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THE APPLICATION OF OPERATIONS RESEARCH IN THE OPTIMIZATION OF AGRICULTURAL PRODUCTION

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This paper describes a project to develop on optimal production plan for crops and livestock in Chang Qing County, People's Republic of China. The production plan was to increase net profit without adverse effects on the environment. We set up four large-scale linear programming models, each having more than 3,000 variables and 100 constraints, for different weather conditions and combinations of crops and livestock production. We obtained optimal solutions using computers. We used game theory to work out an optimal plan least sensitive to weather variations. We used sensitivity analysis to obtain the information for production planning as a function of market prices. The project took 1 year; 20 people were involved. More than 3 million data items were used in the development of the models. The optimal production plan involved a 2-year cycle that began in September 1983. By September 1985, the net profit from crops in the county increased by 12.33% and that from livestock by 53.77%. This success opened up the study of production planning and control of the macroscopic economy in agriculture in China. Optimal production plans are being developed and improved in many parts of China.

Agriculture involves a complicated interplay of nature and economics: It is affected by natural conditions and social demands as well as by factors, such as technology and the economy. It involves planting, livestock, forestry, fishing and related occupations like food processing. Because of the complexity of agricultural production, there are stochastic factors and uncontrollable factors that make planning difficult.

In the past, agricultural producers have not been exposed to concepts of operations research and few operations researchers have worked on problems of agricultural production planning in China. In addition, computers have only recently been popularized; before computers were widely available in China, agricultural production planning was small-scale and experimental. It is not enough to make policy for agriculture on the basis of simple qualitative analysis because such analysis omits some factors and we cannot adequately forecast the future. It often results in an unnecessary economic loss. In recent years, those involved in agricultural planning have come to realize the importance of increased regulation in developing the agricultural economy, and, as computers have become more available, increased agricultural production regulation has become possible in China. As a result, the question that we try to answer in our project is: If various resources and technological equipment are fixed, can production profit be raised through scientific regulation and planning? The governor of Jinan City and the agricultural regulation workers of Chang Qing County came to us for help in answering this question.

1. QUALITATIVE ANALYSIS

We conducted a qualitative analysis of the state of agricultural production in Chang Qing County. With fixed resources and outside conditions, such as policy and social demand, the effect of regulation occurs mainly through the control of production planning; their relationship is shown in Figure 1.

In order to study how regulation affects production, we analyzed agricultural production, using the following train of thought. The agricultural production structure in Chang Qing County includes crop farming, livestock

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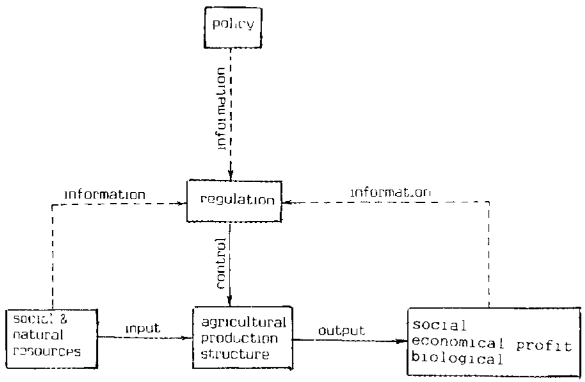

Figure 1. Block diagram for qualitative analysis.

husbandry, forestry, fisheries, and other occupations like food processing. The first two items have a greater influence on the economic profit of the county, so we decided to begin our research with them. Crop production is a function of soils location within the county and the rotation utilized. The *structure of livestock production* refers to the number of different types of livestock in each district. Some of the variables that influence crop and livestock production can be controlled by humans, while other factors, such as weather and market prices, are difficult to control. Agricultural benefits are the economic profit, ecological improvements, and the satisfaction of social demands. In calculating production economics, output and market price must be taken into account. To analyze ecological benefits, we must consider the impact of the state of the ecological systems in the study area on agricultural production and living conditions. When we look at social demands, we must consider the demand for agricultural production in the district. We must analyze the influences of policy, energy, technology, transportation, and important environmental factors upon production forces and structures. We also have to consider the history and present state of the production structure, past successes and failures in production regulation and planning, and existing problems in the production structure.

2. QUANTITATIVE ANALYSIS

We analyzed which factors in the agricultural production structure are easily quantified and which are not. The factors with easily determined quantities are divided into different types: deterministic and random, dynamic and static, continuous and discrete. We also classify these quantities as reliable, distorted, and those based on inadequate information. The data with considerable distortion and those factors derived from inadequate information must be analyzed to determine how to deal with the distortion and how to make up for the inadequate information. As to the factors and their relationships that are not easily determined quantities, special attention must be paid to those that cannot be ignored. Some quantitative relations cannot be set up exactly at the present time or in the future, e.g., the functional relationship between a forest-covered area and an agricultural output. Other quantities are difficult to determine because of large-scale floating, e.g., market prices. Appropriate methods must be worked out to deal with those factors and their relationships. For example, we gave the lower bound of a forest-covered area in the mathematical models. The lower bound was determined according to the demand of the conservation of soil and water and regulating weather. We used sensitivity analysis on the floating market prices. We obtained the effect of weather on crop production by mathematical statistics methods, and so on.

3. GENERAL MODEL STRUCTURE

3.1. Formulating the Model Structure

A framework for setting up models was developed on the basis of the results of the analyses just discussed. The decision variables $X = (x_1, x_2, \ldots, x_n)$ may be used to stand for the agricultural production structure, where x_i is the scale of ith production activity and n is the number of production activities to be considered. For each fixed value of X, there is a corresponding production plan. Economic profit, which is closely related to production structure, may be regarded as a real function of the structure X, $f(X)$. The restrictions that various resources place upon the production structure, the social demands upon the production structure, the restrictions that the factors inside the production structure place upon one another, and so on, form the set of constraints on the production structure, say $g(X) = b$, where $g(X) = (g_1(X), g_2(X), \ldots, g_m(X))$ is a function vector, $b = (b_1, b_2, \ldots, b_m)$ is a vector, and m is the number of constraints. Therefore, this portion of the problem may be expressed as a mathematical programming problem, that is

$$\max f(X)$$

subject to

$$g_i(X) = b_i, \quad i = 1, 2, \ldots, m.$$

Weather is an important factor that cannot be overlooked in agricultural production, but it is difficult to control. Weather forecasting accuracy is often unsatisfactory, and Chang Qing County has the particular problem of being vulnerable to floods from the Yellow River, which affect agricultural production. We employ a gaming model to represent these hard-to-control factors, with nature on one side and farmers on the other side. Drought, flood, drought-and-flood, and no-drought, no-flood are the *policies of nature*. Various optimal production plans under different conditions are the *policies of farmers*. The optimal policy for farmers is selected according to certain standards.

The market prices of crops and livestock affect the profits from agricultural production and livestock husbandry. They, therefore, influence the distribution and structure of agriculture and livestock husbandry. Market prices are not stable. To prevent this instability from affecting the model, the nationally fixed prices were used when setting up the model. We then carried out sensitivity analysis to estimate the effect of the variation in market prices upon the production structure.

There is a close relationship between crops and animal husbandry, so in order to achieve an overall optimal structure, the mutual reliance of these two activities was modeled explicitly. Experience shows that the overall optimal structure so obtained is much better than the separately worked out optimal plans for crops ands livestock.

3.2. Model Formulation

Three key factors must be determined when setting up the programming model: decision variables, the objective function, and constraint conditions.

3.2.1. Determining Decision Variables

The decision variables for crops are determined by the locally suitable crop rotations (time distribution) and land arrangements (space distribution). Considering the local conditions, 14 crops were possible, and, in a two-year cycle, 83 possible crops combinations were defined according to their growing seasons.

Different crops will give different yields on different soils. To seek an optimal distribution of crops, we must analyze the soils for quality and fertility, and analyze the area for the availability of irrigation. The yearly yields from each land or soil type generally reflect its productive capacity. In order to quantify the land classification, we used fuzzy classification analysis.

First, we numbered the lands that will be classified. Then each numbered field was graded according to the factors affecting its productivity, such as the yearly output of various crops, as well as profit, cost, and so on. To reduce the number of fields, it was necessary to merge those fields that have smaller differences between them (or that are similar) into a single field. Therefore, we set up the statistical quantity

$$\gamma_{ij} = \begin{cases} 1 & i = j \\ 1 - q \sum_{t=1}^{T} | a_i^t - a_j^t | & i \neq j \end{cases}$$

which shows the degree of similarity of productivity between the ith and jth fields, where a_i^t is the grade of the tth crop on the ith field and T is the number of crop varieties. The selection of q must make $0 \leqslant r_{ij} \leqslant 1$ hold for every i and j, to say

$$q = \left[\max_{i,j} \sum_{t=1}^{T} | a_i^t - a_j^t | \right]^{-1} .$$

The closer r_{ij} is to 1, the greater the degree of similarity between the ith and the jth fields (see Table I).

Taking all numbered fields as vertices and using the number of fields as the vertex numbers, a complete graph, that is, a graph with an edge connecting every pair of vertices, was drawn. With r_{ij} defined as the weight on the edge connecting points i and j, a weighted graph G is thus obtained. We then seek out the maximum tree G^* for the weighted graph G. (A tree in graph G is a set of connective edges for each vertex in graph G that includes no cycle. The maximum tree is the one among all the trees in graph G that has the greatest sum of weights on each edge.) We cut tree G^* into several disjoint subtrees, by first fixing a classifying index u as a cut quantity according to the different degrees of economic indices among various kinds of divisions, to eliminate edges in G^* with weights $r_{ij} < u$. The type of fields in each subtree can be combined into one type, and the economic index for each can be treated as the same. In addition, we combine the fields that have smaller areas with similar kinds of divisions that have bigger areas, and thus stratify the land into 37 kinds of fields. The planting areas for 83 crop formations on 37 kinds of fields represent the production structure for crops, and form 3,071 decision variables. A unit of the variables is mu (1 mu = 0.16 acre).

The number of head of the 26 varieties of animal groups that can be bred in Chang Qing County in the

Table I
Matrix of Field Similarity

Grades/ Crops	Fields			
	1	2	...	n
1	a_1^1	a_2^1	...	a_n^1
2	a_1^2	a_2^2	...	a_n^2
		...	...	
T	a_1^T	a_2^T	...	a_n^T

mountainous area and the plain along the Yellow River form 52 decision variables, and provide the production structure for animal husbandry.

3.2.2. Determining the Objective Function

The criterion for an optimal production structure is to achieve the greatest economic benefit while meeting social demands and improving the production and ecology of the area. To simplify without losing practicality, social demands and demands for improving the ecological environment are regarded as constraints, and the net economic benefit (output minus cost) is the objective function.

The coefficient for crop planting in the objective function is the net profit from each crop formation on each mu every two years. The coefficient for livestock husbandry is the net profit from each kind of animal every two years. Each coefficient in the objective function comes from dealing with a group of data systems. The net profit comes from crops and animal husbandry. The profit from crops comes from the net profit of various crop formations on various fields. The net profit of the ith crop formation on field j is a function of the planting area X_{ij} and the net profit per mu. The production value per mu is the value of the grain produced and its stalks. The production value of each product is a function of the level of output per mu and the price of the resulting products. The price of a given product has two forms: national price and market price. The quantities sold to the nation and on the market have corresponding production values. The production value of stalks is decided by the stalk output and the market price. The output per mu of stalks may also be obtained by the ratio of the grain output to stalks. The cost per mu is decided by the money invested in crop production, which includes the cost of seeds, fertilizers, agricultural chemicals, agricultural machinery, livestock power and manpower, electricity and water. The amount invested in each item and its price per unit must be calculated separately.

The net profit of animal husbandry comes from various types of animals bred in various areas. It is determined by the breeding amount in a certain area X_{ij} (the breeding amount of the ith stock in area j) and the yearly net profit from each animal. The yearly net profit of each animal is, in turn, determined by the animal's production value and its cost. Production value includes the value of the animal's work and the fertilizer, meat, eggs, milk, skin, fur, bones, and young animals produced as well as money earned by breeding male animals. The cost includes money spent on feed (refined, coarse, and supplementary feeds), buying young stock, preventing and treating disease, administration facilities and energy.

3.2.3. Determining the Constraints

Constraints affect the production structures of crops and animal husbandry. First, there are the constraints on resources; for example, quantities of water, land, fertilizer, working animals, agricultural machinery, seeds, agricultural chemicals, energy, products purchased by the nation, social demands, production needs, storage capacity, processing capacity, market requirements, production facilities, investment, technology, policy, and ecological requirements. The present state of production and internal relationships with the production structure are additional constraints. The relationships between crops and animal husbandry in the areas of labor investment, feed, animal labor, machinery and fertilizer must also be considered. The need for ecological balance must also be taken into consideration when setting up crop rotations, the production of land used for planting, and the ratios among the breeding animals for various types of livestock. When deciding the social demands for agricultural products, we must determine the population and its distribution, the dietary needs of different people, and the amounts and compositions of feed for different types of animals.

The models just described were formulated under four conditions: drought, flood, drought-flood, and normal year. Obviously, under different weather conditions, the coefficients for the objective function and the constraints are different.

4. DETAILS OF THE MODEL

4.1. The Linear Programming Models

The objective functions of the linear programs are:

$$\text{Max } f^{(p)} = C_1^{(p)} X_1^{(p)} + C_2^{(p)} X_{22}^{(p)}$$

where

$p = 1, 2, 3$ and 4 denote the normal year, drought year, flood year and drought-flood year, respectively;

$X_1^{(p)}$ = a vector of the activity levels for crops. Its components are the various types of fields supplied for different combinations of crops under weather p;

$X_2^{(p)}$ = a vector of the activity levels for animals, including the number of animals on ranges (Chang Qing County was divided into two ranges: the plain along the Yellow River and the mountainous range); the components of $X_2^{(p)}$ should be integer variables. To simplify, we regard them as continuous variables and round their values. The error of this approximate method was allowable.

$C_1^{(p)}$ = a vector of the net profit coefficients over a two-year period from various types of fields for the combinations of crops per mu under weather p;

$C_2^{(p)}$ = a vector of the net profit coefficients per head of various kinds of animals over a two-year period under weather p;

$f^{(p)}$ = the total net profit from crops and animals over a two-year period under weather p.

The constraints are as follows.

1. The constraints on the area of various types of fields are:

$$A_{11} X_1^{(p)} \leqslant S_1$$

where

A_{11} = a 0–1 matrix that delineates various types of fields;

S_1 = a vector of the total areas of various types of fields, in mu.

2. The constraints on the area for various crops are:

$$A_{12}^{(p)} X_1^{(p)} \wedge S_2^{(p)}$$

where

$A_{12}^{(p)}$ = a matrix of the proportion of the cultivated area to the area of each type of field in the county and on various ranges under weather p for each crop over a two-year period;

$S_2^{(p)}$ = a vector of the required areas for each crop in the county and on various ranges under weather p over a two-year period;

$\wedge$ = all of the symbols "$=$", "$\leqslant$" and "$\geqslant$".

3. The constraints on the yields of various crops are:

$$A_{13}^{(p)} X_1^{(p)} \wedge E^{(p)}$$

where

$A_{13}^{(p)}$ = a matrix of the yield coefficients of crops per mu on various fields under weather p over a two-year period;

$E^{(p)}$ = a vector of the demand for various crops in the county and on various ranges under weather p over a two-year period;

4. The constraints on the proportion of areas designated for spring and summer crops are:

$$A_{14}^{(p)} X_1^{(p)} = 0$$

where

$A_{14}^{(p)}$ = a matrix of coefficients of the proportional factors of the areas of spring and summer sowing for each crop under weather p; for example, if x_1, x_2 are the areas of spring and summer corn, respectively, and x_1 is 5 times x_2, then the constraint is $x_1 - 5x_2 = 0$ or $(1, -5)\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = 0$ and $A = (1, -5)$.

5. The constraints on the number of each kind of animal is:

$$m^{(p)} \leqslant X_2^{(p)} \leqslant M^{(p)}$$

where

$m^{(p)}$, $M^{(p)}$ = the vectors of the lower and upper bounds on the number of various kinds of animals in the county and on various ranges under weather p, respectively, over a two-year period.

6. The constraint on the ratio of breeding male animals to female animals in one group of animals and among groups is:

$$A_{26} X_2^{(p)} = 7$$

where

A_{26} = a matrix of the proportional coefficients of breeding male animals to female animals in one group of animals and among groups in the county and on various ranges.

7. The constraints on coarse feed (stalk) are:

$$A_{17}^{(p)} X_1^{(p)} - A_{27}^{(p)} X_2^{(p)} \geqslant Q_1^{(p)}$$

where

$A_{17}^{(p)}$ = a matrix of the yield coefficients of the stalks of various crops on each field under weather p over a two-year period;

$A_{27}^{(p)}$ = a matrix of the demand coefficients for coarse feed for various animals under weather p over a two-year period;

$Q_1^{(p)}$ = a vector of the number of stalks needed by other production activities in the county and on various ranges under weather p over a two-year period.

8. The constraints on concentrated feed (grain) are:

$$A_{18}^{(p)} X_1^{(p)} - A_{28}^{(p)} X_2^{(p)} \geqslant Q_2^{(p)}$$

where

$A_{18}^{(p)}$ = a matrix of the amount of grain supplied by various crops on various fields in the county and on various ranges under weather p over a two-year period;

$A_{28}^{(p)}$ = a matrix of the amount of grain utilized by various animals in the county and on various ranges under weather p over a two-year period;

$Q_2^{(p)}$ = a vector of the amount of grain needed by other production activities in the county and on various ranges under weather p over a two-year period.

9. The constraints on natural manure are:

$$A_{19}^{(p)} X_1^{(p)} - A_{29}^{(p)} X_2^{(p)} \leqslant F^{(p)}$$

where

$A_{19}^{(p)}$ = a matrix of the amount of organic fertilizer needed for various crops on the various fields on various ranges under weather p over a two-year period;

$A_{29}^{(p)}$ = a matrix of the amount of manure produced by various animals on various ranges under weather p over a two-year period;

$F^{(p)}$ = a vector of the amount of manure produced by residents and forestry on various ranges under weather p over a two-year period.

10. The constraints on animal labor include:

$$A_{1,10}^{(p)} X_1^{(p)} - A_{2,10}^{(p)} X_2^{(p)} \leqslant 0$$

where

$A_{1,10}^{(p)}$ = a matrix of the requisite amount of animal-labor days (1 animal-labor day = the workload done by one animal in one day) for various crops on various ranges under weather p over a two-year period;

$A_{2,10}^{(p)}$ = a matrix of the amount of animal-labor days supplied by various animals on various ranges under weather p over a two-year period.

11. The constraints on the amounts of available water are:

$$A_{1,11}^{(p)} X_1^{(p)} + A_{2,11}^{(p)} X_2^{(p)} \leqslant N^{(p)}$$

$$\bar{A}_{1,11}^{(p)} X_1^{(p)} + \bar{A}_{2,11}^{(p)} X_2^{(p)} \leqslant \bar{N}^{(p)}$$

where

$A_{1,11}^{(p)}$ = a matrix of the amount of water needed per mu over a two-year period for various combinations of crops on various fields under weather p;

$\bar{A}_{1,11}^{(p)}$ = a matrix of the amount of water needed per mu for various combinations of crops during the peak of water consumption on various fields under weather p;

$A_{2,11}^{(p)}$ = a matrix of the amount of water needed for various animals under weather p over a two-year period;

$\bar{A}_{2,11}^{(p)}$ = a matrix of the amount of water needed for various animals under weather p during the peak water consumption period;

$N^{(p)}$ = a vector of the amount of water provided for crops and animals in the county and on various ranges under weather p over a two-year period;

$\bar{N}^{(p)}$ = a vector of the amount of water provided for crops and animals during the peak water consumption period under weather p (the units of $N^{(p)}$ and $\bar{N}^{(p)}$ are cubic meters).

12. The constraints on the labor force include:

$$A_{1,12}^{(p)} X_1^{(p)} + A_{2,12}^{(p)} X_2^{(p)} \leqslant H^{(p)}$$

$$\bar{A}_{1,12}^{(p)} X_1^{(p)} + \bar{A}_{2,12}^{(p)} X_2^{(p)} \leqslant \bar{H}^{(p)}$$

where

$\bar{A}_{1,12}^{(p)}$, $\bar{A}_{2,12}^{(p)}$ = the matrices of the amount of the labor force needed for crops and animals, respectively, in the county and on various ranges under weather p over a two-year period;

$\bar{A}_{1,12}^{(p)}$, $\bar{A}_{2,12}^{(p)}$ = the matrices of the amount of the labor force needed for crops and animals, respectively, in the county and on various ranges during the period in which there is the greatest demand for labor under weather p;

$H^{(p)}$ = a vector of the amount of worker days in the county and on various ranges under weather p over a two-year period;

$\bar{H}^{(p)}$ = a vector of the amount of worker days during the period in which there is the greatest demand for labor in the county and on various ranges under weather p.

13. The constraints on agricultural machinery and facilities are:

$$A_{1,13}^{(p)} X_1^{(p)} \leqslant G^{(p)}$$

where

$A_s^{(p)}1, 13$ = a matrix of the requisite amounts of various agricultural machinery and facilities for crops during the planting season in the county and on various ranges under weather p;

$G^{(p)}$ = a vector of the amount of various agricultural machinery provided in the county and on various ranges during the planting season under weather p.

4.2. Game Model

We used the yearly weather data in this county to obtain the frequencies p_1, p_2, p_3 and p_4 for a normal year (t_1), a drought year (t_2), a flood year (t_3) and a drought-flood year (t_4). These are decisions of nature, and the four optimal plans obtained from the linear programs are the decisions of farmers (S_1, S_2, S_3, S_4). Thus, the corresponding payoff matrix is obtained (see Table II).

In Table II, b_{ij} is the net benefit when farmers and nature take decision S_i and t_j, respectively. And, $b_{ij} = c^{(j)}X^{(i)}$, where $C^{(j)}$ is the vector of the net profit coefficients over a two-year period from production activities (crops and livestock) per unit under weather t_j; $X^{(i)}$ is the optimal solution of the linear programming under weather t_i.

We next discuss various criteria for selecting the optimal policy. First, we calculate the expected values for each decision S_i of the farmers:

$$a_i = \sum_{j=1}^{4} p_j b_{ij} \quad i = 1,2,3,4 \tag{1}$$

and take

$$a^* = \max\{a_1, a_2, a_3, a_4\} = a_r.$$

Then S_r corresponding to a_r is the optimal decision of the farmers because that plan achieves the largest expected value under various weather conditions.

Next, let

$$h_i = \frac{a_i}{\sum_{j=1}^{4} (b_{ij} - a_i)^2 P_j} \quad i = 1,2,3,4 \tag{2}$$

and take

$$h^* = \max\{h_1, h_2, h_3, h_4\} = h_r.$$

The less variation in benefit that weather causes under a plan and the greater the plan's expected benefit, the better the plan looks under this criterion.

Table II
Payoff Matrix

	t_1 (p_1)	t_2 (p_2)	t_3 (p_3)	t_4 (p_4)
S_1	b_{11}	b_{12}	b_{13}	b_{14}
S_2	b_{21}	b_{22}	b_{23}	b_{24}
S_3	b_{31}	b_{32}	b_{33}	b_{34}
S_4	b_{41}	b_{42}	b_{43}	b_{44}

Let

$$d_i = ea_i + (1-e)h_i \quad i = 1,2,3,4 \quad 0 < e < 1; \tag{3}$$

and take

$$d^* = \max\{d_1, d_2, d_3, d_4\} = d_r.$$

Then the decision S_r corresponding to d_r is the farmers' optimal policy. This criterion takes into account both criteria (1) and (2).

If the proportion of drought and flood years is regarded as unclear, matrix gaming can be used to seek the optimal pure or the optimal mixed policy.

5. PROCESSING AND CALCULATION OF DATA

The reliability of the data in any mathematical model is important to the useful solution of practical problems. Some existing agricultural data are incomplete, and owing to the instability and uncontrollability of certain aspects of agriculture, such as weather, it is difficult to eliminate some interactions of other elements when obtaining data. This results in a large degree of distortion. In order to get reliable results from the linear programming models, we put great effort and time into the collection and processing of data. The agricultural technicians in the county were divided into ten groups, for water resources, weather, management, etc., and they made a thorough and comprehensive investigation of crop and livestock farming in the county during the past 30 years. The resulting data were processed using mathematical statistics and interpolation theory on an IBM Personal Computer. For data that were considered to be incomplete or distorted by the experts, we re-collected the data through many other channels, compared and verified them, and then decided which were reliable. We used the following sources for these data:

1. The yearly statistics of the departments and technical organizations concerned;
2. Standard data that were stipulated nationally;
3. Investigations into data from representative years and production units;
4. Random sampling;
5. Experiences of the agricultural experts and management personnel;
6. Observation and experiment;
7. Comparison with the same kind of data from other areas;
8. The use of historical data together with mathematical methods such as regression analysis to remove random elements and obtain regular data.

As the data to be obtained from investigations came from many fields and the scope of the investigations were extensive, a standard investigation form was developed and the dimension and degree of accuracy for different parameters was coordinated.

When processing the parameters (e.g., the division of agricultural weather years into drought year, flood year, drought-flood year, and normal year, the determination of the output of crops per mu, etc.) we used predictive methods from probability and mathematical statistics, such as extrapolation.

6. ANALYSIS OF THE RESULTS OF CALCULATIONS

The calculations were made on a Sperry 1100 computer. After many calculations, the optimal solutions under different weather conditions were obtained. (The results of the calculations are omitted here.)

The results of the calculations supply production management personnel with helpful information as well as supplying an optimal production structure. For example:

1. The effect on economic profits of years of extreme weather damage to crops and/or animals may be lessened by loosening the constraints on the amount of grain to be produced.

2. The changes in planting areas and output in each optimal plan show certain regular patterns. In the optimal plan for a drought year, the planting areas for summer millet and summer sweet potato increase 20 and 200% over the normal year, and the increased planting areas are in the mountainous areas. This confirms that, as expected, the drought-resistant plants have obvious advantages in drought years and drought areas. In the optimal plan for flood years, the planting area and the output of spring sorghum along the Yellow River increase more than 100 and 60%, respectively, and the flood-resistant plant is the best choice. Summer corn is planted mainly on the plain along the Yellow River, and the planting areas in each optimal plan are basically stable, but in a year of extreme weather the planting area of summer corn in the mountain area is only 30–60% of that in a normal year. This shows that summer corn is easily affected by drought or flood in the mountain area and it has a low economic benefit. It can be replaced by summer millet, summer sweet potato, summer bean, and other crops. Winter wheat has a stable planting area and output, which shows that winter wheat is resistant to extremes of weather.

3. Comparing the optimal structures for various years to the structures of the same types of years in the past, we can see that economic benefits increase when optimal structures are imposed. Great changes occur in the proportions of crops: the planting areas of crops with high protein content, such as soybean and millet increase under the optimal plan. The increased planting of soybeans positively affects soil fertility.

4. In the past, this county always tried to increase the number of pigs, so that the county was viewed as short of refined feed; therefore, production of grain for refined feed was encouraged to supply refined feed, and coarse feed was the surplus. The results of our calculation prove this arrangement to be inefficient. The optimal structure for animal husbandry, compared with the original structure, shows a decrease in the breeding stock of pigs and poultry, and an increase in sheep and domestic rabbits. This change increases the demand for refined and coarse feed and leads to the full utilization of grass, stalks, and other coarse feeds. The changes made in livestock breeding fully utilize the natural resources and increase the economic benefits.

5. Using the optimal plan, there is a greater change in patterns of livestock breeding than in crop planting patterns. In the optimal structure, there is a considerable increase in economic benefit and the ratio of cost utilization, but also an increase in the amount of meat, eggs, milk, skins, fur, and bone produced. Animal labor and organic fertilizer also increase greatly. This creates constructive conditions for the development of crop production.

6. By comparing the optimal production structure with the original structure, we see weaknesses in past production management. Past practices did not allow for large-scale changes, did not take the weather into account enough, and did not consider the relationship between crops and livestock.

7. The payoff matrix and the frequencies p_1, p_2, p_3, p_4 for normal year (t_1), a drought year (t_2), a flood year (t_3) and a drought-flood year (t_4), and the net benefits (in units of million Yuan) of the s_i under various weather conditions, are shown in Table III, where s_i ($i = 1, 2, 3, 4$) are the optimal plans under various weather conditions, respectively.

As $\max_i \min_j b_{ij} = \min_j \max_i b_{ij} = 94.5$ in the table, we have the saddle-point of the game model and obtain the optimal pure policy S_4. By the criterion 5.2(1), $a^* = a_4 = 96.53$; then S_4 is the optimal decision. By the criterion 5.2(2), $h^* = h_4 = 0.57$; again, the policy S_4 is optimal. Comparing the optimal policies obtained by different criteria for optimization, and after discussion with agricultural management personnel, S_4 (the optimal plan for drought-flood year) was determined to be the optimal policy.

8. In order to know the effects of market prices on the optimal agricultural production structure, we conducted sensitivity analysis. Generally, market prices are higher

Table III
Optimal Plans Under Various Weather Conditions

Optimal Plans	Weather t_1	t_2	t_3	t_4			
p_1:	0.2	0.3	0.2	0.3	$\min_j b_{ij}$	a_i	$\frac{a_i}{\Sigma_j (b_{ij} - a_i)^2 p_j}$
S_1	105	94	96.6	89	89	95.22	0.3
S_2	103	96.5	93	90	90	95.15	0.44
S_3	104	95.5	97.7	92	92	96.29	0.54
S_4	100	96	96.9	94.5	94.5	96.53	0.57
$\max_i b_{ij}$	105	96.5	97.7	94.5	$\max_i \min_j b_{ij} = \min_j \max_i b_{ij} = 94.5$		

than nationally fixed prices. Three different factors were selected for changes in prices from the original nationally fixed prices to obtain the corresponding changes in the optimal production structure. The results of the sensitivity analysis show that some of the arrangements for crop formation are basically stable, while others are more sensitive with respect to planting area on certain kinds of land. This furnishes the basis for production management workers to regulate production structure according to market information.

8. IMPLEMENTATION

Our production plan was presented to the production management personnel in Chang Qing County. They found it to be practical and better than their original production plan, and decided to use it. To ensure the smooth implementation of this program, the county leaders formed an advisory group with the county governor as the group leader. The implementation began in September 1983, when winter wheat was being sown. The advisory group assembled the agricultural technicians, management personnel, and experienced farmers to review the practicality and optimization of the planting area for wheat in the optimal plan. The county government then issued a revised production plan. The result of using the plan was that the wheat output for drought-stricken 1984 was higher than in 1983, a normal year. This county was the only one among the four counties around the city of Jinan to increase total wheat output.

Implementation of the optimal production plan went as follows:

1. Two years were allowed for phasing in the planned planting of crops that were most strictly regulated, such as summer millet, summer corn and summer soybeans; the two years were considered sufficient time for farmers to adjust to major changes. Farmers were not coerced but shown how an optimal production structure would benefit everyone. As a result, the farmers were willing to implement the optimal plan, and most farmers' economic benefits increased.

2. A countywide optimal production plan cannot show all aspects of the optimal solution in detail. For example, for planning purposes, the land was divided into 37 types, each with a similar production force and profit value. For local implementation of the plan, in specific villages and households, however, small differences ignored in the large picture become significant. Therefore, slight variations were allowed in following the plan.

3. In the optimal production structure, some crops may be concentrated on a certain kind of land that may extend into several villages. One crop cannot satisfy the needs of the farmers in each village, however, so changes in planting patterns were allowed to suit the farmers.

4. The plan was modified with input from the villages that were involved. According to the proportion of various kinds of land owned by the villages, the production plan was put into their hands. Then necessary changes were made with reference to the production plans of past years, and especially, that of the last year of the project. Thus, a rough plan was made by each village. These plans were collected and discussed with a view to the whole county's production. An official plan was finally made that controlled overall production and took local needs into consideration.

5. Farmers were helped to overcome specific difficulties in implementing the optimal structure. For instance, the plan proposed a large-scale increase in the millet planting area. Farmers faced an inadequate supply of seeds and a lack of experience in growing millet. The production management department helped the farmers to get enough seeds and thousands of booklets on the growing of millet were distributed. As part of a general strategy, advice and instruction centers were set up in

each village and town. Agricultural chemicals, farming tools, and breeding animals as well as prevention and treatment services for diseases were furnished.

6. To insure the farmers against possible losses in income during the implementation of the optimal production structure, the purchasing departments signed buying contracts with the villages or households. This protected the farmers' profits. A fixed proportion of money was prepaid to overcome the farmers' lack of capital.

7. In order to solve problems as they arose, 30 households were used as observation points. To collect information on economic benefits, records were kept of the costs during implementation. This information was the basis for further changes in the plan.

8. ANALYSIS OF THE RESULT OF IMPLEMENTATION

8.1. Analysis of Economic Benefits

The implementation of the optimal plan for planting and animal husbandry led to the large-scale development of both industries. It also speeded up the development of forestry, related industries, and fisheries. Chang Qing County had the greatest rate of increase in total production value in 1985, with an increase of 111.94% over the 1981 value. The yearly increase was 20.66%. In contrast, those counties with similar conditions to those in Chang Qing County increased their production value by 80.87%, and their yearly increase was 15.97%. The total production value of planting in 1985 increased by 87.49% compared with the 1981 value, and the yearly increase was 17.02%. During the same period, the average yearly increase in Jinan City was only 10.61%. The production value of animal husbandry in the county in 1985 increased by 211.57% compared with 1981, with an average yearly increase of 32.86%. The proportion of the production value of livestock breeding to the total production value increased from 15.34% in 1981 to 22.55% in 1985. During this same period, counties with similar conditions increased 115.6% with an average yearly increase of 21.19%. Total output of grain in 1985 increased 51.41% compared with that of 1981 output, with an average yearly increase of 10.93%. This was 4.6% higher than the average increase in Jinan City. The output of grain per mu in 1985 showed an increase of 43.53%, with an average yearly increase of 9.46%, which was 5.24% higher than the average increase in Jinan. The net profit of planting in 1985 showed an increase of 73.48% compared with the 1981 figures.

The increase in net profit from crops resulted from several changes. In order to know objectively the effects of each change in the production structure, we eliminated several other major factors affecting the net profit.

Weather Factors. Table IV shows monthly precipitation in the county. Judging from the precipitation for the whole year, 1985 was a normal year, but the distribution of the rainfall suggests that some areas were affected by flood. In addition, some parts of the county experienced hail. In the fall, some areas were affected by overflow from the Yellow River. In contrast, 1981 showed a pattern of severe drought/slight drought/severe drought. Both years were affected by weather problems.

Comparing the net profit of the normal year 1980 with 1981, the 1980 profit is about 10.53% higher. The theoretical net profit from the calculation of the optimal plan for a normal year showed an increase of 6.1% compared with that of a drought-flood year. The net profit from the calculation of the optimal structure for a

Table IV
Precipitation in the County

		1981	1985	Yearly Average
Whole year	R	362 8	694.9	644 4
	$P(\%)$	−43.7	7.8	
	Weather	Slight drought	Normal	
March–May	R	22.2	150.1	80.9
	$P(\%)$	−72.6	85.5	
	Weather	Severe drought	Severe flood	
June–August	R	299.9	322.0	422.4
	$P(\%)$	−29.0	−23 8	
	Weather	Slight drought	Slight drought	
September–November	R	24.9	209.6	120.3
	$P(\%)$	−79.3	74.2	
	Weather	Severe drought	Severe flood	

drought-flood year under normal weather conditions increased by 11.27%. Thus, to separate the effects of weather factors, we deducted the highest value, 11.27%, from the increase in 1985.

In Table IV we see that:

$$P = \frac{R - \bar{R}}{\bar{R}} \times 100\%$$

where

P = the statistical index of drought and flood;
R = the precipitation in time periods;
$\bar{R}$ = the average yearly precipitation:
normal: $19.9\% \geqslant P \geqslant -19.9\%$,
slight drought: $-20\% \geqslant P \geqslant -49.9\%$,
severe drought: $P \leqslant -50\%$,
slight flood: $20\% \leqslant P \leqslant 49.9\%$,
severe flood: $P \geqslant 50\%$.

System of Production Responsibility. With the implementation of "the system of production responsibility," farmers were to produce and manage their own farms. This was intended to strengthen the connection between their effort and their results; that is, to increase their incentive to produce. Indeed, production increased. As conditions are different from area to area, there were different increases in production, which makes quantification difficult. To solve this problem, we thought it best to express changes in the output per mu of crops. Viewed countywide, 1983, the year the system of production responsibility was put into practice, saw an increase of 26.6% in the output per mu, compared with 1981, when weather conditions were similar. The increase in production also owes something to advances in science and technology. According to an analysis by the Committee of Science and Technology in Shandong Province, the ratio of the system of production to science and technology is 8:2. Thus, 21.3% was deducted from the increase in production in 1985.

Improved Seeds. Improved seeds were first used in 1981. With expansion in the planting of millet, some improved varieties of millet were introduced. According to the statistics of the department for improved variety, in 1985 the increase in production as a result of the improved varieties was 8 to 10%. Thus, 10% was deducted from the increase in 1985.

The Factor of Fertilizers. Basically, the same amount of chemical fertilizer was used in 1981 and 1985. With the implementation of the optimal production structure, an increase of 2450 million Jin (1 Jin = 0.5 kg) of organic fertilizers was provided for 1985 compared with 1981, with $^3/_4$ of the increase going to crops and the rest going to forestry and vegetables. The results of a village experiment on the relationship between organic fertilizers and crop yield shows that the increase of organic fertilizers in 1985 produced a maximum increase of 13.3% in the net profit of planting, compared to that of 1981.

A sum of 55.87% was deducted for these items. To remove the effects of other unrecognized factors, 30% of the remaining percentage improvement in production was deducted. (The experts and managers in the county consider that the effects of other unrecognized factors were less than 30%.) That is, 5.28% was deducted from the net profit from crops in 1981. The total deduction was 61.15%, which is 83.22% of the total increase. Thus, the increase in the net profit of planting in 1985 as a result of the optimal production structure was only 12.33%.

There was a greater increase in livestock production than in crops. Since the implementation of the optimal production structure in 1985, the net profit from livestock increased by 114.55%, compared with 1981. The main reason for this increase was that by adjusting the production structure for livestock, better use was made of the natural resources. In order to show the effects of the adjustment in the structure, that part due to the advances in science and technology should be deducted from the total increase.

First, a comparison was made between 1985 and the 30 years before the implementation of the optimal production structure. During those 30 years, the average yearly increase in the output value of livestock breeding was 6.6%, so 29.1% was deducted for the years between 1981 and 1985.

Then we compared Chang Qing County figures with those of other counties in the same period. The city of Jinan (except Chang Qing County) had an increase of 60.78% in the net profit from livestock breeding in 1985 compared to 1981; this increase was, presumably, the result of factors such as the system of production responsibility, the advances in science and technology, and so on. Thus, 60.78% was deducted from the amount of increase in Chang Qing County to account for these other factors. Still, there remained an increase of 53.77%. To be conservative, the smaller number was selected as the proportion of increase.

Of the total increase in the net profit from planting and livestock breeding (1985 compared with 1981), 28.8% was achieved by the optimization of the production structure.

8.2. Analysis of the Ecological Benefits

With a reasonable pattern of crop planting and the system of production responsibility, the active layer of soil in some mountain areas is thickened, more organic fertilizers are used, and the water-storage capacity of the land is improved. All of this is a foundation for the expansion of wheat planting and the increase in the multiple crop index. (The multiple crop index equals the sown area divided by the area of all fields.)

As a result of the interaction between planting and livestock breeding, a reinforcing cycle begins: livestock breeding provides crops with more organic fertilizer, which increases the grain yields; in return, the increase in the crop output provides livestock with more refined and coarse feed.

With appropriate crop rotations and the multiple crops index, balance was achieved between the utilization and preservation of the land, which increases the output as well as preserves the fertility of the soil.

8.3. Analysis of the Social Benefits

The steady increase in grain output helped develop a diversified economy in Chang Qing County. The food and drink processing and feed processing industries grew.

There was an obvious improvement in the quality of grains. The increase in the output of crops such as wheat, millet and soybean improved the food supply for local residents.

The development in livestock breeding provided more products and this improved the quality of life in the city and the county. It also brought about an increase in foreign trade, with more products to export.

9. CONCLUSIONS

Three years of research and practice has shown that the application of operations research in devising an optimal agricultural production structure has increased the productivity and reduced the risk of serious mistakes in the macroscopic management of agriculture. Accurate data must be acquired for the mathematical models and their parameters. Attention must be paid to the relationship between state plans and the farmers' freedom to produce and manage when farmers are given the optimal plan for their areas; some flexibility should be allowed. Timely help should be given to farmers who run into difficulty in adjusting their production structure. The farmers must gain if they plant according to the optimal production plan, and compensation must be made to farmers who suffer any loss. The optimal production structure is not eternal; changes must be made in the mathematical models and their parameters to account for changes in natural or economic conditions, as well as to incorporate new and improved information. This paper presents a preliminary quantitative evaluation of the optimal production plan's results. Much remains to be accomplished.