IOWA STATE UNIVERSITY
Digital Repository

Retrospective Theses and Dissertations

Iowa State University Capstones, Theses and Dissertations

1981

The trade-off relationship between energy use and environmental quality in US agriculture: a multiobjective linear programming analysis

Pil-Kwon Chung
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/rtd

Part of the Economics Commons

Recommended Citation

Chung, Pil-Kwon, "The trade-off relationship between energy use and environmental quality in US agriculture: a multiobjective linear programming analysis " (1981). *Retrospective Theses and Dissertations*. 7409.
https://lib.dr.iastate.edu/rtd/7409

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

للاستشارات المنارة

www.manaraa.com

INFORMATION TO USERS

This was produced from a copy of a document sent to us for microfilming. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help you understand markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure you of complete continuity.

2. When an image on the film is obliterated with a round black mark it is an indication that the film inspector noticed either blurred copy because of movement during exposure, or duplicate copy. Unless we meant to delete copyrighted materials that should not have been filmed, you will find a good image of the page in the adjacent frame. If copyrighted materials were deleted you will find a target note listing the pages in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed the photographer has followed a definite method in "sectioning" the material. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.

4. For any illustrations that cannot be reproduced satisfactorily by xerography, photographic prints can be purchased at additional cost and tipped into your xerographic copy. Requests can be made to our Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases we have filmed the best available copy.

University
Microfilms
International

300 N. ZEEB RD., ANN ARBOR, MI 48106

8209109

Chung, Pil-Kwon

THE TRADE-OFF RELATIONSHIP BETWEEN ENERGY USE AND ENVIRONMENTAL QUALITY IN U.S. AGRICULTURE: A MULTIOBJECTIVE LINEAR PROGRAMMING ANALYSIS

Iowa State University Ph.D. 1981

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

The trade-off relationship between energy use and environmental quality in U.S. agriculture: A multiobjective linear programming analysis

by

Pil-Kwon Chung

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major: Economics

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1981

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I. INTRODUCTION

The United States is facing the problem of sustaining economic growth while solving an energy shortfall and high energy prices, and improving environmental quality. Because of trade-off relationships between new energy production technologies and environmental quality, depletion of energy resources, and political instability in oil exporting countries, the energy shortage and high energy price problems in the United States will become more and more serious in the future.

The agricultural sector, as a part of our economy, is confronted with the same types of problems. It is generally expected that in the near future United States agricultural production should expand to meet foreign demand as well as domestic demand. However, this increased production can be achieved only through degrading environmental quality and using more energy. The soil loss problem has increasingly become a public concern in the United States since the 1930s because it pollutes the air and water, and reduces the productivity potential of cropland. The soil loss problem due to water which will be considered in this study is influenced by the amount, intensity, and duration of rainfall, amount and velocity of surface flow, nature of the soil, ground cover, slope of the land, and many other factors [41]. Some erosion is natural, but man accelerates the erosion process and induces more soil into streams through his use of the land surface.

Even though only three percent of the total energy consumed in the United States is used in agricultural production, we should note that dramatic increases in agricultural productivity in large part have been the result of technological advances critically dependent on energy for their operation and manufacture [50]. Thus, the energy shortage and high energy price situations which will prevail in the near future are likely to have a significant and lasting impact on the United States' agricultural production patterns and food costs. Furthermore, the United States agricultural sector may be called upon not only to share in energy conservation, but also to produce alternative fuels such as ethanol from grains.

In this situation, we may assume that policy-makers have three objectives to be minimized in U.S. agricultural production. The objectives are minimization of crop production and transportation costs, soil loss, and energy use in producing the given demands. From the policy-makers' point of view, they should know whether these objectives conflict with or complement each other, and what impacts on agricultural production patterns, resources use patterns, soil loss, and others might come about when they try to minimize any possible combination of these objectives. In addition, they may need information about the nature of the trade-off relationship between any two objectives if they conflict with each other.

Objective of the Study

It is generally expected that the situation of high energy prices or an energy shortage makes farmers change their tillage practices from conventional to reduced tillage, which is consistent with soil loss control policy. On the other hand, marginal, highly erosive land will be brought into production as land is substituted for more energy intensive inputs under an energy crisis or energy use minimization policy. Further, since irrigated crops are highly energy intensive, crop production under energy use minimization policy will shift from the arid western regions to the rainfed midwestern and eastern regions where the land is relatively more erosive. These two results clearly increase soil loss, which is contradictory to soil loss control policy. Therefore, it is still an open question whether minimization of soil loss and energy use is conflicting or complementary.

The first objective of this study is to identify the minimum cost production patterns, the maximum achievement of soil loss reduction and energy saving under the feasible set of alternatives where policymakers try to minimize only a single objective without consideration of the other objectives. These solutions also provide us with useful information such as the possible range of conflict between a soil loss control policy and an energy use reduction policy.

The second objective is to trace out a partial trade-off relationship between a soil loss control policy and an energy use reduction policy by using the constraint method.

The third objective is to derive two compromise solutions when considering the three objectives simultaneously, since each objective conflicts with each other and thus, a sacrifice in one objective is required to achieve higher levels of the other objectives under the feasible set.

Degradation of Environmental Quality from Agriculture

Environmental pollution is a national concern. Increased food and fiber production activities to meet domestic and export demands are especially important contributing sources of water pollution. The sediment, a product of erosion, that is carried off sloping lands and transported into surface water supplies has been called the greatest single nonpoint source pollutant of our national waters. It has been estimated that about four billion tons of soil, which are equivalent to about four million acres of good top soil with a six inch depth, are washed into waterways and reservoirs annually [1].

Although soil loss from cultivated land is the prime source of sediment in streams and reservoirs, highway construction, rural roads, gully erosion, housing developments, strip mines, and others are also important sources which produce sediments. The sediment from land erosion also damages fish and wildlife, reduces reservoir storage capacity, the value of streams for recreational purposes, and the carrying capacities of irrigation and drainage systems.

The rapid increase in agricultural chemicals use, such as fertilizers and pesticides, has been due largely to their relatively low cost, and the necessity for higher yields. More than one-third of this nation's food production can be attributed to the use of chemical fertilizers. Some researchers [35] argue that without pesticides, food production would be reduced forty to fifty percent, and the quality would be greatly reduced. However, the degree of water degradation is undoubtedly related to agricultural chemicals application rates. It is estimated that the amount of nitrogen that reaches surface waters ranges from 0.03 to 8.4 pounds per acre and the amount of phosphorus ranges from 0.01 to 0.08 pounds per acre [49]. The acute effects of gross pesticides pollution are well known and depend on the toxicity of the compound in question and its concentration in the environment. Among the compounds in pesticides, DDT has been the most objectionable. Reports of farm pond fish kills were reported soon after 1945 when DDT and other organic pesticides became available to the public. In 1950, extensive fish kills occurred almost simultaneously in fourteen streams tributary to the Tennessee River in Alabama. Investigation showed that the kills were caused by insecticides washed from cotton fields following a series of intensive rainstorm [4].

Confinement production of livestock and poultry in lots, yards, and buildings results in large volumes of accumulated animal wastes. These concentrated animal wastes are potential sources of pollution to ground water and surface water supplies. The pollution potential from livestock production becomes greater when the wastes are allowed to accumulate or are stored on top of the ground in a lot or yard where rainfall can leach and transport portions of the animal waste materials through surface runoff [4].

Since sediment also serves as a transportation method to move agricultural chemicals and animal wastes, and soil erosion is a primary requisite for sediment production, soil erosion must be minimized in order to minimize sediment yield and thus reduce the degradation of environmental quality from agricultural sources. Therefore, soil erosion control is very important to prevent not only a reduction of productivity potential of cropland, but also the contamination of water.

Soil erosion, defined as the detachment of soil or rock fragments by water, wind, ice or gravity can be natural, but can be accelerated by man's activities. Marked reduction of soil erosion can be accomplished by adopting conservation tillage practices such as contouring, strip cropping, and terracing, replacing conventional tillage practices with reduced tillage practices or no-tillage practices, utilizing crop residues, and rotating row crops with sod crops which improves soil structure relative to row-cropping.

U.S. Energy Situation and Future

The United States is presently entering a period of transition from dependency on cheap oil and natural gas for its energy needs to reliance on more expensive alternatives such as coal, nuclear, solar, and geothermal resources [19]. We have been through two previous energy transitions: one from wood to coal and the second from coal to oil and natural gas. Through the 1880s, biomass (primarily wood) was the major energy source in the United States. From the 1880s through the mid 1940s, coal was the dominant source, and oil and natural gas have been the major energy source since then [46].

In 1980, the nation's gross energy consumption was 76 quadrillion (10^{15}) Btu. It dropped 3.4 percent below 1979, and 2.4 percent from the

1978 consumption level [51]. Table 1 summarizes the composition of the primary resources that made up this total. Over 90 percent comes from fossil fuels, with about 20 percent derived from coal and 71 percent from oil and natural gas. Water power contributes 4 percent, and nuclear 3.5 percent. Currently energy consumption by the end-use sector consists of 36 percent residential and commercial, 40 percent industrial, and 24 percent transportation.

Table 2 shows U.S. production of energy by type and percentage distribution. Only coal production in the U. S. is greater than coal consumption. The United States exported 91.7 million tons of coal in 1980, which amounts to an increase at an average annual rate of 7.8 percent between 1973 and 1980. The main source of the total production shortfall in energy is petroleum. The United States consumes over 2 billion barrels more of petroleum per year than it produces domestically. Domestic crude oil production fell to 8.6 million barrels per day in 1980, down from 9.2 million barrels per day in 1973.

The gap between domestic consumption and production is filled by imports. Petroleum imports are the major source of U. S. merchandise trade deficit. Energy imports in 1980 were 79 billion dollars, which is about one-third of total U.S. imports. Even though net energy imports in 1980 into U.S. declined 28.6 percent from the 1979 level, due to a 19.7 percent decline in petroleum imports and an increase of 37.9 percent in coal exports, the value of energy imports (net) increased 30.7 percent (Table 3). This phenomenon is mainly due to an increase

Table 1. U.S. consumption of energy by type in 1973 and 1980 [51]

Type	1973	1980	1973	1980
	(Quadrillion Btu)		(Percentage distribution)	
Coal and coal coke	13.292	15.637	17.8	20.5
Natural gas (dry)	22.512	20.437	30.2	26.8
Petroleum	34.840	34.249	46.7	44.9
Hydro-electric power	3.010	3.126	4.0	4.2
Nuclear electric power	0.910	2.704	1.2	3.4
Other[a]	0.046	0.114	0.1	0.1
Total	74.609	76.267	100.0	100.0

[a] Includes geothermal power, and electricity produced from wood and waste.

Table 2. U.S. energy production by type in 1973 and 1980 [51]

Type	1973	1980	1973	1980
	(Quadrillion Btu)		(Percentage distribution)	
Coal	14.366	18.877	23.0	29.1
Crude oil	19.493	18.246	31.2	28.1
Natural gas plant liquids	2.569	2.266	4.1	3.5
Natural gas (dry)	22.187	19.700	35.5	30.4
Hydro-electric power	2.861	2.913	4.5	4.5
Nuclear electric power	0.910	2.704	1.5	4.2
Other[a]	0.046	0.114	0.1	0.2
Total	62.433	64.821	100.0	100.0

[a] Includes geothermal power and electricity produced from wood and waste.

Table 3. U.S. energy summary in 1973-1980 [51]

Year	Production	Consumption	Imports	Exports	Value of net imports
	(Quadrillion Btu)				(Billion dollars)
1973	62.433	74.609	14.732	2.073	6.5
1974	61.229	72.759	14.417	2.241	22.0
1975	60.059	60.707	14.113	2.389	22.0
1976	60.091	74.510	16.838	2.213	29.8
1977	60.293	76.332	20.092	2.097	40.4
1978	61.204	78.150	19.262	1.951	38.2
1979	63.907	78.968	19.622	2.900	54.4
1980	64.821	76.267	15.752	3.762	71.1

in price of imported crude oil. The price of imported crude oil per barrel in 1980 averaged 33.89 dollars, an increase of 56 percent over the 1979 level.

There are some different views on our energy future. A recent M. I. T. report concludes that the supply of oil will fail to meet increasing demand before the year 2000, most probably between 1985 and 1995, even if energy prices rise 50 percent above the current levels in real terms [52]. A more recent report [20] reaches a more optimistic conclusion: the energy resources of the United States and the world are huge at prices not much more than about double those that prevail today. Use of these energy resources may be constrained by political or environmental factors, but the world is not running out of energy. With proper policies and planning, and a willingness to pay the costs, energy can be produced to meet any reasonable projections of demand, without a gap or physical shortages. These different views result from the different set of assumptions and projections on energy demand and supply. Also, they are affected by prevailing moods of optimism and pessimism.

The United States' identified reserves of energy in terms of physical units, quadrillion Btu, and percentage distribution are shown in Table 4. If all energy sources were readily interchangeable and there were no concerns about public health or environmental quality, there would clearly be no near-term danger of running out of domestic energy resources to satisfy U. S. consumption [38]. For example, coal which is the most

Table 4. U.S. identified reserves of energy [38]

Source	Unit	Physical quantity	Quadrillion Btu	Percentage distribution
Coal	billion tons	260	5,460	88.6
Oil	billion barrels	34	197	3.2
Natural gas liquids	billion barrels	6	25	0.4
Natural gas	trillion cubic feet	209	214	3.5
Uranium (LWR[a])	thousand tons	890	267	4.3
Total			6,163	100.0

[a] LWR means Light Water Reactor.

abundant energy resource in U.S. could support an energy demand of 100 quadrillion Btu per year for fifty years. Additional estimated coal resources beyond those identified as reserves could last 300 years at this rate of consumption. However, such a conclusion holds only for energy resources in the aggregate, and the aggregate is obviously dominated by coal and uranium [20].

The energy problem in the United States is one of the discrepancy between the types of energy consumed and the types of energy reserves. About 71 percent of energy consumption is oil and natural gas, but our reserves of these resources are no more than 7 percent of total reserves. Thus, in the current transition much attention is focused on decoupling economic growth and energy consumption and on developing unconventional energy sources like oil shale, coal liquids, and biomass to substitute for oil [46].

Historically, there is a close relationship between energy consumption and G.N.P. Some rough forecasts of total energy demand are based on the following equation [42]: En = .0807 G.N.P. + 5.5, where En is total energy demand in terms of quadrillion Btu and G.N.P. in billions of 1958 dollars. Using the above relationship and taking into account potential changes in energy availability, technology, environmental cost, and conservation, the projected total energy demand is 150 quadrillion Btu in the year 2000 if the economy continues to grow at 3.6 percent per year. This projected demand, 150 quadrillion Btu, is twice our present national energy consumption. Stan [42] does not expect that new technologies will provide a substantial fraction of the energy produced in the year 2000. To achieve a 150 quadrillion Btu planning target, the nation must continue to use the traditional energy sources. Whether we can satisfy this amount of energy demand depends on the development and economic feasibility of new technologies, political stability in oil exporting countries, and the degree of the environmental impacts of new energy technologies. In this uncertain future, we may conclude that over the coming twenty year period conservation will inevitably become one of the most important energy sources.

Energy Use in U.S. Agriculture

Crops capture solar energy and use it along with substances including water and plant nutrients from the soil and carbon dioxide from the air to produce the grain, fruit, fiber or other products we desire. Human energy also is invested in crop production, as is energy from electricity, petroleum products, and natural gas. This investment of fossil fuel energy in agricultural production permits one U.S. farmer to produce enough food for more than 50 other persons. Also, it allows us to increase the productivity of land and, at the same time, to reduce the amount the human labor required per unit of product [12].

The food system in the United States consumed 22 percent of total energy used in the U.S. in 1974. Of this 22 percent, 16.5 percent was used for food production through consumption: production (2.9 percent), processing (4.8 percent), marketing (1.3 percent), consumption preparation (7.1 percent), and transportation (0.4 percent) [17].

Total direct and indirect energy use in agricultural production in 1978 was about 2 quadrillion Btu, which consisted of 3.5 billion gallons of gasoline, 3.3 billion gallons of diesel fuel, 140 billion cubic feet of natural gas, 1.4 billion gallons of LPG, 32 billion kilowatt hours of electricity, 291 million gallons of fuel oil, and 36,522 tons of coal [47].

In crop production, diesel fuel and gasoline are used for field operations and irrigation, natural gas for irrigation and the production of fertilizers and pesticides, LPG for irrigation and crop drying, and electricity for irrigation and the production of fertilizers and pesticides. Table 5 shows the distribution of energy use in crop production. Field operations, the largest single component of energy use in crop production, are comprised of the activities associated with the growing and harvesting of crops. Nitrogen, the largest energy user of the chemical fertilizer nutrients, requires approximately 490 billion cubic feet of natural gas a year. This represents about 2.5 percent of the total U.S. demand for natural gas [17].

About 10 percent of the energy used in farm production is used for livestock production. The categories of energy use in livestock industry are lighting, space heating, ventilation, feed processing and distribution, general farm travel, water heating, livestock handling, and others. Among these, feed processing and distribution, waste disposal, general farm travel, and water heating are the main categories of energy use in the livestock production [50].

Table 5. Energy use in crop production and percentage distribution by input in 1974 and 1978 [47]

Input	1974	1978	1974	1978
	(Trillion Btu)		(Percentage distribution)	
Field operations	720	778	42.1	42.6
Fertilizers	601	653	35.1	35.8
Pesticides	70	68	4.1	3.7
Irrigation	251	255	14.7	14.0
Crop drying	69	71	4.0	3.9
Total	1,711	1,825	100.0	100.0

It is true that although the amount of energy saved in agriculture may prove to be substantial, it will not have a significant effect on the total U.S. energy demand because of relatively small use of energy in agriculture. However, it is still important to conserve energy use in agriculture whenever it is possible because of the expected energy shortage or high energy prices.

CHAPTER II. METHODOLOGY

The basic mathematical tool used in this study is the multiobejctive linear programming technique. Mathematically, the multiobjective linear programming problem with three objectives can be expressed as follows:

[Problem I]

$$\text{Min } Z = \begin{bmatrix} Z_1\ (\chi) \\ Z_2\ (\chi) \\ Z_3\ (\chi) \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \chi \qquad (1)$$

$$\text{subject to } A\chi \leq b \qquad (2)$$

$$\chi \geq 0 \qquad (3)$$

where:

$Z_1(\chi)$, $Z_2(\chi)$, and $Z_3(\chi)$ are minimization of production and transportation costs, soil loss, and energy use, respectively; C_i is an 1 x n vector, i = 1, 2, 3; χ is an n x 1 vector of activities; A is an m x n matrix of interaction coefficients; and b is an m x 1 vector of resource restraints and demand requirements.

In the multiobjective problem, optimality is replaced by the notion of noninferiority. Thus, the vector optimization problem is the problem of finding all solutions that are nondominated. A nondominated solution in the vector minimization problem, χ^o, is a feasible solution, for which there exists no other feasible solution, χ^1, such that

$Z_i\ (\chi^1) < Z_i\ (\chi^o)$ for some i = 1, 2, 3 and

$Z_j\ (\chi^1) \leq Z_j\ (\chi^o)$ for $j \neq i$.

Theoretically, we can generate all nondominated solutions by employing the constraint method or weighting method if the nondominated solutions set is strictly convex [8]. Then, policy-makers will select a particular policy from these solutions on the basis of institutional, political and other considerations which are not a part of the optimization model. However, there are some problems in this approach. First, it might be very difficult to select a particular solution because of too large a number of nondominated solutions. Secondly, computing costs to generate all nondominated solutions can be a binding factor if the problem involves a large number of activities and constraints.

To attack these problems two approachs are possible. One is that analysts may select several nondominated solutions by making several probable scenarios and comparing them. Then policy-makers may refer to these solutions in implementing some policies. The other approach is a compromising technique which tries to find the subset of nondominated solutions by making several assumptions. The well-known compromising techniques are goal programming, interactive programming, and L_p-metrics method.

To accomplish the first objective, we will solve problem II.

[Problem II]

$$\text{Min } Z_i(\chi) = C_i\chi \tag{4}$$

$$\text{subject to } A\chi \leq b \tag{5}$$

$$\chi \geq 0 \tag{6}$$

$$C_j\chi - Z_j = 0 \quad j \neq i \quad i, j = 1, 2, 3 \tag{7}$$

Solution of this problem is the optimal solution for objectives i over the feasible region, ignoring the other two objective functions. We may note that from equation (7), the two other objective functions are added as accounting rows.

Suppose we find the solutions to the problem II by changing i from 1 to 3. Let the optimal solution for objective i be X^i and the value of the objective function be Z_i (X^i). Further, we will denote the value of the other objective functions at X^i as Z_j (X^i). For example, $Z_2(X^1)$ and $Z_3(X^1)$ represent the level of soil loss and amount of energy use, respectively, when we try only to minimize crop production and transportation costs. Here, we define the set of the minimum value of each objective function over the feasible set as the ideal solution,

$$\bar{Z} = [Z_1(X^1), Z_2(X^2), Z_3(X^3)] = [\bar{Z}_1, \bar{Z}_2, \bar{Z}_3].$$

Table 6 presents the value of each objective function evaluated at the optimal solution X^i. Even though we know that $Z_i(X^i)$ is the minimum element in the ith row, we do not know whether $Z_1(X^2)$, $Z_2(X^1)$, and $Z_3(X^1)$ are larger or smaller than $Z_1(X^3)$, $Z_2(X^3)$, and $Z_3(X^2)$, respectively. However, we can determine when any combination of two

Table 6. The value of each objective function under alternative solutions

Objective \ Solution	X^1	X^2	X^3
Cost objective, Z_1	$Z_1(X^1)$	$Z_1(X^2)$	$Z_1(X^3)$
Soil loss objective, Z_2	$Z_2(X^1)$	$Z_2(X^2)$	$Z_2(X^3)$
Energy use objective, Z_3	$Z_3(X^1)$	$Z_3(X^2)$	$Z_3(X^3)$

objectives is in conflicting for a fixed level of the other objective. From Table 6 we can infer that if soil loss is less than $Z_2(\chi^3)$ or energy use is less than $Z_3(\chi^2)$, then there is a trade-off relationship between minimization of soil loss and energy use for a fixed level of Z_1.

Now we know the possible ranges of trade-off relationships between these two objectives and then we can examine the shape of a partial trade-off curve by using the constraint method. We will employ the constraint method rather than the weighting method because of the generality of the constraint method [8]. We may solve problem III to derive a partial trade-off curve between energy use and soil loss by parametrically changing the value of E_3 for a given level of E_1.

[Problem III]

$$\text{Min } Z_2(\chi) = C_2\chi \tag{8}$$

$$\text{subject to } A\chi \leq b \tag{9}$$

$$\chi \geq 0 \tag{10}$$

$$C_1\chi \leq E_1 \tag{11}$$

$$C_3\chi \leq E_3 \tag{12}$$

where E_i, $i = 1, 3$ are the maximum tolerable levels. If the Lagrangian values of constraints (11) and (12) are positive, then these values represent trade-off ratios between the soil loss objective and the other two objectives, respectively. It can be shown that there exists a direct correspondence between the positive Lagrangian values of constraints (11) and (12) and the nondominated set to the problem III on the one hand, and between the zero Lagrangian values of constraint (11) and/or (12) and dominated set to the problem III.

We may define the Lagrangian L of problem III:

$$\text{Min } L(\chi, u, \lambda_1, \lambda_3) = C_2\chi + u(A\chi - b) + \lambda_1 (C_1\chi - E_1) + \lambda_3(C_3\chi - E_3) \qquad (13)$$

where:

u is an 1 x m row vector; and

u, λ_1 and λ_3 are Lagrangian multipliers.

The Kuhn-Tucker conditions are:

$$\frac{\partial L}{\partial \chi} = C_2 + uA + \lambda_1 C_1 + \lambda_3 C_3 \geq 0 \qquad (14)$$

$$\frac{\partial L}{\partial \chi} \cdot \chi = (C_2 + uA + \lambda_1 C_1 + \lambda_3 C_3) \cdot \chi = 0 \qquad (15)$$

$$\chi \geq 0 \qquad (16)$$

$$\frac{\partial L}{\partial u} = A\chi - b \leq 0 \qquad (17)$$

$$\frac{\partial L}{\partial \lambda_i} = C_i\chi - E_i \leq 0 \qquad (18)$$

$$u \cdot \frac{\partial L}{\partial u} = u(A\chi - b) = 0 \qquad (19)$$

$$\lambda_i \cdot \frac{\partial L}{\partial \lambda_i} = \lambda_i (C_i\chi - E_i) = 0 \qquad (20)$$

$$u, \lambda_i \geq 0 \qquad (21)$$

Among these Kuhn-Tucker conditions, we may focus on equation (20), which is of interest to analysis. Clearly, condition (20) holds if and only if $\lambda_i = 0$ or $C_i\chi - E_i = 0$ or both. However, when the ith constraint is inactive (not binding), the Lagrangian multiplier is identically zero. In addition, the λ_i corresponding to the binding constraint is nonnegative. From equation (13), we can derive

$$\lambda_i = -\partial L/\partial E_i \qquad i = 1, 3 \tag{22}$$

Further, we can find $L\ (\chi^*, u^*, \lambda_1^*, \lambda_3^*\ ) = C_2\chi^* = Z_2^*$ by using above Kuhn-Tucker conditions and thus

$$\lambda_i = -\partial Z_2^*/\partial E_i \tag{23}$$

where χ^*, u^*, λ_1^*, and λ_3^* are optimal solution for equation (13). Since the ith binding constraint implies $C_i\chi = E_i = Z_i^*$, we can replace equation (23) as following form.

$$\lambda_i = -\partial Z_2^*/\partial Z_1^* \tag{24}$$

If $\lambda_i > 0$, then there is a degradation in the ith objective function for any improvement achieved in the second objective function. Thus, this solution corresponds to the nondominated solution. If $\lambda_i = 0$, then we can improve the second objective without a degradation in the ith objective, which implies that the solution is dominated. Therefore, we should be careful to parameterize the levels of E_1 and E_3.

Finally, we will derive two compromise solutions. Zeleny [54, 55, 56] and others [16, 21, 22] have proposed several compromise programming techniques. Zeleny [54, 56] argues that the decision maker, instead of maximizing an unknown utility function, tries to find a solution which would be as close as possible to the ideal solution. Such a fuzzy statement of human purpose is probably more realistic than maximization of utility. Then he proposed a compromise solution by using L_p-metrics. We will follow his proposed method to find two compromise solutions.

We define the distance from the ideal solution as

$$d_i(\chi) = (C_i\chi - \tilde{Z}_i)/\tilde{Z}_i \qquad i = 1, 2, 3 \qquad (25)$$

which is the percentage deviation of objective i from the ideal solution and allows us to avoid the different measuring units problem of the three objective functions. Then, we employ a family of L_p-metrics which provides a wide range of geometric measures of closeness possessing some desirable properties. L_p-metrics is defined as

$$L_p\ (\lambda_i, \chi) = [\Sigma_{i=1}^{3}\ \lambda_i^p\ d_i^p(\chi)]^{1/p},\ 1 \leq p \leq \infty \qquad (26)$$

where λ_i is the relative weight of objective i. If we solve problem IV, then the optimal solution, χ^*, is called a compromise solution with respect to p.

[Problem IV]

$$\text{Min } L_p\ (\lambda_i, \chi) = [\Sigma_{i=1}^{3}\ \lambda_i^p\ d_i^p\ (\chi)]^{1/p},\ 1 \leq p \leq \infty \qquad (27)$$

$$\text{subject to } A\chi \leq b \qquad (28)$$

$$\chi \geq 0 \qquad (29)$$

The squared loss function (p=2) has been widely used to approximate the policy-makers' implicit, true welfare or utility function [44, 45]. However, there is no reason why p = 2 is better than p = 1, ∞ or another values. Because the true utility function is unknown, the selection of any $L_p(\lambda_i, \chi)$ is necessarily arbitrary. Minimization of $L_p(\lambda_i, \chi)$ for $p \geq 2$ leads to a nonlinear optimization problem while $L_1(\lambda_i, \chi)$ and L_∞ (λ_i, χ) can be minimized by the simplex method of linear programming.

If we can assume that policy-makers consider three objectives as equally important and try to minimize the sum of the percentage deviations from the ideal solution, then we may choose p = 1 and solve problem V to get the first compromise solution.

[Problem V]

$$\text{Min } W_1 + W_2 + W_3 \tag{30}$$

$$A\chi \leq b \tag{31}$$

$$C_i\chi - \bar{Z}_i W_i = \bar{Z}_i \qquad i = 1, 2, 3 \tag{32}$$

$$\chi \geq 0 \tag{33}$$

$$W_i \geq 0 \tag{34}$$

where W_i is the percentage deviation of objective i from the ideal solution.

To derive the second compromise solution, we assume that policy-makers consider three objectives as equally important since we have no prior information about the relative weights of the three objectives. Further, it is assumed that they try to minimize the maximum percentage deviation of each objective function from the ideal solution, which implies that $p = \infty$ is an appropriate choice.

If these two assumptions are met, we may convert problem IV into problem VI.

[Problem VI]

$$\text{Min } L_p\,(\chi) = [\Sigma_{i=1}^{3}\, d_i^p]^{1/p} = [\Sigma_{i=1}^{3}\, (C_i\chi/\bar{Z}_i - 1)]^{1/p} \tag{35}$$

$$A\chi \leq b \tag{36}$$

$$\chi \geq 0 \tag{37}$$

where $p = \infty$.

As p increases, more and more weight is given to the largest distance. Ultimately, the largest distance completely dominates and for $p = \infty$ problem VI becomes problem VII.

[Problem VII]

$$\operatorname*{Min}\ \operatorname*{Max}_{i}\ (C_i\chi/\bar{Z}_i-1) \tag{38}$$

$$A\chi \leq b \tag{39}$$

$$\chi \geq 0 \tag{40}$$

Problem VII is equivalent to the following linear programming problem.

[Problem VIII]

$$\text{Min } W \tag{41}$$

$$A\chi \leq b \tag{42}$$

$$C_i\chi - \bar{Z}_i W \leq \bar{Z}_i \qquad i = 1, 2, 3 \tag{43}$$

$$\chi \geq 0 \tag{44}$$

$$W \geq 0 \tag{45}$$

where W is the minimum value of the maximum percentage deviation of each objective function from the ideal solution. If we solve problem VIII, we will get the second compromise solution.

Alternative Solutions and Their Assumptions

Nine nondominated solutions will be examined in this study. These nine alternative solutions may be classified by three categories. The three solutions included in the first category are found by assuming that policy-makers have a single objective, such as production and transportation costs (solution 1), soil loss (solution 2), and energy use (solution 7), to be minimized.

Four nondominated solutions (solution 3, 4, 5, and 6) on the partial trade-off curve are included in the second category. When we derive solutions on the partial trade-off curve, we assume that the total cost of production and transportation is 41.2 billion dollars (in 1975 dollars) which is the same level of the cost of production and transportation when policy-makers try only to minimize the energy use in U.S. crop production. This total cost is also equivalent to increase in 8.7 percent from the minimum cost of production and transportation to meet the given demands under the feasible set. The different levels of energy use are assumed for the solutions on the trade-off curve. The levels of energy use are 105 percent (solution 3), 100 percent (solution 4), 97 percent (solution 5), and 95 percent (solution 6) of the energy use in solution 1. Further, we assume that these decreasing levels of energy use could be realized by an increase in the relative prices of energy inputs or allocation of energy due to a severe energy shortage or a government's energy use reduction policy. Therefore, we will use these terms such as high energy prices or a severe energy shortage or an energy use reduction policy interchangeably when we compare the solutions which result from the different levels of energy use.

Since the solutions on the trade-off curve are efficient, the points on the trade-off curve represent the minimum levels of soil loss given the chosen levels of energy use or the minimum levels of energy use given the chosen levels of soil loss over the feasible set. Thus, the energy minimization solution (solution 7) can serve as an ending point on the partial trade-off curve because the assumed level of cost of production and transportation for the solutions on the partial trade-off curve is exactly the same as the level of cost in solution 7.

The third category includes the two compromise solutions. The first compromise solution (solution 8) is derived by assuming that policy-makers consider the three objectives as equally important and try to minimize the sum of percentage deviations from the ideal solution. The second compromise solution (solution 9) is obtained by assuming that policy-makers also regard three objectives as equally important and try to minimize the maximum percentage deviation of each objective function from the ideal solution.

The analysis of the nine nondominated solution in chapter IV is divided into two sets. The first set includes solution 1, 2, 7, 8, and 9 to show how production patterns and resources use patterns are different under single objective and multiobjective functions. The second set includes solutions on the partial trade-off curve (solutions 3, 4, 5, 6, and 7).

An Overview of Other Solution Techniques of Multiobjective Linear Programming

We have already discussed the constraint method and L_p-metrics method in the previous section. Therefore, we will confine ourselves to a brief review of the weighting method, goal programming, and interactive programming.

The weighting method

The weighting method is another way to generate all nondominated solutions if the nondominated solutions set is strictly convex. This method follows directly from the Kuhn-Tucker conditions for noninferiority and has been used extensively in the literature [5, 37]. The weighting method converts problem I as the following formulation:

$$\text{Min } \Sigma_{i=1}^{3} \ \theta_i \ C_i\chi$$

subject to $A\chi \leq b$

$\chi \geq 0$

$\theta_i \geq 0 \qquad i = 1, 2, 3$

where θ_i is the relative weighting coefficient of objective i. Parameterization of weighting coefficients allows us to find the nondominated solutions.

Goal programming

Goal programming is a modification and extension of linear programming. The works of Charnes and Cooper [7], Ijiri [26], Lee [28], and Ignizio [25] have resulted in a systematic methodology, known as goal programming, for solving linear multiple objective problems wherein preemptive priorities and weightings are associated with the objectives. One of the primary advantages of this method is that it employs the simplex algorithm on a modified basis in its computations.

Following Ignizio's [25] notation, we may convert problem I to the following form:

$$\text{Min } a = \{P_1[g_1(n,p)]P_2[g_2(n,p)], \cdots P_k[g_k(n,p)]\}$$

subject to $A\chi \leq b$

$\chi \geq 0$

$Z + n - p = T$

$n, p \geq 0$

where:

a is the achievement function (or vector) which is an ordered vector; $g_k(n,p)$ is a linear function of the deviation variables; n and p are 3 x 1 vectors which are the negative and positive deviations from T; T is a 3 x 1 vector representing a desired level of objectives; P_k is the preemptive priority factor associated with g_k (n,p); $k \leq 3$, i.e., the number of preemptive priorities are equal to or less than the total number of objectives.

The highest priority is indicated by P_1, the next highest by P_2, and so forth. We may note that the preemptive priority factors have the relationships of $P_k >>> P_{k+1}$ which implies that the multiplication of m, however large m may be, cannot make P_{k+1} greater than or equal to P_k.

Recently Dauer and Krueger [13] developed a finite iteration algorithm for solving general goal programming problems by noting that goal programming by its definition is iterative in nature. However, there are some difficulties in applying the goal programming method to deal with a real world problem. It is very difficult to determine the proper priority level for a given objective, and to quantify the target level of each objective and relative weight within a priority level.

Cohon and Marks [9] demonstrated a possible situation where we may get a dominated solution by using goal programming. Further, Morse [33] questions the general applicability of goal programming because of difficulties previously mentioned and because of a lexicographic preference ordering which is inconsistent with the existence of a utility function.

In spite of these difficulties and questions on the goal programming technique, numerous applications of this technique can be found in the literature. Applications include financial analysis [28, 30], academic planning [28, 29], economic policy analysis [28], environmental protection [8], production planning [28, 31], and health care planning [28].

Interactive programming

Since 1970, a number of multiobjective decision-making methodologies based on some kind of "decision maker-analyst" interaction has emerged. Chankong and Haimes [6] identify the common framework underlying each of these techniques. First, the analyst generates the nondominated solutions based on a mathematical model representing the structure of the system. Secondly, along with each nondominated solution the analyst obtains all necessary and meaningful information to interact with the decision maker. Finally, the decision maker assesses his preference based on this information. Based on decision maker's preference assessment, the preferred final solution is then chosen from the nondominated set. But the methods differ greatly from one another in the way which each of the above steps is treated and emphasized.

Various interactive methods for multiobjective linear programming have been proposed by Benayoun et al. [3], Belenson and Kapur [2], and Haimes and Hall [24].

The basic problem in this approach is that the estimation of subjective indifference trade-off values by the decision maker is, in practice, very difficult to accomplish.

CHAPTER III. MODEL DESCRIPTION

An interregional linear programming model, which is a modified version of the National Water Assessment (NWA) model described by Meister and Nicol [32], will be used in this study. The year 1990 is selected as the basis for the analysis to provide a time span long enough to allow for the implied adjustments in technology and interregional shifts in production pattern.

We will specify the three objective functions, the set of constraints and activities. The objective functions are minimization of the total cost of crop production and transportation, minimization of gross soil loss, and minimization of direct and indirect energy use. The constraints in the model are the availability of land, water, fertilizer, and regional commodity demands. The set of activities includes endogenous crop production activities, water use activities, commodity transportation activities, nitrogen buy activities, and land development and conversion activities.

Endogenous crop production activities are specified for barley, corn grain, corn silage, cotton, legume hay, nonlegume hay, oats, sorghum grain, sorghum silage, soybean, wheat, and summer fallow.

The projected production levels of all other crops (fruits, vegetables, tobacco, potatoes, rice, peanuts, buckwheat, etc) and all livestock including beef cows, beef feeding, dairy cows, hogs, turkeys, broilers, egg production, sheep and lambs, and others are exogenously determined.

There are approximately 1,200 resource constraints and more than 30,000 activities in the model. Further, we will assume that energy coefficients for field operations on the same crop for different land classes and conservation methods in a producing area (PA) are the same.

Regional Delineation

Four sets of regions are defined within the model including producing areas, aggregate subareas, market regions, and reporting regions.

The producing areas (PAs) (Figure 1) are the 105 regions which are derived from the Water Resource Council's 99 aggregated subareas (ASAs). The PAs are identical to the ASAs with the exception of six ASAs which are divided in two to be more consistent with agricultural production in these regions.

Each producing area is an aggregation of contiguous counties approximating an ASAs boundaries. Producing areas 48 to 105 serve dual purposes since they define both agricultural production and water supply regions. Crop production activities, crop acreage restraints, water availability, and the land base are defined within each of these producing areas.

The 28 market regions (MRs) (Figure 2) are an aggregation of the 105 producing areas. Each market region represents an established commercial and transportation center and serves as the hub of commodity demands and transportation. The market regions also serve as the market framework for nitrogen purchasing activities.

A final set of regions are defined by aggregating adjacent market regions into seven major regions (Figure 3). The regions are the North

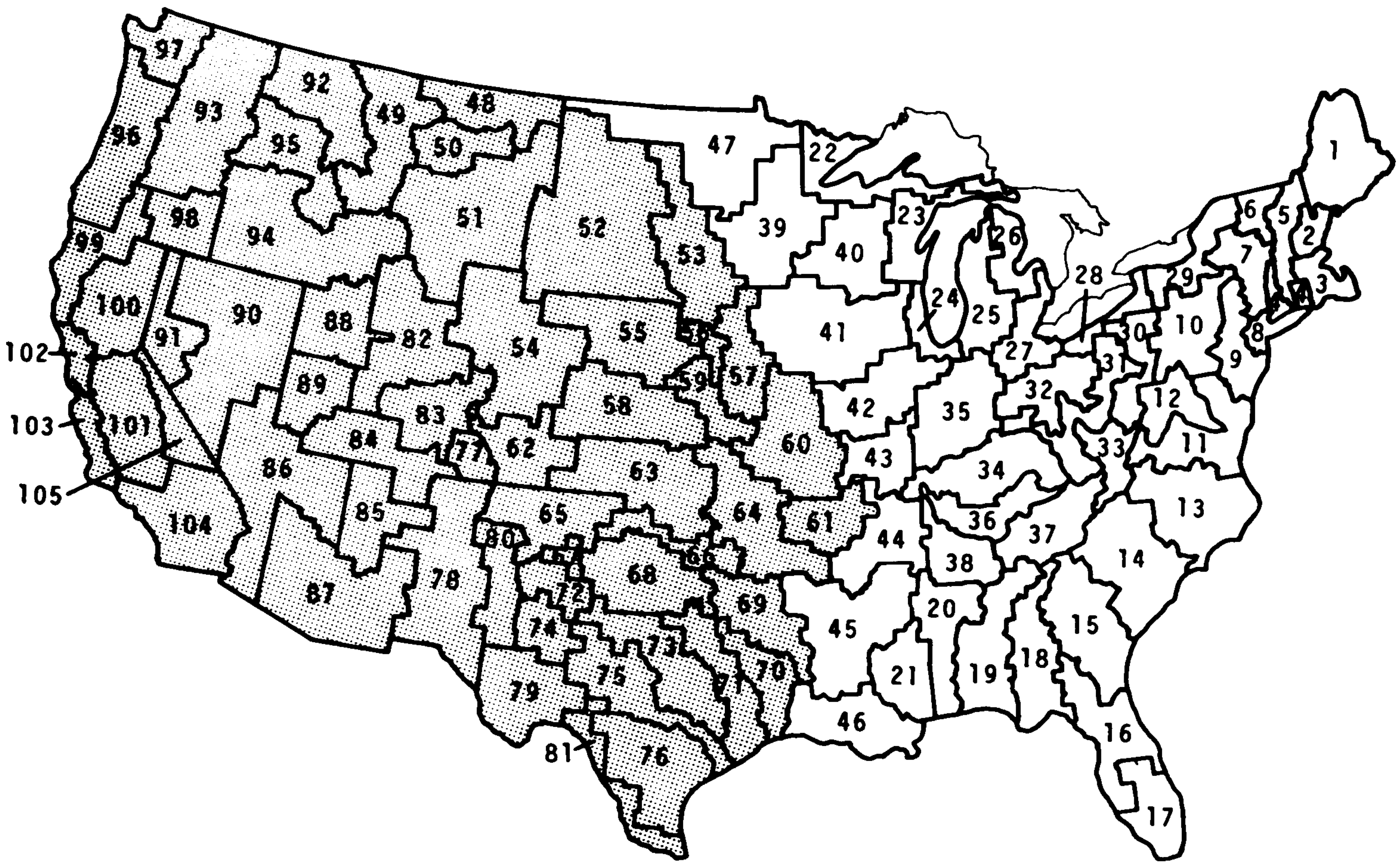

Figure 1. The producing areas with irrigated lands

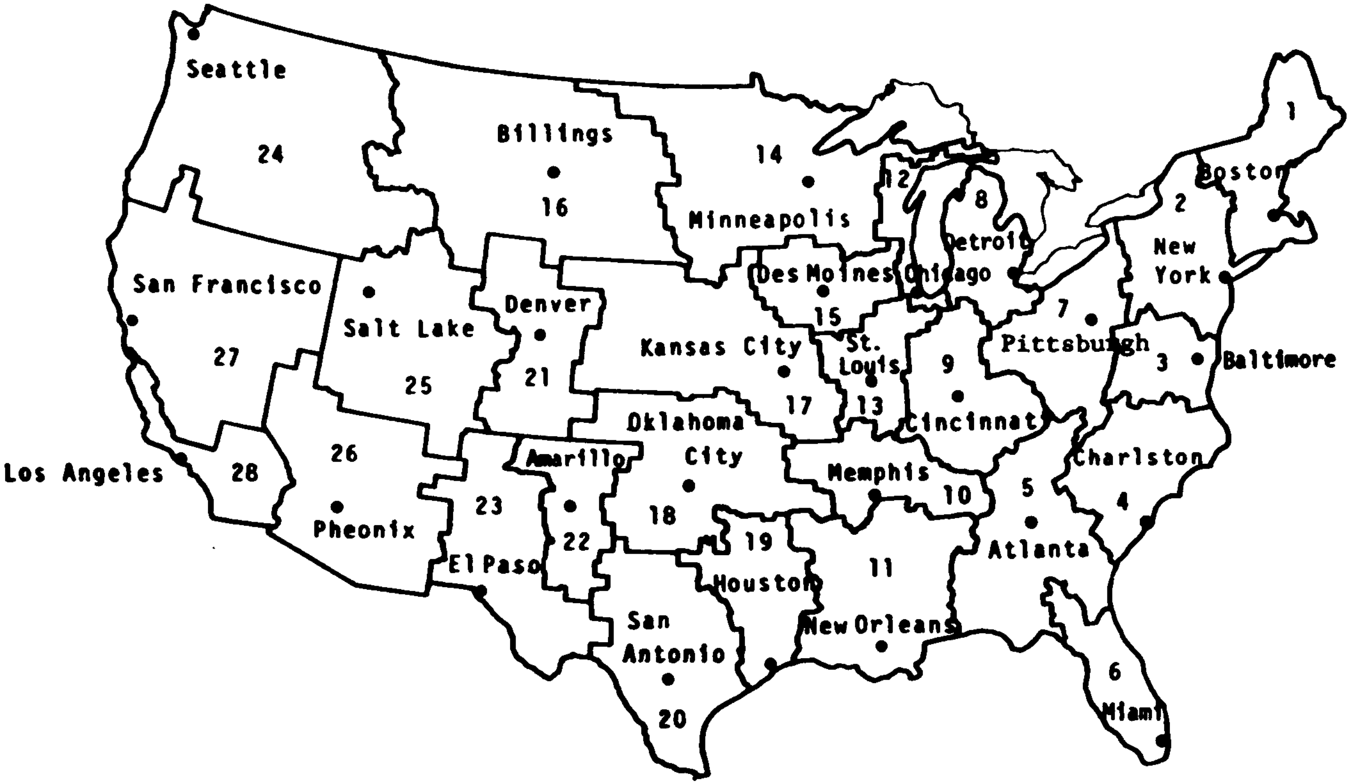

Figure 2. The 28 market regions

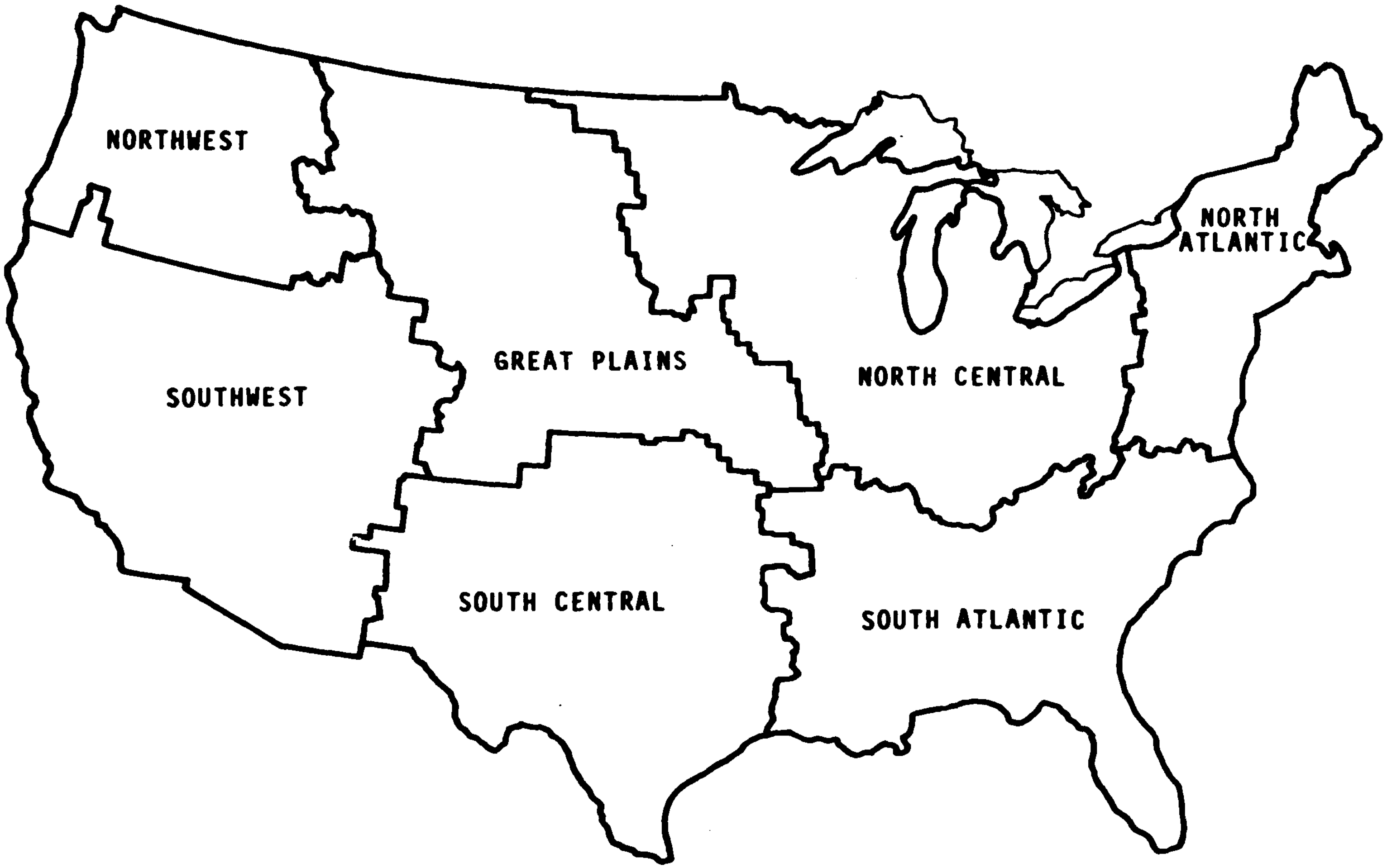

Figure 3. The 7 reporting regions

Atlantic, South Atlantic, North Central, Great Plains, South Central, Northwest, and Southwest.

The Objective Functions

Three objective functions are used in the study. The first objective function minimizes the total cost of crop production and transportation. Costs included in the objective function are labor, machinery, pesticides, fertilizers, water, transportation of raw material commodities, and land development and conversion. These costs are specified in 1975 dollars. The cost minimization objective function is of the form:

$$\begin{aligned} Z_1\ (\chi) = {} & \Sigma_i \Sigma_j \Sigma_k \Sigma_m\ X_{ijkm}\ XC_{ijkm} \\ & + \Sigma_r (W_r^s WC_r^s + W_r^g WC_r^g) \\ & + \Sigma_u \Sigma_v\ W_{uv}^a\ WC_{uv}^a + \Sigma_n \Sigma_s \Sigma_t\ T_{nst}\ TC_{nst} \\ & + \Sigma_i (LD_i DC_i + RD_i RC_i) + \Sigma_n\ F_n FC_n \end{aligned}$$

The second objective to be minimized in the model is gross soil loss from cropland. The soil loss minimization objective function is of the form:

$$Z_2\ (\chi) = \Sigma_i \Sigma_j \Sigma_k \Sigma_m\ X_{ijkm}\ SL_{ijkm}$$

The third objective function minimizes the total amount of energy consumed in crop production and transportation. The types of energy in this objective function are diesel fuel for field operations, irrigation, and commodity transportation, liquid petroleum gas (LPG) for crop drying and irrigation, and natural gas and electricity for irrigation and production of fertilizers and pesticides.

All different energy types[1] are converted to the common unit, British thermal unit (Btu).

The energy minimization objective function is of the form:

$$Z_3\ (\chi) = \Sigma_i \Sigma_j \Sigma_k \Sigma_m\ X_{ijkm}\ KBX_{ijkm} + \Sigma_r (W_r^s\ KBW_r^s + W_r^g\ KBW_r^g) + \Sigma_n \Sigma_s \Sigma_t\ T_{nst}\ KBT_{nst} + KBF\ \Sigma_n F_n$$

i = 1,•••, 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 and tillage alternatives,

n = 1,•••, 28 for the market regions,

r = 1,•••, 58 for the water supply regions,

s = 1, 2, 8, 11, 13, 15, for the commodities[2] transported,

t = 1,•••, 176 for the transportation routes defined, and

u, v = 1•••, 52 for the aggregate subareas (ASAs).

where:

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

---

[1] The conversion factors used here are: diesel fuel, 140,000 Btu per gallon; LPG, 94,500 Btu per gallon; natural gas, 1,067,500 Btu per 1000 cubic feet; electricity, 3,408.77 per KWH.

[2] The endogencus commodities and their respective numbers used is as follows: barley, 1; corn grain, 2; corn silage, 3; cotton, 4; legume hay, 5; nonlegume hay, 6; oats, 8; sorghum grain, 11; sorghum silage, 12; soybean, 13; wheat, 15; summer fallow, 17.

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

W_r^s is the number of acre feet of surface water purchased in water supply region r;

WC_r^s is the cost per acre-foot of surface water purchased in water supply region r;

W_r^g is the number of acre feet of ground water purchased in water supply region r;

WC_r^g is the cost per acre-foot of ground water purchased in water supply region r;

W_{uv}^a is the amount of water transferred from aggregate subarea u to aggregate subarea v;

WC_{uv}^a is the cost of artificial water transfer per acre-foot from aggregate subarea u to aggregate subarea v;

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

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

LD_i is the number of acres of land drained and converted to cropland in producing area i;

DC_i is the per acre cost for draining and converting land to cropland in producing area i;

RD_i is the number of acres developed for irrigation under private development in producing area i;

RC_i is the cost per acre for private irrigation development in producing area i;

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;

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

KBX_{ijkm} is the energy needed, in 1000 Btu, for field operations, pesticides, and nonnitrogen fertilizers by the rotation k with conservation-tillage practice m in producing area i on land class j;

KBW_r^s is the energy needed, in 1000 Btu, to obtain and apply one acre foot of surface water in region r;

KBW_r^g is the energy needed, in 1000 Btu, to obtain and apply one acre foot of ground water in region r;

KBT_{nst} is the energy needed, in 1000 Btu, to transfer a unit of commodity s over route t from market region n; and

KBF is the energy needed, in 1000 Btu, to produce one pound of nitrogen fertilizer.

Restraints

The restraints in the model are defined either at the producing area, water supply region, market region, or national level.

Restraints at the producing area level

Two sets of restraints are defined at the producing area level. The equations are as follows:

Dryland restraint by land class

$$\Sigma_k \Sigma_m X_{ijkm} AD_{ijkm} - LD_i \; LDP_{ij} + RD_i \; RDP_{ij} \leq DA_{ij}$$

i = 1,..., 105 for the producing areas,

j = 1,..., 5 for the land classes,

k = 1,..., 330 for the rotations defined,

m = 1,..., 12 for the conservation and tillage alternatives;

Irrigated land restraint by land class

$$\Sigma_k \Sigma_m X_{ijkm} \; AI_{ijkm} - RD_i \; RDP_{ij} \leq IA_{ij}$$

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 and tillage alternatives.

where:

X_{ijkm} is the level of rotation k using conservation-tillage practice 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 practice 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 practice 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;

LD_i is the level of the land drainage in producing area i;

LDP_{ij} is the proportion of the land drainage in producing area i which is on land class j;

RD_i is the level of irrigated land development in proudcing area i; and

RDP_{ij} is the proportion of the irrigated land developed in producing area i which is in land class j.

Restraints at the water supply region level

Two sets of restraints are defined in each of the water supply regions (producing areas 48 to 105). These restraints balance the dependable water supply in the region, including natural flow and artificial transfer of surface water, and the many water uses in 1990.

In developing these restraints, it is assumed that nonagricultural users, livestock demands, fish and wildlife demands, downstream requirements, and the irrigation of exogenous cropland are higher valued uses than irrigation of endogenous cropland. Thus, the restraints for surface water availability are calculated as the difference between total water available and the water required by these exogenous demands. Further information on the water sector is available from Colette [10], and Short, et al. [40].

Restraints at the market region level

Two sets of restraints are defined at the market region level. These restraints include commodity transfer restraints and nitrogen fertilizer transfer restraints.

Commodity demand restraints are defined as the following form:

$$\Sigma_i \Sigma_j \Sigma_k \Sigma_m X_{ijkm} W_{ijkmu} CY_{ijkmsu} - \Sigma_t T_{nst} + \Sigma_r WH_r DA_{rs} \geq CD_{ns}$$

$i = 1, \cdots, 105$ for the producing areas,

$j = 1, \cdots, 10$ for the land classes,

$k = 1, \cdots, 330$ for the rotations,

$m = 1, \cdots, 12$ for the conservation-tillage practices,

$n = 1, \cdots, 28$ for the market regions,

$r = 48, \cdots, 105$ for the producing areas in irrigated regions,

$s = 1, 2, 3, 5, 6, 8, 11, 12, 13, 15$ for the commodities, balanced at the market region,

$u = 1, \cdots, 17$ for the crops,

$t = 1, \cdots, 176$ for the transportation activities defined.

where:

X_{ijkm} is the level of crop rotation k using conservation-tillage practice 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 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;

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 supply region r; and

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 $s \neq 5$.

Nitrogen fertilizer transfer restraints are as follows:

$$\Sigma_i \Sigma_j \Sigma_k \Sigma_m X_{ijkm} \quad W_{ijkmu} N_{iku} - F_n \leq NR_n$$

$i = 1, \cdots, 105$ for producing area,

$j = 1, \cdots, 10$ for the land classes,

$k = 1, \cdots, 330$ for the rotations,

$m = 1, \cdots, 12$ for the conservation-tillage practices,

$n = 1, \cdots, 28$ for the market regions, and

$u = 1, \cdots, 17$ for the crops.

where:

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

N_{iku} is the quantity of nitrogen for crop u in rotation k in producing area i;

F_n is the amount of commercially produced nitrogen, in pounds, purchased for the endogenous crops in market region n; and

NR_n is the quantity of nitrogen supplies by exogenous livestock less the quantity required for exogenous crop production in market region n.

Restraints at the national level

The demand for cotton is defined at the national level:

$\Sigma_i \Sigma_j \Sigma_k \Sigma_m X_{ijkm} \; W_{ijkmu} \; CY_{ijkmu} \geq CD_u$

i = 1,···, 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 practices, and

u = 4, for cotton.

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

CD_u is the demand for cotton u at a national level.

Activities

The activities in the model include crop production activities, commodity transportation activities, resource supply activities such as nitrogen and water, and two sets of land conversion activities.

Crop production activities

Crop production activities of endogenous crops are defined on each land class in each producing area. These activities represent crop management systems, incorporating rotations of one to four crops, covering from one to eight years, with a given conservation treatment, and a given tillage practice. The crop rotations defined in each producing area are selected from 330 unique rotations developed from the Soil Conservation Service Questionnaire [32]. 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. For each of the crop management systems developed on each land class in each producing area, costs, soil loss, energy requirements, crop yields, fertilizer use, and water use coefficients are calculated. The derivation of energy use for crop production is detailed in [14, 15].

Commodity transportation activities

Transportation routes are defined between each pair of contiguous consuming region. Over each route two activities are defined for each commodities, one activity for shipment in each direction. Commodity transportation activities are defined for the following six crops: barley, corn, oats, sorghum, soybeans, and wheat. Cost and energy requirements for transportation activities are calculated. For the purpose of deriving the energy need in the transportation coefficients, it is assumed that all grains are moved by railroad and that one gallon of diesel fuel is required for every 297 ton-mile of shipment [14].

Nitrogen buy activities

Commercially produced nitrogen buy activities are unbounded, which allows the model to purchase as much nitrogen as required for the optimal solution. These activities are defined in each of the market region with the 1975 normalized state nitrogen prices. The commercial nitrogen buy activities supply nitrogen and consume natural gas and electricity for nitrogen production. The estimation method of energy requirement for nitrogen production can be found in [14, 15].

Activities in water sector

Five sets of activities are defined in the model. These activities include surface water buy activities, ground water buy activities, the natural flow of surface water activities, artificial transfer activities, and water hay activities.

The water buy activities allow the purchase of dependable supplies of surface and groundwater. The price of surface water in each irrigable PA is defined as the sum of average reimbursable costs of Bureau of Reclamation water projects and energy costs for pumping and applying the surface water. The price of the groundwater in each irrigable PA is defined only by the energy costs for pumping and applying the groundwater. The energy coefficients for irrigation are given in [39].

Two sets of water transfer activities are defined to allow surface water to be transferred between producing regions within a river basin through natural flows and within and between river basins through man-made methods of transporting water. Costs of artificial transfers represent canal operation costs.

The water hay activities allow exogenous dryland hay to be converted to irrigated hay land. These activities produce only hay and use only water. Additional information on the water sector is available in [10].

Land development and conversion activities

Two sets of land conversion activities are defined in the model. The first set allows the model to determine whether additional irrigation is desirable. The second set converts forest and pasture lands to nonirrigable cropland.

The tables for the cost of land conversion, potential public and private irrigated development, and potential wetland development by producing area, and a detailed description of the land base adjustment methods are available in Meister and Nicol [32].

Soil Loss

Gross soil loss represents the average annual tons of soil leaving the field. This measurement of soil loss does not represent the amount of sediment since only a small portion of erosion is transported to rivers. Two separate procedures are used to calculate the gross soil loss per acre. For the areas east of the Rocky Mountains, the Universal Soil Loss Equation is used to develop the gross soil loss for each crop production activities. The soil loss equation is represented by the following form:

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

where:

A is the average annual soil loss per acre;

R is the average rainfall erosion index per year;

K is the soil erodibility factor;

L is the slope length factor;

S is the slope gradient factor;

C is the crop 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.

Further detailed information is available from Wischmeier and Smith [53]. For the areas west of the Rocky Mountains, an alternative procedure is developed, which is reported in Meister and Nicol [32].

Land Base

The total surface area of the United States is about 2.36 billion acres. Of this, two-thirds and one-third are nonfederal land and federal land, respectively. In 1977, the 1.5 billion acres of nonfederal land in the United States consisted of 413 million acres of cropland, 414 million acres of range land, 377 million acres of forest land, 134 million acres of pasture land, and 178 million acres of others. Of the 413 million acres of cropland, 58 million acres are irrigated and 356 million acres nonirrigated [48].

The land available for crop production in each producing area is determined from the Conservation Needs Inventory (CNI) [11]. The eight land capability (I to VIII) classes are defined in 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 four subclasses reflect susceptibility to erosion (e), subsoil exposure (s), drainage problem (w), and climatic conditions preventing normal crop production (c). These 29 capability class-subclasses are then aggregated into five land classes (Table 7).

Table 7. Aggregate land capability classes

Land class	Inventory class-subclass
1	I, II_{wa}, III_{wa}
2	Rest of II, III_c, III_w, III_s, IV_c, IV_w, IV_s, all of V
3	III_e
4	IV_e
5	all of VI, VII, and VIII

An adjustment is made for the projected changes in urban land needs, other nonagricultural needs, land use by exogenous crops, and double cropping in the year 1990.

Commodity Demands

The levels of the total commodity demands used in this study are given in Table 8. Total demands for each commodity are composed of domestic consumption and net exports for 1990. The annual projected domestic human commodity demands for 1990 are derived by multiplying per capita demand times projected population. The levels of exports assumed in the study are high. The study also assumes a U.S. population of 250 million by 1990.

Table 8. Projected U.S. total commodity demands for 1990

Commodity	Unit	Projected total demand
		----(Million unit)----
Barley	bushel	749.9
Corn grain	bushel	8,822.4
Oats	bushel	1,002.9
Sorghum grain	bushel	1,159.8
Soybeans	bushel	2,648.9
Wheat	bushel	3,133.3
Cotton	bale	12.3
Hay	ton	145.3
Silage	ton	107.6

CHAPTER IV. ANALYSIS OF RESULTS

Two sets of analyses will be made at national and regional levels. The first set includes the solutions of the minimization of crop production and transportation costs (solution 1), soil loss (solution 2), energy use (solution 7), and the two compromise solutions (solutions 8 and 9). For the second set, the solutions on the trade-off curve (solutions 3, 4, 5, 6, and 7) will be selected.

The first set of analyses will demonstrate what is the minimum level of production and transportation costs, soil loss, and energy use to meet the given levels of demands specified in the model if the policy-makers pursue only a single objective. Further, we will derive the two compromise solutions under specific assumptions about the policy-makers' objective function since we cannot achieve these three goals simultaneously under the feasible set. Then, we will compare these five solutions in terms of production patterns and resources use patterns. Also, the compromise solutions will show how much we may wish to allow each of the three objectives to differ from the ideal solution if these objectives are conflicting to one another.

The second set of analyses will provide the shape of a partial trade-off relationship between national soil loss and energy use, and changes in land use patterns, other resource use patterns, and the regional distribution of endogenous crop production.

However, the analyses involving shadow prices of constraints such as returns to land, supply prices of the agricultural commodities, and farm income distribution under the alternative solutions are not made since shadow prices of resources are expressed in terms of soil loss (solutions 2, 3, 4, 5, and 6), energy (solution 7), or percentage deviation from the ideal solution (solutions 8 and 9) and thus, they are incomparable under alternative solutions.

Single Objective versus Multiobjective

From the agricultural policy-makers' point of view, they may have multiple objectives such as efficient production, reduction of soil erosion and energy use, conservation of water, minimizing discharge of toxic pollutants, providing adequate food at reasonable and stable prices, and solving the instability problems of price and income. Some objectives are conflicting and others are complementary. If they pursue only the efficiency goal in the sense that the cost of production and transportation is the minimum, then the production patterns associated with the minimum cost could be inefficient since the marginal social cost would be greater than the marginal social value of crop production. Further, these production patterns could be nonoptimal in the sense that energy use in the production process is higher than the minimum level of energy use to meet the given demands if policy-makers try to minimize the energy use in U.S. agriculture.

In this study, we restrict ourselves by assuming that policy-makers have only three objectives. These objectives are minimization of production and transportation costs, soil loss, and energy use.

Solution 1, solution 2, and solution 7 show the production patterns with the minimum levels of cost, soil loss, and energy use, respectively, if policy-makers pursue only a single objective.

Solution 8 and solution 9 are compromise solutions since we cannot achieve three objectives simultaneously under the feasible set. Solution 8 is derived by assuming that the policy-makers consider three objectives as equally important and try to minimize the sum of percentage deviations from the ideal solution. Solution 9 is found by assuming that policy-makers try to minimize the maximum percentage deviation of each objective from the ideal solution. The detailed methods are explained in Chapter II.

Before we analyze the results of the solutions, we may note some assumptions and limitations in the linear programming techniques. The basic assumptions are proportionality and additivity. The proportionality assumption means complete divisibility of all the commodities and constant returns to scale. Therefore, fractions of decision variables must be acceptable in the solution and the marginal products for the inputs are constant over the relevant range. The additivity assumption implies there are no interactions among activities. That is, there are no external economies or diseconomies. Further, fixed coefficients and no risk are assumed in the model. All the above assumptions are not fully consistent with the real world.

The assumptions made for the linear programming technique cause the model to be a static or normative one. Thus, the model does not provide any information on how the transformation from one alternative to the other can be accomplished with the least impact during the transformation period, but it allows us to analyze the impacts of alternative policies and structural changes such as changes in resource availability, changes in the levels of demands, changes in institutional restrictions, and changes in farming techniques [32].

It is true that the minimization of soil loss (solution 2) or energy use (solution 7) is more unrealistic assumptions and thus, more politically infeasible than the minimization of production and transportation costs (solution 1). However, the results of all solutions should not be treated as an exact prediction of the real world. Rather, they show the direction and relative strength of impacts due to changes made in the assumptions.

The data in Table 9 provide an aggregate summary of the alternatives. The minimum levels of cost of production and transportation excluding land cost, soil loss, and energy use under the feasible set are 38 billion dollars (in 1975 dollars), 188 million tons, and 1,106 trillion Btu, respectively. The ideal solution consists of these three numbers. The largest cost of production and transportation is needed when policy-makers try to minimize the level of soil loss. The possible reductions of soil loss and energy use under the feasible set are 78 percent and 8 percent from the levels in solution 1.

The first compromise solution (solution 8) suggests that the policy-makers may want to give up 14 percent of the minimum cost goal, 6 percent of the minimum soil loss goal, and 9 percent of the minimum energy use goal, respectively, from the ideal solution. The second compromise solution (solution 9) indicates that we need to increase the costs by

Table 9. Total cost, soil loss, energy use, land use, nitrogen use, pesticide use, and water use under alternative solutions in 1990

Item	Unit	Solutions				
		1	2	7	8	9
Cost	billion dollars[a]	37.9	48.4	41.2	43.3	42.8
Soil loss	million tons	862.5	187.5	609.1	197.8	211.8
Energy	trillion Btu	1,197.5	1,399.1	1,106.1	1,260.3	1,218.9
Dryland	million acres	344.8	322.9	356.4	323.9	331.0
Irrigated land	million acres	26.4	41.9	24.2	39.8	36.4
Total land	million acres	371.2	364.8	380.6	363.7	367.5
Nitrogen fertilizer	billion pounds	15.0	16.4	13.5	15.6	15.0
Pesticides	billion dollars[a]	3.1	5.5	5.0	5.3	5.3
Surface water	million acre-foot	31.7	39.1	36.3	38.7	38.4
Ground water	million acre-foot	10.5	27.6	4.8	20.4	16.6
Total water	million acre-foot	42.2	66.7	41.1	59.1	55.0

[a] Dollars are in terms of 1975 dollars.

4.9 billion dollars (in 1975 dollars), soil loss by 24.3 million tons, and 102.8 trillion Btu, respectively, from the ideal solution.

Total land use varies from 364 million acres to 381 million acres to meet the given levels of demands. When energy use is the minimum (solution 7), the use of dryland is the maximum and the use of irrigated land is the minimum, which is a reflection of the substitution of cropland for energy inputs. On the other hand, solution 2 indicates that the minimum level of soil loss could be achieved by utilizing higher level of irrigated land and lower level of dryland to meet the given demand, which is consistent with the relatively high erosive nature of the rainfed midwestern and eastern regions compared to the arid western regions.

Application of nitrogen fertilizers is the minimum when the level of energy use is the minimum since the production of nitrogen input requires a significant amount of energy use. Application of pesticides is directly related to tillage practices. Increased use of reduced tillage to reduce energy use and/or soil loss requires increased use of pesticides to control weeds and insects. The levels of pesticide use of the two compromise solutions are between the levels found in solution 2 and solution 7.

The levels of total water use are closely related to the number of irrigated acres. Under the minimum levels of soil loss and energy use, the levels of total water use are the maximum and minimum, respectively. When energy use is the minimum, a drastic decline in groundwater use occurs because energy requirements to obtain and apply groundwater are substantially greater than these for surface water.

Soil loss

Table 10 provides the annual average rate of erosion per acre by the 7 regions in the nation for the alternative solutions. When we

Table 10. Soil loss per acre by major region under alternative solutions in 1990

Region	Solutions				
	1	2	7	8	9
	------------(Tons per acre)-----------				
United States	2.33	0.51	1.60	0.54	0.58
North Atlantic	2.01	0.55	1.56	0.61	0.62
South Atlantic	4.09	0.62	2.61	0.66	0.67
North Central	1.75	0.50	1.31	0.52	0.54
Great Plains	2.14	0.44	1.38	0.47	0.50
South Central	2.93	0.65	2.03	0.68	0.77
Northwest	1.73	0.20	0.62	0.23	0.23
Southwest	1.82	0.51	1.77	0.55	0.60

minimize the total cost of production and transportation, about 2.33 tons per acre or about 863 million tons of soil are eroded from U.S. cropland. As we allow costs to increase, the annual soil erosion rate could decline from 2.33 tons per acre to 0.51 tons per acre. This decline in erosion may be achieved through an increase in conservation tillage practices and interregional adjustments in crop production patterns. The erosion hazards in the South Atlantic and South Central regions are great. On the other hand, the western regions have a relatively low level of soil loss which is consistent with their low annual run-off rates.

The data in Table 11 indicate the annual average rate of soil erosion per acre by land class for the alternative solutions.

Table 11. Soil loss per acre by land class under alternative solutions in 1990

	Solutions				
	1	2	7	8	9
	-----------(Tons per acre)-----------				
Dryland	2.42	0.50	1.65	0.53	0.57
I	2.14	0.76	1.56	0.76	0.81
II	1.74	0.53	1.37	0.54	0.58
III	2.19	0.29	0.77	0.38	0.39
IV	6.60	0.31	1.24	0.33	0.44
V	26.63	0.36	19.70	0.39	0.39
Irrigated	1.27	0.64	0.92	0.64	0.66
I	2.19	1.18	1.61	1.21	1.20
II	0.74	0.52	0.50	0.49	0.49
III	0.54	0.18	0.27	0.16	0.17
IV	1.51	0.39	0.91	0.38	0.36
V	4.58	2.09	7.07	14.56	14.56

In soution 1, dryland is more erosive than irrigated land by about a factor of two. Even though land class I of the dryland is in general less erosive than the other land classes, all of the alternatives show that soil loss per acre in land class II is the smallest. This is because a relatively large share of erosive crops, such as soybeans, cotton and silage crops is produced on land class I, and the lands in land class I are intensively used to produce these crops.

Land use patterns and crop yields

Abundant land resources are the major input to meet the domestic and foreign demands for agricultural commodities. The availabilities of land by region and class serve as the most binding constraints in the model. The data in Table 12 indicate U.S. crop acreage for the alternative solutions. About a one-third of the total endogenous cropland is used for feed grain production. In the minimum level of soil loss solution (solution 2), all crops except hay crops utilize more irrigated land to reduce soil loss when compared to the solution 1. The decrease in irrigated hay crops may be due to the relatively low erosion rate of hay crops, and the limited availabilities of land and water in the western regions. The decline in irrigated hay acreage leads to a significant increase in dryland hay acreage to meet the hay demands for exogenous livestock production.

The decline in the irrigated acreage of all crops compared to solution 1, under the minimum level of energy use (solution 7), is a sharp contrast to the increase in the irrigated acreage in solution 2. In production of most crops, the two compromise solutions show the intermediate levels of land use patterns of the solution 2 and 7.

The direct reflection of land use patterns by crop is the crop production patterns for the alternative solutions even though the regional differences in yield will affect the total amount of crop production. Table 13 provides crop production by dryland and irrigated land.

Table 12. U.S. crop acreages under alternative solutions in 1990

Crop	Solutions				
	1	2	7	8	9
	-----------(Thousand acres)-----------				
Feed grains[a]					
dryland	112,284	107,646	118,295	111,295	112,016
irrigated	11,393	19,631	9,031	15,450	14,650
Soybeans					
dryland	77,582	74,886	77,722	76,690	78,166
irrigated	29	4,099	1	3,132	2,335
Wheat					
dryland	77,129	78,306	76,196	73,428	75,549
irrigated	4,245	7,302	5,406	10,646	8,714
Cotton					
dryland	7,056	5,131	6,134	5,150	5,116
irrigated	2,220	2,663	1,830	2,563	2,552
Hay					
dryland	41,147	44,177	45,694	42,863	43,232
irrigated	7,028	6,640	6,602	6,501	6,624
Silage					
dryland	5,157	5,458	5,649	5,268	5,272
irrigated	1,456	1,589	1,275	1,523	1,521

[a] Feed grains consist of corn, barley, oats, and sorghum.

Table 13. U.S. crop production on dryland and irrigated land under alternative solutions in 1990

Crop	Unit	Solutions				
		1	2	7	8	9
		---------------(Million unit)---------------				
Dryland						
Feed grains[a]	bushel[b]	9,886.9	9,008.4	10,190.1	9,394.9	9,502.8
Soybeans	bushel	2,647.4	2,448.9	2,648.8	2,495.6	2,536.1
Wheat	bushel	2,837.1	2,658.4	2,753.0	2,439.0	2,545.0
Cotton	bale	8.5	7.7	9.2	7.8	7.7
Hay	ton	113.0	118.4	119.2	116.1	117.6
Silage	ton	77.2	78.1	81.7	77.7	77.6
Irrigated						
Feed grains[a]	bushel[b]	1,311.2	2,189.6	1,007.9	1,803.1	1,695.2
Soybeans	bushel	1.5	200.1	0.1	153.3	112.7
Wheat	bushel	296.2	474.9	380.3	694.3	588.2
Cotton	bale	3.8	4.6	3.1	4.6	4.6
Hay	ton	33.2	30.3	29.4	29.8	30.4
Silage	ton	30.4	29.6	25.9	30.0	30.0

[a] Feed grains consist of corn, barley, oats and sorghum.

[b] Indicates corn equivalent bushels.

Another important aspect of the changes in land use patterns is the changes in acreage utilization by land class. The data in Table 14 provide endogenous land use by land class and the percentage changes from solution 1. About 56 percent of total endogenous cropland use comes from land class II under the minimum cost production (solution 1).

Under the minimum level of soil loss (solution 2) and the two compromise solutions (solutions 8 and 9), the utilization rate of the dryland portion of all land classes is reduced when compared to solution 1. Reduced utilization of land classes IV and V, which are the most erosive land, is especially significant. The reductions in the use of total dryland are 6.4 percent, 6.1 percent, and 4 percent under solutions 2, 8, and 9, respectively, as compared to solution 1.

When the level of energy use is minimized, acreages of dryland portion of every land class increase compared to solution 1. This is because of substitution of cropland for energy inputs to reduce energy use without consideration of cost and soil loss.

Further, we will investigate how conservation-tillage practices might be affected under the different objective functions. The data in Table 15 indicate the land use patterns by conservation-tillage practices.

In solution 1, 30 percent, 53 percent, 5 percent, and 12 percent of the farming are straight row, contour farming, strip cropping, and terracing, respectively. Solutions 2, 7, 8, and 9, when compared to solution 1, show increases in contour farming and terracing, and decreases in straight row farming as a reflection of a relatively lower

Table 14. Endogenous land use by land class in solution 1 and percentage changes for the alternative solutions in 1990

Land class	Solutions				
	1	2	7	8	9
	(Million acres)	(Percentage change from solution 1)			
Dryland					
I	54.9	-10.8	4.3	-8.9	-5.6
II	193.3	-4.8	1.7	-4.8	-2.7
III	72.4	-3.7	0.7	-3.1	-1.7
IV	21.1	-9.8	5.7	-9.5	-6.9
V	3.1	-64.2	140.6	-85.8	-85.5
Total	344.8	-6.4	3.4	-6.1	-4.0
Irrigated					
I	9.1	16.4	-26.2	19.6	18.1
II	14.2	60.5	0.2	50.6	37.8
III	2.2	149.4	-11.5	127.7	84.5
IV	0.8	276.1	10.5	223.0	159.1
V	0.1	-8.6	220.3	-87.5	-87.5
Total	26.4	59.0	-8.4	51.0	38.0
All land					
I	64.0	-7.0	-0.1	-4.9	-2.3
II	207.5	-0.34	1.6	-1.0	0.1
III	74.6	0.7	0.3	0.7	0.7
IV	21.9	1.1	6.0	-0.6	-0.5
V	3.2	-62.0	139.7	-85.8	-85.6
Grand total	371.2	-1.7	2.6	-2.0	1.0

Table 15. Land use by conservation-tillage practice under alternative solutions in 1990

Conservation-tillage practice	Solutions 1	2	7	8	9
	(Million acres)				
Straight row					
Residue removed	2.85	0.28	2.12	0.20	0.20
Residue left	46.19	6.54	13.60	7.05	7.05
Reduced tillage	60.64	55.18	66.64	59.88	61.55
Contours					
Residue removed	2.04	0.29	2.42	0.24	0.24
Residue left	70.03	3.32	6.64	3.81	3.16
Reduced tillage	124.65	200.27	194.03	198.87	201.64
Strip cropping					
Residue removed	0	0	0.01	0	0
Residue left	3.76	0.71	1.98	0.71	0.73
Reduced tillage	14.74	0.22	8.22	1.48	1.81
Terraces					
Residue removed	0.61	0.05	0.05	0.05	0.05
Residue left	36.90	9.24	9.57	8.11	7.45
Reduced tillage	8.77	84.67	75.30	85.26	83.57

level of national soil loss. Tillage practices shift from conventional tillage practices to reduced tillage practices to achieve the minimum levels of soil loss and energy use, and to minimize the sum of deviations and the maximum deviation from the ideal solution. The use of reduced tillage practices is 56 percent in solution 1 and increases to 94 percent, 90 percent, 95 percent, 95 percent in solutions 2, 7, 8, and 9, respectively. This increased adoption of reduced tillage practices results in a substantial increase in the use of pesticides since chemical controls are substituted for mechanical controls as a means of controlling pests.

National average yields are a reflection of changes in land class utilization by crops, the proportion of crops grown on dryland and irrigated land, the regional allocation of crops, rotations, and conservation-tillage practices. Other things being equal, increased utilization of irrigated farming tends to increase the average yield for a crop.

Data in Table 16 show average U.S. crop yields under alternative solutions. Average corn yield per acre varies from a low of 51 bushels in solution 2 to a high of 65 bushels in solution 7.

Table 16. Average U.S. crop yields under alternative solutions in 1990

Crop	Unit	Solutions				
		1	2	7	8	9
		(Unit per acre)				
Corn	bushel	63.25	51.20	64.79	52.47	52.91
Barley	bushel	109.82	104.48	107.25	106.53	106.78
Oats	bushel	68.67	77.18	72.85	69.08	69.96
Sorghum	bushel	68.56	76.34	58.79	76.72	74.64
Soybeans	bushel	33.74	33.54	33.69	33.18	32.90
Wheat	bushel	38.50	36.60	38.40	37.27	37.18
Cotton	bale	1.33	1.58	1.55	1.60	1.61
Hay	ton	3.03	2.93	2.84	2.96	2.97
Silage	ton	16.27	15.27	15.54	15.85	15.85

Energy Use

The use of energy inputs in farming has increased enormously during the past 50 years. This has been an important factor in increasing agricultural productivity in the United States as capital inputs are substituted for labor inputs. The data in Table 17 show energy use by fuel source under alternative solutions. When the cost of production and transportation is the minimum (solution 1), the total energy used to produce the endogenous crops in 1990 is about 1.2 quadrillion Btu, which is equivalent to about 2 percent of the total U.S. energy consumption in 1980.

Table 17. Energy use by fuel source under alternative solutions in 1990

Fuel Source	Unit	Solutions				
		1	2	7	8	9
		(Millions)				
Diesel	gallon	4,471.0	5,111.5	4,211.7	4,462.2	4,413.2
Natural gas	1000 ft^3	424.6	507.5	376.5	468.5	440.2
LPG	gallon	876.3	950.0	807.7	937.0	914.9
Electricity	KWH	10,446.5	15,241.9	11,218.5	13,745.2	13,109.1
Total	10^6 Btu	1,197.6	1,399.1	1,106.1	1,206.3	1,218.9

In solution 1, diesel fuel use for field operation, irrigation and transportation is 4.5 billion gallons, natural gas use for irrigation and production of fertilizers and pesticides is 424.6 billion cubic feet, liquid petroleum gas (LPG) use for irrigation and crop drying is 876 million gallons, and electricity use for irrigation and production of fertilizers and pesticides is 10.4 billion KWH.

Increased use of diesel fuel and electricity when soil loss is minimized (solution 2), compared to solution 1 can be explained by using Table 18 which provides information on energy use by input for crop production under alternative solutions. Table 18 shows that the energy for field operations, nitrogen fertilizers, and irrigation accounts for more than 80 percent of total energy used for endogenous crop production.

Table 18. Energy use by input in crop production under alternative solutions in 1990

Input	Solutions				
	1	2	7	8	9
	------------(Trillion Btu)---------------				
Machinery	513.1	509.6	480.6	494.3	492.5
Irrigation	65.8	147.4	39.5	118.1	94.7
Crop drying	74.0	71.2	71.3	73.0	73.7
Nitrogen fertilizers[a]	393.7	429.3	353.4	407.6	393.0
Nonnitrogen fertilizers	30.5	33.1	31.8	32.4	32.3
Pesticides	32.5	43.9	41.2	42.2	42.2
Transportation	88.5	164.7	88.2	92.6	90.5
Total	1,197.6	1,399.1	1,106.1	1,206.3	1,218.9

[a] Energy for nitrogen fertilizers includes energy for commercially purchased nitrogen fertilizer only.

Increased use of diesel fuel in solution 2 compared to solution 1 is primarily due to the increase in energy requirements for transportation and irrigation. As crop production shifts to the western regions to reduce the national level of soil loss, more agricultural commodities must be shipped to the eastern regions to meet the given regional demands. The increase in diesel fuel for transportation in solution 2 compared to solution 1 is about 76 trillion Btu which is equivalent to 543 million gallons of diesel fuel. Increased use of electricity by 46 percent in solution 2 compared to solution 1 is mainly due to increases in water use, nitrogen fertilizer use, and pesticide use.

The energy minimization solution (solution 7) shows us the possible directions of energy reduction in U.S. crop production. The means for achieving energy savings are the increased adoption of reduced tillage practices to reduce energy for field operations, the reduced use of irrigation, and the increased use of organic nitrogen rather than inorganic nitrogen fertilizers. However, approximately 27 percent of energy saved through the increased adoption of reduced tillage practices is offset by the increased use of pesticides when energy use is minimized.

It is interesting to note that the two compromise solutions (solutions 8 and 9) suggest a slight increase in energy use compared to solution 1. This is due to relatively lower ratios of trade-off between the soil loss goal and the energy use goal when the level of energy use in U.S.

endogenous crop production is greater than 1.2 quadrillion Btu (which is shown in Figure 4 in next section).

The data in Table 19 indicate average U.S. energy use per unit of output and per acre by crop under alternative solutions. When the level

Table 19. Average U.S. energy use per unit of output and per acre by crop under alternative solutions in 1990

Crop	Unit	Solutions				
		1	2	7	8	9
		--------(Million Btu per unit of output)------				
Feed grains[a]	bushel[b]	0.055	0.070	0.051	0.060	0.058
Soybeans	bushel	0.051	0.058	0.050	0.056	0.054
Wheat	bushel	0.068	0.070	0.061	0.068	0.064
Cotton	bale	4.817	4.749	4.107	4.491	4.395
Hay	ton	0.901	0.986	0.862	0.902	0.902
Silage	ton	0.361	0.354	0.340	0.362	0.357
		------------(Million Btu per acre)----------				
Feed grains[a]	bushel[b]	5.02	6.16	4.46	5.31	5.13
Soybeans	bushel	1.73	1.93	1.70	1.86	1.78
Wheat	bushel	2.61	2.55	2.33	2.53	2.37
Cotton	bale	6.41	7.52	6.37	7.19	7.07
Hay	ton	2.74	2.88	2.45	2.67	2.68
Silage	ton	5.87	5.41	5.28	5.73	5.66

[a] Feed grains consist of corn, barley, oats and sorghum.

[b] Indicates corn equivalent bushels.

of soil loss is minimized (solution 2), energy requirements per unit of output for all crops, except silage crops, are greater than the other alternatives. This implies that the most inefficient allocation of energy to provide the same amount of agricultural commodities occurs when the level of soil loss is the minimum. In solution 7, the most significant reduction of energy use per unit of output occurs in cotton production.

The energy requirements per unit of output for the two compromise solutions (solution 8 and 9) compared to solution 1 are greater for feed grains, soybeans, and hay production, and smaller for cotton production.

Table 19 also shows that the most energy intensive crop per acre is cotton and the next most is corn silage. The energy requirements for soybean production per acre is only 1.73 million Btu in solution 1. This low level of energy use per acre in soybean production is largely due to the facts that soybeans require little nitrogen fertilizer and most soybeans are produced in rainfed regions.

Table 20 provides energy use by crop under alternative solutions. More than half of the total energy used for endogenous crops is used for feed grain production and about 15 percent for wheat production. About 50 percent and 10 percent of total energy reduction from solution 1 to solution 7 are achieved in feed grain and cotton production, respectively.

Table 20. Energy use by crop under alternative solutions in 1990

Crop	Solutions				
	1	2	7	8	9
	(Trillion Btu)				
Feed grains[a]	620.6	784.7	568.3	673.5	649.7
Soybeans	134.2	152.6	132.2	148.1	143.4
Wheat	212.7	218.5	190.2	212.6	199.8
Cotton	59.5	58.6	50.7	55.4	54.2
Hay	131.8	146.6	128.1	131.7	133.4
Silage	38.8	38.1	36.5	38.9	38.4
Total	1,197.6	1,399.1	1,106.1	1,260.3	1,218.9

[a] Feed grains consist of corn, barley, oats and sorghum.

The data in Table 21 show energy use by region. These data are a reflection of tillage practices and regional production patterns. In solution 2, all regions except the North Central region utilize more energy inputs compared to solution 1. One reason for the reduction of energy use in the North Central region compared to solution 1 is that the production of corn, an energy intensive and erosive crop, in the North Central region is significantly reduced, and the production of barley and oats, less energy intensive and erosive crops, are increased to achieve the minimum level of soil loss.

It is interesting to note that under the energy use minimization policy (solution 7), energy use in the North Atlantic region, South Atlantic region, and Northwest region is increased even though

Table 21. Energy use[a] by region under alternative solutions in 1990

Region	Solutions				
	1	2	7	8	9
	(Trillion Btu)				
North Atlantic	42.4	44.1	44.6	42.5	42.9
South Atlantic	128.9	138.4	145.3	136.8	137.4
North Central	494.9	481.0	456.2	482.9	476.9
Great Plains	194.8	273.0	190.2	252.0	243.9
South Central	179.2	219.8	114.2	180.6	154.8
Northwest	33.7	44.4	36.9	41.6	41.0
Southwest	31.5	33.5	30.4	31.1	31.5

[a] Energy for transportation is not included.

total energy use declines by 8 percent from solution 1. A common factor of increased use of energy in the North Atlantic and South Atlantic regions is the substantial increase in corn production in these regions in order to minimize the national level of energy use. Further, solution 7 may serve as a guideline for the efficient regional allocation of energy under a severe energy shortage situation.

Nitrogen fertilizer use and pesticide use

Economic growth causes farmers to substitute capital for labor as the supply of capital increases relative to labor and thus, the real price of capital becomes lower. The high levels of crop production in modern agriculture have been achieved through the increased use of capital inputs such as fertilizers and pesticides. However, increased application of agricultural chemicals becomes a source of degrading water quality. Nitrogen fertilizers can be a cause of high nitrate levels in surface, ground, and reservoir waters.

Data in Table 22 indicate nitrogen fertilizer use by crop. About 80 percent of nitrogen use for endogenous crop production is used to produce feed grains and wheat. Under the minimum level of energy use, the application of nitrogen fertilizer declines by 10 percent from solution 1, which may suggest that the two goals to reduce energy use and to improve water quality are complementary. The most significant increase in nitrogen use occurs when the level of soil loss is minimized.

Table 22. Nitrogen use by crop under alternative solutions in 1990

Crop	Solutions				
	1	2	7	8	9
	(Million pounds)				
Feed grains[a]	8,531.7	10,474.1	7,754.6	9,577.7	9,138.9
Soybeans	482.6	419.2	439.7	443.1	419.0
Wheat	3,378.5	3,148.9	3,016.5	3,173.7	3,101.3
Cotton	931.0	729.7	701.5	719.4	700.5
Hay	1,265.8	1,275.2	1,214.6	1,240.6	1,246.6
Silage	446.3	346.6	371.5	411.8	404.2
Total	15,035.8	16,393.8	13,498.3	15,566.3	15,010.5

[a] Feed grains consist of corn, barley, oats and sorghum.

This result indicates that the land with high productivity and less erosive hazards is farmed more intensively. Comparing the two compromise solutions (solutions 8 and 9), nitrogen use in the first compromise solution is higher than in the second one. This result is consistent with a lower level of soil loss and a higher level of energy use in solution 8 compared to solution 9.

Pesticide use, as previously indicated in Table 9, increases from solution 1 under all other alternatives. This comes from the increased adoption of reduced tillage practices. The substantial increase in pesticide use also occurs under the soil loss minimization policy. Decreased soil loss, and thus, decreased sediment will undoubtedly improve water quality. However, the increased use of nitrogen fertilizers and pesticides when soil loss is minimized can degrade water quality. Therefore, policy-makers should carefully consider these adverse effects on water quality when they implement soil loss control policies.

Regional distribution of crop production

The model allows comparisons of changes in regional crop production patterns for the seven major regions under each alternatives. The regional distributions of crop production under different alternatives represent efficient ways producing crops to achieve the minimum value of each objective function. Therefore, shifts in regional production patterns under different objective functions are expected. Clearly, these changes in regional crop production patterns resulted from different policy alternatives affect resource use patterns and income distributions in a particular region.

Tables 23-26 show the regional distribution of crop production under alternative solutions. Among the endogenous crops, corn, soybeans, wheat, and cotton are selected to be analyzed for changes in regional production patterns. The distribution of production of other crops such as silage and hay crops remains very stable under alternative solutions.

The data in Table 23 indicate regional distribution of corn production in solution 1 and absolute changes for the alternative

Table 23. Corn production by major region in solution 1 and absolute changes for the alternative solutions in 1990

Region	Solutions				
	1	2	7	8	9
		(Absolute change from solution 1)			
	------------(Million bushels)---------------				
United States	8,822.4	0	0	0	0
North Atlantic	468.6	-2.7	96.4	-5.6	7.0
South Atlantic	86.1	188.0	61.5	208.4	177.3
North Central	6,796.9	-975.9	-588.4	-627.9	-589.5
Great Plains	764.6	973.9	403.9	883.6	782.8
South Central	549.8	-36.5	26.3	-312.3	-236.4
Northwest	0	0	0	0	0
Southwest	156.4	-146.8	0.3	-146.3	-141.2

solutions. The required level of corn production to meet domestic and foreign demands is 8,822.4 million bushels. Corn production in the North Central region accounts for about three-quarters of national corn production in solution 1. Using solution 1 as the base, corn production under the other alternatives shifts from the North Central region to the South Atlantic and Great Plains regions. These shifts occur partly because some marginal lands used for corn production in the North Central region produce corn at lower cost per bushel due to the good natural conditions such as climate and soil, but are more erosive and energy-intensive per bushel in comparison to the lands producing corn in the South Atlantic and Great Plains regions.

Table 24 presents regional shares of soybean production by major region. Over 2,600 million bushels of soybeans are produced in

Table 24. Regional shares for soybean production by major region under alternative solutions in 1990

Region	Solutions				
	1	2	7	8	9
	------------(Percentage distribution)--------				
North Atlantic	1.7	1.9	0.3	1.9	1.7
South Atlantic	15.5	23.0	22.8	24.2	24.0
North Central	48.3	56.1	49.2	51.8	51.3
Great Plains	23.5	12.3	15.3	13.7	13.2
South Central	11.0	6.7	12.4	8.4	9.8
Northwest	0	0	0	0	0
Southwest	0	0	0	0	0

1990. Most soybeans are produced on dryland. The North Central region also has a large share, about half, of national soybean production. The regional share of soybean production declines in the Great Plains region and increases in the South Atlantic and North Central regions under the other alternative solutions as compared to solution 1.

Table 25 shows wheat production patterns at regional levels. Wheat, the most important export crop of the United States, is produced in all major regions. Over 3.1 billion bushels are required to meet the foreign as well as domestic demands in 1990.

Table 25. Wheat production by major region in solution 1 and absolute changes for the alternative solutions in 1990

Region	Solutions				
	1	2	7	8	9
		(Absolute change from solution 1)			
	(Million bushels)				
United States	3,133.3	0	0	0	0
North Atlantic	53.4	-2.2	16.1	-3.2	-3.3
South Atlantic	1,019.2	-482.1	-280.5	-551.0	-509.4
North Central	440.0	-11.8	37.5	-45.1	-59.8
Great Plains	742.3	126.0	142.3	151.2	139.7
South Central	452.9	269.6	19.8	372.1	357.6
Northwest	340.7	118.4	57.5	74.7	70.6
Southwest	84.7	-17.9	7.3	1.4	4.6

The South Atlantic and Great Plains regions account for almost half of the total wheat production under all alternative solutions. A significant decrease in wheat production occurs in the South Atlantic region and an increase in the Great Plains, South Central and Northwest regions under the other alternatives as compared to solution 1. These shifts make the Great Plains to be a major region in wheat production under the other alternatives.

Cotton, highly erosive and highly energy intensive, is produced in only three major regions, the South Atlantic, South Central, and Southwest regions. Data in Table 26 indicate regional shares of cotton

Table 26. Regional shares for cotton production by major region under alternative solutions in 1990

Region	Solutions				
	1	2	7	8	9
	--------(Percentage distribution)--------				
North Atlantic	0	0	0	0	0
South Atlantic	22.0	61.0	73.2	61.0	61.0
North Central	0	0	0	0	0
Great Plains	0	0	0	0	0
South Central	65.0	16.2	10.5	15.4	14.6
Northwest	0	0	0	0	0
Southwest	13.0	22.8	16.3	23.6	24.4

production by major region. The required production level of cotton to meet the given demands is 12.3 million bales. Under all other alternatives, cotton production shifts mainly from the South Central region to the South Atlantic region as compared to solution 1.

The Partial Trade-off Curve between Soil Loss and Energy Use

The partial trade-off curve between soil loss and energy use is derived by assuming that the levels of energy use are 105 percent (solution 3), 100 percent (solution 4), 97 percent (solution 5), 95 percent (solution 6), and 92.4 percent (solution 7) of energy use in the base solution. The cost of production and transportation of the solutions on the trade-off curve is restricted by 41.2 billion dollars (in 1975 dollars) which is the same level of the cost of production and transportation when policy-makers try only to minimize energy use in U.S. crop production.

The solutions on the trade-off curve are nondominated or efficient since the solutions represent the minimum levels of soil loss (energy use), given some fixed levels of energy use (soil loss), production and transportation costs, resources, and the demand for agricultural commodities specified in the model.

The shape of the trade-off curve is shown in Figure 4. The numbers on the trade-off curve correspond to the five solutions. Figure 4 implies that the reduction of energy use from point 6 to point 7 may require society to give up a large amount of the environmental goal,

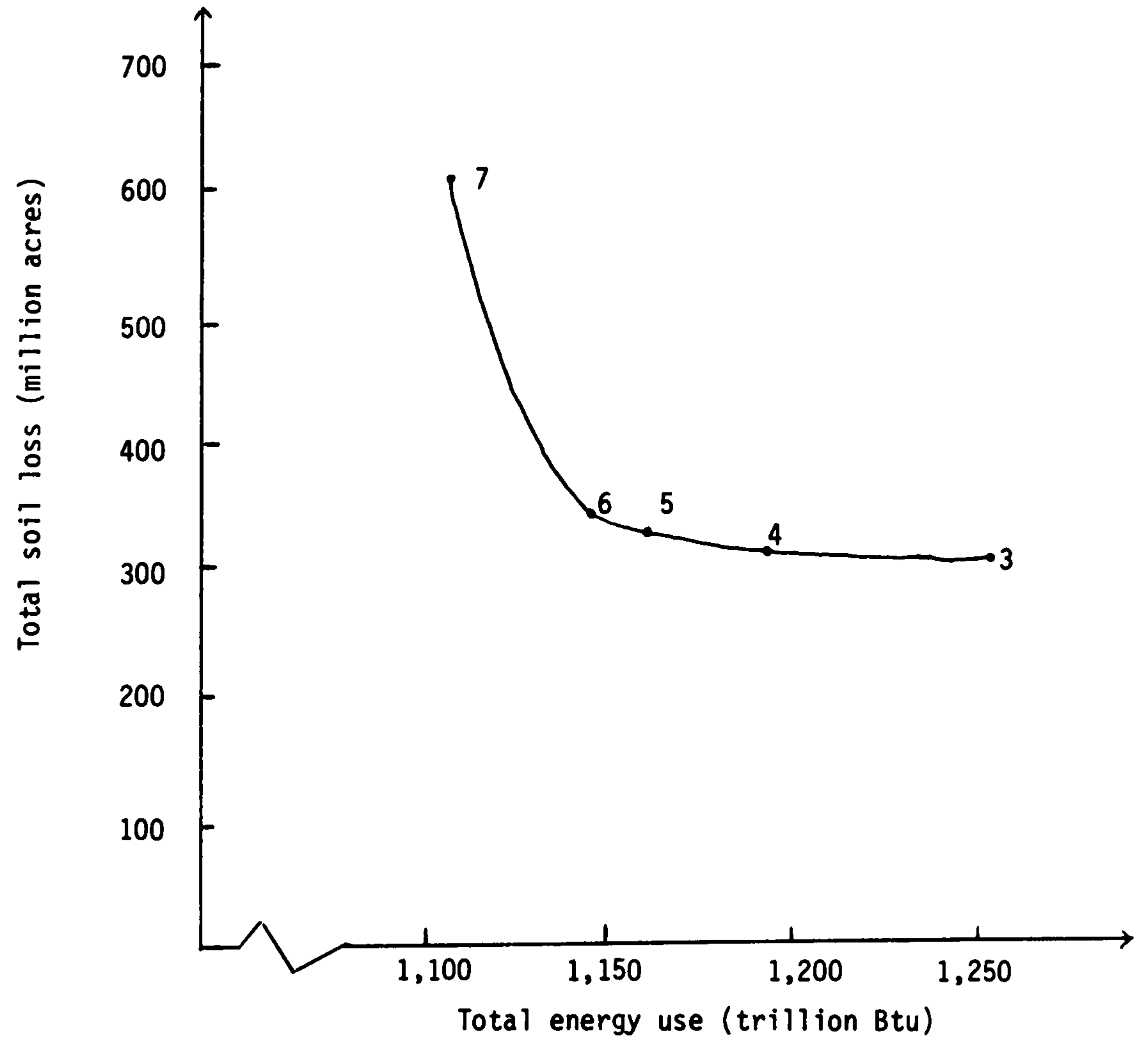

Figure 4. The partial trade-off curve between soil loss and energy use in U.S. crop production when the cost of production and transportation is 41.2 billion dollars (in 1975 dollars)

i.e., a 111 percent increase in soil loss is needed to reduce energy use in crop production by three percent. However, a relatively large amount of reduction in the energy used can be achieved without a great sacrifice of the environmental goal when moving from point 3 to point 6 on the trade-off curve.

In general, the reduction in energy use in crop production may be achieved by substituting the cropland currently not in crop production for energy inputs, converting irrigated land to dryland, changing tillage practices from conventional tillage practices to reduced tillage practices, and adjusting interregional crop production. The adjustment process of reducing energy use involves opposite forces under the minimization of soil loss.

An increase in reduced tillage practices will clearly result in a reduction of soil loss as well as energy use, which may lead us to conclude that the environmental goal and the energy reduction goal are complementary. However, we should note that the energy reduction makes crop production to shift from the arid western regions to the rainfed midwestern and eastern regions where the land is more susceptible to soil erosion. Further, the substitution of land for energy in all regions to meet the specified demands in the model will increase soil loss because marginal land brought into production not only has low yields, but also is highly susceptible to soil erosion. The last two factors, crop production shift and substitution of land for energy inputs, will increase soil loss in the adjustment process, which makes the two goals to be conflicting. Under the constant level of the cost of production and transportation and the high demand situation, the net national change in soil loss is positive as we reduce energy use in crop production. Therefore, there exists a trade-off relationship between energy use and soil loss from the national point of view.

The levels of soil loss and energy use on the trade-off curve vary from 229.3 million tons to 609.1 million tons, and from 1,106.1 trillion Btu to 1,254.6 trillion Btu, respectively,when the cost of production and transportation is 41.2 billion dollars (in 1975 dollars).

The shape and the position of the partial trade-off curve depend on the levels of the cost of production and transportation. If policymakers restrict the cost of production and transportation to less than 41.2 billion dollars (in 1975 dollars), then the trade-off curve should shift upward since for the same level of energy use, soil loss would increase if we try to reduce the cost of production and transportation. Otherwise, the points on the trade-off curve are inefficient because we can choose a point where the cost of production and transportation is less than 41.2 billion dollars (in 1975 dollars) with the same levels of soil loss and energy use.

The data in Table 27 show the overall picture of the solutions on the trade-off curve when we minimize the national level of soil loss (energy use) under chosen levels of energy use (soil loss) and the cost of production and transportation. The national level of soil loss is increased by 165 percent as we move from solution 3 to solution 7.

Table 27. Total cost, soil loss, energy use, land use, nitrogen use, pesticide use, and water use for the solutions on the partial trade-off curve in 1990

Item	Unit	Solutions				
		3	4	5	6	7
Cost	billion dollars[a]	41.2	41.2	41.2	41.2	41.2
Soil loss	million tons	229.3	243.3	262.8	288.4	609.1
Energy	trillion Btu	1,254.6	1,193.5	1,161.6	1,140.6	1,106.1
Dryland	million acres	323.3	332.7	339.6	343.2	356.4
Irrigated land	million acres	37.3	34.2	30.5	28.4	24.2
Total land	million acres	360.6	366.9	370.1	371.6	380.6
Nitrogen fertilizers	billion pounds	15.5	14.3	13.9	13.8	13.5
Pesticides	billion dollars[a]	4.2	4.6	5.0	5.1	5.0
Surface water	million acre-foot	35.4	37.2	37.0	37.7	36.3
Ground water	million acre-foot	19.1	15.1	11.7	9.4	4.8
Total water	million acre-foot	54.5	52.3	48.7	47.1	41.1

[a] Dollars are in terms of 1975 dollars.

However, the opportunity to reduce energy use in crop production is only 12 percent on the trade-off curve because of the very inelastic demand for energy in U.S. agriculture.

An important part of the changes under an energy reduction policy involves bringing marginal land into crop production. For example, dryland use increases by 33 million acres to meet the given levels of domestic and foreign demands. Clearly, the increased crop acreage would be the dominating factor in increasing the national level of soil loss. Even though irrigated land declines by 13 million acres, the net effect of the substitution of cropland for energy increases crop acreage by 20 million acres when we reduce the energy use by 148 trillion Btu.

The uses of energy intensive inputs such as nitrogen fertilizers from commercial sources and groundwater decline when policy-makers try to reduce energy use in U.S. agriculture. Undoubtedly, the energy reduction policy will result in a greater use of manure and legume crops. Thus, overall nitrogen use including inorganic and organic nitrogen may show a slight declining trend. Since groundwater is more energy intensive than surface water, surface water is substituted for groundwater under an energy reduction policy. Groundwater use declines by 14.3 million acre-feet as we reduce energy use by 12 percent.

The application of pesticides increases under an energy reduction policy. This is because of an increase in the use of reduced tillage practices to reduce soil loss and energy use. The increase in pesticide use has an offsetting effect on energy use and a degrading impact on environmental quality.

In the next subsections, we will briefly analyze changes in land use patterns and U.S. average yields, energy use patterns, and regional production patterns on the trade-off curve. However, we will not include solution 7 in the following tables to avoid the possible repetition of the first section of this chapter.

Soil loss

Data in Table 28 show annual average soil loss at regional levels. The average annual rates of erosion per acre vary from 0.24 tons in the Northwest region to 0.94 in the South Central region and are drastically reduced under all alternatives as compared to solution 1 (Table 10). Solution 1 shows an annual average soil loss per acre is of 2.3 tons in the United States (Table 10). This drastic reduction in erosion stems mainly from the fact that the model chooses the most

Table 28. Soil loss per acre by major region for the solutions on the partial trade-off curve in 1990

Region	Solutions			
	3	4	5	6
	----------(Tons	per acre)-----------		
United States	0.64	0.66	0.71	0.78
North Atlantic	0.67	0.69	0.77	0.80
South Atlantic	0.76	0.76	0.90	0.93
North Central	0.54	0.61	0.65	0.71
Great Plains	0.65	0.67	0.70	0.78
South Central	0.84	0.82	0.81	0.94
Northwest	0.29	0.25	0.24	0.24
Southwest	0.61	0.69	0.85	0.90

efficient pattern of producing crops in order to minimize the national level of soil loss, given that the cost of production and transportation increases 8.7 percent from the minimum cost solution (solution 1) for chosen levels of energy supplies. The increased level of cost may allow some marginal croplands to be contoured or terraced along with an increased adoption of reduced tillage methods.

All of the regions, except the Northwest region, show a trend of increasing soil loss per acre as the supply of energy declines. Regionally, the South Atlantic and South Central regions still have more erosion hazards compared to other regions.

Land use patterns and crop yields

Data in Table 29 indicate U.S. crop acreages of solutions on the trade-off curve. Increased dryland cropping and decreased irrigated cropping under restriction on energy use are the general trend of land use, except for hay crops. Among these endogenous crops, the most significant change in land use patterns occurs in soybean production. A partial reason for the decrease in irrigated soybeans is due to the relatively high energy intensity of irrigated soybeans compared to other crops. For example, a previous study [14] shows that relative ratios of average energy use of irrigated crops to dryland crops for soybeans, wheat, and cotton are 3.5, 2.5, and 2.6, respectively.

Table 30 indicates regional land use changes. The most significant increase in total cropland acreages occurs in the South Atlantic region.

Table 29. U.S. crop acreages for the solutions on the partial trade-off curve in 1990

Crop	Solutions			
	3	4	5	6
	(Thousand acres)			
Feed grains[a]				
dryland	111,053	112,221	112,461	114,154
irrigated	14,205	13,008	11,885	11,074
Soybeans				
dryland	75,469	76,743	78,055	78,966
irrigated	2,835	2,137	900	0
Wheat				
dryland	72,763	74,988	78,174	76,328
irrigated	9,559	8,326	6,991	6,826
Cotton				
dryland	5,387	5,231	5,564	5,591
irrigated	2,670	2,566	2,334	1,896
Hay				
dryland	41,112	41,629	42,464	42,123
irrigated	6,479	6,696	6,900	7,259
Silage				
dryland	5,284	5,318	5,303	5,482
irrigated	1,551	1,448	1,471	1,396

[a] Feed grains consist of corn, barley, oats, and sorghum.

Table 30. Endogenous land use by major region for the solutions on the partial trade-off curve in 1990

Region	Solutions			
	3	4	5	6
	-----------(Thousand acres)----------			
North Atlantic	11,824	11,899	11,900	11,941
South Atlantic	43,801	46,087	47,514	47,721
North Central	143,510	144,056	144,193	144,639
Great Plains	79,244	80,231	81,350	31,534
South Central	60,305	62,245	62,247	62,630
Northwest	15,337	15,473	15,531	15,680
Southwest	6,597	6,883	7,309	7,455
	----(changes from solution 3)----			
North Atlantic	100	100.6	100.6	101.0
South Atlantic	100	105.2	108.5	109.0
North Central	100	100.4	100.5	100.8
Great Plains	100	101.3	102.7	102.9
South Central	100	103.2	103.2	103.9
Northwest	100	100.9	101.3	102.2
Southwest	100	104.3	110.8	113.0

Almost 4 million acres of marginal land are brought into crop production to meet the given demand as the availability of energy declines from 1.255 quadrillion Btu to 1.141 quadrillion Btu. The increase in absolute acreages is a main factor contributing to the increase in the national level of soil loss under the energy reduction policy. In the Southwest region, an increase in land use of 13 percent occurs from solution 3 to compensate for the reduction in irrigated land.

Data in Table 31 and 32 show the land use patterns by conservation-tillage practices and their percentage distribution under alternative solutions. As the supply of energy declines, conventional tillage practices (residue removed and residue left) are replaced by reduced tillage practices in order to reduce energy use as well as soil loss.

Table 31. Land use by tillage practice and percentage distribution for the solutions on the partial trade-off curve in 1990

Tillage practice	Solutions			
	3	4	5	6
	----------(Million acres)------------			
Residue removed	1.50	0.97	1.15	1.18
Residue left	71.00	48.73	33.89	22.81
Reduced tillage	288.12	317.2	335.01	347.62
	------(Percentage distribution)-----			
Residue removed	0.4	0.3	0.3	0.3
Residue left	19.7	13.3	9.2	6.1
Reduced tillage	79.9	86.4	90.5	93.5

Along with shifts in tillage practices, there are minor changes in conservation practices. In terms of absolute acreage, straight row farming remains almost constant at 70 million acres, and the acreages of contoured, and terraced land show a slightly increasing trend as the supply of energy declines. However, we may note that the national level of soil loss increases as the supply of energy declines even

Table 32. Land use by conservation practice and percentage distribution for the solutions on the partial trade-off curve in 1990

Conservation practice	Solutions			
	3	4	5	6
	----------(Million acres)------------			
Straight row	70.03	70.87	70.80	70.60
Contours	201.34	203.63	205.26	206.38
Stripcropping	5.58	3.18	3.46	3.18
Terraces	83.87	89.22	90.53	91.45
	-----(Percentage distribution)--------			
Straight row	19.4	19.3	19.1	19.0
Contours	55.8	55.5	55.5	55.5
Stripcropping	1.5	0.9	0.9	0.9
Terraces	23.3	24.3	24.5	24.6

though the changes in conservation-tillage practices force a reduction in the level of soil loss. This is primarily due to increased cropland use to meet the given levels of demands under a reduced energy supply situation.

Data in Table 33 present average U.S. crop yields by crop, dryland, irrigated, and all land. The ratios of irrigated crop yields per acre to dryland yields vary from a low of 1.31 for silage crops to a high of 1.96 for wheat under solution 3. As we mentioned before, average crop yields are function of land class utilization by crops, the proportion of the crop grown on dryland and irrigated land, regional allocation of crops, rotations, conservation-tillage practices, and

Table 33. Average U.S. crop yields for the solutions on the partial trade-off curve in 1990

Crop	Unit	Solutions			
		3	4	5	6
		(Unit per acre)			
Dryland					
Feed grains[a]	bushel[b]	86.36	86.28	87.05	86.80
Soybeans	bushel	33.18	33.10	33.31	33.49
Wheat	bushel	34.22	34.08	33.79	34.77
Cotton	bale	1.46	1.51	1.53	1.54
Hay	ton	2.78	2.76	2.72	2.72
Silage	ton	14.63	14.59	14.54	14.36
Irrigated land					
Feed grains[a]	bushel[b]	113.17	116.52	118.47	116.42
Soybeans	bushel	49.17	48.50	49.08	NA[c]
Wheat	bushel	67.28	69.34	70.40	70.20
Cotton	bale	1.69	1.73	1.64	1.68
Hay	ton	4.80	4.71	4.65	4.60
Silage	ton	19.54	20.71	20.73	20.69
All land					
Feed grains[a]	bushel[b]	89.40	89.42	90.06	89.42
Soybeans	bushel	33.76	33.51	33.49	33.49
Wheat	bushel	38.06	37.61	36.79	37.68
Cotton	bale	1.53	1.58	1.56	1.57
Hay	ton	3.05	3.03	2.99	2.99
Silage	ton	15.74	15.90	15.88	15.64

[a] Feed grains consist of corn, barley, oats and sorghum.

[b] Indicates corn equivalent bushels.

[c] Indicates that the result is not available for this solution.

others. U.S. average cotton yields on dryland tend to increase from solution 3 to solution 6. This is partially due to the fact that cotton production shifts from the South Central region to the South Atlantic region.

Energy use

In the previous overview section, the use of energy related inputs such as nitrogen fertilizers, pesticides, and water was briefly analyzed. As previously mentioned, nitrogen fertilizer use from commercial sources and total water use tend to decline, but pesticide use increases under energy reduction policy while the minimum level of soil is maintained under the feasible set. Substitution of surface water for groundwater in response to reduced energy supply occurs in regions where this substitution is possible.

The data in Table 34 present energy use by region under alternative solutions. This table may show an efficient way of regional energy allocation under an energy shortage situation while the minimum level of soil loss is maintained under the feasible set. As the national level of energy use in endogenous crop production declines by 9 percent, drastic reductions in energy use occur in the Great Plains and South Central regions. However, some regions such as the North Atlantic and South Atlantic regions tend to use more energy when national energy supply is reduced to some fixed level. For example, the 9 percent total energy reduction is achieved by a 34 percent energy reduction in the South Central region and an 18 percent energy reduction in the Great Plains region.

Table 34. Energy use[a] by major region for the solutions on the partial trade-off curve in 1990

Region	Solutions			
	3	4	5	6
	----------(Trillion Btu)-----------			
North Atlantic	42.6	43.1	44.7	43.7
South Atlantic	128.0	138.7	135.2	136.2
North Central	505.2	486.4	485.8	486.0
Great Plains	238.5	209.4	196.5	195.2
South Central	179.9	155.1	139.4	119.5
Northwest	40.7	40.1	39.4	39.5
Southwest	29.6	29.8	29.2	29.5

[a] Energy for transportation is not included.

Another way of evaluating changes in energy use patterns is energy use by crop. Table 35 shows all endogenous crops, except hay crops, utilize less energy under a reduced energy supply situation, which is a good contrast with the regional energy use pattern. The most significant decrease in energy use occurs in cotton production. However, the percentage reduction in the production of other crops is almost the same as the overall percentage reduction in energy use.

Regional shares of crop production

The different levels of energy supply are also closely related to the regional location of crop production. Tables 36-39 present the regional distribution of crop production. Feed grain production at the regional level is shown in Table 36. All different energy supply

Table 35. Energy use by crop for the solutions on the partial trade-off curve in 1990

Crop	Solutions 3	4	5	6
	(Trillion Btu)			
Feed grains[a]	666.7	630.1	607.7	595.5
Soybeans	145.6	141.1	136.5	134.7
Wheat	214.7	198.8	196.5	192.5
Cotton	57.5	54.6	51.7	49.5
Hay	130.3	130.0	130.9	131.0
Silage	39.7	38.7	38.3	37.4
Total	1,254.6	1,193.5	1,161.6	1,140.6

[a] Feed grains consist of corn, barley, oats and sorghum.

Table 36. Regional shares for feed grain[a] production by major region for the solutions on the partial trade-off curve in 1990

Region	Solutions 3	4	5	6
	(Percentage distribution)			
North Atlantic	4.5	4.4	5.1	5.0
South Atlantic	2.4	3.1	2.0	1.8
North Central	66.5	66.7	67.9	68.1
Great Plains	16.3	15.4	15.1	14.8
South Central	8.0	7.8	6.9	7.2
Northwest	1.0	1.1	1.1	1.1
Southwest	1.3	1.5	1.9	2.0

[a] Feed grains consist of corn, barley, oats and sorghum.

situations have the effect of increasing the share of feed grain production in the North Central region and Southwest region, and slightly decreasing their production in the Great Plains region. Other regions retain their shares of national feed grain production.

Several variations in the distribution of soybean production occur in the analysis. The percentage share of soybean production in the North Central region declines from 48 percent to 40 percent as the level of energy use declines (Table 37). To meet the given demand for soybeans under a reduced energy supply while minimizing the national level of soil loss, there are significant shifts of soybean production from the North Central region to the South Atlantic and South Central regions.

Table 37. Regional shares for soybean production by major region for the solutions on the partial trade-off curve in 1990

Region	Solutions			
	3	4	5	6
	------(Percentage distribution)------			
North Atlantic	1.8	1.8	1.3	1.2
South Atlantic	24.8	25.2	27.3	27.0
North Central	48.4	43.5	42.5	40.3
Great Plains	19.4	20.1	20.0	20.9
South Central	5.6	9.4	8.9	10.6
Northwest	0	0	0	0
Southwest	0	0	0	0

Data in Table 38 present the regional share of wheat production by major region. Wheat production in the Great Plains and South Central regions account for more than half of the national wheat production under all alternatives. Only wheat production in the South Atlantic region shows a consistently increasing trend under a reduced energy supply. The percentage share of wheat production in the western United States changes very little.

Table 38. Regional shares for wheat production by major region for the solutions on the partial trade-off curve in 1990

Region	Solutions			
	3	4	5	6
	-----(Percentage distribution)-----			
North Atlantic	2.0	1.9	1.7	2.0
South Atlantic	14.6	14.7	15.8	16.1
North Central	10.2	14.8	13.7	16.1
Great Plains	27.5	26.3	25.7	27.0
South Central	30.3	26.9	27.7	23.3
Northwest	13.2	12.7	12.7	12.7
Southwest	2.2	2.7	2.7	2.8

Table 39 provides the regional distribution of cotton under alternative solutions. The major shift of cotton production occurs from the South Central region to the South Atlantic region in response to a reduced energy supply. This significant shift of cotton production partly explains the drastic decline in energy use in the South Central region and more energy use in the South Atlantic region when the national level of energy use declines (Table 34).

Table 39. Regional shares for cotton production by major region for the solutions on the partial trade-off curve in 1990

Region	Solutions			
	3	4	5	6
	-----(Percentage distribution)-----			
North Atlantic	0	0	0	0
South Atlantic	57.7	62.6	67.4	73.2
North Central	0	0	0	0
Great Plains	0	0	0	0
South Central	24.4	17.9	16.3	12.2
Northwest	0	0	0	0
Southwest	17.9	19.5	16.3	14.6

CHAPTER V. SUMMARY AND POLICY IMPLICATIONS

This study examines how production patterns, resource use patterns, cost, and soil loss will be changed in response to single objectives versus multiobjectives. A partial trade-off relationship between soil loss and energy use is also derived under the multiobjective framework. Three objectives are assumed in the study. The objectives are minimization of the cost of production and transportation, soil loss, and energy use.

An interregional linear programming model used in this study also has a set of constraints and a set of activities. The constraints are the availability of land, water, fertilizer, and regional commodity demands. These constraints are defined either at the producing area, water supply region, market region, or national level. The set of activities include endogenous crop production activities, water buy activities, nitrogen buy activities, commodity transportation activities, and land development and conversion activities. Endogenous crop specified in the model are barley, corn grain, corn silage, cotton, legume hay, nonlegume hay, oats, sorghum grain, sorghum silage, soybeans, wheat, and summer fallow. The projected production levels of all other crops and all livestocks are exogenously determined.

Single Objective Versus Multiobjective

Five solutions are compared in terms of soil loss, land use patterns and crop yields, energy use, nitrogen and pesticide use, and regional distribution of crop production. The objective functions of these solutions are the minimization of the cost of production and transportation (solution 1), soil loss (solution 2), energy use (solution 7), the sum of the percentage deviations from the ideal solution (solution 8), and the maximum percentage deviation of each objective function from the ideal solution (solution 9), respectively. Solution 1, 2, and 7 are derived by assuming that policy-makers have only one objective. On the other hand, solutions 8 and 9 assume that they have three objectives (cost, soil loss, and energy) and are willing to compromise these goals. Solution 1 is a base solution and used for comparison with the other alternatives. Solution 2 and 7 show us the maximum achievement in terms of soil loss reduction and energy saving, respectively, under the feasible set of solutions.

Under the solution 1, 37.9 billion dollars (in 1975 dollars), 862.5 million tons of soil loss, and 1,197.5 trillion Btu of energy use are required to produce the given levels of endogenous crops. The national level of soil loss under solution 2 and energy use under solution 7 could be reduced by 78 percent and 8 percent from solution 1, respectively. However, the minimum level of soil loss (solution 2) can be achieved only through increases in cost and energy use by 10.5 billion dollars (in 1975 dollars) and 202 trillion Btu, (equivalent to 1.44 billion gallons of diesel fuel), respectively. The first compromise solution (solution 8) suggests that the policy-makers may give up 14 percent of the minimum cost goal, 6 percent of the minimum soil loss goal, and 9 percent of the minimum energy use goal, respectively, from the ideal solution. The second compromise solution (solution 9) indicates that we need to increase the allowed cost of production by 4.9 billion dollars (in 1975 dollars), soil loss by 24.3 million tons, and energy use by 102.8 trillion Btu, respectively, from the ideal solution.

Soil loss minimization solution

The annual average rate of erosion per acre declines 2.33 tons per acre in the base solution to 0.51 tons per acre in the soil loss minimization solution. This drastic decline in soil loss is achieved through shifts in production to the less erosive and more productive class I and II land, increase in irrigated farming, increased adoption of reduced tillage practices and conservation tillage practices such as contouring and terracing, changes in rotations, and interregional adjustment in production patterns. The shift in production to the less erosive and more productive lands results in total land use decreasing by 6 million acres compared to solution 1.

However, substantial increases in fertilizer and pesticide use due to the intensive use of less erosive and more productive lands, and increased adoption of reduced tillage practices can result in degradation of water quality as compared to the base solution. Further, a 17 percent increase in energy use from the base solution comes from increased use of agricultural chemicals and water,and a increase in transportation requirements to meet the given regional demands.

Energy use minimization solution

The maximum energy saving under the feasible set as compared to the base solution is about 90 trillion Btu, which is equivalent to 643 million gallons of diesel fuel. This energy saving results from increased adoption of reduced tillage practices and a shift of crop production from irrigated land to dryland, even though the increased use of pesticides has an offsetting effect. Regional energy reductions are not proportional to the national energy reduction. Energy use in the North Atlantic, South Atlantic, and Northwest regions is increased though total energy use declines by 8 percent from the base solution.

A large amount of cropland is subsituated for energy inputs. Irrigated land use declines by 2 million acres, but dryland use increases by 11 million acres and thus, total land use increases by 9 million acres as compared to the base solution.

A significant amount of surface water is substituted for groundwater since groundwater is more energy intensive to use than is surface water. The application of nitrogen fertilizers falls by 10 percent, but pesticide use increases by 61 percent due to the increased adoption of reduced tillage practices.

Two compromise solutions

The significant decrease in soil loss under the two compromise solutions is accompanied by a large increase in cost and a slight increase in the total energy use as compared to the base solution.

The land use patterns under the two compromise solutions show decrease in dryland use and increase in irrigated land use as compared to solution 1, but total land use declines by 8 million acres and 4 million acres, respectively. The reductions in total cropland use are accomplished by increased use of agricultural chemicals and water, and shifts from dryland farming to irrigated farming.

To reduce soil loss as well as energy use, a substantial increase in the adoption of reduced tillage practices occurs under the two compromise solutions as compared to solution 1.

An increase in energy use under the two compromise solutions from the base solution may come from the fact that relatively lower trade-off ratios between the soil loss goal and energy use goal appear when the level of energy use in U.S. endogenous crop production is greater than 1.2 quadrillion Btu. In general, the two compromise solutions show similar crop production patterns and resources use patterns.

A Partial Trade-off Relationship between Soil Loss and Energy Use

One of the main objectives in the study is to trace out the partial trade-off curve between soil loss and energy use by using the constraint method. Five nondominated solutions including an energy minimization solution (solution 7) are plotted to demonstrate the partial trade-off relationship between the environmental goal and energy goal. The energy minimization solution serves as an ending point of the partial trade-off curve. The chosen levels of energy use on the trade-off curve are 105 percent (solution 3), 100 percent (solution 4), 97 percent (solution 5), 95 percent (solution 6), 92.4 percent (solution 7) of energy use in the base solution.

The selected level of production and transportation costs is 41.2 billion dollars (in 1975 dollars) which is the same level of costs under the energy minimization solution (solution 7) and an increase of 3.3 billion dollars (in 1975 dollars) from the base solution.

The partial trade-off curve is shown in Figure 5. The numbers on the trade-off curve correspond to the five solutions. Figure 5 implies that the reduction in energy use from point 6 to point 7 may require society to give up a large portion of the environmental goal in order to achieve the energy use minimization goal. That is, a 111 percent increase in soil loss is needed to reduce energy use in crop production by 3 percent. However, a relatively large amount of the energy saving can be made without a great sacrifice in the environmental goal when moving from point 3 to point 6 on the trade-off curve. Obviously, the choice of optimal point on this trade-off curve depends on the policy-makers' preference.

The adjustment process of reducing energy use involves opposite forces under the minimization of soil loss. Increased adoption of reduced tillage practices undoubtedly results in a reduction of soil loss and energy use. However, crop production shifts from the western regions to the rainfed regions, and the substitution of land for energy in all regions to meet the specified demands in the model increase soil loss. The solutions on the partial trade-off curve show

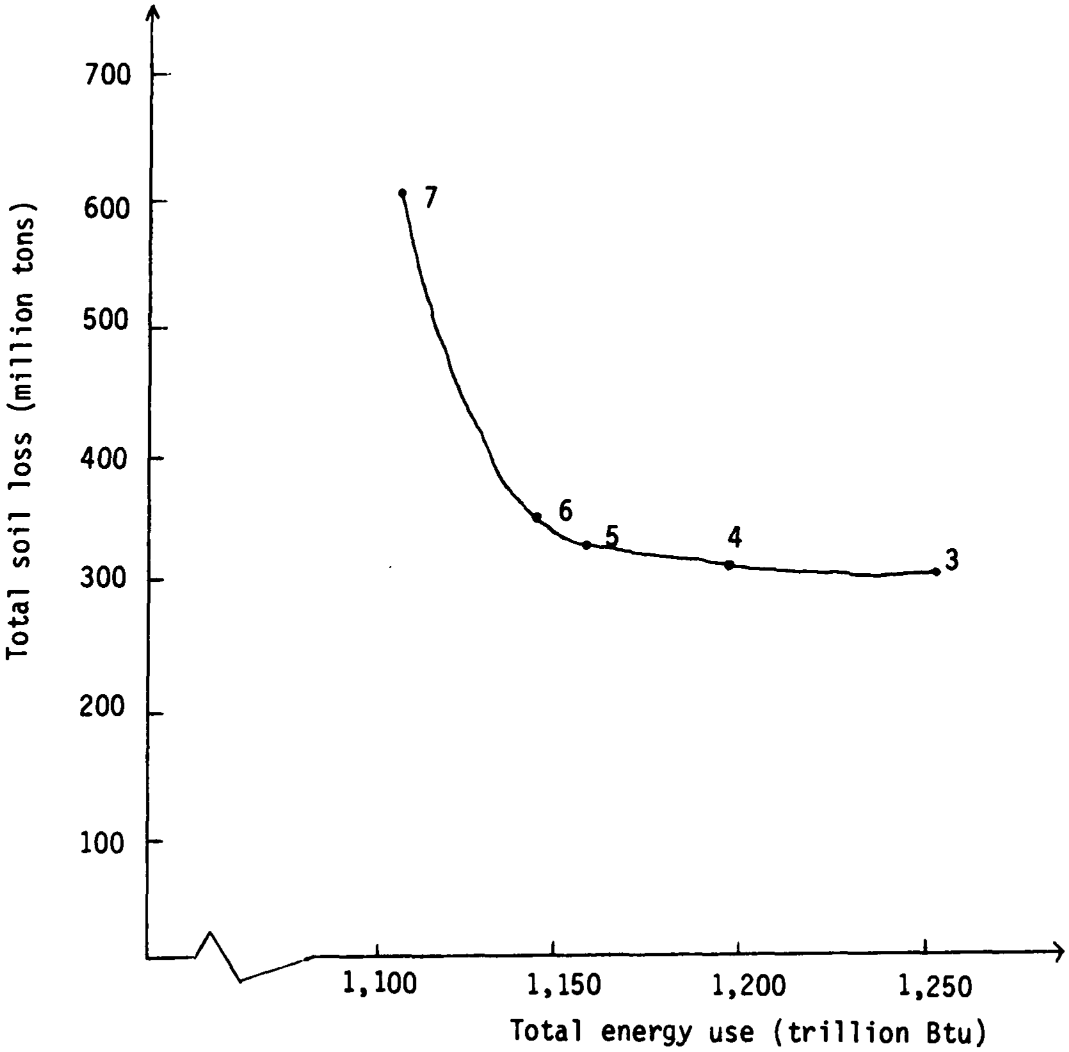

Figure 5. The partial trade-off curve between soil loss and energy use in U.S. crop production when the cost of production and transportation is 41.2 billion dollars (in 1975 dollars)

that for a constant level of production and transportation costs, the net national change in soil loss is positive as the level of energy use in endogenous crop production declines. Therefore, there exists a trade-off relationship between energy use and soil loss from the national point of view.

Solutions on the partial trade-off curve

Increased dryland cropping and decreased irrigated cropping are the general trends, except for the hay crops, as the levels of energy use decline. The most significant change in land use patterns occurs in irrigated soybean production. A partial reason for this is due to the relatively high energy intensity of irrigated soybeans compared to other crops. A sharp increase in total cropland acreages occurs in the South Atlantic region. Almost 11 million acres of marginal land in U.S. is brought into crop production from solution 3 to solution 6. This increase in absolute acreages is a major contributing factor to the increase in the national level of soil loss under the energy use reduction policy.

As the levels of energy use decline, conventional tillage practices (residue removed and residue left) are replaced by reduced tillage practices. Along with shifts in tillage practices, there are minor changes in conservation practices. However, we may note that the national level of soil loss increases as energy use declines even though the changes in conservation-tillage practices force a reduction in the level of soil loss.

Nitrogen fertilizer use from commercial sources and total water use tend to decline, but pesticide use increases as the level of energy use declines. A significant substitution of surface water for groundwater in response to the reduced energy supply occurs in regions where this substitution is possible.

Policy Implications

Improvements of environmental quality, and energy production and conservation for present and future generations have become important goals of our society. However, improvement of one goal is in general accompanied by degradation of the other goal since energy use as well as new energy production technologies result in contamination of water and air which are vital to public health. For example, ethanol production from grain crops and agricultural by-products has a potential for increasing soil erosion and thus, reducing the productivity potential of cropland and degrading water quality by bringing marginal, highly erosive lands into crop production even though production of ethanol from agricultural crops may be economically and politically feasible.

Furthermore, as the study indicated, there exists a partial tradeoff relationship between soil loss and energy use under a multiobjective framework. The shape of the partial trade-off curve indicates that when energy uses are at relatively low levels, further reduction of energy use cannot be achieved without substantial increases in soil loss. When energy uses are, however, at relatively high levels, a relatively large amount of energy saving can be obtained by increasing only a small amount of soil loss. One implication of these results is that when the policy-makers implement soil loss control policies, they should also consider the impacts of these policies on energy use in U.S. crop production since the two goals to reduce the levels of soil loss and energy use are conflicting from the national point of view.

Previous studies [14, 15, 18, 34, 37] have shown that restrictions on energy use or soil loss in general result in an increase in production and transportation costs and thus, food costs. Combining this study and previous studies, we may conclude that the three objectives (minimization of costs, soil loss, and energy use) conflict with each other. Under specific assumptions on policy-makers' objective function, we derived two compromise solutions of these three goals. The results of the two compromise solutions in the study suggest that the levels of energy use and costs are higher, but the level of soil loss is lower in comparison to the base solution.

A common characteristic of the two solutions, the soil loss minimization solution and the energy use minimization solution, is an increased adoption of reduced tillage practices. This implies that the switch in tillage practices from conventional tillage practices to reduced tillage practices is an important and effective strategy to reduce soil loss and energy use. However, increased adoption of reduced tillage practices is in general accompanied by increased use of pesticides since chemical controls are substituted for mechanical means of controlling pests. The increased application of pesticides has the potential to pollute water and increase in energy use.

Further, regulations on appropriate use of pesticides resulting from environmental concerns, in addition to requirements for new farming skills and the purchase of new equipment can be binding factors on the feasibility of reduced tillage practices in the future.

There are two categories of policies to control soil loss. One is the voluntary approach and the other is the mandatory approach. The strictly voluntary approach appears to be inadequate because farmers may get little financial benefit from conservation, at least in the short run and are required to invest a significant amount of money to change tillage practices and install conservation practices. Another means to reduce soil loss is to give economic incentives to farmers who are willing to participate in the soil conservation programs. The incentives may be provided in different forms such as income tax credits, cost-share grants, farm loan benefits, or others. If the voluntary approach is not effective in reducing soil loss to society's desired level, then we may resort to the mandatory approach such as taxing soil loss directly or prohibiting a soil loss of more than a specified numbers of tons per acre per year by law. However, the choice between the voluntary approach and the mandatory approach should be carefully considered since the mandatory approach may be a more effective instrument to reduce soil loss, but requires higher costs to implement and causes a greater disturbance in income distribution than the voluntary approach.

Finally, as the study indicated, the potential to reduce energy use in crop production under the feasible set of alternatives is not great because of very inelastic demand for energy in U.S. agriculture. But a relatively small decrease in energy use due to high energy prices or a severe energy shortage may cause prices of agricultural commodities to rise significantly and the national level of soil loss to increase. Therefore, a relatively high priority should be set on energy use in agriculture when policy-makers consider national priorities for allocating scarce energy supplies in the near future.

BIBLIOGRAPHY

1. Beasley, Robert P. *Erosion and Sediment Pollution Control*. Ames: Iowa State University Press, 1972.

2. Belenson, Sheldon M., and Kapur, Kailash C. "An Algorithm for Solving Multicriterion Linear Programming Problems with Examples." *Operations Research Quarterly* 24, No. 1 (March 1973): 65-77.

3. Benayoun, R.; Montgolfier, J.; Terghy, J.; and Laritchev, O. "Linear Programming with Multiple Objective Functions: Step Method (Stem)." *Mathematical Programming* 1, No. 3 (December 1971): 366-375.

4. Browning, Geroge M. "Agricultural Pollution - Sources and Control." In *Water Pollution Control and Abatment*, pp 150-160. Edited by *Ted. L. Willrich and N. William Hines*. Ames: Iowa State University Press, 1965.

5. Candler, W., and Boehlje, M. "Linear Programming in Capital Budgeting with Multiple Goals." *American Journal of Agricultural Economics* 53, No. 2 (May 1971): 325-330.

6. Chankong, V., and Haimes, Yacov Y. "The Interactive Surrogate Worth Trade-off Method for Multiobjective Decision Making." In *Lecture Notes in Economics and Mathematical Systems*, No. 155, pp 42-67. Edited by S. Zionts. Berlin: Springer - Verlag, 1978.

7. Charnes, A., and Cooper, W. W. *Management Models and Industrial Applications of Linear Programming*. New York: John Wiley and Sons, 1961.

8. Cohon, Jared L., and Marks, David H. "Multiobjective Screening Models and Water Resource Investment." *Water Resources Research* 9, No. 4 (August 1973): 826-836.

9. Cohon, Jared L., and Marks, David H. "A Review and Evaluation of Multiobjective Programming Techniques." *Water Resources Research* 11, No. 2 (April 1975): 208-220.

10. Colette, Arden W. *The Conceptualization and Quantification of a Water Supply Sector for a National Agricultural Analysis Model Involving Water Resources*. Ames: Center for Agricultural and Rural Development, Iowa State University, 1976.

11. Conservation Needs Inventory Committee. *National Inventory of Soil and Water Conservation Needs 1967*. U.S.D.A. Statistics Bulletin No. 461, 1971.

12. Council for Agricultural Science and Technology. Energy Use in Agriculture: Now and for the Future. CAST Report No. 68. Ames, Iowa: CAST, 1977.

13. Dauer, Jerald P., and Krueger, Robert J. "An Iterative Approach to Goal Programming." Operational Research Quarterly 28, No. 3 (1977): 671-681.

14. Dvoskin, Dan, and Heady, Earl O. U.S. Agricultural Production Under Limited Energy Supplies, High Energy Prices, and Expanding Agricultural Exports. CARD Report 69. Ames, Iowa: Center for Agricultural and Rural Development, Iowa State University, November 1976.

15. Dvoskin, Dan; Heady, Earl O.; and English, Burton C. Energy Use in U.S. Agriculture: An Evaluation of National and Regional Impacts from Alternative Energy Policies. CARD Report 78. Ames, Iowa: Center for Agricultural and Rural Development, Iowa State University, March 1978.

16. Ecker, J. G., and Shoemaker, Nancy E. "Multiple Objective Linear Programming and the Trade-off-Compromise Set." In Lecture Notes in Economics and Mathematical Systems, No. 177, pp 60-73. Edited by G. Fandel and T. Gal. Berlin: Springer - Verlag, 1980.

17. Economics Research Service. Current Energy Use in the Food and Fiber System. U.S. Department of Agriculture. Unpublished Briefing Paper. Washington, D.C.: U.S. Government Printing Office, June 1977.

18. English, Burton C., and Heady, Earl O. Short and Long-term Analysis of the Impacts of Several Soil Loss Control Measures on Agriculture. CARD Report 93. Ames, Iowa: Center for Agriculture and Rural Development, Iowa State University, 1980.

19. Ford Foundation. A Time to Choose: Americas' Energy Future. Cambridge, Massachusetts: Ballinger Publishing Co., 1974.

20. Ford Foundation. Energy: The Next Twenty Years. Cambridge, Massachusetts: Ballinger Publishing Company, 1979.

21. Freimer, M., and Yu, P. L. "Some New Results on Compromise Solutions for Group Decision Problems." Management Science 22, No. 6 (February 1976): 683-693.

22. Gearhart, W. B. "Compromise Solutions and Estimation of the Non-inferior Set." Journal of Optimization and Applications 28 (May 1979): 29-47.

23. Geoffrion, Arthur M. "Solving Bicriterion Mathematical Programs." *Operation Research* 15, No. 1 (January 1967): 39-54.

24. Haimes, Yacov Y., and Hall, Warren A. "Multiobjective in Water Resource Systems Analysis: The Surrogate Worth Trade Off Method." *Water Resources Research* 10, No. 4 (August 1974): 615-624.

25. Ignizio, James P. *Goal Programming and Extensions*. Boston, Massachusetts: Lexington Books, D.C. Heath and Company, 1976.

26. Ijiri, Y. *Management Goals and Accounting for Control*. Chicago: Rand-McNally and Co., 1965.

27. Kornbluth, JSH. "A Survey of Goal Programming." *OMEGA* 1, No. 2 (April 1973): 193-205.

28. Lee, Sang M. *Goal Programming for Decision Analysis*. Philadelphia: Auerbach Publishers, Inc., 1972.

29. Lee, Sang M., and Clayton E. R. "A Goal Programming Model for Academic Resource Allocations." *Management Science* 18, No. 8 (April 1972): 395-408.

30. Lee, Sang M., and Lerro, A. J. "Optimizing the Portfolio Selection for Mutual Funds." *Journal of Finance* 28, No. 5 (December 1972): 1087-1101.

31. Lee, Sang M., and Moore, Laurence J. "A Practical Approach to Production Scheduling." *Production and Inventory Management* 15, No. 1 (First Quarter 1974): 79-92.

32. Meister, Anton D., and Nicol, Kenneth J. *A Documentation of the National Water Assessment Model of Regional Agricultural Production, Land and Water Use, and Environmental Interaction*. Ames, Iowa: Center for Agricultural and Rural Development, Iowa State University, December 1975.

33. Morse, J. N. "A Theory of Naive Weights." In *Lecture Notes in Economics and Mathematical Systems*, No. 155, pp 384-401. Edited by S. Zionts. Berlin: Springer - Verlag, 1978.

34. Nicol, Kenneth J.; Heady, Earl O.; and Madsen, Howard C. *Models of Soil Loss, Land and Water Use, Spatial Agricultural Structure, and the Environment*. CARD Report 49T. Ames, Iowa: Center for Agricultural and Rural Development, Iowa State University, July 1974.

35. Peters, Don C., and Petty, H. B. "Workshop Session." In *Agricultural Practices and Water Quality*, pp 224-227. Edited by Ted L. Willrich and George E. Smith. Ames, Iowa: Iowa State University Press, 1970.

36. Ross, Marc, H., and Williams, Robert H. Our Energy: Regaining Control. New York: McGraw-Hill Book Company, 1981.

37. Saygideger, Orhan; Vocke, Gary F.; and Heady, Earl O. A Multigoal Linear Programming Analysis of Trade-offs between Production Efficiency and Soil Loss Control in U.S. Agriculture. CARD Report 76. Ames, Iowa: Center for Agricultural and Rural Development, Iowa State University, January 1977.

38. Schurr, Sam H. Energy in Americas' Future: the Choices Before Us. Baltimore: The Johns Hopkins University Press, 1979.

39. Short, Cameron. Groundwater Mining in the Ogallala Aquifer in Relation to Rising Energy Prices and Agricultural Production. Unpublished Ph.D. Dissertation, Iowa State University, 1980.

40. Short, Cameron; Turhollow, Anthony F., Jr; Heady, Earl O.; and Lee, Kun C. Regional Impacts of Groundwater Mining from the Ogallala Aquifer with Increasing Energy Prices 1990 and 2000. CARD Report 98. Ames, Iowa: Center for Agricultural and Rural Development, Iowa State University, 1981.

41. Stallings, James H. Soil Conservation. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1957.

42. Stan, Chauncey. Current Issues in Energy. New York: Pergamon Press, 1979.

43. Steinman, M. Energy and Environmental Issues: The Making and Implementation of Public Policy. Boston, Massachusetts.: Lexington Books, 1979.

44. Theil, Henri. Economic Forecasts and Policy. Amsterdam: North-Holland Publishing Co., 1961.

45. Tinbergen, J. Economic Policy: Principles and Design. Amsterdam: North-Holland Publishing Co., 1956

46. Tyner, Wallace E. "Our Energy Transition: The Next Twenty Years." American Journal of Agricultural Economics 62, No. 5 (December 1980): 957-964.

47. U.S. Department of Agriculture. Energy and U.S. Agriculture 1974 and 1978. Economics, Statistics, and Cooperatives Service, Statistical Bulletin No. 632, 1980.

48. U.S. Department of Agriculture. *1980 Appraisal Part I Soil, Water and Related Resources in the United States: Status, Condition, and Trend*. Soil and Water Resources Conservation Act, 1981.

49. U.S. Department of Agriculture. *1980 Appraisal Part II Soil, Water and Related Resources in the United States: Status, Condition, and Trend*. Soil and Water Resources Conservation Act, 1981.

50. U.S. Department of Agriculture and Federal Energy Administration. *Energy and U.S. Agriculture, 1974 Data Base*. Washington, D.C.: Economic Research Service, 1976.

51. U.S. Department of Energy, Energy Information Administration. *Monthly Energy Review March 1981*. Washington, D.C.: U.S. Government Printing Office, 1981.

52. Wilson, Canal L. *Energy: Grobal prospects 1985-2000*. New York: McGraw-Hill Book Company, 1977.

53. Wischmeier, W. H. and Smith, D. D. *Predicting Rainfall - Erosion Losses from Cropland East of the Rocky Mountains*. U.S.D.A. Agricultural Handbook No. 282, 1965.

54. Zeleny, M. *Linear Multiobjective Programming*. Lecture Notes in Economics and Mathematical Systems, No. 95. Berlin: Springer - Verlag, 1974.

55. Zeleny, M. "A Concept of Compromise Solutions and the Methods of the Displaced Ideal." *Computers and Operations Research* 1 (1974): 479-496.

56. Zeleny, M., and Cochrane, J. L. "A Priori and a Posteriori Goals in Macroeconomic Policy Making." In *Multiple Criteria Decision Making*, pp 373-391. Edited by J. L. Cochrane and M. Zeleny. Columbia: University of South Carolina Press, 1973.

57. Zionts, Stanley, and Wallenius, Jyrki. "An Interactive Programming Method for Solving the Multiple Criteria Problem." *Management Science* 22, No. 6 (February 1976): 652-663.

ACKNOWLEDGMENTS

I wish to thank many people for the help they have provided in the past four years.

First, I wish to thank Dr. Earl O. Heady, my major professor, for his help and guidance during my graduate studies. I also wish to thank the members of my advisory committee, Dr. Dennis R. Starleaf, Dr. James A. Stephenson, Dr. Roy D. Hickman, and Dr. Young W. Kihl.

I am grateful to and thank Dr. Burton C. English, Dr. Cameron Short, Anthony Turhollow, and Stanley Schraufnagel for their helpful discussion. In addition, I want to thank Bruce Eveland and Doug Haney for their computer programming contributions.

I am also much indebted to my family, especially my twin brother, Pil-Hoon, for his spiritual support and encouragement.

I reserve a very special thanks for my mother. Without her inspiration, I may not have accomplished my studies.

Finally, I really appreciate my beloved wife, Eul-Mee, for her devotion.