,736	21,921	22,768	23,168	16,214
Hays	3,953	4,848	4,650	5,247	7,470

Changes in livestock production and feed consumption patterns

The combinations of a rising output of small grains and hay and the declining production of corn and sorghum grain silage requires a two-fold adjustment within the livestock sector in the North Central region. As shown in Table 18, compared to Solution 1, the beef cattle industry expands, dairying is stable, and hog production varies up and down as interregional adjustments in crop production patterns occur in the North Central region. The increased availability of hay and grass favors the expansion of stock cow herds thus indirectly stimulating the beef feeding industry of this region as local feeder calves increase. Despite the

Table 18. Livestock numbers under alternative solutions in 1985, the North Central region

Livestock	Solutions 1	2	3	4	5
			(000 head		
Beef Cows	4,264	4,488	4,363	4,438	5,482
Beef Feeding	2,973	2,970	2,904	3,311	3,175
Dairy	3,161	3,161	3,161	3,161	3,161
Hogs	89,285	82,479	81,686	95,700	96,948

decrease in corn production, the North Central region retains its comparative advantage in livestock, particularly in hog production.

Besides allowing interregional adjustments in livestock production, the model provides for substitution among feedstuffs for the livestock raised in each region. Small grains and hay are substituted for corn and sorghum silage in the livestock ration when the cost assigned to the soil loss goal increases (Table 19). Total consumption of corn and sorghum grain is stable even though total output of these crops declines in the region. The implication of these results is that the livestock industry of the North Central region is not disadvantaged as protection of the topsoil increases. As costs are assigned to soil loss, the production of crops such as corn for export declines because it is cheaper to raise the crop elsewhere (in this case the Great Plains).

Changes in resource use

Assigning a cost to the soil loss goal alters resource use in crop production in the North Central region (Table 20). Despite the increase of acres cropped, the use of both nitrogen and pesticides declines. Fertilizer usage decreases because small grain and hay replace corn and sorghum production. Because small grains and hay use less fertilizer (and in the case of legume hay, produce nitrogen), nitrogen use declines. Pesticides expenditure declines for the same reason.[1]

Table 19. Feed consumed by all classes of livestock under alternative solutions in 1985, the North Central region

Commodity groups	Solutions 1	2	3	4	5
			(000 tons)		
Corn and Sorghum grains	51,366	50,396	47,263	53,209	51,414
Barley, Oats and Wheat	--	220	1,577	2,909	7,106
Corn and Sorghum Silage	23,658	9,897	17,236	14,988	2,650
Hays	35,620	38,953	37,712	39,509	47,702
Oilmeals	7,987	7,318	7,281	8,106	7,786

Table 20. Resource use in crop production under alternative solutions in 1985, the North Central region

Solutions	Land used (000 acres)	Nitrogen used (000 tons)	Pesticide exp. (000 dollars)[a]
1	142,144	3,561	966,183
2	142,394	3,236	964,575
3	143,810	3,166	960,865
4	144,393	3,155	957,459
5	144,570	3,242	951,866

[a] Expenditures are in terms of 1972 dollars

The Great Plains Region

Total soil erosion in the Great Plains region declines as the cost assigned to the soil erosion goal rises, even though more acres of

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[1] Small grains and nonlegume hay use more potassium and phosphorous than the crops they replace. However, these elements are not inventoried since they have a smaller environmental impact than nitrogen.

cropland are tilled (Tables 3 and 14). The quantity of soil eroded from these additional acres is more than offset by a declining average rate of soil erosion for the Great Plains region. Reductions in soil erosion rates are substantial, particularly in the Eastern areas of the region where the proportions of row crops are high. Soil erosion rates decline as the rising cost per ton of eroded soil favors those conservation and tillage practices.

Conservation and tillage practices

Substantial increases in the use of terracing and reduced tillage farming protects the soil from erosion (Tables 21 and 22). The use of terracing is concentrated in the intensive row cropping areas in the Eastern portion of the Great Plains where soil erosion is a problem. Protecting the topsoil is a smaller problem in the rest of the Great Plains because of lower rainfall and less intensive row cropping.

Table 21. Percentage of acres by conservation practices under alternative solutions in 1985, the Great Plains region

Conservation practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Straight Row	21	13	13	13	13
Contour Farming	46	48	45	45	44
Strip Cropping	13	6	4	5	5
Terracing	20	33	37	37	38

Table 22. Percentage of acres by tillage practices under alternative solutions in 1985, the Great Plains region

Tillage practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Conventional Residue Removed	21	8	9	9	8
Conventional Residue Left	67	60	60	60	57
Reduced Tillage	12	32	31	31	35

Changes in production patterns

As the cost assigned to the soil erosion goal rises, U.S. agricultural production is reorganized. Utilization of available cropland in the Great Plains region increases 4 percent when Solution 5 is compared to Solution 1 (Table 23). A smaller erosion hazard favors shifting of corn and soybean production from the North Central and South Atlantic regions to the Great Plains, thus increasing the total number of acres of row crops in this region. Substituting hay for silage in feeding livestock and a declining beef cattle industry in the Great Plains results in a substantial decline in silage production and an increase in the production of hay (Table 23). Both changes provide more protection for the topsoil as soil erosion is assigned a higher cost.

Greater corn production could occur mainly in those parts of the Great Plains which have sufficient rainfall. Also, part of the corn acreage comes from land previously devoted to grain sorghum and silage and a small amount comes from barley and oats. Wheat acreage is of about the same magnitude in Solution 5 as in Solution 1 in the Great Plains region.

The land shifted to corn would be irrigated or in the eastern part of the region. Some loss of wheat acreage to the South Atlantic region occurs. However, the South Atlantic region would gain wheat acreage more at the expense of the North Central region and only a modest shift would occur in the mix of soft and hard red winter wheat produced. The supply of hard red winter wheat would still be large enough to meet domestic and most export demands for food grians. Some of the soft wheat would go into livestock feed.

Changes in livestock production and feed consumption patterns

The comparative advantage of the Great Plains is altered due to changed crop production patterns over U.S. agriculture. The rising profitability of grass and hay crops in other regions (i.e., the North Central and the South Atlantic regions) as higher costs are assigned per ton of soil eroded, causes the beef cattle industry in the Great Plains to become disadvantaged (Tables 24 and 25).

Table 23. Great Plains acreage of different crops under alternative solutions in 1985, the Great Plains region

Commodities	Solutions 1	2	3	4	5
			(000 acres)		
Row Crops	30,002	32,877	32,093	32,773	36,240
Corn Grain	3,348	5,241	7,987	11,961	12,959
Sorghum Grain	6,986	10,021	6,817	3,869	4,573
Sorghum and Corn Silage	8,521	3,275	3,704	2,891	3,595
Soybeans	11,147	14,340	13,585	14,052	15,113
Small Grains	22,543	18,943	20,306	19,680	21,178
Barley	2,973	3,656	4,010	3,647	1,796
Oats	2.138	2,332	2,259	2,363	1,930
Wheat	17,432	12,955	14,037	13,680	17,452
Hays	9,266	11,909	15,928	16,126	13,980

Table 24. Livestock numbers under alternative solutions in 1985, the Great Plains region

Livestock	Solutions 1	2	3	4	5
			(000 head)		
Beef Cows	14,436	11,856	13,850	13,745	12,940
Beef Feeding	11,088	9,415	10,799	10,389	8,886
Dairy	555	555	555	555	555
Hogs	26,533	33,321	34,133	15,823	14,368

United States swine production shifts back and forth between the North Central and the Great Plains regions under alternative cost levels per ton of soil lost. Assigning a relatively low cost to the soil loss goal increases the comparative advantage of the Great Plains hog industry compared to the North Central region. The higher cost levels assigned in Solutions 4 and 5, however, shift this comparative advantage back to the North Central region.

Table 25. Feed consumed by all classes of livestock under alternative solutions in 1985, the Great Plains region

Commodity group	Solutions 1	2	3	4	5
			(000 tons)		
Corn and Sorghum Grain	11,863	14,966	15,843	10,784	10,906
Barley, Oats and Wheat	6,451	6,457	5,861	5,778	2,062
Corn and Sorghum Silage	137,261	60,680	69,122	48,610	47,878
Hays	57,824	67,141	78,996	80,330	74,155
Oilmeals	3,531	2,958	3,098	1,646	1,554

Changes in resource use

Changing agricultural production practices and patterns in the Great Plains region increases the use of cropland, fertilizer, and pesticides (Table 26). In general, higher weights on the soil loss variable cause increases in the use of cropland, fertilizer, and pesticides (Table 26). More of the available cropland in the Great Plains region is utilized as agriculture adjusts to reduce soil loss. The use of nitrogen fertilizer increases substantially as the acreage of corn increases. Expanded corn production in the Great Plains as the cost assigned to the soil loss goal rises is part of the explanation for the increase in pesticide expenditures in the region. Increasing pesticide expenditures also is partly due to the increased use of reduced tillage in crop production.

Table 26. Resource use in crop production under alternative solutions in 1985, the Great Plains region

Solutions	Land used (000 acres)	Nitrogen used (000 tons)	Pesticide exp. (000 dollars)[a]
1	75,271	1,488	186,963
2	73,868	1,633	50,430
3	77,677	1,910	540,334
4	77,783	2,151	604,661
5	79,165	2,311	747,772

[a] Expenditures are in terms of 1972 dollars

The South Atlantic Region

The South Atlantic region has the highest erosion rate among the reporting regions (Table 3). The soil loss rate is high because of the interaction between high rainfall, sloping fields, erosive cropping practices, and the growing of crops that do not adequately protect the soil.

The average annual soil erosion rate is substantially reduced as costs are assigned to the soil loss goal (Table 3). Agriculture in the South Atlantic region conserves its topsoil by changing cropping practices, reducing the production of highly erosive crops, and taking the land most susceptible to erosion out of production.

Conservation and tillage practices

Changing cropping practices is an important factor reducing soil erosion rates in the South Atlantic region. Increasing the costs assigned to the soil loss goal causes land not too susceptible to soil erosion to shift from straight row farming to contour farming (Table 27). Similarly, land highly susceptible to erosion is terraced whenever the land is productive enough to cover the expense of constructing the terraces. Conventional tillage first declines substantially and then increases again in the last solution (Table 28). The result is partly due to the significant increase in hay production in rotations and the decrease in row crops. The need for reduced tillage is thus lessened in the last solution.

Table 27. Percentage changes of acres by conservation practices under alternative solutions in 1985, the South Atlantic region

Conservation practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Straight Row	42	31	32	34	25
Contour Farming	45	54	53	50	59
Strip Cropping	9	1	1	1	1
Terracing	4	13	14	15	15

Table 28. Percentage changes of acres by tillage practices under alternative solutions in 1985, the South Atlantic region

Tillage practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Conventional Residue Removed	5	5	2	2	5
Conventional Residue Left	84	39	59	41	73
Reduced Tillaged	11	51	39	57	22

Changes in production patterns

A cost assigned to the soil loss goal alters the comparative advantage of the South Atlantic region for production of some crops (Table 29). Generally, row crops are greatly disadvantaged because of the cost penalty attached to each ton of soil loss. For this reason small grains and particularly hay and grass crops are grown in the place of the row crops. Soybeans acreage declines over 60 percent in the region when Solution 5 is compared to Solution 1. This decline in soybeans acreage and the large increase in the acreage of hay and grass are the major adjustments in cropping patterns in the South Atlantic region as soil erosion is made increasingly costly for agriculture. Wheat acreage increases progressively from Solution 1 to Solution 5 in the South Atlantic region and parallels a shift of wheat out of the North Central region. Since the shift is mainly between these two regions, little change is implied of the mix of hard and soft wheats produced.

Table 29. South Atlantic acreage of different crops under alternative solutions in 1985, the South Atlantic region

Commodities	Solutions 1	2	3	4	5
	(000 acres)				
Row Crops	39,067	32,154	31,208	27,732	18,933
Corn Grain	902	1,377	2,706	4,582	3,131
Corn and Sorghum Silages	1,362	1,292	796	784	18
Soybeans	30,984	23,706	22,215	16,473	11,558
Cotton	5,819	5,779	5,491	5,893	4,226
Small Grains	1,619	2,888	3,732	4,052	5,692
Barley	398	350	666	344	--
Oats	114	191	221	249	444
Wheat	1,107	2,347	2,845	3,459	5,248
Hays	1,037	5,820	5,922	6,646	12,156

Changes in livestock production and feed consumption patterns

The livestock industry in the South Atlantic region is affected by the adjustments in crop production patterns to conserve the soil. The increased production of hay and grass crops as a soil conservation measure provides increased feed supplies favoring the production of livestock (Tables 30 and 31). Consequently, beef cattle are increased substantially. As the supply of feeders in the South Atlantic region is expanded, an economic incentive is created to feed out more calves (Table 30). There also is a substitution between the grain consuming livestock as the cost assigned to the soil loss goal increases.

Table 30. Livestock numbers under alternative solutions in 1985, the South Atlantic region

Livestock	Solutions 1	2	3	4	5
			(000 head)		
Beef Cows	3,691	5,552	5,437	6,031	6,660
Beef Feeding	3,364	4,495	3,809	3,609	2,257
Dairy	2,824	2,799	2,802	2,797	2,797
Hogs	--	--	--	4,295	4,503

Table 31. Feed consumed by all classes of livestock under alternative solutions in 1985, the South Atlantic region

Commodity groups	Solutions 1	2	3	4	5
			(000 tons)		
Corn and Sorghum Grain	6,001	5,775	5,787	7,035	7,024
Barley, Oats and Wheat	--	--	--	769	769
Corn and Sorghum Silages	20,313	19,708	12,220	12,023	70
Legume and N.Legume Hays	26,299	38,775	39,271	41,245	44,924
Oilmeals	2,099	2,016	1,915	2,093	1,949

Changes in resource use

The effects of improving soil conservation in U.S. agriculture on the inputs used in the South Atlantic region are shown in Table 32. Cropland not productive enough to cover added expense of erosion control and still produce crops competitively is taken out of production (Table 32). Nitrogen use increases with the expanding acreage of corn in the South Atlantic region as higher costs are placed on soil erosion. Pesticide expenditures increase as soil conservation improves in the region partly because of the larger acreage of corn and partly because of the increasing use of reduced tillage farming practices.

Table 32. Resource use in crop production under alternative solutions in 1985, the South Atlantic region

Solution	Land used (000 acres)	Nitrogen used (000 ton)	Pesticide exp. (000 dollars)[a]
1	47,997	481	181,237
2	47,136	721	264,028
3	47,136	838	338,096
4	44,704	982	411,794
5	44,905	1,068	390,985

[a] Expenditures are in terms of 1972 dollars

The South Central Region

The South Central region does not have a high erosion hazard because the land is relatively level and rainfall is modest. Soil erosion in the South Central region declines as crop production practices change in response to placing higher values on eroded soil (Table 3). Because the erosion hazard is not so high, changing cropping patterns are often an adequate control measure.

Conservation and tillage practices

The major adjustment in conservation practices as soil conservation improves in the South Central region is the substitution of contour farming for straight row farming. The data on conservation practices, displayed in Table 33, show a large increase of contour farming and a relatively small increase in the use of terracing as soil conservation measures. Terracing is allowed as an activity only on soils which are deep enough to support it.

As the weight assigned to the soil loss goal increases, some slight shifts in tillage practices occur to provide more protection for the topsoil.

As shown in Table 34, reduced tillage is substituted for conventional tillage practices.

Table 33. Percentage changes of acres by conservation practices under alternative solutions in 1985, the South Central region

Conservation practices	Solutions 1	2	3	4	5
	(percentage of acres)				
Straight Row	47	31	22	19	19
Contour Farming	26	37	44	46	46
Strip Cropping	-	-	-	-	-
Terracing	27	32	34	35	35

Table 34. Percentage changes of acres by tillage practices under alternative solutions in 1985, the South Central region

Tillage practices	Solutions 1	2	3	4	5
	(Percentage of acres)				
Conventional Residue Removed	27	29	24	23	26
Conventional Residue Left	73	70	72	69	64
Reduced Tillage	-	1	4	8	10

Changes in production patterns

As the value assigned to the soil loss goal is increased, a greater incentive to conserve soil is created. The comparative advantage for the production of crops in the South Central region is altered accordingly. Generally, the acreage of row crops and small grains declines slightly while the acres of hay and grass increase (Table 35). Soybean acreage increases as production shifts to the South Central region from the South Atlantic region because of the lower erosion hazard associated with row cropping in the former region. Small grain production declines slightly in this region as it shifts to the North Central and South Atlantic regions.

Table 35. South Central acreage of different crops under alternative solutions in 1985, the South Central region

Commodities	Solutions 1	2	3	4	5
	(000 acres)				
Row Crops	32,195	26,203	23,784	27,376	27,981
Corn Grain	1,183	1,431	1,140	1,125	1,125
Sorghum Grain	9,016	6,466	9,144	8,258	8,179
Corn and Sorghum Silages	16,848	14,441	9,654	9,011	9,382
Soybeans	4,202	3,335	3,581	8,243	9,142
Cotton	946	530	265	199	153
Small Grains	10,796	11,796	9,883	8,513	7,242
Barley	1,043	828	1,041	1,135	270
Oats	1,002	1,018	1,547	1,570	1,315
Wheat	8,751	9,950	7,295	5,814	5,657
Hays	16,934	21,447	24,245	23,513	23,655

Corn and sorghum silage acreage declines almost 50 percent in Solution 5 compared to Solution 1. The acres of silage decline because of the erosion hazard created by its production. The acreage of hay and grass crops increases 40 percent and provides a substitute feed for livestock raised in the region.

Changes in livestock production and feed consumption patterns

The livestock industry in the South Central region changes slightly in response to the reorganization of U.S. agriculture as the cost assigned to the soil loss goal rises (Tables 36 and 37). The region's beef-calf industry is placed at a slight disadvantage as cows shift to the North Central and South Atlantic regions. Additional grass and hay is produced in the latter two regions as a soil conservation measure. Beef cattle feeding in the South Central region increases somewhat because of lower per head nonfeed costs in the region and the decreased availability of feed grains in the North Central region.

Table 36. Livestock numbers under alternative solutions in 1985, the South Central region

Livestock	Solutions 1	2	3	4	5
			(000 head)		
Beef Cows	26,280	27,247	25,005	23,191	21,932
Beef Feeding	18,371	18,984	18,070	17,371	19,638
Dairy	1,084	1,075	1,064	1,062	1,131

Table 37. Feed consumed by all classes of livestock under alternative solutions in 1985, the South Central region

Commodity groups	Solutions 1	2	3	4	5
			(000 tons)		
Corn and Sorghum Grain	3,884	3,495	2,625	2,697	3,101
Barley, Oats, and Wheat	225	857	1,859	1,697	1,668
Corn and Sorghum Silages	213,723	193,618	137,119	101,702	104,292
Hays	100,625	113,878	121,362	122,411	121,701
Oilmeals	5,170	4,839	4,003	3,529	3,714

Changes in resource use

Although land and nitrogen use is relatively constant, pesticide expenditures increase substantially in Solutions 4 and 5 because of the expanding soybeans acreage (Table 38).

Table 38. Resource use in crop production under alternative solutions in 1985, the South Central region

Solutions	Land used (000 acres)	Nitrogen used (000 acres)	Pesticide exp. (000 dollars)[a]
1	62,986	1,913	44,784
2	62,455	1,926	39,649
3	60,521	1,925	68,237
4	61,521	1,912	147,371
5	61,881	1,905	205,872

[a] Expenditures are in terms of 1972 dollars.

The North Atlantic, North West and South West Regions

The North Atlantic region has one of the highest regional soil erosion rates. The soil erosion rates in the Northwest are below the national average while those in the Southwest are are almost negligible in Solution 1 (Table 3).

Soil losses in the North Atlantic Region are reduced as the result of changing conservation practices and substituting hay for more erosive crops in the rotations. Conservation practices in the North West and South West regions do not change greatly under alternative solutions. The practice of straight-row farming declines as the cost assigned to the soil loss goal increases (Table 39). Substituting hay for row crops conserves soil in the North West. Erosion hazards of row cropping in the South West are relatively low due to climatic conditions. Hence, some row cropping shifts to the South West region (Table 40).

Changing crop production patterns affects livestock production in these three regions (Table 41). Generally, beef cows increase in those regions where production of small grain, hay, and grass crops are expanded to protect the topsoil from erosion.

Table 39. Percentage of acres by conservation practices under alternative solutions in 1985, the North Atlantic, North West and South West regions

Conservation practices	Solutions 1	2	3	4	5
	(percentage of acres)				
North Atlantic					
Straight Row	28	17	17	19	19
Contour Farming	60	61	63	60	60
Strip Cropping	7	9	9	8	8
Terracing	5	13	11	13	13
North West					
Straight Row	61	58	58	60	54
Contour Farming	18	19	19	18	17
Strip Cropping	18	17	17	16	15
Terracing	3	6	6	6	14
South West					
Straight Row	89	79	85	87	88
Contour Farming	8	15	10	8	8
Strip Cropping	3	3	3	3	3
Terracing	0	3	2	2	1

Table 40. North Atlantic, North West and South West acreages of different crop groups under alternative solutions in 1985

Commodity groups	Solutions 1	2	3	4	5
	(000 acres)				
North Atlantic					
Row Crops	5,089	4,547	4,529	4,942	6,121
Small Grains	4,717	4,743	4,621	3,595	1,123
Hays	1,955	1,928	1,888	2,780	4,123
North West					
Row Crops	2,766	2,172	1,769	1,381	1,122
Small Grains	7,622	7,632	7,487	7,704	8,177
Hays	1,010	991	2,104	3,650	3,915
South West					
Row Crops	2,556	2,692	3,080	3,258	3,276
Small Grains	2,511	2,130	1,839	2,886	2,900
Hays	3,946	3,730	3,615	3,966	4,145

Table 41. Livestock numbers under alternative solutions in 1985, the North Atlantic, North West, and South West regions

Livestock	Solutions 1	2	3	4	5
	(000 heads)				
North Atlantic					
Beef Cow	--	--	--	506	1,169
Beef Feeding	978	978	978	1,282	1,696
Dairy	2,606	2,606	2,606	2,606	2,606
North West					
Beef Cow	1,786	1,776	2,572	3,245	3,077
Beef Feeding	1,376	1,242	1,142	1,057	1,078
Dairy	316	316	316	316	316
South West					
Beef Cow	6,153	6,074	5,624	5,741	5,767
Beef Feeding	4,591	4,657	5,017	5,661	5,908
Dairy	961	961	961	961	961

technique identified an efficient set of points, or efficient vector x^* within which the solution lies. The x^* is efficient if there is no other feasible vector x^{**} such that

$$f_i(x^{**}) \geq f_i(x^*) \quad \text{for all } i = 1, 2$$

$$f_i(x^{**}) > f_i(x^*) \quad \text{for some } i$$

where $f_i(x)$ is the ith goal function.

The generation of the efficient set to (35) begins by transforming the vector-valued objective function in (35) to the scalar-valued function in (37).

$$\text{Min} \sum_{i=1}^{2} w_i f_i(x) \tag{37}$$

where the w_i's are the relative weights assigned to each objective and all $w_i \geq 0$ and at least one $w_i > 0$. Systematically varying the w_i's in (37) will yield a trade-off curve. In this study w_i is selected to be equal to unity making F_1 (i.e., the cost of production and transportation) the numeric goal.

To generate the trade-off curve in Figure 10, six linear programming solutions each obtained with a different weight assigned to the soil erosion goal are considered in this study. The analysis is summarized around the five solutions setting different weights on (a) farming efficiency as reflected in the organization of the nation's agriculture to minimize the cost of food production and (b) soil loss.[1] The weights used in the six solutions are: Solution 1 has a weight of $1.00 for the farming efficiency goal and zero for the soil loss goal. In Solutions 2, 3, 4, and 5 the weights on the efficiency goal are kept at $1.00, but the

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[1] The results of Solution 6 are not applicable to the real world because production costs do not enter into the optimization. For this reason the results of Solution 6 are not presented in this study.

weights on the soil loss goal are $2.50, $5.00, $10.00, and $20.00, respectively. As the magnitude of soil loss goal increases, society is placing a penalty on soil erosion. For Solution 6, the efficiency goal has a zero weight while the soil loss goal has a weight of $1.00. Hence, in Solution 6, society is giving zero weight to the efficiency goal. Each solution is an efficient point between the two goals and, when plotted, can be used to draw the trade-off curve between the goals. The shape of this trade-off curve as indicated in Figure 10 implies that society may need to make a sizable sacrifice in one goal in order to optimize the other goal taken alone. If society is interested only in economic efficiency in U.S. agriculture, then minimizing only the cost of production (Point 1 in Figure 10) results in high rates of soil erosion from U.S. cropland. Conversely, if a high level of soil conservation alone is desired (Point 6 in Figure 10), then minimizing only the soil loss goal greatly increases the cost of production. The intermediate solutions indicate a "corner" for the trade-off curve between the goals.

Changes in Soil Loss and Farming Practices

The results obtained from the alternative solutions indicate that U.S. agriculture needs to make major adjustments in farming methods and cropping patterns to significantly improve soil conservation. Reduced tillage practices are substituted for conventional tillage practices to increase the quantity of plant residues on the soil surface. Contour farming is substituted for straight-row farming on land with a relatively small erosion hazard, while terracing is used on those fields subject to severe erosion problems but have soils deep enough to support it. In

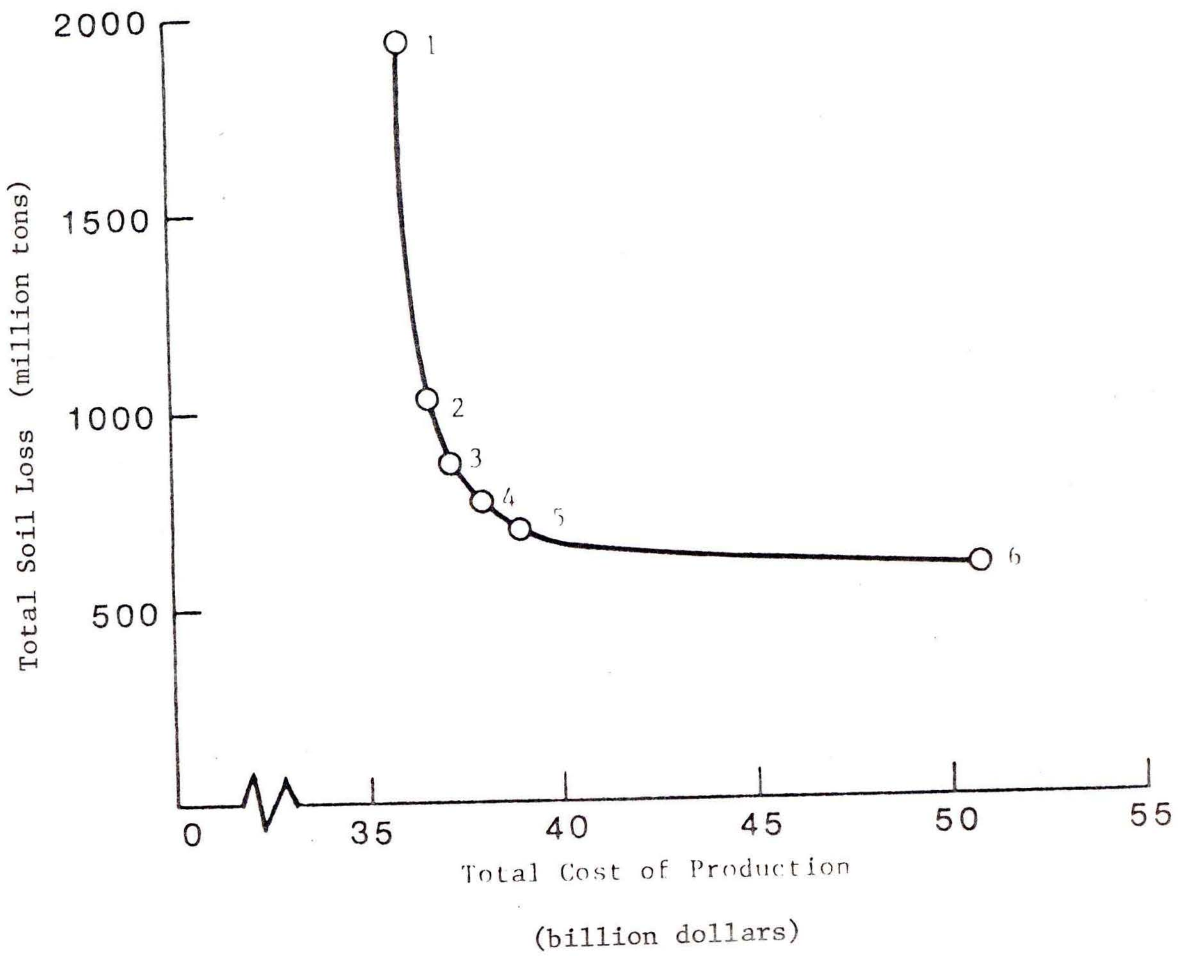

Figure 10. Trade-off frontier between goals for cost of production and soil conservation in an efficient agriculture. Totals for the United States.

Solution 1, 33 percent of the cropland is under straight-row farming. Straight-row farming drops to 23 percent of the cropland in Solution 5. Cropland acres protected by terracing increase from 11 percent of the total in Solution 1 to 23 percent in Solution 5. Terracing offers more effective protection against erosion than strip cropping or contouring but is more expensive.

Changes in Land Utilization and Production Patterns

The total acres cropped varies less than 2 percent between alternative solutions as the level of soil conservation increases (Table 42). The total acres allocated to various crops categories have reasonable trends over the whole range of the solutions (Table 42). Hay acreage, in particular, shows a steady and substantial increase as the level of soil conservation rises. Hay acreage expands because it is an economical soil conservation measure relative to alternatives such as additional terracing. A consequence of this expanding supply of hay is the substitution of hay for silage in livestock rations. A significant portion of the decline in the acres of row crops is due to the declining acres of corn and sorghum silage.

Assigning a cost penalty per ton of soil eroded significantly alters the comparative advantage of growing crops in those regions most susceptible and least susceptible to soil erosion. The high erosion hazard associated with row cropping in the South Atlantic region results in a substantial shift of soybeans and cotton production away from the South Atlantic region. Legume hay, grass and small grains substitute for these crops because of the protection they provide for the topsoil. This

Table 42. Land utilization and production patterns under alternative solutions in 1985

	Solutions				
	1	2	3	4	5
	(000 acres)				
Total cropland	370,826	366,144	369,469	370,468	373,974
Row Crops	219,749	205,657	201,685	199,823	202,311
Small Grains	72,675	73,530	75,140	75,944	75,333
Hays	38,098	50,679	58,359	61,934	65,070
Others[a]	40,304	36,278	34,285	32,767	31,290

[a] Fallow, sugar beet and exogenous crops.

changing crop mix favors the further development of beef cattle in the South Atlantic region.

The low erosion hazard of row cropping gives a relative advantage to corn and sorghum grain production in the Great Plains, in those parts of the region adapted to these crops in terms of moisture, under a national soil conservation policy for U.S. agriculture. The acreage of small grains declines slightly in the Great Plains because production shifts to the South Atlantic and North Central regions as a soil conservation measure. Some shift in wheat from the Great Plains to more humid regions would change somewhat the mix of soft and hard red winter wheat produced. However, the amount of hard wheat would still far exceed domestic demand and the slight increase in soft wheat would substitute for hard wheat in exports and livestock feed.

Acreages of legume hay, grass and small grains increase in the North Central region as the agriculture in the region shifts away from continuous row crop rotations of corn and soybeans to lessen erosion. The

increasing availability of grass and hay, as the emphasis on soil conservation increases, favors expansion of beef cow herds in the North Central region. At the same time, the beef feeding industry in this region declines because of the reduced acreage of corn. While the corn produced is ample to feed livestock produced in the region under other solutions, the comparative advantage of the region in feeding shifts with the relocation of some grain production and the complex of transport costs which prevail relative to the point and level of exports.

Change in Farming Technology

The use of fertilizer and pesticides increases steadily as agriculture is reorganized to provide more protection for the cropland (i.e., in Solution 5 as compared to Solution 1). Changing farm practices, such as the expanding use of reduced tillage increasing pesticide requirements of crop production, can significantly alter the use of inputs by U.S. agriculture (Table 43). The principal reason the use of fertilizer increases as the level of soil conservation rises is due to interregional adjustments in corn production. When agriculture is organized without consideration of the consequences of soil erosion, the production of corn is concentrated on the most productive land, especially in the North Central region. As the cost penalty assigned per ton of soil loss rises, this concentration declines because hay, grass, and small grain crops must be grown in rotation with the corn to control erosion. Thus, as corn production is forced to shift to less productive land, e.g., the Great Plains, the amount of fertilizer and pesticides required to raise a bushel of corn increases.

Table 43. Acres and resources used in an efficient agriculture in the alternative solutions in 1985

Solutions	Land cultivated (000 acres)	Nitrogen fertilizer used (000 ton)	Pesticide expenditures (000 dollars)[a]
1	370,837	9,350	1,527,964
2	366,144	9,351	1,908,280
3	369,469	9,705	2,053,998
4	370,468	10,041	2,268,421
5	374,004	10,442	2,458,863

[a] Expenditures are in terms of 1972 dollars.

Supply Prices

Changes in farm practices (such as the increased use of terracing, and adjustments in cropping patterns, growing corn in rotation with grass and hay and shifting some of the corn acreage in the North Central region to the Great Plains) cause only modest increases in the cost of producing crops in the United States up to Solution 3. However, between Solution 3 and Solution 5 supply prices increase by a large amount (Table 44). These large cost increases would raise food costs for U.S. consumers and disadvantage U.S. agriculture in world commodity markets.

Table 44. Percentage changes in the index of supply prices for the major agricultural commodities in the alternative solutions in 1985 (Solution 1 = 100)

	Solutions				
Commodities	1	2	3	4	5
Corn	100	104	115	144	198
Soybeans	100	113	134	184	280
Cotton	100	92	104	115	136
Pork	100	105	113	133	174
Beef	100	101	107	123	155

Policy Implications

The purpose of this study has been to provide information about the trade-offs between (a) the cost of producing and transporting agricultural products to current consumers and (b) preventing soil loss and maintaining a productive cropland base for future generations. The derivation of the trade-off function between these two goals should provide policy makers with valuable information for decision making.

As presented in Figure 10, the points on this trade-off curve show attainable combinations of total production costs and total soil erosion for U.S. agriculture. The determination of the optimal point on this trade-off curve should depend on the preferences of decision makers representing society.

The shape of the trade-off curve indicates that the costs of soil erosion abatement are not likely to vary proportionately to the amount of erosion abated. At a very high level of soil loss, a given reduction in erosion can be obtained without substantial cost to society. When soil losses are at relatively low levels, however, further reductions are very expensive. In summary, the more soil loss is reduced on U.S. cropland, the costs will rise sharply for further reductions.

Society has several policy options for achieving a desired level of erosion abatement in U.S. agriculture. These options include a per unit tax for each ton of soil lost from the farmer's field. Application of such a tax would provide an incentive for the farmer to reduce soil erosion to the desired level. Alternatively, the farmer could be paid for reductions in soil loss. Several soil conservation bills have been before Congress recently [12, 29]. These bills would require expenditures of several billion dollars to achieve their objectives.

Changes in farm practices required to abate soil erosion require new management skills and a larger capital investment by farmers. In general, farms with land susceptible to severe erosion, thus requiring costly conservation practices, stand to be economically disadvantaged. Farmers with land not subject to severe erosion can generate more income and raise the capitalized value of their farms. A national program of erosion abatement also would cause a relative redistribution of income among regions. Regions of heavy rainfall and sloping lands are forced into less intensive agriculture and may have an income reduction accordingly. Regions of moderate rainfall and level lands have the opportunity to farm more intensively and increase income accordingly. These differential impacts should be recognized in national policies directed at reduced soil erosion.

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APPENDIX: MATHEMATICAL STRUCTURE OF THE MODEL

The mathematical model used is a multi-goal linear programming model. The two objectives considered in this study are (a) production and transportation costs and (b) soil erosion, respectively.

The model consists of approximately 1,200 equations and 24,000 variables. In matrix notations the model is as follows:

$$\text{Min } F = Cx \tag{22}$$

$$\text{Subject to } Ax \leq b \tag{23}$$

$$x \geq 0 \tag{24}$$

where F is a 2 x 1 vector

$$\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} \tag{25}$$

C is a 2 x n matrix of costs and soil loss

$$\begin{bmatrix} C_{11}\ C_{12}, \ldots, C_{1n} \\ C_{21}\ C_{22}, \ldots, C_{2n} \end{bmatrix} \tag{26}$$

A is an m x n matrix of input output coefficients

X is an n x 1 vector of production and transportation activities

b is an m x 1 vector of resource restraints and demand requirements

The first objective function to be minimized in the model is:

$$F_1(x) = \sum_i \sum_j \sum_k \sum_m X_{ijkm} XC_{ijkm} + \sum_n \sum_p \sum_q L_{npq} LC_{npq} + W_r WC_r$$
$$+ F_n FC_n + IB_r IC_r + \sum_n \sum_s \sum_t T_{nst} TC_{nst} \tag{27}$$

$i = 1, \ldots, 105$ for the producing areas,
$j = 1, \ldots, 10$ for the land classes,
$k = 1, \ldots, 330$ for the rotations defined,
$m = 1, \ldots, 12$ for the conservation and tillage alternatives per rotations,
$n = 1, \ldots, 28$ for the market regions,
$p = 1, \ldots, 4$ for the endogenous livestock classes,
$q = 1, \ldots, 32$ for the livestock rations,
$r = 1, \ldots, 58$ for the water supply regions,
$s = 1, 2, 4, 5, 7, 8, 10, 11, 13, 14, 15$ for the commodities transported, and
$t = 1, \ldots, 176$ for the transportation routes defined.

where:

$F_1(x)$ represents cost of production and transportation;

X_{ijkm} is the number of acres of rotation k with conservation tillage m in producing area i on land class j;

XC_{ijkm} is the cost per acre of rotation k with conservation-tillage practice m in producing area i on land class j;

L_{npq} is the number of units of livestock activity p receiving ration q in market region n;

LC_{npq} is the cost per unit of livestock activity p receiving ration q in market region n;

W_r is the number of acre feed to water purchased in water supply region r;

WC_r is the cost per acre foot of water purchased in water supply region r;

F_n is the number of pounds of nitrogen fertilizer purchased in market region n;

FC_n is the cost per pound of nitrogen fertilizer purchased in market region n;

IB_r is the acre feet of water transferred out of region r;

IC_r is the cost differential on a per acre foot basis for water in region r;

T_{nst} is the number of units of commodity s transported over route t from market region n; and

TC_{nsr} is the cost per unit of commodity s transported over route t from market region n.

The second objective to be minimized in the model is soil loss from cropland. In the model the soil loss by cropping management system is weighted to the producing area from the SCS data area as follows:

$$F_2(x) = S_{ijm} = \sum_k SL_{ijk}A_{jkm}/A_{jm} \qquad (28)$$

$i = 1, \ldots,$ the number of crop management systems defined in the producing area,
$j = 1, \ldots, 10$ for the land classes,
$k = 1, \ldots,$ for the parts of the 165 SCS data areas, and
$m = 1, \ldots, 105$ for the producing area.

where:

S_{ijm} is the soil loss for crop management system i on soil group j in producing area m;

SL_{ijk} is the soil loss from crop management system i on soil group j consistent with SCS data area k;

A_{jkm} is the acres of tillable soil group j in the part of SCS data area k in producing area m; and

A_{jm} is the total tillable acres of soil group j in producing area m.

Each producing area has restraints for land availability by the five dry and five irrigated land classes. The equations for the ith producing area are as follows:

Dryland restraint by land class

$$\sum_{k}\sum_{m} X_{ijkm}AD_{ijkm} \leq DA_{ij} \qquad (29)$$

i = 1, ..., 105 for the producing areas,
j = 1, ..., 5 for the land classes,
k = 1, ..., 330 for the rotations defined, and
m = 1, ..., 12 for the conservation-tillage alternatives.

Irrigated land restraint by land class

$$\sum_{k}\sum_{m} X_{ijkm}AI_{ijkm} \leq IA_{ij} \qquad (30)$$

i = 48, ..., 105 for the producing areas,
j = 6, ..., 10 for the land classes,
k = 1, ..., 330 for the rotations defined, and
m = 1, ..., 12 for the conservation-tillage alternatives.

Hay acreage restraint

$$\sum_{j}\sum_{k}\sum_{m} X_{ijkm}W_{ijkm5} \leq HR \left[\sum_{j}\sum_{k}\sum_{m} X_{ijkm}W_{ijkm6} + \sum_{j}\sum_{k}\sum_{m} X_{ijkm}W_{ijkm5}\right] \qquad (31)$$

i = 1, ..., 105 for the producing areas,
j = 1, ..., 10 for the land classes,
k = 1, ..., 330 for the rotation defined, and
m = 1, ..., 12 for the conservation-tillage alternatives.

where:

X_{ijkm} is the level of rotation k using conservation-tillage method m on land class j in producing area i;

AD_{ijkm} is the acres of dryland used per unit of rotation k using conservation-tillage method m on land class j in producing area i;

AI_{ijkm} is the acres of irrigated land used per unit of rotation k using conservation-tillage method m on land class j in producing area i;

DA_{ij} is the acres of dryland available on land class j in producing area i;

IA_{ij} is the acres of irrigated land available on land class j in producing area i;

HR_{i} is the proportion of all hay which can be legume hay in market region i; and

W_{ijkmu} is the rotation weight for crop u in rotation k using conservation-tillage method m on land class j in producing area i.

In the producing areas 48-105, water supplies and irrigation activities are defined. Equation 32 controls the allocation of water to the endogenously determined agricultural uses.

$$\sum_{j}\sum_{k}\sum_{m}\sum_{u} X_{ijkm}W_{ijkmu}CWU_{iu} + \sum_{n}\sum_{p}\sum_{q} Y_{npq}LWU_{npq}LW_{npr} - WH_{r}WA_{r} \leq WS_{r} \qquad (32)$$

i = 48, ..., 105 for the producing areas,
j = 1, ..., 10 for the land classes,
k = 1, ..., 330 for the rotations defined,
m = 1, ..., 12 for the conservation-tillage alternatives,
n = 1, ..., 28 for the market regions,
p = 1, ..., 4 for the endogenous livestock types,
q = 1, ..., 32 for the livestock rations,
r = i-47 to give the water supply region number, and
u = 1, ..., 15 for the possible irrigated crops.

where:

X_{ijkm} is the level of crop rotation k using conservation-tillage method m on land class j in producing area i;

W_{ijkmu} is the rotation weight for crop u in rotation k using conservation-tillage method m on land class j in producing area i;

CWU_{iu} is the acre feet per acre water use coefficient for crop u in producing area i;

Y_{npq} is the level of livestock type p consuming ration q in market region n;

LWU_{npq} is the acre feet per unit water use coefficient for livestock type p consuming ration q in market region n;

WS_r is the per acre feet of water available for use by the endogenous agricultural sector;

LW_{npr} is the proportion of livestock type p from market region n in water supply region r;

WH_r is the level of dryland to irrigated pasture conversion in water supply region r; and

WA_r is the per acre water use coefficient when converting one acre of dryland pasture to irrigated pasture in water supply region r.

Each commodity market region has a set of equations to balance the supply and demand of the commodities. The equations are:

$$\sum_i \sum_j \sum_k \sum_m X_{ijkmn} W_{ijkmu} CY_{ijkmsu} + \sum_p \sum_q Y_{npq} LY_{npqs} - \sum_t T_{nst} + \sum_r WH_r DA_{rs} \geq CD_{ns} \qquad (33)$$

i = 1, ..., 105 for the producing areas,
j = 1, ..., 10 for the land classes,
k = 1, ..., 330 for the rotations,
m = 1, ..., 12 for the conservation-tillage practices,
n = 1, ..., 28 for the market regions,
p = 1, ..., 4 for the endogenous livestock types,
q = 1, ..., 32 for the livestock rations,
s = 1, 2, 4, ..., 9, 11, ..., 15 for the commodities balanced at the market region,
u = 1, ..., 15 for the crops, and
t = 1, ..., 176 for the transportation activities defined.

where:

X_{ijkmn} is the level of crop rotation k using conservation-tillage system m on land class j in producing area i which is included in market region n;

W_{ijkmu} is the weight of crop u in rotation k using conservation-tillage system m on land class j in producing area i;

CY_{ijkmsu} is the per acre production of commodity s from crop u in rotation k using conservation-tillage system m on land class j in producing area i;

Y_{npq} is the level of production of livestock type p using ration q in market region n;

LY_{npas} is the per unit interaction coefficient for commodity s with livestock type p consuming ration q in market region n (this will be positive for the livestock products and negative for the ration components);

CD_{ns} is the exogenously determined demand for commodity s in market region n;

T_{nst} is the net export of commodity s over transportation route t defined in market region n;

WH_r is the level of dryland to irrigated pasture conversion in water region r;

DA_{rs} is the increase in hay yield associated with the conversion of an acre of dryland pasture to irrigated pasture in water supply region r. $DA_{rs} = 0$ for all $s \neq 5$.

The equations which are defined at the national level to balance commodity demand are as follows:

$$\sum_i \sum_j \sum_k \sum_m X_{ijkm} W_{ijkmu} CY_{ijkmsu} \geq CD_s \qquad (34)$$

$i = 1, \ldots, 105$ for the producing areas,
$j = 1, \ldots, 10$ for the land classes,
$k = 1, \ldots, 330$ for the rotations defined,
$m = 1, \ldots, 12$ for the conservation-tillage alternatives,
$s = 3, 14$ for the commodities cotton and sugar beets, and
$u = 4, 14$ for the crops cotton and sugar beets.

where

X_{ijkm} is the level of crop rotation k using conservation-tillage practice m on land class j in producing area i;

W_{ijkmu} is the rotation weight for crop u in rotation k using conservation-tillage practice m on land class j in producing area i;

CY_{ijkmsu} is the per acre production of commodity s from crop u in rotation k using conservation-tillage practice m on land class j in producing area i; and

CD_s is the demand for commodity s at the national level.

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