DECISION-MAKING AND SIMULATION STRATEGIES FOR THE SYSTEM OF MODELS FOR AGRICULTURAL PLANNING OF THE STAVROPOL REGION: (MATHEMATICAL DESCRIPTION)

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FOREWORD

The Food and Agriculture Program at IIASA focuses its research activities on understanding the nature and dimension of the world's food problems, on exploring possible alternative policies that can help alleviate current problems and prevent future ones.

As a part of the research activities investigations of alternative paths of technological transformation in agriculture in the context of resource limitations and long term environmental consequences are being investigated. The purpose is to identify production plans strategies which are sustainable. The general approach and methodology developed at IIASA for this investigation is being applied in several case studies on the regional level in different countries with the help of collaborating institutions. One of these case studies is for the Stavropol region of the U.S.S.R.

In this paper the authors provide mathematical description of some alternative simulation models developed for the Stavropol Case Study.

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Decision-making and simulation strategies for the system of models for agricultural planning of the Stavropol Region: (mathematical description)

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1. Introduction

The Stavropol case study of FAP's task on technological transformation of agriculture is directed to exploring the interactions of resources, environmental and technological alternatives in the economic development of the region. The main questions addressed are: What sustainable production potential can be achieved with the given resources and considering the environmental consequences in the region? What are the appropriate technologies for realizing this production potential?

The environmental processes involved in the modification of soil productivity as a result of agricultural production are sufficiently complex and non-linear to conceive of one unified optimizing framework. Instead a set of models are developed to be used in simulation mode to explore alternatives.

From the formal mathematical viewpoint the formulation of problems of decision-making requires a system of mathematical models describing the dynamics of crops growth, of the soils transformation depending upon climatic and other natural factors describing economic aspects of the agricultural production and containing decision variables.

The elements of the system can be schematically shown as in Figure 1. A recursive programming model may seem an obvious approach and yet a number of difficulties crop up in such an approach. Beginning with one soil type depending upon the crop grown and the technology and input intensities selected for the crop, the quality of soil in the next period is modified. Thus in very few time periods the number of soil classes to be considered becomes very

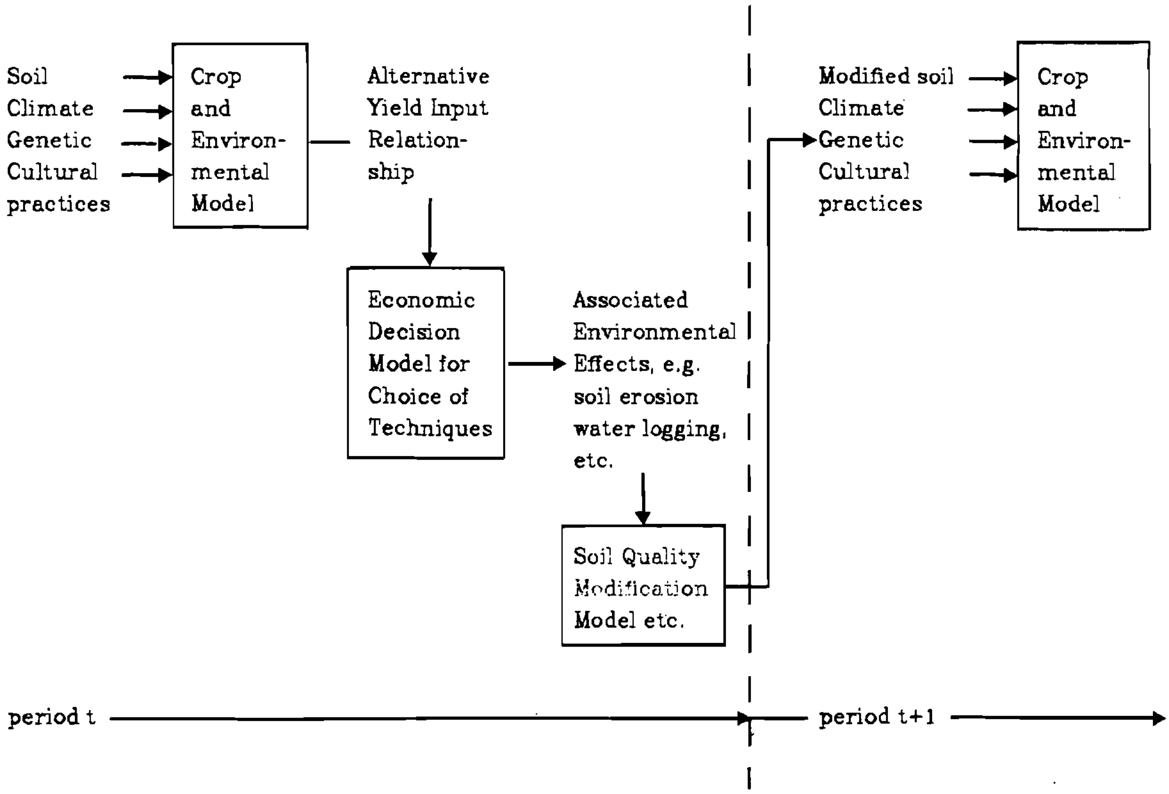


Figure 1. Schematic diagram of analytical elements

large--and soon becomes impracticable. One can develop some alternative approaches based on various simplifying assumptions. This has the obvious limitations that we do not have an optimizing system, but such approaches do provide practical simulation tools.

This type of a system is of high dimension and can only be used for simulation runs based on experts' jugdements. The experts provide indicators used for evaluating the policies (decisions) under analysis, they also develop scenarios that is the means of concretizing values of the decision variables. They also analyze the values of the indicators obtained in interactive computer runs and may also change during the analysis the values of parameters and even some relationships in the models.

To make such computer based analysis easier the automatization of the computer runs should be achieved taking into account that linking different blocks (models) in a system depends substantially on the formulation of relevant problems.

In this paper we present mathematical formulations for decision-making problems based on a physical crop production model which relates soil and climate data to crop productivity through agronomic principles (PCP-model) (including soil quality modification through erosion processes) and also on an economic model developed for the Stavropol case study. Procedures for an interactive analysis of this system of models are also outlined.

This paper contains a concretization of general methodological approach for a region to use a system of models describing agricultural production which is outlined in K.Parikh, and F.Rabar (1981). According to this approach the perspectives of the agricultural production in a region depend substantially upon the potential biological possibilities of different types of soils in the region as well as other natural conditions, and also on the policies of the use of resources implemented taking into account various economical considerations and environmental impacts from the implementation of those policies.

2. PCP-model

Based on agronomic and soil science principles, we have developed a model to quantify the longer-term yield effects of using alternative agricultural techniques.

A physical crop production model (PCP) in the tradition of De Wit (Centre for World Food studies, 1980) can be represented schematically as was shown in Figure 1.

Based on data on soil, climate and crop characteristics, the PCP model gives a relationship between yield and fertilizer application.

We have extended such a model to include the Soil Quality Modification (SQM) Model as was also shown in Figure 1.

Updating our input characteristics from year to year offers us the possibility of quantifying the effect of alternative agriculture techniques in the long run.

These models are computerized. They are used to generate information on the yield responses of crops to various inputs and on the consequences of such input uses for future yield.

The Physical Crop Production Model (PCP-model) [N.Konijn (1982)] describes the crop growth process using a decade (10 days)* as a time step, and also soil transformations using one year as a time step. For our purposes, that is for formulating problems of decision-making it suffices to consider the dynamics of the regional system using the time step of one year since one year is a characteristic interval for making economic decisions in the region under study. We describe first the state variables, decision variables and parameters of the PCP-model. We use symbol t for numbering years. The region is assumed to consist of subregions with uniform characteristics (the uniformity is explained later on).

Parameters of the model

The following parameters define a region:

- percentage of clay, silt, sand and gravel,
- size of the soil granules,
- permeability of soil horizon,
- kation exchange capacity for mineral components of soils,

for each soil horizon,

*The term decade is used in this paper for a 10-day period.

- geographical coordinates of the part of the region considered.

State variables

Ph^t - vector of physical characteristics with the following components:

- thickness of three soil horizons,
- porosity of the horizons,
- density of the horizons

Ch^t - vector of chemical characteristics with the following components for each of the three horizons:

- contents of the organic matter in the soil,
- nitrogen content,
- soil acidity,
- concentration of available phosphorus,
- concentration of available potassium,
- soil quality (ratio of carbon to nitrogen)

Or^t - vector of characteristics of the structure of the organic matter in soil with the following components (for six fractions of organic matter and for three soil horizons):

- percentage of a fraction in the total quantity of organic matter,
- quality (the ratio of carbon to nitrogen),
- percentage of carbon,
- cation exchange capacity.

Ws^t - vector of variables characterizing soil moisture for the three horizons,

Thus, the vector of state variables, z^t, has the form

$$z^t = (Ph^t, Ch^t, Oh^t, Ws^t)$$

Decision variables

We include into this class the following variables:

N^t - quantity of nitrogen fertilizers applied during a year,

P^t - quantity of phosphorus fertilizers applied during a year,

K^t - quantity of potassium fertilizers applied during a year,

O^t - vector characterizing the use of organic fertilizers with components:

- quantity of organic fertilizers applied during a year,
- decade when the fertilizers are appleid,
- structure of fertilizers (percentages of the six fractions and quality).

W^t - vector of variables characterizing water use for irrigation systems of three types (by basin, by furrow, by sprinkler) with components:

- total amount of water available
- maximum delivery capacity of an irrigation system

The PCP-model computes for each decade water demands by crops and also computes the available water supply using predetermined rules taking into account the maximum capacity of the irrigation systems and the total availability of water resources.

c^t - number of a crop grown on a given land,

A^t - vector of agrotechnical practices with components determined by the number of a crop c^t, type of ploughing and its characteristics. One of the components of this vector is equal to 1 if crop residuals are removed from the field and is equal to 0 otherwise. Thus the vector of control variables, u_t, is

$$u^t = (N^t, P^t, K^t, O^t, W^t, c^t, A^t)$$

Noncontrollable factors

The vector of noncontrollable factors ξ^t is determined by weather and climatic conditions and consists of series of decade average observations during a year:

- air temperature,
- relative air humidity,
- wind velocity,
- duration in hours of sunshine,
- precipitation.

The vector of production, y^t, is the output of the PCP model. The components of y^t are the output of the basic and supplementary production:

$$y^t = \Psi(z^{t-1}, N^t, P^t, K^t, O^t, W^t, c^t, \xi^t, p) \tag{1}$$

The associated water soil erosion, e^t, is also calculated in the PCP model:

$$e^t = \Phi(z^{t-1}, u^t, \xi^t, p) \tag{2}$$

The dynamic state equation in the PCP-model can generally be written as follows:

$$z^t = F(z^{t-1}, u^t, \xi^t, e^t, p) \tag{3}$$

where p is the vector of parameters defining the subregion.

The outcome of the PCP model is thus (y^t, z^t, e^t).

3. Simulation system

As is discussed in K.Parikh, F.Rabar the output (y^t, z^t, e^t) of the PCP-model serves as an input for the economic model and for the decision module. To formulate the economic model we divide the region's territory into L uniform subregions. We denote by s_l the area of subregion l and by S total area of the arable land in the region. The uniformity of a subregion means that all physical, chemical and other relevant characteristics are assumed to be the same over the area of the subregion. We shall also assume that only one crop and one technology h can be used in any subregion. Note, that under this assumption the number of the uniform subregions L considered remains constant in time, whereas without it this number generally grows.

We denote by L_{ch}^t the set of subregions which at the year t are allocated for growing crop c using technology h. Then the corresponding set for subregions allocated for crop c is:

$$L_c^t = \bigcup_h L_{ch}^t$$

and

$$L = \bigcup_c L_c^t$$

The number of elements in L is determined on one hand by the uniformity of the soils in the region in terms of physical and chemical characteristics (the minimum number; for the Stavropol region we have 15 classes of soil types considered to be uniform in the characteristics mentioned), and on the other hand by economic considerations, since we must have a sufficient representation of the technologies and crops to be able to analyze, for instance, the required production levels. Therefore, the set L can contain considerable number of elements.

In this case, the simulation system for the whole region is of the form:

PCP-model:

$$z_l^t = F(z_l^{t-1}, u_l^t, \xi_l^t, p_l)$$
$$y_l^t = \Psi(z_l^{t-1}, N_l^t, P_l^t, K_l^t, O_l^t, W_l^t, c_h^t, \xi_l^t, p_l) \tag{4}$$

(crop production from unit area in part l)

$$e_l^t = \Phi(z_l^{t-1}, u_l^t, \xi_l^t, p_l),\ l \in L,\ t \in T.$$

Economic model

$\sum_l s_l y_l^t = y^t$ - vector of production, with $y^{t,j}$, $j \in J_1$ - production of basic goods, and $y^{t,j}$, $j \in J_2$ - production of supplementary goods. s_l is area of subregion l. Denote by $d^{t,j}$ a part of the basic production used as feeds for cattle. All supplementary production is used as feeds. Then the production of feeds of type ν is given by

$$\sum_{j \in J_1} \beta_j^\nu d^{t,j} + \sum_{j \in J_2} \gamma_j^\nu y^{t,j} = d^{t,\nu}$$

where the coefficients β_j^ν, γ_j^ν describe amount of product j used to produce feed ν.

$\sum_{c,h} \sum_{l \in L_{ch}^t} r_{ch}^k s_l = r^{t,k}$ - demand for resource k, $k \in K$.

r_{ch}^k - consumption of k-th resource by technology h for crop c per unit area.

K - set of indices of resources, specific characteristics of which are:

- electric energy,
- fuel,
- chemicals,
- tractor services
- transport services
- grain harvesters services
- corn harvesters services
- beatroot harvesters services

$\sum_i k_i^\nu g_i^t = b^{t,\nu}$ - demand for feed of type ν.

with

k_i^ν -consumption per animal head of feed ν,

g_i^t - number of structural units of animal of type i (cows, pigs, sheep, poultry).

$\sum_i \alpha_{im} g_i^t = a^{t_m}$ - production output for animal of type m.

α_{im} - output of product m from structural animal unit of type m.

The economical model together with PCP-model constitute a description of a general simulation model, which we refer to as GM.

Simulation experiments

The controls in the model are:

$$set L_{ch}^t, N_l^t, P_l^t, O_l^t, W_l^t, A_l^t, g_i^t$$

By specifying various scenarios of choosing values of the control variables and using Eq. (4) we obtain sequences of values of

$$y^t, r^{t,k}, b^t, a^t, e^t$$

using which we can compute the values of the indicators of interest. Here we shall consider the following quantitative indicators:

- production output in a given proportion (or gross production),
- soil erosion,
- disbalance between demand and production of feed.

We assume that the available amounts of fertilizers and water are limited, therefore the objective of simulation is to help experts choose controls satisfying the following conditions:

$$\sum_l N_l^t \leq F^{1,t},\ \sum_l P_l^t \leq F^{2,t},\ \sum_l K_l^t \leq F^{3,t},\ \sum_l O_l^t \leq F^{4,t},\ \sum_l w_l^t \leq W^t,$$

where values $F^{1,t}, F^{2,t}, F^{3,t}, F^{4,t}, \overline{W}^t$ as well, as L are fixed at the beginning of the simulation run.

The use of these models for analyzing optimization problems (including multiobjective problems) is hindered by the high complexity and dimension of the models, and also by the discrete character of the controls.

4. Crop rotation type of a model

To simplify the elaboration of scenarios for GM we introduce the following assumptions. We assume that for every part of the territory with index l there exist such initial state of the soil z_l^o, such time interval T, such sequence of controls u_l^t that for some stationary weather conditions $\xi star_l$ ($\xi_l^t = \xi star_l$ for all $t \in T$) the final state of the soil is the same as the initial one:

$$z^{T_l} = \bar{F}(z_l^o, z_l{}^1, \ldots, z_l^{T-1}, u_l{}^1, u_l{}^2, \ldots, u_l^T, \xi star_l, \xi star_l, \ldots, \xi star_l . p_l) = z_l^o$$

We use this periodicity property in the following way. We divide a given area of land l into T equal subregions, and implement a given sequence of controls in each of them. Let $C=(c^1, c^2, \ldots, c^T)$ be the corresponding sequence of crops. Let us also choose the initial state for each of the subregions in such a way that at time $t=1$ the initial state of subregion i, $i=1,\ldots,T$ is z_l^{i-1} and it is allocated to crop $c_i \in C$. Then the state of subregion l at time $t=1$ is $(z_l{}^1, z_l^2, \ldots, z_l^{T-1})$, and although the states of the subregions change with time as is shown on Table 1, the actual state of subregion l remains the same as can be seen from Table 1.

Table 1.

Time Subregion	t=1	t=2	...	t=i	...	t=T
1	z_l^o	$z_l{}^1$	...	z_e^{i-1}	...	$z_l{}^{T-1}$
2	$z_l{}^1$	$z_l{}^2$	...	z_l^i	...	$z_l{}^1$
.	.	.		.		.
.	.	.		.		.
.	.	.		.		.
T	$z_l{}^{T-1}$	z_l^o	...	$z^{l^{i-2}}$	...	$z_l{}^{T-2}$

In this case at any time t all crops will be present in subregion l and production from this subregion will be constant from year to year under stationary weather conditions. This production structure will be refferred to as *crop rotation*. Crop rotations are widely used in agriculture and for our purposes here we obtained the necessary information from the book by [A.Nikonov (1980)].

The relationships describing soil transformation in part l in this case are the same for all parts. Therefore, we can use this type of a relationship only for part 1 for which the initial crop is c_l^1 and the initial state is z_l^o:

$$\begin{aligned} z_n^t &= F(z_n^{t-1}, u_n^t, \xi^t, p) \\ y_n^t &= \Psi(z_n^{t-1}, N_n^t, P_n^t, K_n^t, O_n^t, W_n^t, c_n^t, \xi^t, p) \\ e_n^t &= \Phi(z_n^{t-1}, u_n^t, \xi^t, p) \end{aligned} \tag{5}$$

where n is the index of a crop rotation.

Divide the territory of the region into L parts for which there exist sets of crop rotations: N_l^1 - for irrigated lands, N_l^2 - for nonirrigated lands. Denote by $x_n^{1,l}$ the area allocated for crop rotation n in part l without irrighation. Assume also that only one production technology is used for each crop rotation. Denote by $y_n^{1,l}$ vector of production on irrigated lands and by $y_n^{2,l}$ the corresponding vector for nonirrigated lands. Then:

Vector of production in the region:

$$\sum_l \Big(\sum_{n \in N_1} y_n^{1,l} x_n^{1,l} + \sum_{n \in N_2} y_n^{2,l} x_n^{2,l} \Big) = y$$

Demand in resources:

$$\sum_l \Big(\sum_{n \in N_1} r_n^{1,l} x_n^{1,l} + \sum_{n \in N_2} r_n^{2,l} x_n^{2,l} \Big) = r^k, \ k \in K$$

Constraints on the areas of irrigated lands:

$$\sum_{n \in N_1} x_n^{1,l} \le S_l^1 \tag{6}$$

Constraints on the areas for part l:

$$\sum_{n \in N_1} x_n^{1,l} + \sum_{n \in N_2} x_n^{2,l} \le S_l \tag{7}$$

Demand for feeds in the region:

$$\sum_i k_i^\nu g_i = b^\nu$$

Animal production of type m:

$$\sum_i \alpha_{im} g_i = a_m .$$

5. Decision-making problems

In principle, the formulation of the crop rotation problem will have a closed form if a problem of choice of the decision variables is formulated. Note, that by introducing crop rotations we changed a discrete control problem into a continuous one. Nevertheless, in this case possibilities of solving optimization or multiobjective problems are also limited. For this reason it apperars worthwhile to use decomposition procedures for this model. In what follows we outline the use of optimization models for screening out irrational alternatives and for the elaboration of scenarios for the general model. In formulating optimization problems we shall use the same indicators as in the simulation runs using the general model.

Consider a problem of increasing the production of agriculture in a given proportion (or increasing the gross agricultural production) under a given level of soil erosion and disbalances in feeds. We determine a finite set of technologies using PCP-model and then we use these technologies in the economic block to obtain a formulation of an auxillary linear programming problem.

The required set of technologies can be obtained using system (5) for a finite tuple of possible amounts of fertilizers N,P,K,O and of water W for various crop rotations C_n for given sequences $\xi^1, \ldots, \xi^{T_n}$ which reflect experts' jugements with regard to the uncertainty in weather conditions. Table 2 illustrates the procedure of generating technologies for the decomposition of the model.

Table 2.

production output	y^1	y^2	$\dots y^t$	$\dots y^{T_n}$
crop index	c_n^1	c_n^2	$\dots c_n^t$	$\dots c_n^{T_n}$
weather	ξ^1	ξ^2	$\cdots \xi^t$	$\cdots \xi^{T_n}$
amount of fertilizers	N^1	N^2	$\dots N^t$	$\dots N^{T_n}$
amount of fertilizers	P^1	P^2	$\dots P^t$	$\dots P^{T_n}$
amount of fertilizers	K^1	K^2	$\dots K^t$	$\dots K^{T_n}$
amount of fertilizers	O^1	O^2	$\dots O^t$	$\dots O^{T_n}$
amount of water	W^1	W^2	$\dots W^t$	$\dots W^{T_n}$
state	z^0	z^1	$\dots z^t$	$\dots z^{T_n-1}$
erosion	e^0	e^1	$\dots e^t$	$\dots e^{T_n-1}$

From this table we can find amounts of fertilizers and water actually used:

$$f_n^1 = \frac{1}{T_n}\sum_t N^t, \quad f_n^2 = \frac{1}{T_n}\sum_t P^t, \quad f_n^3 = \frac{1}{T_n}\sum_t K^t,$$
$$f_n^4 = \frac{1}{T_n}\sum_t O^t, \quad v_n = \frac{1}{T_n}\sum_t W^t,$$

soil erosion;

$$e_n = \frac{1}{T_n}\sum_t e^t,$$

and crop productivity:

$$y_n = \frac{1}{T_n}\sum_t y^t,$$

which are used in the economic block.*

Now we add relationships describing demands for fertilizers and water to the economic block:

$$\sum_l \Big(\sum_{n \in N_1} f_n^{1,k} x_n^{1,l} + \sum_{n \in N_2} f_n^{2,k} x_n^{2,l} \Big) = f^k, \ k = 1,2,3,4.$$

* Amounts of water may not be fixed, but obtained as water demands of crops

with $f_n^{1,k}$, $f_n^{2,k}$ being consumptions per unit area of nitrogen (k=1), phosphorous (k=2), potassium (k=3), organic fertilizers (k=4) for irrigated and nonirrigated crop rotations, obtained as discussed earlier.

Water demand:

$$\sum_{n \in N_1} v_n x_n^{1,l} = W^l .$$

Total erosion of soils in the regions is given by:

$$e = \sum_{l,n} (e_n^1 x_n^{1,l} + e_n^2 x_n^{2,l}).$$

Now we can formulate a supplementary optimization problem:

$$\max_x \left[\min \left(\min_{j \in J_1} \frac{y^j - d^j}{Y^j}, \ \min_m \frac{a^m}{A^m}, \ \frac{E-e}{E} \right) \right]$$

s.t. Eq. (6), (7) and

$$\begin{array}{c} r^k \le R^k, \ k \in K\text{- } resources, \\ f^k \le F^k, \ k = 1,2,3,4 \text{ - } fertilizers, \\ w^l \le W^l, \ l \in L\text{- } water, \\ \sum_{j \in J_1} \beta_j^\nu d^j + \sum_{j \in J_2} \gamma_j^\nu y^j \ge b^\nu\text{- } feeds \end{array} \qquad (8)$$

This problem can be reduced to the following linear programming problem:

$$\max_x \rho \rightarrow$$

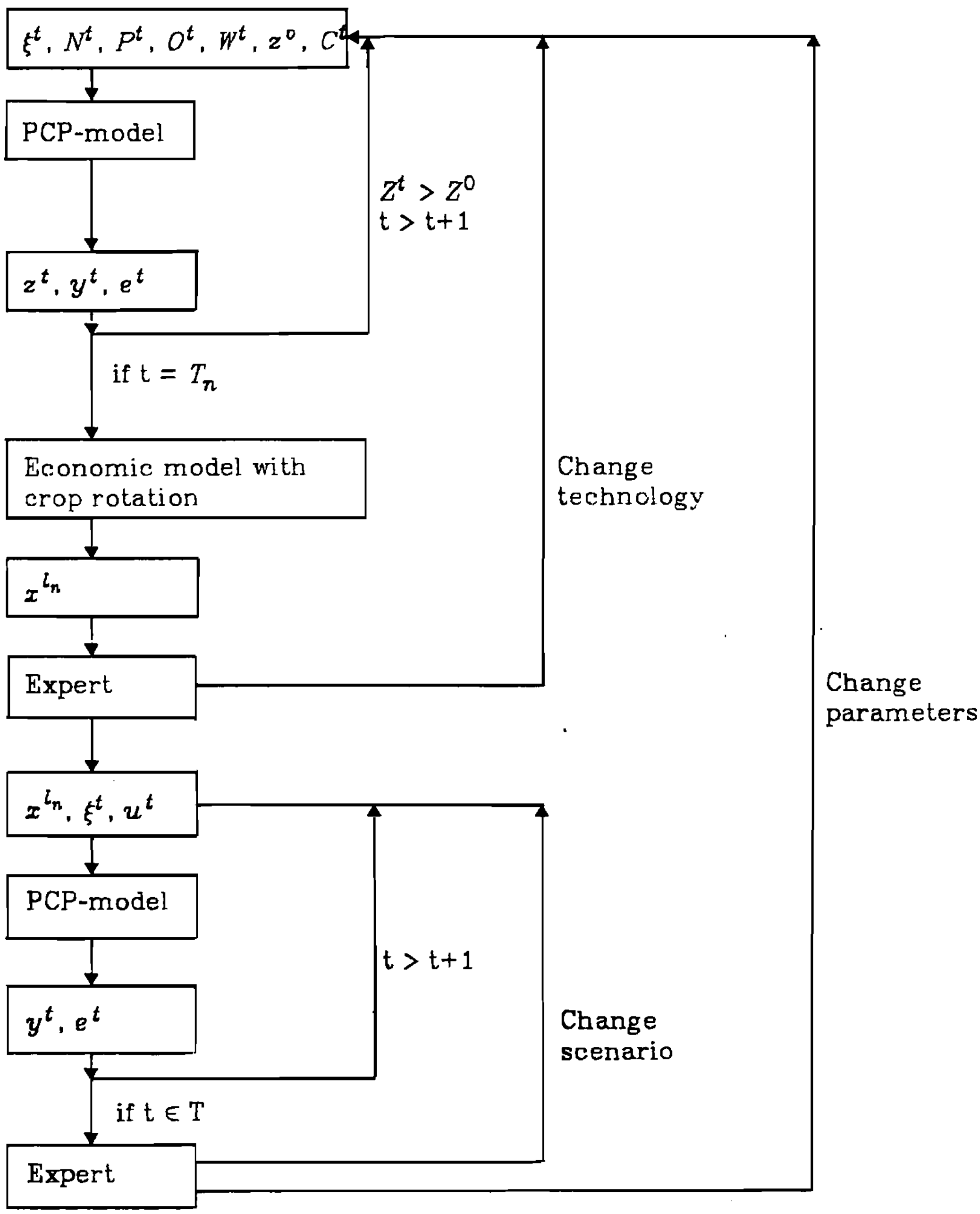
s.t.

$$y^j - d^j \ge \rho Y^j, \ j \in J_1,$$

$$a^m \ge \rho A^m, \ m = 1,2,3,4; \ e \ge \rho E$$

plus constraints (6) - (8).

After having obtained the solution of the auxillary crop rotation problem we should perform its evaluation. This can be achieved by solving system (4) and computing values of the indicators. If the solution obtained does not satisfy the experts, the whole procedure can be repeated from any of the previous stages. The whole experimentation procedure can be depicted as follows:



$\xi^t, N^t, P^t, O^t, W^t, z^o, C^t$
PCP-model
$Z^t > Z^0$
t > t+1
z^t, y^t, e^t
if t = T_n
Economic model with crop rotation
Change technology
x^{l_n}
Expert
Change parameters
x^{l_n}, ξ^t, u^t
PCP-model
t > t+1
y^t, e^t
Change scenario
if t ∈ T
Expert

6. One stage monocrop model

We describe here a variant of a one stage monocrop model that was developed at the first research stage as an approximate formulation of crop rotations. The region's territory was divided into subregions with uniform characteristics (soil classes). Finite sets of technologies were also specified by experts for each crop together with the corresponding factors of the resources consumption $k \in k$. From a given series of weather conditions an expert chose reporesentative years $t \in T_1 = (t_1, \ldots, t_\nu)$ together with the corresponding frequences (probabilities) p_q^t, $q \in Q$ of their occurence, representing expert's jugements with regard to the uncertainty in weather. A problem was considered of allocating the agricultural production ensuring a certain level of production in a given proportion under some prespecified limit of soil erosion. Now we turn to a formulation of this problem.

Denote by $S_{ch}^{1,l}$ $(S_{ch}^{2,l})$ an area allocated for crop c with technology h on part l with irrigation (without irrigation). For each $t \in T_1$ with fixed amounts of fertilizers and water we have a form of PCP-model for one step:

$$\begin{aligned} z_l^1 &= F(z_l^o, u_l, \xi_l, p_l) \\ y_{l,ch} &= \Psi(z^{o_l}, N_l, P_l, K_l, O_l, W_l, ch, \xi_l, p_l) \qquad (9) \\ e_l &= \Phi(z^{o_l}, u_l, \xi_l, p_l). \end{aligned}$$

using which we can compute production outputs $(y_{l,ch}^{1,t}, y_{l,ch}^{2,t})$ and soil erosion $e_{l,ch}^t$.

We introduce the notation:

$$y_q^j = \sum_{t \in T_1} p_q^t [\sum_l (\sum_{c,h} s_{ch}^{1,l} y_{l,ch}^{1,t,j} + \sum_{c,h} s_{ch}^{2,l} y_{l,ch}^{2,t,j}) - d^{t,j}]$$

for the average production for distribution q.

Now we can formulate a problem of maximizing guaranteed average production:

$$\max_{\{S\}} \min_{\substack{\{p_q^t\} \\ q \in Q}} \min \left[\min_{j \in J_1} \frac{\sum_{t \in T_1} P_q^t Y_q^j}{Y^j},\ \min_m \frac{\alpha^m}{A^m},\ \frac{E - \sum_{t \in T_1} \sum_{l,c,h} l_{l,ch}^t P_q^t}{E} \right]$$

with $\{Y^j\}$ being a given vector of vegetable production, $\{A_m\}$ being a given vector of animal production, E being a givem level of soil erosion, under constraints:

on areas:

$$SL_c^{i,l} \le \sum_h s_{ch}^{i,l} \le SU_c^{i,l},\ i=1,2 \tag{10}$$

for irrigation systems:

$$\sum_h s_{ch}^{1,l} \le S^{1,l}$$

for subregion l:

$$\sum_{c,h} s_{ch}^{1,l} + \sum_{s_{ch}^{2,l}} \le S^l$$

for resources:

$$\sum_{l,c,h} r_{ch}^{1,k} s_{ch}^{1,l} + \sum_{l,c,h} r_{ch}^{2,k} s_{ch}^{2,l} = r^k \le R^k,\ k \in K$$

for fertilizers:

$$\sum_{l,c,h} f_{ch}^{1,k} s_{ch}^{1,l} + \sum_{l,c,h} f_{ch}^{2,k} s_{ch}^{2,l} = f^k \le F^k,\ k=1,2,3,4$$

for water:

$$\sum_{ch} v_{ch} s_{ch}^{1,l} \le W^l,\ l \in L,$$

$$\sum_{j \in J_1} \beta_j^v d^{t,j} + \sum_{j \in J_2} \gamma_j^v \sum_{l,c,h} (s_{ch}^{1,l} y_{l,ch}^{1,t,j} + s_{ch}^{2,l} y_{l,ch}^{2,t,j}) \ge \sum_i k_i^v g_i,\ t \in T_1.$$

with R^k, F^k, W^l - resources available in the regions.

This problem is reduced to the following linear programming problem:

$$\rho \to \max$$

$$y_q^j \ge \rho Y^j$$

$$E - \sum_{t \in T_1} \sum_{c,h} e_{l,ch}^t p_q^t \ge \rho E,\ q \in Q$$

plus the above constraints.

Solution to this problem gives some allocation pattern for various crops with different technologies $s_{ch}^{opt,i,l}$, $i=1,2$. Using thia allocation pattern we can determine the corresponding allocation for crop rotations:

$$\sum_h s_{ch}^{opt,i,l} = \sum_{n \in N_i} \alpha_c^n x_n^{i,l},\ i=1,2$$

with α_c^n being fraction of crop c in crop rotation n *.

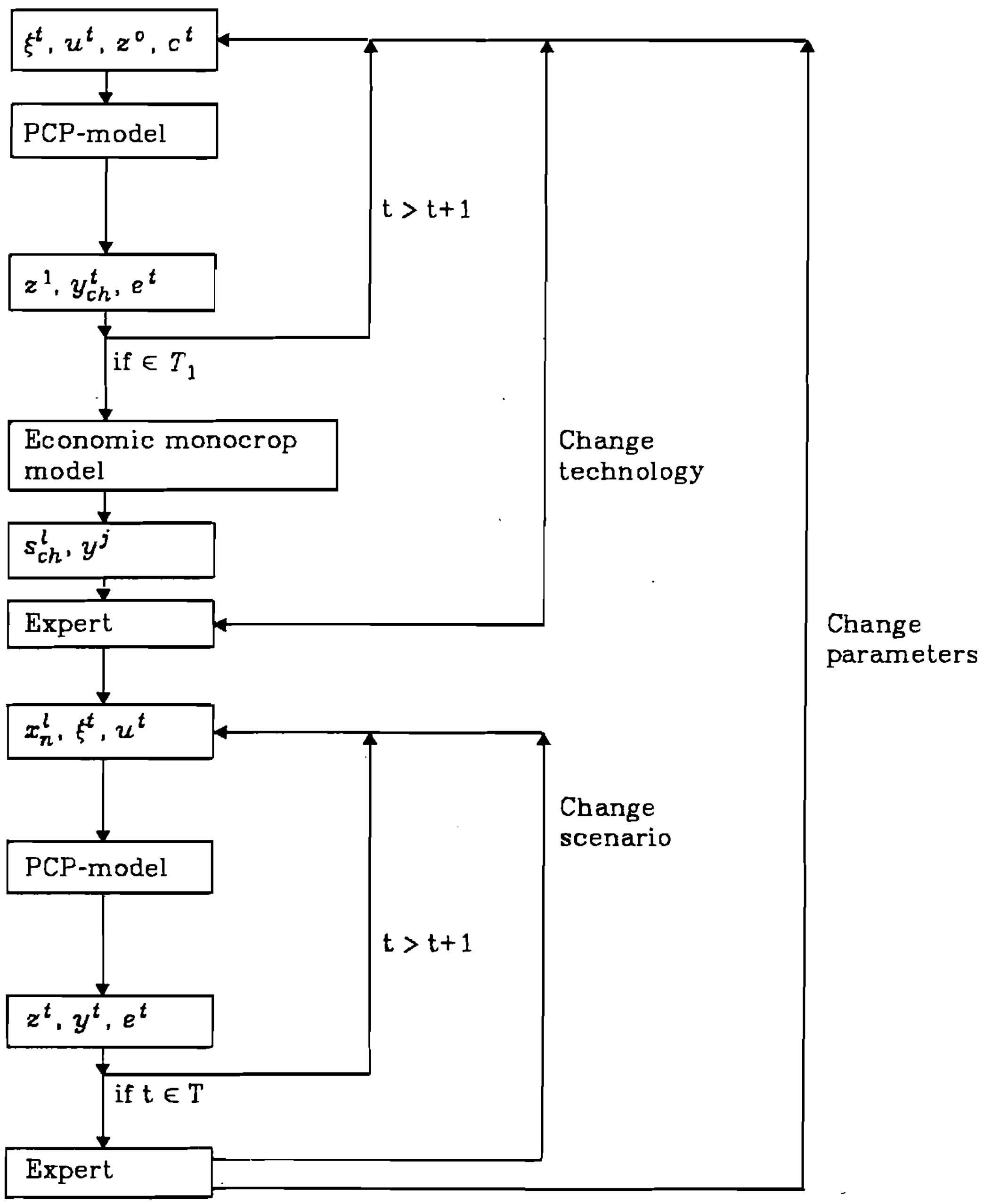
The crop rotation solution obtained can be analyzed using simulation runs as has been outlined earlier. We should note that the monocrop solution is also of interest to the experts. It can be used, for example, to determine a sequence

$$\sum_{c,h} s_{ch}^{1,l} y_{l,ch}^{1,t} + \sum_{c,h} s_{ch}^{2,l} y_{l,ch}^{2,t} = y^t$$

of productions for a fixed allocation of land and technologies with varying weather conditions. However, it appears not justified to make any conlusions with regard to the dynamics of the agricultural production.

The procedure for performing the analysis using the monocrop model can be depicted in the following form:

* Bounds SL and SU in constraints (10) are chosen to provide for the existence of a solution to this system


ξ^t, u^t, z^o, c^t
PCP-model
z^1, y^t_{ch}, e^t
t > t+1
if ∈ T_1
Economic monocrop model
s^l_{ch}, y^j
Expert
Change technology
Change parameters
x^l_n, ξ^t, u^t
PCP-model
Change scenario
t > t+1
z^t, y^t, e^t
if t ∈ T
Expert

7. Computer experiments

The computational procedure outlined in this paper was implemented for the Stavropol project on IIASA's VAX computer and also in the Computing Center of the USSR Academy of Sciences. Data for those experiments were prepared by experts (biologists and economists) for the simulation system described in sect. 2 of this paper. In particular, this included not only data for resources $k \in K$ but also data concerning crop productivities, demands for fertilizers and water resources. Using these data computer programs were elaborated for the analysis of the optimization problems outlined in this paper. In parallel to this analysis on the basis of PCP-models production of crops was determined for various amounts of fertilizers applied and water used for irrigation. Using the results obtained new technologies were introduced into the optimization models outlined in this paper.

All the procedures discussed here have been implemented for the analysis of the agricultural production in Novo-Aleksandrovski, and subsequently the whole Stavropol region has been analyzed on the basis of one stage monocrop approach.

References

1. K. Parikh and F. Rabar (eds.), 1981. SR-81-2. *Food for All in a Sustainable World.* The IIASA Food and Agricultural Program.

2. N. Konijn, 1982. *A Physical Crop Production Model and Its Environmental Feedback.*

3. A.A. Nikonov (ed.), 1980. *The Systems of Agriculture of Stavropol Region.*