# MODELING REGIONAL AGRICULTURAL SYSTEMS

## Proceedings of the International Seminar on "Results of the Development of Mathematical Models for Regional Systems of Farm Management"

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This seminar, which was held at Stavropol on August 9-12, 1982, was organized jointly by:

The USSR Academy of Sciences
The V.I. Lenin All-Union Academy of Agricultural Sciences
The International Institute for Applied Systems Analysis
The Stavropol Research Institute of Agriculture

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# Foreword

A part of the research activities of the Food and Agriculture Program at IIASA focused on the investigations of alternative paths of technological transformation in agriculture in the context of resource limitations and long-term environmental consequences. The purpose was to develop general approach and methodology through work at IIASA and in several case studies at the regional level in different countries with the help of collaborating institutions. The case studies help not only to validate the general methodology but also to develop an analytical tool for detailed investigations for a particular region which could then be applied to other regions. Moreover, these case studies addressed certain specific questions which permit a comparative analysis.

The case study of the Stavropol region of the USSR was a major study in this effort involving many institutions in the USSR and was strongly supported at the highest level by the V.I. Lenin All-Union Academy of Agricultural Sciences of the USSR.

In the course of this case study an international seminar was held on "Results of the Development of Mathematical Models for Regional Systems of Farm Management" at Stavropol on August 9-12, 1982. The seminar was organized jointly by the USSR Academy of Sciences, the V.I. Lenin All-Union Academy of Agricultural Sciences, the International Institute for Applied Systems Analysis, and the Stavropol Research Institute of Agriculture.

This volume contains some of the papers presented at the seminar. These papers were published in Russian in the Journal Vestnik Selskochoziastvennoi Nauki (Proceedings of Agricultural Sciences). Translation into English was done by Ms. E.M. Stolyarova who also helped in editing. Translation and editing across distance has taken some time, but it is still considered worthwhile to bring out this proceedings as the Stavropol case study represents a very successful collaboration in applied policy research between IIASA and institutions in the USSR.

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# CURRENT STAGE OF THE DEVELOPMENT OF AGRICULTURAL MANAGEMENT SYSTEMS IN THE USSR

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Problems related to agricultural management systems have invariably received a great deal of attention, both in the pre- and post-revolutionary periods. At various stages of the development of agricultural economics considerable contribution has been made by A.T. Bolotov (1738-1833), M.G. Pavlov (1793-1848), A.V. Sovetov (1826-1901), A.N. Engelgardt (1832-1893), I.A. Stebut (1833-1923), A.P. Lyudogovsky (1840-1882), A.S. Yermolov (1846-1916), A.I. Skvortsov (1846-1914), A.F. Fortunatov (1856-1925), A.N. Chelintsev (1874-1962), A.V. Chayanov (1888-1949), A.P. Makarov (1887-1981), L.M. Zaltsman (1896-1982), and M.I. Kubanin (1898-1941). But in the past such studies were undertaken by individual researchers, with the results obtained being little introduced into the general practice of agricultural management.

In the 1960s, agricultural management systems enjoyed a large-scale development. Scientists of numerous central and regional research institutions became involved. In 1960-65 agricultural management systems for 39 natural and economic zones were elaborated; in 1971-75 the recommendations covered 44 zones. By the early 1980s systems had been developed for a total of 154 regions, territories, and republics. The shift to systems dependent on the administrative borders of regions was effected in order to facilitate the introduction of scientific developments into practice.

However, the systems developed in the recent past are mainly of a descriptive nature, being confined to production technology and not covering the whole complex of factors that form the system. That is why those systems could not be used as a tool for the optimization of resource use. A new, qualitative change in the approach to the development of agricultural management systems is related to the introduction of systems analysis. The development of modern agriculture is characterized by a rapid growth of the resource potential and by an intensification of the production process, with organizational structures, as well as intra- and inter-industry relations, becoming more sophisticated. Under these conditions the problem of the optimization of resource use – which is considerable now and will continue to increase – becomes more urgent (Table 1).

Table 1. Resource potential of Soviet agriculture (data provided by the Central Statistical Bureau of the USSR)

| Index | 1960 | 1970 | 1980 |
|---|---|---|---|
| Agricultural land ($10^6$ha) | 515.4 | 545.8 | 553.6 |
| arable land | 220.0 | 223.5 | 226.4 |
| reclaimed land | 16.3 | 19.2 | 31.0 |
| Power capacities ($10^6$hp) | 155.9 | 322.1 | 603.9 |
| Electric energy consumption ($10^{12}$kWh) | 9.9 | 38.6 | 111.0 |
| Fixed productive assets in agriculture ($10^9$ roubles) (comparable prices of 1973) | 43.9 | 94.7 | 227.0 |
| Mineral fertilizer supplies to agriculture ($10^6$ tonnes of nutrients) | 2.6 | 10.3 | 18.8 |
| Annual average number of full-time employees, including seasonal workers ($10^6$) | 26.1 | 24.1 | 22.9 |

The USSR Food Programme envisages a considerable increase in the growth rates of agricultural production, an increase of its stability under unfavorable weather conditions, and an improvement of the structure of both the agricultural sector and the total agro-industrial complex. The above goals can be achieved provided the introduction and establishment of agricultural management systems is effected at all levels of the economy – national, regional, and district levels, as well as at the individual enterprise level. This problem is becoming increasingly urgent.

Recently, in the USSR the elaboration of crop farming systems was finalized. Studies aimed at the development of rational animal breeding and feed production systems are under way. Being as important as they are, these links are characteristic of individual systems blocks only. Nowadays, we face the problem of attaining a proper interdependence among the system blocks and their close correspondence with the resource potential; we have to substantiate and put into practice efficient methods of management and resource use.

Let us consider the general characteristics of those factors that form the system, in the light of recent changes, and show their effect upon the agricultural management systems. The factors to be considered fall into seven general groups: political, economic, social and demographic, scientific and technical, organizational and legal, biological and natural (Figure 1). It stands to reason that the above grouping is very relative.

## Political Factors

*International situation.* Since the routing of fascism in Europe, our country has been at peace for almost four decades, due to the peaceful policy of the Soviet Government. This provides for a regular development of and considerable investment in the national economy. But the existing international tension still forces us to give due attention to defence problems.

*World market.* The USSR is closely interlinked with the world market. Calculated in comparable prices, the index of foreign trade volume in 1980 was four times that in 1960, with an increase from 10 to 110 $\times 10^9$ roubles during the same period, in current prices. Agricultural produce constitutes a considerable share

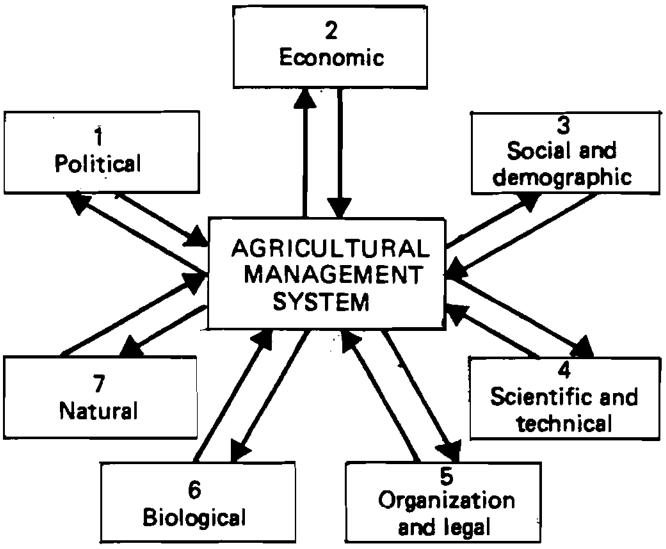

Figure 1. System forming factors affecting agricultural management systems

in the total foreign trade balance. Soviet foreign trade relations are certain to develop. But as far as grain is concerned, we shall stop being dependent on the world grain market in the near future, but will continue to import goods which, due to climatic conditions in the USSR, are either not produced or whose production is limited.

*Agrarian policy.* The USSR agrarian policy is aimed at the stimulation of production growth, and at the consistent intensification and industrialization of agriculture. The share of agricultural investments accounts for 27% of the total input to the national economy. In the foreseeable future this share is likely to remain unchanged.

## Economic Factors

*The Demand* for agricultural produce is very high, with requirements not being fully satisfied and the domestic market having a high capacity. Producers' *prices* for agricultural produce are rather stable, and are revised approximately every five years. The last rise in prices took place early in 1983, according to the decree issued by the Plenary Session of the Central Committee of the Communist Party of the Soviet Union (the Session took place in May 1982). This measure made it possible to eliminate the difference between the purchase prices paid for agricultural produce, on the one hand, and the rapidly growing prices for the industrial means of production in the agricultural sector, on the other hand. But the price mechanism is of a dynamic nature and is to be adjusted constantly. Price level and price ratio can serve both as stimulating and limiting factors, depending on the economic situation.

The *financial policy* of the Government favors the development of agriculture with wide possibilities for obtaining credit. The level of agricultural *investments* is rather high, but still is not sufficient to satisfy the requirements. That is why the efficient and economical use of capital investments is important.

*Economic interests* are of crucial importance. Private interests are to be reasonably combined with collective ones. Possible contradictions are to be foreseen and eliminated. Infringement on private, collective, or state interests has, invariably, a detrimental effect upon production development and restricts its growth. In this connection it should be emphasized that decisions made recently were aimed at the elimination of the above contradictions.

### Social and Demographic Factors

The *human factor* has invariably played a decisive role in any production development. Man, with his mental, physical, and ethical capacities, has been and will remain the principal productive force of society. No technical equipment or automatic machines can diminish the importance of this factor. On the contrary, its importance is increasing, since with time the scientific and technical progress is becoming a greater challenge to man.

*Urbanization and population density* have a considerable impact upon the formation of agricultural management systems in the USSR. In the last 20 years the share of urban population increased from 50 to 64%. In the rural sector the number of those employed (including their family members) accounts for 24%. Rural population is decreasing, both in absolute terms and in percentage, which results in a growth of the number of net-consumers of agricultural produce.

*The provision of agriculture with labor resources* in general seems to be rather high – the share of those engaged in the agricultural sector amounts to 20% of the total number employed. But the distribution of labor resources is not uniform – southern regions, especially Central Asia, are characterized by an abundance of labor force, while northern and western regions are currently experiencing labor shortages. The organization and technology of agricultural management are aimed at retaining the labor force.

The *sex-age structure* of the rural sector has changed considerably in recent years; the percentage of the aging population has increased. In a number of regions, owing to the shortages of working places that would meet young people's demands, the migration of girls to urban areas has increased. Thus, the present situation urges the speeding up of the industrialization of agriculture and of the improvement in living and working conditions. With this in mind the skill of those employed in agriculture is to be improved. For this purpose an extensive network of higher and secondary technical schools has been established.

The *social infrastructure* in agriculture is somewhat lagging behind those in other sectors of the agro-industrial complex. For this reason agricultural investments in the 1980s will be increased considerably.

### Scientific and Technical Factors

*Development of science and the availability of scientific information.* In this sphere of crucial importance is the development of the biological, technical, and socioeconomic sciences, as well as the availability of scientific and technical information. In the USSR there are several hundred scientific establishments for agriculture, including 240 research institutions. Research work is also conducted in 104 higher educational institutions on agriculture. The V.I. Lenin All-Union

Academy of Agricultural Sciences has 127 research institutions. A scientific base has been established in all the regions of the country; however, its level varies. In eastern regions the scientific personnel is not as numerous as is desirable or as exists in other regions of the USSR. However, the network of scientific institutions makes it possible to carry out research work at both the national and regional levels.

*The development of techniques in power engineering, transportation, and the chemical industry* provides for the establishment of a material and technical base for agriculture, and this is a major part of the resource potential. The development of these branches of the national economy follows a rather dynamic pattern, though the agricultural sector is constantly in need of an increased supply of industrial means of production.

*Progress in the technology of production, of storage, and of processing the produce* not only determines, to a considerable extent, the pattern of development of the economy, but provides for the qualitative and quantitative growth of production as well. Under current conditions we face an urgent problem of controlling losses in every possible way and of improving the quality of agricultural produce throughout the process from farm field to consumer.

*Agricultural service and the production infrastructure* of agriculture are closely related to the production process proper. This sector needs to be thoroughly amended and modernized. For this reason, in the 1980s it is planned to increase considerably investments in the processing industry, in storage facilities, in road construction, and in transport and trade.

### Organization and Legal Factors

These factors, along with the economic factors, constitute the management mechanism, their importance increasing with time.

*Legal rules and legislation* follow a dynamic pattern of development. Thus, in the last two years a number of important decrees was issued, aimed at stimulating the initiative of the working teams.

*Systems and methods of production management.* Currently, measures are being taken aimed at the gradual switching to economic methods of agricultural management, at the control and supervision of the whole agro-industrial complex, and at establishing interindustry, democratic administrative bodies at all levels – national, regional, etc.

In *production planning* there is a trend toward increasing the independence of production enterprises, and decreasing the number of target figures ("aggregated target figures"), with a maximum coordination of the latter with the resource potential.

The *division of labor* is becoming more profound. In agriculture a greater differentiation of production groups (production "links") is taking place. Independent, administrative bodies and organizations are being established to be responsible for certain limited fields of activity.

*Cooperation and integration of production processes* is closely related to the differentiation process. Cooperation and integration should closely follow the pattern of labor division processes to prevent individual departments and groups from being isolated.

*Discipline* – technological, labor, state – is an important management factor. Measures aimed at maintaining strict discipline in the relations between production branches and individual enterprises, as well as in working teams, will favor the development of the whole production process.

## Biological Factors

Biological factos are of crucial importance, since agriculture as a branch of social production is based on the use of plant and animal organisms and on the strict observance of biological laws.

The crop farming system depends to a considerable extent on the *crops and varieties* used. In recent years Soviet plant breeders have developed dozens of highly productive varieties and hybrids of cultivated plants. However, only 30 to 40% of their biological potential (50 to 60% at the most) is used; neither has the genetic potential been exhausted. Owing to the severe climatic conditions of the country the greatest emphasis is to be laid on the development of highly resistant varieties and hybrids.

*Kinds and breeds of animals* are of considerable importance in the animal breeding system. In the USSR a great diversity of breeds and breed groups of cattle, swine, and poultry has been developed; however, their biological potential – like that of plant resources – is not sufficiently used. Soviet agriculture is still facing the problem of improving animal breeds, increasing their productivity, and improving the feed conversion ratio.

*Phyto- and zoo-hygienic conditions.* In the USSR a ramified network of veterinary and plant protection stations has been established. Many harmful pests and diseases have been completely eradicated, but pest and disease control still remains quite an urgent problem. Moreover, with the intensification of agriculture the importance of this factor increases.

## Natural Factors

*Climate.* In the USSR zones of agricultural production are characterized by quite diverse climatic conditions. Up to 70% of agricultural land is in arid and semiarid zones. The sum of active temperatures (over 10 °C) ranges from 400 °C in the Arctic belt, where only protected-ground farming is possible, to 4600 °C in the south of Central Asia. The annual precipitation rate also ranges widely on the climatic zone – from 100 to 800 mm. In the majority of agricultural areas the annual precipitation rate is within the range 350 to 500 mm. The duration of the frost-free period ranges from 60 to 240 days, and the intensity of solar radiation varies.

A comparison of the natural conditions for agricultural management in the USSR with those in the USA shows the latter to be in a far better position (Table 2).

As can be seen from Table 2, natural conditions for agricultural management in the USSR are much more severe than those in the USA. However, many regions of our country are notable for a favorable combination of temperature and moisture supply factor. Therefore, in general our bioclimatic potential provides for a considerable increase of output (despite the fact that, on average, the output-per-hectare index for the USA is 2.3 times that for the USSR). Different combinations of climatic factors call for an individual approach to the development of systems of agricultural management.

*Soil cover* in the USSR is quite diverse, not only by geographical zones, territories, and regions, but also within the limits of individual farms as well. The *relief* is diverse and exerts a strong influence upon the agricultural management systems.

*Water supply.* While the average water supply index for the country is high, for the southern regions it is far from satisfactory. This has urged the development of projects that envisage a part of the run-off of the northern rivers to be channelled to the south regions. On the whole, water is becoming a limiting factor

Table 2. Natural conditions for agricultural management in the USSR and USA

| Index | USSR | USA |
|---|---|---|
| Agricultural land as a percentage of the total territory | 25 | 68 |
| Percentage of agricultural land lying south of the 48th parallel | 33 | 100 |
| Percentage of arable land lying in the zones with annual precipitation rate: | | |
| over 700 mm | 1.1 | 60.0 |
| from 400 to 700 mm | 58.9 | 29.0 |
| below 400 mm | 40.0 | 11.0 |
| Percentage of arable land lying in the zone with the annual average temperature below 5 °C | 60 | 10 |

in the most of the USSR. For this reason the whole of production technology should imply the economical and efficient use of water resources.

*Environmental control.* In the first place we have to provide for an efficient control of wind and water soil erosion, and to prevent the exhaustion and pollution of water sources; in other words we have to provide for an efficient nature-conservation service. This means that all the management systems have to be environment-oriented, providing for the prevention of any possible negative ecological consequences.

Considerable climatic diversities result in a great variety in the levels of the intensification of agricultural production. The ratio between the economic regions with the lowest and the highest output from the unit area is within the range of 1:25 (see Figure 2).

Thus, the *essence of the agricultural management system* – how it is understood now – comes down to organizational, economic, and technological principles that are basic to a design of the locally-dependent management system that meets the population's demand for agricultural produce.

Consequently, a management system is a complex of scientific principles that meet the requirements laid down by the systems approach, rather than a set of individual, technological methods as it was believed to be; these principles includes the integrity, proportion, and validity of structures, their relationships and functions, and the dynamic pattern of their development with the efficient use of the resource potential.

The objective of an agricultural management system is not to achieve intermediate goals, such as obtaining a high yield or increasing animal productivity, but to achieve the final results that production is aimed at – meeting the population's demand for food products. A management system is supposed to consider the whole complex of objective conditions with an integrated approach to their evaluation and to provide for the efficient use of the whole of the resource potential.

A system of agricultural management can be regarded both as an objective the research work is aimed at and an object to be realized. This means that the notion "management systems" implies both its development and introduction into practice.

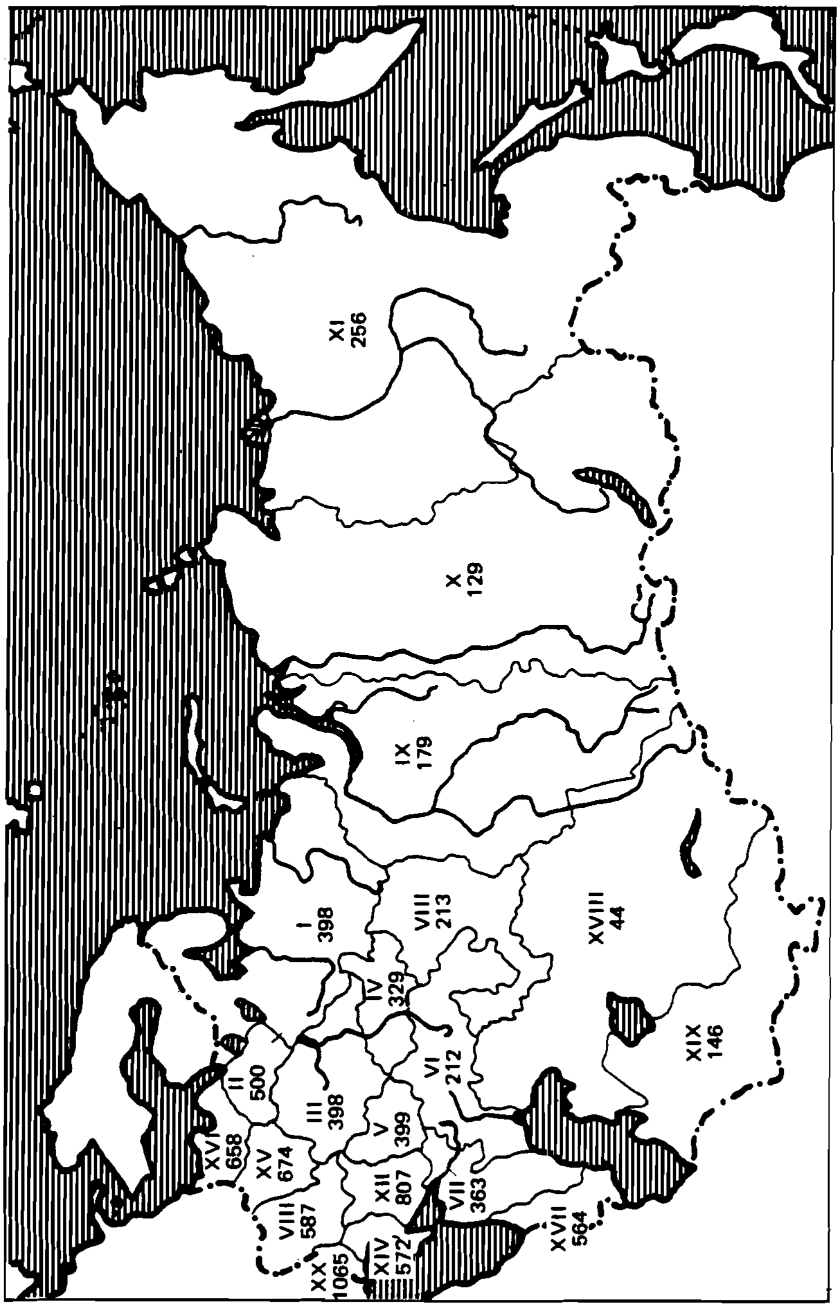

Figure 2. The agricultural production intensity by economic regions of the USSR (gross output per 1 hectare of agricultural lands, roubles): I, North region; II, North-West; III, Central; IV, Volgo-Vyatka; V, Central Chernozem; VI, Volga; VII, North Caucasus; VIII, Urals; IX, West Siberia; X, East Siberia; XI, Far East; XII, Donets-Dnieper; XIII, South-West; XIV, South; XV, Byelorussia; XVI, Baltic; XVII, Transcaucasia; XVIII, Kazakhstan; XIX, Central Asia; XX, Moldavia.

The structure of agricultural management systems is rather complex, having a dual nature. On the one hand, it is a complex of production branch systems – soil technology and crop farming, plant growing, feed production, animal breeding, which in their turn include numerous subsystems; on the other hand, management systems are regarded as an integrity of a number of components and characteristics. These are:

- *Socioeconomic form of enterprises.* In the USSR public enterprises prevail: state (state farms) and cooperative (collective farms).
- *Organization,* including production branch structure, specialization, and cooperation.
- *Technology,* which is going to become more industrialized with an extensive introduction of automated mechanisms.
- *Economic mechanism of management* as a whole.

All these factors taken together constitute a method for the use of the resource potential.

What problems are the agricultural management systems now faced with? *Maximization* of the high-quality produce output per unit of resource potential. The latter includes a bioclimatic potential, as well as land, water, labor, plant, energy, and other resources. *Minimization* of the resource input per unit of the production output, another aspect of the maximization problem, but these targets are not identical. Another problem is to increase *resistance* to unfavorable factors. The management systems are to be *adequate* for the objective conditions of production. The possible *social and economic consequences* must also be considered.

The requirements laid down for management systems and the very essence of the systems necessitate a strict methodological approach. Descriptions, general considerations, and recommendations are utterly inadequate. Systems analysis with economic and mathematical modeling must be the basis for the development of any management system.

We have developed many and various models at both All-Union and regional levels, the first of note being the Food Programme; other models include those of food subcomplexes, models for the use of individual resources (e.g., water resources), production allocation models, regional models of the agricultural development. But the present situation necessitates their thorough improvement, with a maximum coordination of their components, an introduction of modern technologies, and a reflection of the whole complex of changing environmental conditions.

Now agrarian science is faced with the problem of developing such recursive dialogue models (the problem "at large"). Therefore, of considerable importance is the experience gained by the cooperation between institutions of the All-Union Academy of Sciences, the USSR Academy of Sciences, and the International Institute for Applied Systems Analysis. The Stavropol Research Institute of Agriculture has become one of the first to take part in such cooperation.

Of considerable scientific and practical interest are problems related to the organization of research work and the development of regional models of agricultural management systems (to be followed by models at the All-Union level). Therefore, in all the leading and regional research institutions groups should be organized that are responsible for the development of model systems for a particular production branch or region. Obviously, special training of the scientific personnel must be planned in order to master new methods of investigation in this particular field. Both statistical and empirical data need to be accumulated. These data banks must be constantly systematized, replenished, and updated.

It is planned to supply research institutions with modern computers, their efficient use presupposing cooperation. But the principal factor is the professional skill of those who operate and use the computers. This sphere is to be given special consideration; we have to keep pace with the progress being made in science and technology, and provide for control over the realization of the systems, with the necessary adjustments to be made according to changing weather, economic, and other conditions. Systems of agriculture are dynamic; therefore situational models are of considerable importance. A system of management which is to become a system of models and modules should be elaborated at all the hierarchical levels, i.e., for every administrative unit – region, territory, republic (and, subsequently, for every location and farm).

Researches being conducted at the Stavropol Research Institute of Agriculture can be regarded as the beginning of these important activities. Systems of agricultural models for the Stavropol region, and the Novoalexandrovsk region have been developed in cooperation with the Computing Center of the USSR Academy of Sciences and the International Institute for Applied Systems Analysis. Quantitative analysis of the impact of natural conditions upon the economic characteristics have been carried out; several possible versions of agricultural production development were given; requirements for additional inputs have been evaluated. In other words, important factors have been revealed that provide for better control over the development of the agro-industrial complex of a region and its administrative units.

Naturally, many items in the models need elaboration. This refers first of all to the evaluation of the impact of the above-mentioned factors upon the regional agricultural management system. This research work should be expanded and continued. Thus, a methodological basis for agricultural management systems will be created for separate regions, with the All-Union model to follow.

Such are the state and prospects of activities in modeling agricultural management systems in the USSR. The extensive development of research activities will call for cardinal decisions to be made regarding the advanced training of specialists, the changing of structures of research institutions, and the establishment of an information base. These problems have to be solved. Goals to be attained conform to the economic policy adopted by our Government for the 1980s. The strategy is aimed at optimally meeting people's demand, on the basis of the dynamic and intensive development of the national economy and a rational use of resources.

# ON THE METHODOLOGY OF MATHEMATICAL MODELING OF AGRICULTURAL PRODUCTION PROCESSES

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Methods of mathematical modeling with the use of computers are gradually gaining ground. In the last 10-15 years they have been successfully used for the analysis of problems of agricultural management and for decision making in the studies of biological nature. The process of assimilating new methods for production management and for the organization of research work is under way in all the developed countries, reflecting an objective demand for improved methodological tools for managers and scientists.

Being gradually accumulated are experience and understanding of the spheres of, and ways of application of, methods of management and research based on the use of mathematical modeling. At the same time there are still many points that require clarification. The solution of a number of problems is often restrained by a poor understanding of the fundamentals of mathematical modeling. For this reason the assimilation of the new methodology is one of the most important problems to be solved in many of the studies being made by specialists employing mathematical models.

Mathematical modeling is but one of numerous methods of processing empirical data. Like any other method this one is not universal. A researcher – no matter what field of knowledge he deals with – biology or economics – should know all the advantages and disadvantages of the method, and when exactly it has to be applied. Any experimenter is aware of the simplest methods of mathematical modeling – those methods of multifactorial regression analysis. With a number of empirical values being influenced by various factors, a researcher can make assumptions regarding the nature of the functional relationships between the various parameters. With the use of the least-squares method he has an analytical expression that relates the value in question to the factors this value is dependent on. This expression is the simplest mathematical model. It can be used for prognoses and decision making.

The use of such a model for prognoses is based on the assumption that the established relationship is universal, and that the actual environmental conditions determining the process being prognosed are identical to those of the study.

Such approaches are known to have been quite satisfactory in practice. However, approaches based on statistical methods are also being actively developed. Thus, in recent years many new concepts have been proposed by Professor A.G. Ivakhnenko and his colleagues in Kiev, that have provided for a successful handling of small samples.

Let us assume now that we have some information describing the nature of the relationships being analyzed. This information will provide for a more suitable class of functions to be used for the approximation of actual functional relationships. Such relationships often have the form of various balance ratios (laws of conservation) that have to be adhered to. They reduce considerably the number of independent factors and, consequently, the amount of experimental work to be done. Ignoring these laws and relationships usually results in serious errors. Let us take a simple example.

Assume that we are studying factors that determine the profit gained by an agricultural enterprise from the plant growing sector. Factors referred to are the amount of fertilizers, the labor force, the size and structure of the acreage, the average crop yields, etc. Of course, we can derive directly a linear regression function; processing the series of values will result in a functional relationship that describes the profit as influenced by the above-mentioned factors. But if we wish to use the model obtained for prediction purposes, we discover that it leads to results that poorly conform to the real situation. The reason for such discrepancy lies in the fact that we have not taken into account relationships between the above-mentioned factors. The profit from any crop is always proportional to the product of average crop yield and the area under the crop. Consequently, linear regression equations are not applicable here. All this is very well-known; yet mistakes of this kind are still very frequent.

At the present time principles of mathematical modeling are based on the laws of physics, including first of all the law of conservation of mass, the law of conservation of energy, and the law of conservation of impulse. Mathematical modeling does not exclude the use of statistical methods. Balance ratios (laws of conservation), as a rule, afford no opportunity to build a closed model: a number of values always remains undetermined. To determine their magnitude, special experiments and regression analyses must be carried out. But the combination of the laws of physics and statistical methods affords the possibility of building a mathematical model which provides for a better validity of the prognoses, as compared to those based on the use of models of a purely regression type. However, the direct transfer of modeling methods used in physics to the spheres of biology and economics may sometimes prove to be a failure. Let us dwell upon this, and first consider problems related to the use of mathematical models in biological research.

Extensive use of balance ratios for the description of processes taking place in nature commenced after the publication of scientific works by an outstanding Italian mathematician and naturalist, Vito Volterra. The success of his studies gave rise to a kind of "scientific euphoria": it seemed that a consistent use of the principles of mathematical descriptions of physical processes would be as successful in biology and economics as in physics. But the situation proved to be much more problematic. The development of modeling in physics is based on the so-called "reduction" principle, i.e., the more comprehensive the study of a phenomenon is, the more accurate the model will be. In other words, all the characteristics of the whole can be derived from the characteristics of individual parameters of the process in question. Therefore, when cognizing processes that take place in inanimate nature, researchers seek to reduce the study of a phenomenon to a detailed analysis of the particulars. Let us assume that the phenomenon of gas movement is being studied. If the laws of the interaction of molecules are known, then the behavior of any gas volume under any conditions can be calculated beforehand, using the continuous medium equations. In this case macrolevel characteristics – the behavior of a given gas volume – are determined by microlevel characteristics, i.e., the nature of the interaction between molecules and the environmental impacts. That is why a physicist seeks to build models that most accurately reproduce the details of the phenomena in question. Understanding of such details is basic to the study of a phenomenon as a whole.

The "reduction" principle in biology and economics very often does not work at all. In agricultural science as a rule an integral systems approach is required. The integral approach, as a scientific concept, deals with principles of the self-organization of animate matter and the creation of new integrities. This means that for such objects their integrity must be considered. We can, for instance, cut off one or two leaves from a plant, but it will still retain its integrity. But under certain conditions, having disturbed the structure of a plant, we find that it has ceased to exist because it has lost its integrity. One can be fully aware of the photosynthetic processes occurring in leaves, and can make a comprehensive study of the physical and chemical processes occurring in the root system and of the interaction of the latter with soil; one can know well all the subtleties of the functioning of plant elements, but such knowledge is insufficient to describe the plant life as a whole. Just as the behavior of the herd is impossible to describe from knowledge of the traits of an individual animal. There is an abundance of similar examples.

And yet mathematical models of biological processes based on the principles of physics successfully serve practical purposes. If we seek to summarize the general characteristics of "good" models, in particular those of the Volterra type which have proved their value, we discover the following thing. The best predictive models are those that describe the process in a sufficiently aggregated way. When used to describe populations that are big enough to "wipe off" the effect of the behavior of individual species, the Volterra models describe the real situation well.

In compliance with the above an experiment is to be programmed. If in studying population dynamics we are going to use data that describe the characteristics and behavior of individual animals or plants, we are certain to fail to build a "good" predictive model. Such an approach will not reveal the integral traits inherent in the population.

Thus, low-detail ("rough") models often prove to be more suitable for practical purposes, better describing the integral characteristics of the system in question than do high-detail models.

In the USSR and other countries research work is under way to derive a set of models that describe plant development. All the studies of this kind have one thing in common – maximum detailing of a process, with the maximum possible number of factors and interactions being considered. This results in the derivation of rather complex models that are difficult to have "saturated" with the necessary information and "linked" to a concrete object. For instance, models that well describe processes of the growth and development of a crop on acid soils, do not work on alkaline soils, etc. This results in the derivation of a large number of different models that have to be individually adapted to local conditions. It is just these high-detail models that d not account for the integrity of an organism, which primarily manifests itself in the adaptive power of organized matter. An organism is capable of redistributing its resources, optimizing their use, compensating for defects, etc. These traits are characteristic not only of individual plants, but also of the given sown area as a whole.

While observing the integrity characteristics, a researcher often fails to provide an adequate verbal description. And it is no wonder. The integral approach as a scientific concept is in its initial stages and adequate methods to construct integral descriptions are unlikely to appear in the near future. However, our present understanding of the problem makes it possible to give a number of practical recommendations.

*First*, the use of complex, high-detail plant-growth models for management purposes (allocation of areas under different crops, fertilizer application systems, choosing the right tillage system, etc.) is believed to be irrational. But the use of aggregated models calls for an experiment to be specially organized. The problem of building models and organizing the experiment have to be solved simultaneously. Thus, of crucial importance now is the problem of organizing a monitored and controlled experiment in order to build models containing few parameters.

*Second*, plant growth models based on the detailed description of the processes of photosynthesis and plant-soil interactions are to be intensively developed as well. But their objective is different. They are to provide for the understanding of the nature of mechanisms that determine the growth and development of plants and to facilitate studies of the possibilities of adaptation and self-organization. Such models are primarily designed for research work, but they can be used successfully for practical purposes as well. Using these models we can parameterize a number of relationships, thus simplifying the model run.

There are some other recommendations of a purely pragmatic nature. One of these is the so-called "stability principle", which has the following implications. If an empirical model proves to be too sensitive to the impact of individual factors – i.e., small changes in the factors cause considerable changes of a variable in question – then such a model is sure to be inadequate. In such cases we have to look for other combinations of variables.

For studies of agricultural economic problems with the use of mathematical models, we face difficulties similar to those being encountered in studies of biological processes. The human factor brings about an additional level of uncertainty.

The system of mathematical models in economics is still far from perfect, which reflects, to a certain extent, the level of economic science itself. Models that have actually proved their value are those of an "account type". This term is assumed to cover calculations of various balances and normative characteristics of the economy. But as a rule such balance models are insufficient to solve economic problems. Without upsetting the balance conditions, the manager of an enterprise can practice various allocations of economic resources. This means that the final result will depend on the decisions made regarding resource allocation.

In economics various optimization approaches are widely used. They can help avoid the multivaluedness inherent in balance models, since they determine the resource allocation. Optimization approaches play an important role in economic analysis, reflecting the nature of the decision-making processes. Indeed, when seeking to achieve a goal, one tries to do so in the cheapest way. For this reason optimization methods are an important element of economic calculations. But the problem of objective functions always remains unclear. This issue received too little attention in economics. However, the problem is quite urgent, the more so as the objectives are usually rather contradictory; thus, quality improvement always results in the increase of expenditures, etc. Strictly speaking, it is impossible simultaneously to decrease the production costs, while improving the quality, thus affecting "maximum production at minimum production expenditures".

Similar conflicts occur in the objectives and interests of various organizations; of course, their interests are not antagonistic, but they do not coincide either, and this is something to be taken into consideration. Regional "monopolists", such as Selkhoztechnika, Selkhozkhimia, and construction organizations, serve as typical examples – while seeking to attain their own objectives they often ignore farm interests.

Reality, according to the scientific conception of dialectics, is a constant clash and fight of opposites, aspirations, and interests. Therefore, economic processes can be regarded not only as technological problems and production activities, but also as processes of social development. "Pure" production activity can be modeled; indeed it is being studied in detail, but in reality no "pure" economics exists. Representatives of the vulgar bourgeois political economy, such as Valras, Menger, and other "ideologists" of that period (at the close of the nineteenth century) sought to develop the "pure" economics concept, but without success. According to Marxism, economic and social factors are to be considered in their integral unity. As Marx put it, man's activities are invariably aimed at meeting his various demands.

Therefore, one of the most important objectives of a socialist economy is to study the effect of social factors upon the characteristics of the national economy, the structure of production relationships, as well as those interests, aspirations, and local objectives that production relationships give rise to in production teams and individual farm managers. That is why agricultural management is to be oriented not only to the simplest mechanisms – planning mechanisms using balance-type models – but also to the real mechanisms governing the human element. It should be always kept in mind that target figures and objectives which are set by a few people are realized by millions of working people. Therefore, the objective of the science is to develop a management system that will provide for the maximum labor productivity to be attained by millions of working people.

In the centralized, socialist economic system we have many possibilities for the purposeful development of such management mechanism. Actually, this is what the Communist Party calls for, this is an objective set by the Party decrees that emphasize the necessity for the consistent improvement of management mechanisms.

The scientists are currently faced with a big problem related to the development of a theory of management mechanisms which, while operating in the self-acting regime, would provide for the maximum possible labor productivity. This activity has already commenced, but there is much to do. So far only management mechanisms of the cooperative type have been fully accomplished, analyzed theoretically with their value proved under practical conditions (for details see *Methodology of Projecting an Economic Management Mechanism for a Regional Agrarian Association*, Computing Center, USSR Academy of Sciences, State Committee of Science and Technics, 1983). This is the simplest type of mechanism, since it operates under conditions in which the association of enterprises results not only in an increased total efficiency, but also in higher benefits for any cooperating member whose interests actually coincide. Under such conditions, when projecting a cooperation mechanism the only thing to be done is to provide for the extra profit results from the cooperation to be correctly distributed between cooperating members.

Quite a different situation arises when mechanisms of interactions between enterprises of different interdepartmental subordination come into being. The establishment of interindustry management mechanisms calls for efforts to be made by both economists and lawyers. At present one of the principal objectives is to develop a management mechanism theory that provides for correct decisions to be made under similar situations, as well as for the management system to become automatic; such a system is quite indispensable, since with our diversified economy no computers can be effective.

We have seen how modeling problems and the use of information facilities bring about the necessity of studying deep-seated biological and social processes. While existing principles of building economic and mathematical models are sufficient for the elaboration of agricultural land-use systems to be introduced by agricultural enterprises, good models of the economic mechanisms are necessary to issue recommendations as to the management decisions to be made.

Like any method of research and management, mathematical modeling is not universal. Not always do we manage to build adequate models that can be saturated with the necessary information and used for practical purposes. Naturally, models, as well as the methods of their building and use, are improving constantly, But, as we can see, problems of mathematical modeling are related to some fundamental problems still to be solved. Therefore, mathematical modeling is developed in combination with traditional methods of research and management. This is attained through the development of a special software system that provides for a "man-computer" dialogue.

A computer can perform all the routine calculations much faster and with greater precision, tracing the logic chains of relationships and interdependence. But not all the relationships can be formalized and expressed mathematically. Therefore a direction providing for the optimum combinations of a researcher's intuition and experience with tne capacity of a computer to process information is promising.

There are numerous technical facilities enabling the "man-computer" dialogue. They include various graphic plotters, drawing facilities and, most important, various displays providing for information to be given to a researcher in a visual form. With the use of the above facilities a researcher is able to carry on a dialogue with the machine, obtaining answers in a visual form, and then making adjustments in the model and in the input information. Any research work or management decision-making process is always a dialogue. With a researcher conducting an experiment this is always a dialogue with nature. An experiment in itself is a question being put to nature. Having interpreted the results obtained – i.e., having received an answer to the question put – a researcher asks a new question and makes another experiment. This is the process of cognition of the unknown. The same thing occurs with the manager. Before making a decision he analyzes all possible consequences, thus interrogating his own experience.

The dialogue technical facilities and software permit the method of mathematical modeling to be included in traditional programmes of research and management-decision preparation. Modern and traditional methods of information processing are to be combined and not opposed.

Naturally, this new technology of research and management is not going to become just a simple combination of methods of mathematical modeling and traditional methods of research and decision making. This combination will result in the transformation of both model building and traditional methods. Methods of research and managerial activity are to be considered in parallel. One of the most important consequences of the extensive development of methods of information science and mathematical modeling will be the gradual rapprochement of the research and management activities. In fact, to make a well-founded choice one has to compare the alternatives and study the consequences of the decisions being made; this is the most important element of any investigation. All the possibilities are provided for by informatics.

The possibilities provided by informatics to experimental investigations will favor considerable changes to be made in the organization system of the experiment, primarily in its planning. Both experiments and mathematical models are to be regarded as elements of the cognition process.

Such a comprehensive understanding of the importance and principles of informatics and mathematical modeling, as well as their difficulties and capabilities, will help overcome the psychological threshold inherent in the use of any new technology.

# TECHNOLOGICAL TRANSFORMATIONS IN AGRICULTURE: RESOURCE LIMITATIONS AND ENVIRONMENTAL CONSEQUENCES

## A Status Report on the IIASA Research Program*

*Kirit S. Parikh*

### 1. Genesis

Food problems -- efficient production or procurement of food and the appropriate distribution of food among members of family and society – are endemic problems of mankind. Yet the nature and dimensions of these problems have been changing over time. As economic systems have developed, specialization has increased; and this has led to increased interdependence of rural and urban areas, of agricultural and nonagricultural sectors and of nations. The importance of public policies in resolving these problems has grown with this growing interdependence of nations, reflected in increasing volumes of food trade, and this requires that the exploration of national policy alternatives be carried out in the context of international trade, aid, and capital flows.

When we began our research in the field of food and agriculture in 1976, we started with these objectives:

- to evaluate the nature and dimensions of the world food situation
- to identify factors affecting it
- to suggest policy alternatives at national, regional and global levels
    - – to alleviate current food problems and
    - – to prevent food problems in the future

Though we began with an emphasis on policies from a medium term, 5 to 15 years perspective, it was soon recognized that a long-term perspective is also required for a comprehensive understanding of the food problems of the world. Policies directed to solving current problems should be consistent with the longer term objectives of having a sustainable productive environment.

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* Paper presented at the International Seminar held at the Stavropol Research Institute of Agriculture, USSR, on "Results of the Development of Mathematical Models for Regional Systems of Farm Management".

Agricultural activities, almost by definition, affect the environment. When one produces corn, one also produces some associated changes in the soil. Erosion may be increased and if chemical inputs are used, the chemical residues in the soil and in water flowing or percolating through such fields will alter their chemical compositions. What would be the impact of such changes on future productivity of this soil? What practices could improve or preserve soil productivity? How important are these questions? How important are these likely to be in future? The answers to these questions depend on the technology used in cultivation.

One expects that with the rising demand for food from the growing population of the world which is also becoming richer, these questions of resources to produce adequate food, the efficiency of techniques, and environmental consequences will become increasingly more important in future. This expectation is based on certain trends that we perceive.

(a) Land will have to be cultivated much more intensively than at present.

(b) The increases in inputs required to raise yields will be significant, and the costs of some of the inputs will rise substantially. Not only is arable land use likely to reach the limits of its potential, but water needs may approach the limits to exploitable supplies as well.

(c) As the basic agricultural resources -- land, water and fertilizer -- become more scarce and more expensive, a technological transformation of agriculture will have to take place. The higher yields required, and changes in the relative prices of land, water fertilizer and other factors and inputs required for agricultural production, will clearly lead to changes in the techniques of production.

(d) The increasing expense and uncertainty in energy supply will both increase the demand for land and make it harder to obtain higher yields through conventional techniques.

(e) A choice of agricultural production techniques offers alternatives not only of intensive as opposed to extensive cultivation but also of the intensification of various inputs such as fertilizer and water. Understanding the nature of technology is critical in formulating appropriate policies for promoting adoption and development of appropriate techniques.

(f) Past estimates indicate a more than adequate ultimate food production potential in the world but these estimates have not fully taken account of environmental consequences and feedbacks in land productivity.

We conclude from the foregoing (Parikh and Rabar, 1981) that over the coming decades a technological transformation of agriculture will take place that will be constrained by resource limitations and whose environmental implications pose questions concerning the sustainability of adequate production to feed mankind.

## 2. Issues and approach

Since we anticipate over the coming decades a technological transformation of agriculture that will be constrained by resource limitations and that could have serious environmental consequences, a number of important questions arise.

- What are the alternative technologies likely to be available within the next 20 years and beyond?

- What would be the appropriate combinations of these technologies in a given region (country) under various scenarios for resource availability and food demand?
- What sustainable potential production can be achieved with the given resources, with the available technological alternatives, and considering the possible environmental consequences in a region, in a country, and at a global level?

The elements of the system and its dynamics that we have to study are shown schematically in Figure 1.

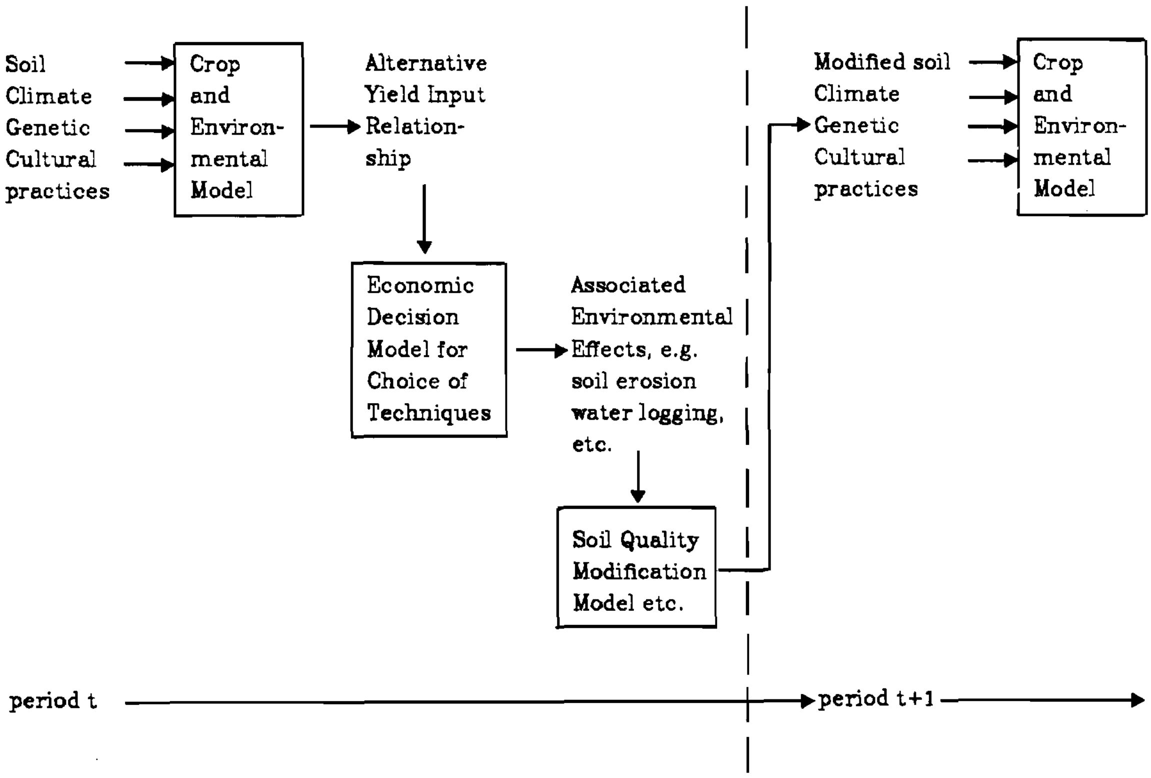

**Figure 1.** Schematic diagram of analytical elements

Table 1. **Technological transformation of agriculture: analytical framework -- concept**

**Given** $\{P^{W}_{it}\}$ **Trade Prices**

$\{R_{it}\}$ **Regional Requirements and**

**Resource Base**

$\{A^{z}_{fo}\}$ **Area in zone z fertility class f**

$\{F^{z}_{o}\}$ **Fixed capital stock, Water, Energy**

**Find** **Activity Intensities** $\{x_t\}$ **which**

**Maximize** **net trade surplus meet domestic requirement and are sustainable**

$\boxed{\text{Maximize}}$ $\sum_{t} \frac{1}{(1+\phi)^t} \sum_{i} \left[\left(P^{W}_{it}E_{it} + P^{W}_{it}R_{it} - P^{d}_{it}Y_{it}\right) - C_t(B_t, B_{t-1}, \ldots)\right]$

**s.t.** **Inputs** **Bads** $\begin{Bmatrix} Y_t \\ B_t \end{Bmatrix} = \left[a_t\right]\{x_t\}$

**Resource Limits** $\{x_t\} < \{A^{z}_{ft}\}; [b]\{Y_t\} < \{F^{z}_{t}\}$

**Output Levels** $\{Q_t\} = [u]\{x_t\}$

$\boxed{\text{Sustainability}}$ $\{Q_t\} > \{Q_{t-1}\}$

**Demand** $\{Q_t\} > \{R_t\} + \{E_t\}$

**Feedback of Bads** $[a_t] = f[A^{z}_{f,t-1}]$

$\{A^{z}_{ft}\} = g[A^{z}_{f,t-1}, B_t]$

**Multi-objective**
**Large System Optimization**

*Source:* Food for All in a Sustainable World , IIASA, Laxenburg, SR-81-2, pg 21.

The initial conception of the problem and approach are described in Hirs, J. (1981) and in Reneau, van Asseldonk and Frohberg (1981). A conceptual framework is shown in Table 1. The model shown can be used for a nation or for a subregion in a nation. Given the prices at which the region can trade externally, its domestic prices and domestic requirements, those agricultural activities are to be selected that would maximize net income from agriculture subject to certain constraints. Among these is included a sustainability constraint as well as environmental feedback relations.

Based on this framework a number of subtasks were identified and work was organized around that. Our program approach is different from past approaches in that we take into account both environmental feedbacks and economic considerations in an integrated framework.

In addition we are carrying out, with the help of a network of collaborating institutions (Table 2), a number of case studies which help in validating our approach and in understanding the complexity of the system. The case studies are so selected as to represent various agricultural and economic organizational systems. We shall also obtain a broad global perspective.

**Table 2. Network of Collaborating Institutions**

Bulgarian Academy of Sciences, Research Laboratory "Problems of the Food Complex", Sofia, Bulgaria

Biological Faculty, Sofia University, Bulgaria

Research Institute for Economics of Agriculture and Nutrition, Prague, CSSR

Institute for Rational Management and Work, Prague, CSSR

Dept. for Research and Development, Institute for the Rationalization and Management of Agriculture, Trnava, CSSR

Humboldt University, Dept. of Crop Production, Berlin, German Democratic Republic

Karl-Marx University of Economic Sciences, Dept. of Agricultural Economics, Budapest, Hungary

Agricultural University, Debrecen, Hungary

CNR - IATA, University of Florence, Italy

The Food and Agriculture Organization of the United Nations, Rome, Italy.

Kyoto University, Agricultural Engineering Dept. Faculty of Agriculture, Japan

Centre for World Food Studies, Wageningen, the Netherlands

United Nations Fund for Population Activities, N.Y., U.S.A.

National College of Food Technology, University of Reading, U.K.

The Center for Agricultural and Rural Development, Iowa State University of Science and Technology, U.S.A.

Texas A & M University, Dept. of Agricultural Economics, U.S.A.

U.S. Dept. of Agriculture, Agriculture Research Service, Southeast Watershed Research Laboratory, Tifton, GA. U.S.A.

All-Union Institute of Information and Technical Economic Research in Agriculture, Moscow, U.S.S.R.

Lenin All Union Academy of Agricultural Sciences, U.S.S.R.

Moscow State University, U.S.S.R.

The Stavropol Research Institute of Agriculture, U.S.S.R.

Computer Centre of the USSR Academy of Sciences, U.S.S.R.

Institute of Agrochemistry and Soil Sciences, U.S.S.R.

## 3. Subtasks

The various subtasks we identified are as follows:

(a) A global perspective: estimation of the population supporting capacity of the world with and without conservation

(b) Description of technological alternatives including associated environmental bads and goods which come as joint products

(c) Modeling of the environmental feedback mechanism.

(d) Development of an analytical framework for decision making.

(e) Country case studies

  (i) Nitra district, CSSR

  (ii) Stavropol region, USSR

  (iii) Iowa State, U.S.A.

  (iv) Suwa Region, Japan

  (v) Mugello Region, Italy

  (vi) Hungary

These subtasks and the progress achieved in them are now described in turn.

### 3a. Global Perspective

Objectives of part of this subtask were realized through a collaborative study with FAO and UNFPA. Estimates of population supporting capacities of the developing countries were made.

The world has adequate resources to feed mankind now and in the future. Estimates of the population supporting capacities of the developing countries of the world based on agro-climatic data show that most developing regions, though not all countries, have adequate potential to support projected populations by 2000. These results, summarized in Table 3, show that the land of the five regions together could, even with low level of inputs, meet the food need of 2.0 times the year 1975 population and 1.5 times the food needs of the projected year 2000 population. Even individually the regions have the potential to be self-sufficient using low level of inputs excepting South West Asia which would need high level of inputs.

With high level of inputs the potential population supporting capacity of the developing countries is 9 times the projected population of the year 2000.

It should be emphasized, however, that these estimates are for agronomic potentials and do not tell us how much it will cost to realize them. The large agricultural potential of developing countries would require much resources of capital, knowledge, skills and organization. Moreover it is also assumed that measures would be taken to conserve soil productivity. These conservation measures would also need additional resources. The scope for external assistance from governments and industry is large, and unless it is mobilized today's hunger problem will remain with us for a long time.

**Table 3. Potential/present population ratios under alternative technologies**

| | Year 1975 Potential: Present Population Ratios | | | | | |
|---|---|---|---|---|---|---|
| Level of Inputs | Africa | Southwest Asia | South America | Central America | Southeast Asia | Average |
| Low | 2.8 | 0.8 | 5.9 | 1.6 | 1.1 | 2.0 |
| Intermediate | 10.8 | 1.3 | 23.9 | 4.2 | 3.0 | 6.8 |
| High | 31.6 | 2.0 | 57.2 | 11.5 | 5.1 | 16.3 |
| | Year 2000 Potential: Projected Population Ratios | | | | | |
| Low | 1.5 | 0.7 | 3.5 | 1.4 | 1.1 | 1.5 |
| Intermediate | 5.4 | 0.9 | 13.3 | 2.6 | 2.3 | 4.1 |
| High | 15.5 | 1.2 | 31.5 | 6.0 | 3.3 | 9.1 |

*Source:* Higgins, Kassam, and Naiken (FAO), Shah (IIASA) and Calderoni (UN): Can the land support the population -- the results of a FAO/UNFPA/IIASA study, "Land resources for populations of the future". Populi, UNFPR, N.Y., Vol. 9, 1982.

The results shown in Table 3 are from a study carried out by FAP of IIASA jointly with FAO and UNFPA. soil data at the level of units of 10000 hectares with climatic data were evaluated from agronomic principles to arrive at crop production potential for various suitable crops. These were further processed to construct various scenarios for agricultural production for different countries. These evaluations give us guidance on the following:

- How does the country's cropping pattern reflect its natural advantages?
- Which areas and which crops offer the most chance for further development?
- How much resources would be needed to realize desired growth potentials.

### 3b. Description of Technological Alternatives

Description of technological alternatives was approached from a number of different perspectives.

(a) Comparative assessment of present technologies

Through a number of collaborative publications (Nazarenko. V. 1981, 1982a, 1982b, and Nazarenko et al 1983a, 1983b), comparative description of present technologies in different countries for selected activities were described. This was the outcome of our collaboration with the All Union Institute of Information and Technical Economic Research in Agriculture, Moscow.

(b) Non traditional technologies

Non-traditional technologies which are, or are likely to be available during the next 20 years for the production of food, feed or bio-energy from non-traditional sources were reviewed through a series of three task force meetings held at IIASA, Tbilisi State University, USSR and Sofia University, Bulgaria. The proceedings of these task force meetings are already published: (see: Hirs, J. (1981), Hirs, J. and S. Münch (1982), Worgan J. (1983)). The preparatory work for the task force meetings was carried out jointly with the Department of Food, Science and Technology, Tbilisi State University, USSR, the National College of Food Technology, University of Reading, U.K., the Academy of Sciences, Bulgaria and the University of Sofia Bulgaria.

(c) Description of mechanical aspects of crop production.

Quantitative descriptions of technological alternatives available to produce a particular product or service follow one of two paths, depending on disciplinary bias as well as on the problem at hand. Thus engineers and technologists who are usually concerned with decisions at the field or factory level prefer descriptions which refer to specific machines used in particular processes. Economists concerned with decisions at the industry or the economy level, on the other hand, prefer a production function in which only an aggregate measure of machinery and equipment -- e.g. dollars or roubles worth of capital -- is used.

The dichotomy between the description of field-level techniques and sector-level production function is particularly severe for agriculture, where the soil and climate characteristics seem to make each field a separate and non-reproducible observation. This poses a formidable difficulty in exploring at a regional level optimum strategies for agricultural development in a way that satisfactorily deals with the interactions between agricultural technology, cultivation and management practices, the environmental consequences of these, and their impact on soil and water resource quality.

A desirable scheme for description of technological options should as far as possible meet the following requirements:

(a) It should relate specific micro-level processes and operations to a relatively aggregated production function.

(b) It should facilitate a representation of technological options that can be used in analysis for system-level optimization. This means that the resulting analytical model should be computationally manageable. For example, if the model is a linear programming one, the size of LP that is generated should be reasonable.

(c) It should account for technological progress in a way that could be useful for projecting such progress.

(d) It should identify the elements of technology which are site and situation specific and those which provide a universal description of technology which is applicable to other situations, so that with every case study the data bank grows in a meaningful way.

We have outlined a scheme that meets these needs. This will result in a data bank with following components:

A. Crop production activity matrix

Note here that neither part A nor part B of the matrix is affected by the technical progress that takes place in mechanical equipment development. Part A embodies the information from the genetic and agronomic aspects and varies only when there is genetic technical progress. Part B embodies agronomic aspects relating to soil and remains invariant to technological developments in the machinery sector as well as to genetical progress.

B. Operation output activity matrices

For each operation one matrix will define the alternatives available for producing the output of that operation.

As new machines are developed and new data are available, these matrices have to be augmented by additional rows and columns. But it should be noted that these matrices are largely independent of variations in soil and climate. Thus they are "universal" descriptions of technology.

Crop production activity matrix

| | Inputs | Activities | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | soil 1 | | | | | | | soil 2 | ... | soil s |
| | | crop 1 | | | | | | crop c | | | |
| | | alternatives | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | ... | m | | | | |
| A | Main yield | -1 | -1 | -1 | -1 | | | | | | |
| | Joint yield 1 | - | - | - | - | | | | | | |
| | Joint yield 2 | - | - | - | - | | | | | | |
| | Seeds | $s_1$ | $s_2$ | $s_3$ | $s_4$ | | | | | | |
| | Fertilizer | $f_1$ | $f_2$ | $f_3$ | $f_4$ | | | | | | |
| | Pesticides | $p_1$ | $p_2$ | $p_3$ | $p_4$ | | | | | | |
| B | Operation $O_1$ | $O_{11}$ | $O_{12}$ | $O_{13}$ | $O_{14}$ | | | | | | |
| | Operation $O_2$ | $O_{21}$ | $O_{22}$ | $O_{23}$ | $O_{24}$ | | | | | | |
| | . | . | . | . | . | | | | | | |
| | . | . | . | . | . | | | | | | |
| | . | . | . | . | . | | | | | | |
| | Operation $O_n$ | $O_{n1}$ | $O_{n2}$ | $O_{n3}$ | $O_{n4}$ | | | | | | |

To illustrate how this can be done, we have estimated output functions for some agricultural operations based on experimental data from Hungary.

For demonstration purposes we neglect equipment and labor and consider just two attributes of tractors, horsepower and date of first use.

A general model is postulated for all the operations.

$$\begin{bmatrix}\text{hectares}\\ \text{operated}\\ \text{per hour}\end{bmatrix} = e^{(\sigma_0 + \sigma_1 s_1 + \sigma_2 s_2)} \begin{bmatrix}\text{intensity}\\ \text{of}\\ \text{operation}\end{bmatrix}^{\gamma} \left[e^{\beta t} H_t\right]^{\alpha}$$

where

$s_1$ and $s_2$ are dummy variables for soil type 1 and 2;

intensity of operation refers to

depth in cms for ploughing and discing

width in cms between rows for cultivation

yield of grains in tons/hectares

$H_t$ is the horse power of the tractor first introduced in year t

t is vintage year (t = 66 for 1966, etc.)

The results of the various regressions are given in Table 4. The regression results are remarkably good. The t statistics are mostly highly significant and the signs of coefficients are with one exception right. Thus the approach suggested here is very promising and systematic work can be very fruitful. This is described in greater detail in Parikh (1983).

(d) Describing agronomic and chemical aspects of crop production.

Whereas the technological options of labour and capital substitutions may be considered to be more or less universally applicable, the relationship between water and fertilizer inputs and crop yields depend critically on soil and climate. Moreover, erosion levels and soil chemistry changes also depend on soil and climate. Since we want to explore the dynamics of technological alternatives soil quality changes have to be quantitatively generated in such a dynamic context. Thus we have to relate climate, soil, genetic and cultural practices to outputs a shown schematically in Figure 2.

A major effort was made at IIASA to extend and computerize the Crop and Environmental model (CE) model originally developed by the Centre for World Food Studies, (1980). This is described in greater detail by Konijn N. (1983). Examples of the type of output that can be obtained from such a model are shown graphically in Figure 3a and 3b. The CE model has been applied extensively for the Stavropol region and hundreds of runs have been made for different crops, soils and climate years. What is now under progress is validation of the model. Ideally we would like to see that the plots in Figure 4 will be a straight line through the origin with a slope of 1 (45 degrees).

However, since no model can include everything, we are satisfied if we obtain a relationship as shown in Figure 5, which can then be used as a calibration curve.

Such validation, calibration work is currently under progress. This is being carried out with the help of Stavropol Institute of Agriculture, and is described in detail by Petrova L. (1983).

Table 4. Estimated Agricultural Operations Output Functions.

| | Coefficent of | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Operation | Constant<br>$\sigma_0$ | Soil 1 dummy<br>$\sigma_1$ | Soil 2 dummy<br>$\sigma_2$ | intensity of operation<br>$\gamma$ | vintage* of tractor<br>$\beta$ | tractor horse power<br>$\alpha$ | DF | $\bar{R}^2$ | F |
| Ploughing | -2.826 | -.103 | -.188 | -.906 | .102 | .438 | | 0.60 | 36.4 |
| | (-5.46) | (-1.47) | (-2.38) | (-8.10) | (5.18) | (4.47) | 113 | | |
| Discing | -4.892 | -.199 | -.066 | -.017 | .079 | .561 | | 0.69 | 70.6 |
| Operation | (-6.37) | (-4.43) | (-1.49) | (-.32) | (3.40) | (10.0) | 151 | | |
| Precultivation | -4.948 | .466 | .260 | .256 | .016 | .889 | | 0.64 | 38.4 |
| Operations | (-4.73) | (5.58) | (2.43) | (2.28) | (.81) | (8.17) | 100 | | |
| Row | -4.156 | -.141 | 0.83 | .330 | .0056 | 1.14 | | 0.53 | 24.0 |
| Cultivation | (-3.98) | (-1.49) | (-1.47) | (3.03) | (.31) | (6.79) | 97 | | |
| Maize | -6.03 | | -2.65 | -.554 | .040 | .819 | | 0.42 | 11.7 |
| Harvesting | (-4.62) | | (-2.30) | (-1.73) | (.92) | (2.23) | 55 | | |

* Vintage (years of first introduction of tractor) coefficient $\beta$ obtained by dividing the estimated coefficient $\beta\alpha$ by $\alpha$, the coefficient of tractor horse power; the t-values shown under $\beta$ are t values of ( $\beta\alpha$ )

Values in ( ) are t-values

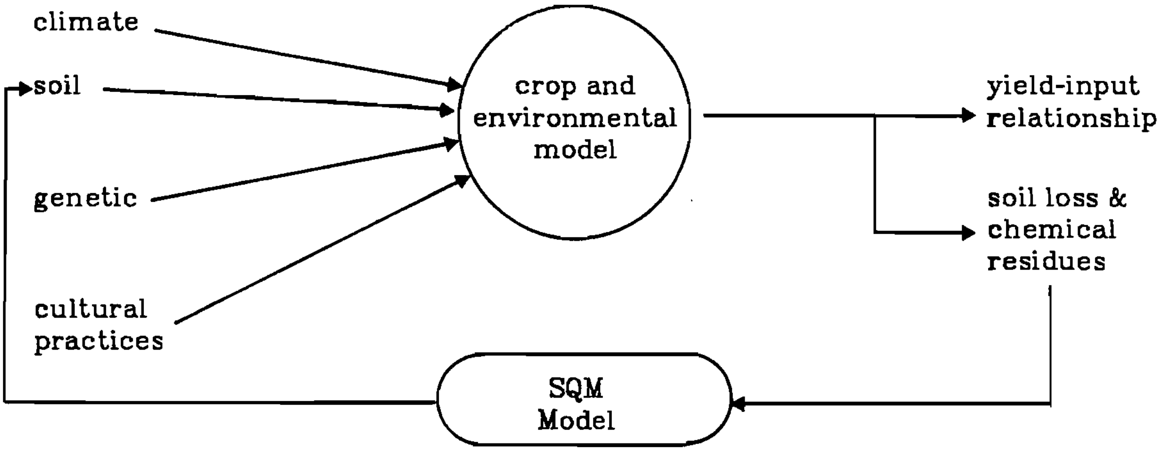

Figure 2. The Crop and Environmental Model in a dynamic context

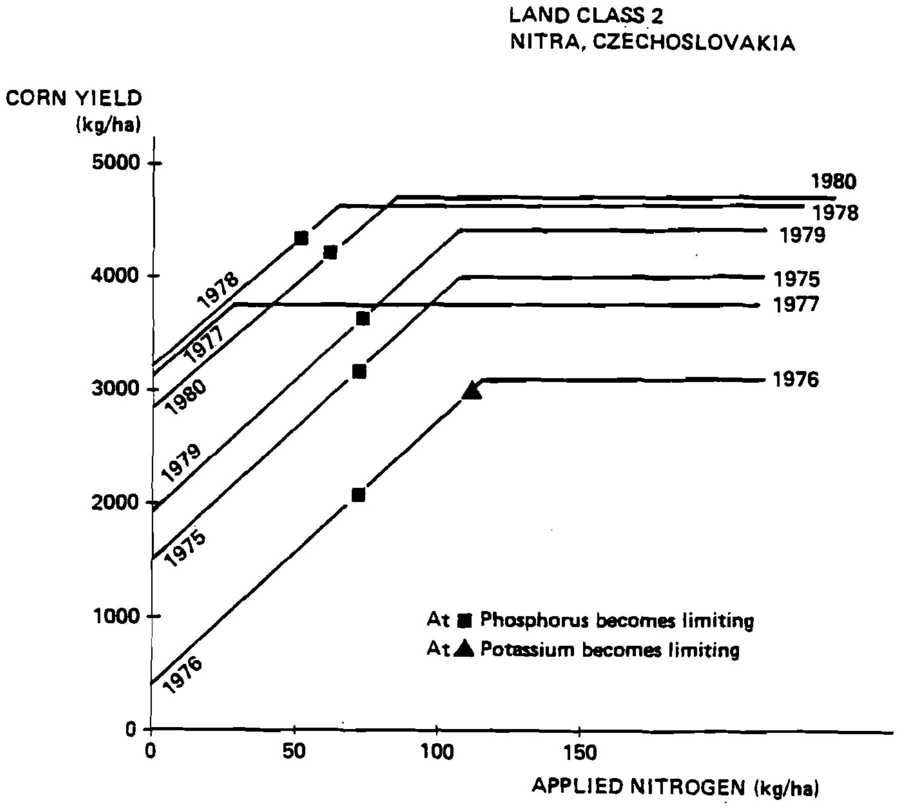

Figure 3a. Yield response to fertilizers of corn under climates of different years.

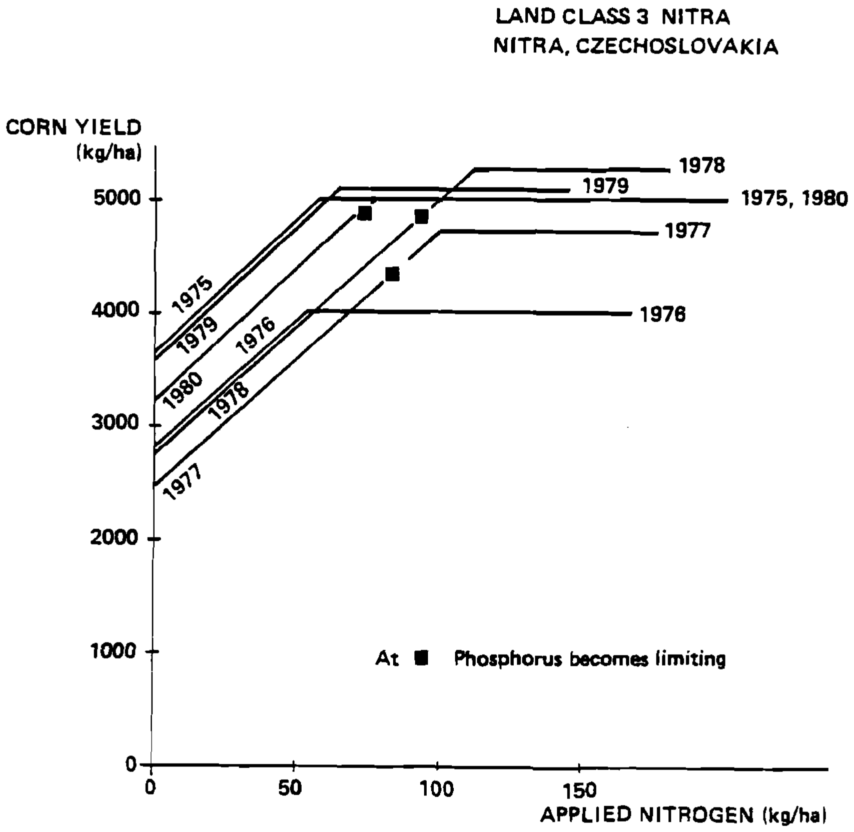

Figure 3b. Yield response to fertilizers of corn under climates of different years.

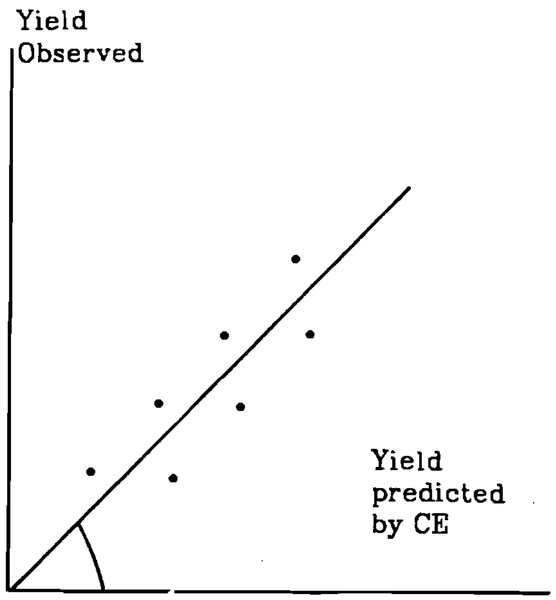

**Figure 4. Validation of the crop and environmental model.**

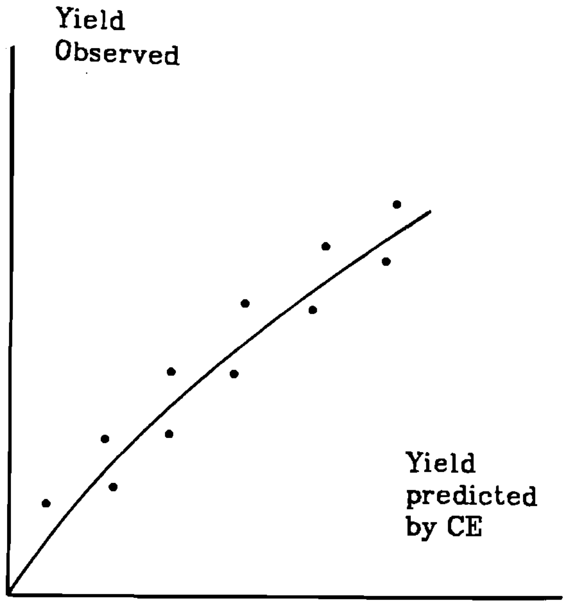

**Figure 5. Calibration of the crop and environmental model.**

### 3c. Modeling of Environmental Feedback

An environmental feedback has been developed as a part of the Crop and Environmental Model for the Stavropol Case Study developed by Konijn N. (1983). The effects on soil quality of erosion due to wind and water, and of chemical changes due to applications of fertilizers and pesticides, water leaching and waterlogging and due to organic matter decay should be modeled.

Currently, erosion due to water and changes due to fertilizers, water leaching and organic decay are taken into account. It is proposed to introduce wind erosion in future, whereas effects of water logging is not planned for the near future. The schematic relationship of the CE model and the model of environmental feedback (= SQM = soil quality modification model) are shown in Figure 2.

### 3d. Development of an Analytical Framework for Decision Making.

In the recursive scheme of Figure 1, the economic decision model can be a conventional choice of technique type linear programming model. Yet an important technical problem arises in that the number of soil classes increases exponentially. Starting with one soil class, if each year $x$ crops are grown, it is conceivable that in $t$ years $x^t$ soil classes will result. The problem soon becomes computationally impracticable.

To get around the problem a simplifying assumption is needed. Three alternative approaches are suggested.

(i) Assume that only one crop is grown on one type of soil and with only one technology.

(ii) The same constancy of number of soils can be obtained by permitting growing of different crops on one soil but by averaging all the soil quality changes due to these crops for the same soil.

(iii) Consider that each multi-period rotation is a separate activity and a choice is made among such rotations spanning many years.

The mathematical description of decision making schemes are given in Ereshko (1983).

### 3e. Country Case Studies

The different country case studies are at various stages of completion their current status and expected date of completion are indicated below.

#### (i) Nitra district, CSSR.

Data collection and model formulation have been completed. Preliminary results from the model have already been obtained. Results are expected by the end of 1983.

#### (ii) Stavropol Region, USSR.

As is obvious from the various papers presented at this seminar, data collection and modeling are completed. Preliminary runs have been made. A process of intensive testing and parameter turning of the CE model is under way and a fully operational model can be expected by early 1984. (see also, Nikonov et al. 1982)

#### (iii) Iowa State, USA

The case study model was the first to get ready (Heady and Langley, 1981), and results are now already available.

#### (iv) Suwa Region, Japan

Data collection is completed and modeling is in progress and results are expected in early 1984.

#### (v) Mugello region, Italy

Soil and climate data are computerized and automatic processing system set up. Use of CE model is started. Results are expected to be available in 1984. (Maracchi, G. 1982)

#### (vi) Hungary

The study covers the whole country. Following an assessment of the agro-economical potential of Hungary (Harnos, Z. 1982), the modeling methodology was defined (Csaki, Harnos, Valyi, 1982). The study is progressing well and results are expected by early 1984.

### 4. Plans and Prospects

The contribution of FAP of IIASA in these case studies have been of two types. We have developed the methodology and we have played a catalytic role in initiating studies as well as triggering collaboration among different institutes even within a country. By the end of 1983 our work in methodological refinement would be completed.

What then remains is to bring together the results at the various case studies, make a comparative evaluation and prepare a final report. When such a get together of the various case study participants can be organized depends on the actual progress of the case studies. Yet spring of 1984 seems a reasonable date.

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# THE APPLICATION OF A CROP AND ENVIRONMENT MODEL IN SIMULATION EXPERIMENTS

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## 1. Introduction

In recent years in the USSR and elsewhere, mathematical modelling of complex biological and production systems has received increasing attention. The cooperation between the Stavropol Research Institute of Agriculture, the International Institute for Applied Systems Analysis and the Computing Center of the Academy of Sciences of the USSR aimed at developing a system of mathematical models for the agricultural production in the Stavropol Territory, U.S.S.R. One of the most complex parts of this system of models is the model that describes the growth and development of plants, i.e. the Crop and Environmental model.

Basically, the structure of the Crop and Environmental model is the same as the model of Physical Crop Production developed at the Centre for World Food Studies (1980). The module has the purpose to generate under a given physical environment all kinds of agricultural production alternatives. These alternatives are meant to feed an economic module, which would make a selection out of the many production possibilities. This is shown in Figure 1. It is obvious that the various alternatives of production are realized by varying such input characteristics like fertilizers and irrigation with the kind of crop and/or soil.

It is the objective of this paper to give a detailed description of the various biological processes involved and to describe the simplifications and aggregation necessary in order to get an applicable model. The model was run at the Stavropol Research Institute of Agriculture and the Computing Center with a data base for the physical environment of the Stavropol Territory covering a 12 year period (1971-1982). This would allow us to answer a variety of questions, based on the estimation of the crop production for various soil and climate conditions: evaluation of the possibilities for increasing crop production as a result of fertilizer

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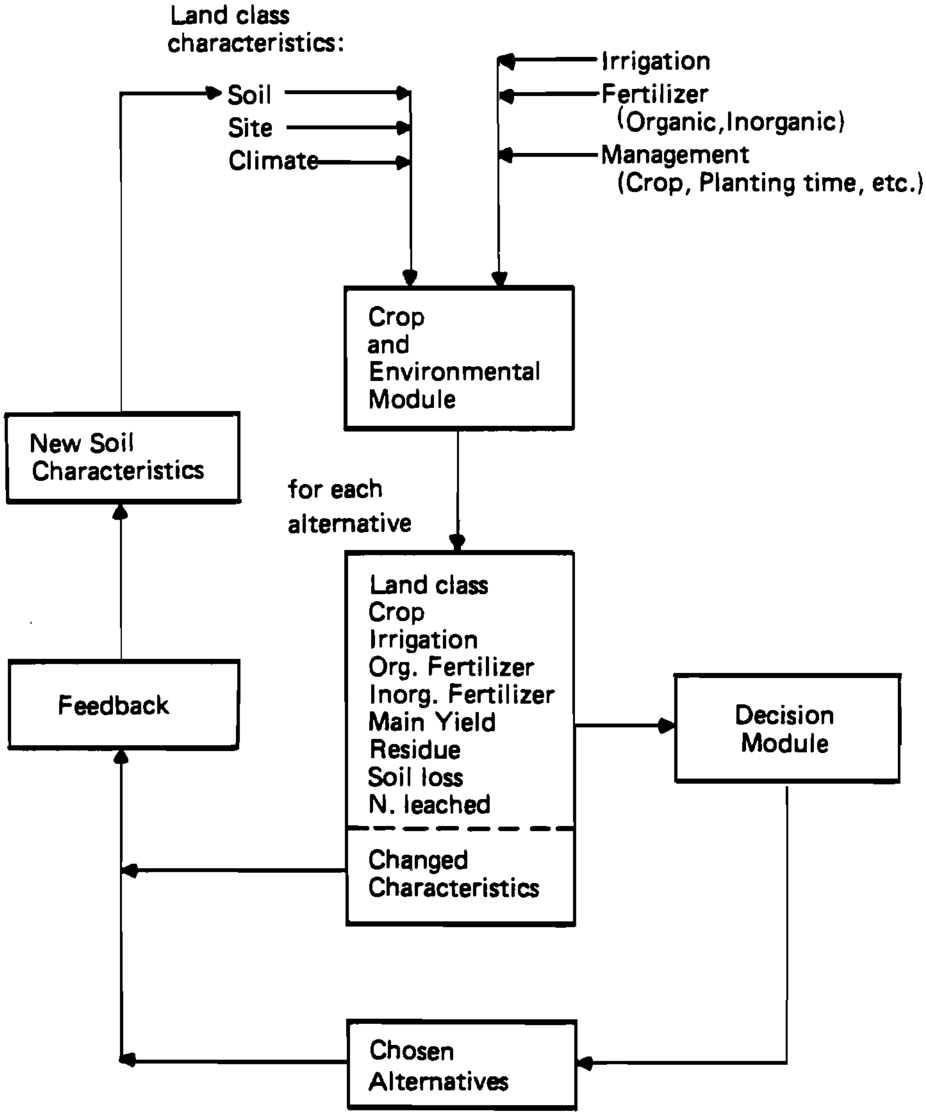


Figure 1. The place of the Crop and Environmental Module in the general model structure.

applications, irrigation and/or the application of various management practices, the consequences of changes taking place in the soil during continuous crop cultivation; the comparison of the effect of various management practices on yields, the soil and the environment, in particular as a result of soil erosion.

Assuming various possible meteorological scenarios for the future, the model could estimate for the various soil and climatic zones of the Stavropol Territory the production of various crops. From such estimations, the production for the administrative units, and for the whole Stavropol Territory can be detected. Moreover, that can serve as a base for the optimization of resource allocation at a regional level.

## 2. Description of the processes in the crop production model

In the crop production model processes that take place in the crop stand and its environment, which comprises the meteorological conditions are described. The following processes, determining the crop growth have been considered: photosynthesis and respiration; the development of the crop; the water regime in the root zone; transformations of soil organic matter; uptake by plants of nitrogen and other nutrients; yield formation specifically related to cultural practices, organic and mineral fertilizer application rates; water erosion.

The model is able to keep track of annual changes in the physical and chemical soil properties that may be affected by the aforementioned processes during the cropping season.

The frequent use of the minimum land is a characteristic feature of the model; this feature determines the arrangement of the modules in the model. This finds expression in the sequence of calculations, where the next calculation will never surpass the preceding one.

$Y(w) \leq Y(r)$ with $Y(w) = f(Y(r), E)$ and

$Y(n) \leq Y(w)$ with $Y(n) = f(Y(w), N)$

where

| | |
|---|---|
| $Y(r)$ | is the production determined by the radiation and temperature |
| $Y(w)$ | is the production as restricted by water availability |
| $Y(n)$ | is the production considering the availability of nutrients |
| $E$ | stands for the transpiration and |
| $N$ | for the availability of nutrients |

It is impossible to give a comprehensive description of all technical details, we shall limit ourselves to a somewhat restricted description of the model, this hopefully may lead to a better understanding between system analysts and agronomists. It should be emphasized that the authors realize the subjective nature of the description.

### 2.1. Photosynthetic dry matter production

Plants are assumed to consist of four parts being regarded as "sinks" accumulating carbohydrates during the process of photosynthesis - leaves (i=1), stems (i=2), roots (i=3) and reproductive organs (i=4). The time increment in the estimations is equal to 10 days ($\Delta t=10$). Let us denote "$m_i$" as the dry biomass of plant organs altogether. The dry biomass increment for each $\Delta t$ is $\Delta m_i$:

$$\Delta m_i = \rho_i \Phi - R_i m_i - R'_i \Delta m_i \qquad (i = 1, 2, 3, 4) \qquad (1)$$

The dry matter increase of a plant organ is equal to total assimilates less the loss as a result of the growth respiration and due to the breakdown "maintenance respiration". The processes are denoted resp. by $R_i$ and $R'_i$. They are temperature dependent.

The growth function denoted by $\rho_i$ (eqn. 1) allocates the assimilates over the various plant organs. $\rho_i$ is genetically determined and depends on the development of the crop. The $\rho$-values have been empirically determined and are summarized in the form of a table with time increments equal to a $\frac{1}{10}$ total growth period.

Based on the radiation, temperature and latitude, the values $\Phi$, $R_i$ and $\Delta m_i$ are derived in consecutive order for the time increment of $\Delta t$.

The dry biomass of each plant organ at the end of the 10-day period "t" is determined by summing biomass increments $\Delta m_i^\tau$ for all 10-day periods preceding the current period "t".

$$m_i^t = \sum_{\tau \leq t} \Delta m_i^\tau \tag{2}$$

The following expression is used for the calculation of the photosynthesis of a crop (De Wit, 1965). It relates the $CO_2$ assimilated to the photosynthetic active radiation (PAR):

$$P = \frac{I}{a+I} \cdot P_{max} \tag{3}$$

$P_{max}$ is the photosynthesis at high light intensities. It depends among others upon $CO_2$ diffusion resistance, ambient air velocity, etc. The "a" is a crop specific constant. The radiation absorbed by a leaf depends on the time of the day, angle of the leaf exposure, the index of a current 10-day period "t", latitude "$\varphi$", cloudiness "n". A table has been derived for standards conditions based on equation (3). For various latitudes ($\varphi$ = 0°, 10°, 20°, ..... 70°) and for every decade of a month (t = 1, 2, .....,36) the dry matter production for a clear day (n = 1) and a cloudy day (n = 2) have been calculated. The table content can be symbolized by $\Phi_1$ (t, $\varphi$), $\Phi_2$ (t, $\varphi$), where the indices 1 and 2 represent resp. the clear and cloudy day. A similar procedure has been used for the derivation of a table for the clear day radiation, $I_1(t,\varphi)$. Numerical tables for $\Phi_1$, $\Phi_2$ and $I_1$ are used as input information for the model. Given the average radiation values for the current 10-day period and knowing the latitude, the potential photosynthesis $\Phi_0$ (t, $\varphi$,I) is:

$$\Phi_0\,(t,\varphi,I) = \Phi_2 + (\Phi_1 - \Phi_2) \cdot (1-n), \tag{4}$$

$$1-n = \frac{I-I_2}{I_1-I_2}, \qquad I_2 = 0.2 \cdot I_1,$$

where $\Phi_1, \Phi_2, I$ are derived by linear interpolation using a value for the geographical latitude.

The value $\Phi_0 = \Phi_0(t,\varphi,I)$ can be regarded as the potential photosynthesis which would have been reached in the absence of soil moisture deficiency.

## 2.2. The role of water in crop production

The actual soil moisture level is calculated by means of a water balance. The following factors are finally determining the soil water available for plant growth: the evapotranspiration, runoff, applied irrigation water, drainage and of course the amount of precipitation.

Calculations of potential levels of evaporation and evapotranspiration are done by means of the Penman equation (Penman, 1948; Frère and Popov, 1979). The soil energy balance plays an important role in the Penman equation. The components of the energy balance are shown in Figure 1.

Let us denote by "r" the coefficient of the reflection of the incoming shortwave radiation "(I)" and by the outgoing longwave radiation ($R_L$).

$$R_{nt} = (1-r) \cdot I - R_L \tag{5a}$$

A part of "I" -value is available for the heat transfer by the evapotranspiration stream $\chi \cdot TR$. Another part is available for the convective heat transfer $K = K_H(T_l - T_a)$. The heat flow from and into the soil is neglected. When $T_l$ and $T_a$ are resp. the temperature of leaves and the air, thus

$$R_{nt} = \chi \cdot TR + K_H \cdot (T_l - T_a) \tag{5b}$$

where $\chi$ is the latent heat of evaporation and $K_H$ is the convection coefficient. In the determination of the evapotranspiration rate TR is based upon knowledge of the mechanism of water evaporation from the leaf surface.

The water vapor diffusion E' is assumed to be proportional to the difference between the vapor pressure at saturation $d_H$ and the actual vapor pressure ($d_a$ ):

$$E' = A \cdot (d_H - d_a), \tag{5c}$$

The conductivity coefficient A is inversely proportional to the sum of water flux diffusion resistance values, i.e., stomata resistance ($r_{st}$) and the resistance of the ambient air ($r_a$). The latter to a considerable extent depends on the wind velocity (v) near the crop, therefore

$$A = f(v,r_{st}). \tag{5d}$$

To obtain TR we multiply the Eqns. 5b and 5c:

$$TR = L \cdot f(v,r_{st}) \cdot (d_H - d_a). \tag{5e}$$

where L presents the total leaf area per hectare. The stomatal resistance control both the water and the $CO_2$ regimes of the crop and depends on the radiation, accumulation of assimilates, temperature, leaf water potential and inversely on soil moisture. As in rough approximation, this stomatal resistance is believed to be a function of soil moisture "w". In the model, for convenience the expression for TR (5a) has been modified:

$$TR = \lambda(w,L/L_0) \cdot TR_0 \tag{5f}$$

where $TR_0 = f(v) \cdot (d_H - d_a)$ and the $\lambda$ describes the shape of the curve as shown in Figure 2. At $L = L_0$ and high "w"-values, TR becomes equal to $TR_0$. $TR_0$ is a potential evapotranspiration for a closed canopy with the highest possible leaf area index, $L_0$. It is assumed that no moisture deficiency exists in the soil that is the stomata are entirely opened and, consequently, there is no stomatal resistance. "w" will be high and, $\lambda$ will be close to unity (Figure 2). It follows from the expression (5f) that $TR_0$ can be regarded as the potential evapotranspiration of a crop, while the term $\lambda(w,L/L_0)$ is to be considered as a limiting factor depending on "w".

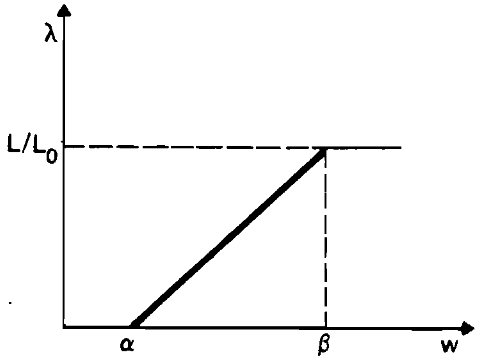


Figure 2. Soil moisture "w" as affected by the limited available water.

Experiments have shown that the ratio $\gamma = \dfrac{K_H}{\chi \cdot f(v)}$

is stable under changing environmental conditions (temperature, wind velocity). Substituting $TR_0$ for TR and $K_H(T_l - T_a)$ for K in (5a) in the Penman formula gets the following shape.

$$TR_0 = \frac{R_{nt} + \chi \cdot \gamma \cdot \Delta^{-1} E_a}{(1 + \gamma \cdot \Delta^{-1})}, \tag{6}$$

where $\Delta = \left[ \frac{\partial d_H}{\partial T} \right]_{\cdot T = T_a}$

is the rate of variation of saturated air vapor pressure as influenced by temperature. In $E_a = f(v) \cdot (d_H - d_a)$, $d_H$ is the saturated air vapor pressure at temperature $T_a$ and f(v) is a function for the wind velocity.

For the estimation of $TR_0$ , the 10-day average data for each of the 36 decades are used. These data included the average values for the air temperature ( $T_a$ ), the air vapor pressure ( $d_a$ ) , the wind speed (v), the incoming short wave radiation (I). If the shortwave radiation is not available it can be replaced by the number of sunshine hours.

For the calculation of the potential transpiration the subsequently following estimations are carried out:

- the net radiation is determined by e.g. (5a), the value for the crop reflection (r) is assumed to be equal to 0.25 (Monteith, 1973)
- next the convective transport ($E_a$) is estimated (Eqn. 5c) and in addition the rate of saturated vapor pressure at the current air temperature ($\Delta$)
- finally we obtained the potential evapotranspiration by Eqn. 6.

The value of "λ" used for the estimation of TR (see eqn. 5f) results from the determination of moisture value "w" by the soil water balance.

Potential evaporation $E_0$ is calculated like the potential evapotranspiration. However, a different reflection applies. For the evaporation we use the coefficient of 0.05, as for a free water surface. If there is a reduction in soil available water as determined by the water balance for a bare soil, the actual evaporation will be lower than the potential evaporation.

The water balance equation for the root zone (the depth of the root zone is denoted by "rt") is essential for the calculations of 10 day average values of soil moisture content (w) and soil water potential $\Psi$.

$$\frac{w^{t+1}}{100} \cdot rt = \frac{w^t}{100} \cdot rt + R^t - RF^t(w^t) - TR^t + I_r^t - D^t, \tag{7}$$

where

$t$ = the current decade (t = 1, 2,...., 36)

$w^t$ and $w^{t+1}$ = soil moisture at resp. the beginning and the end of the 10-day period, in volumetric percentages.

$R^t$ = precipitation in cm

$RF^t$ = overland flow in cm

$TR^t$ = evapotranspiration in cm

$I^t$ = irrigation in cm

$D^t$ = drainage in cm

rt = rooting depth in cm

The soil moisture content at the beginning of a 10-day period is changed with the amount of the precipitation $R^t$, the runoff $RF^t(w^t)$, irrigation water supply $I_r^t$, the evapotranspiration $TR^t$, and the percolation $D^t$ .

The surface runoff is described by the following empirical expression (Soil Conservation Service, 1972)

$$RF = 0, \text{ if } R < 0.2\,S, \tag{8}$$

$$RF = \frac{(R - 0.2 \cdot S)^2}{R + 0.8 \cdot S}, \text{ if } R \geq 0.2 \cdot S;$$

$$S = \left[\frac{1000}{CN} - 10\right] \cdot \left[1 - \frac{w}{w_p}\right] \tag{8a}$$

The variable S describes the part of the rainfall that infiltrates. Its value depends on the soil porosity ( $w_p$) and the curve number (CN). The CN-number depends on the kind of crop (row crop, non-row crop, fallow), infiltration rate (soil dependent), the crop's leaf area. With a decrease in soil moisture content and an increase in infiltration rate or an increase in leaf area, the S-value will increase. This consequently leads to more water available for plant growth.

If the amount of rainfall $R < 0.2 \cdot S$, then there is complete infiltration and no runoff will occur.

The evapotranspiration $TR^t$ has already been discussed (see eqn. 5f) The factor $\lambda$ is determined by soil moisture content "w" and this has been visualized in Figure 2. The parameter $\alpha$ is determined by plant properties, below that particular value soil moisture content, plants start wilting. $\beta$ is the soil moisture content below which water stressed plants cannot maintain their stomata completely open. An empirical expression describes the relationship for $\beta$ between the soil structure and the crop.

The component $I_r^t$ of the water balance in the equation (7) accounts for the amount of water (in cm) supplied during a 10-day period t in a certain irrigation system. The amount of $I_r^t$ applied at the field level depends on the amount of water available for the whole irrigated area. So there may be constraints on the amount and/or the frequency of water applications. For each 10-day period, an index for the available water in the soil, $\eta^t$ is calculated.

$$\eta^t = \frac{w^t - w_{wp}}{w_p - W_{wp}},$$

where:

$w^t$ is the present soil moisture content

$w_{wp}$ is soil moisture content at permanent wilting point

$w_p$ is soil moisture content at field capacity

The current water supply is compared to the critical level $\eta_{cr}$. If $\eta^t > \eta_{cr}$ the program "switches on" the irrigation. The volume of irrigation water $I_r^t$ is determined based on the above limitations to have the value of $\eta^t$ as close to unity as possible. How far irrigation will be applied, that is how much water will be used and at what time has to be indicated by the user.

There will be percolation $D^t$ when the following inequality holds:

$$\frac{w^t}{100} \cdot rt + R^t - RF^t - TR^t > \frac{w_{fc}}{100} \cdot rt$$

In this inequality $w_{\pi}B$ is soil moisture content at field capacity. In this case $D^t$ becomes

$$D^t = \frac{w^t}{100} \cdot rt + R^t - RF^t - \frac{1}{2} \cdot TR^t - \frac{w_{fc}}{100} \cdot rt$$

The calculation of the soil moisture content $w^t$ for a bare soil is also done by means of the water balance equation (7). However, the evapotranspiration $TR^t$ is replaced by the evaporation, $E^t = \varepsilon(w^t)E_0^t$ for a free water surface with $\varepsilon(w)$ a limiting factor similar to the one shown in Figure 2, but only soil type dependent.

Based on equation (7) the soil moisture content is calculated for each of the 36 10-day periods. For this purpose the following input data are required:

| | |
|---|---|
| $w^1$, | soil moisture by the end of the preceding year; |
| $R^t$, | total precipitation rate for each 10-day period; |
| M, | the crop number; |
| $L/L_0$, | leaf area index ratio for each 10-day period; |
| $w_p$, | average porosity of the soil horizons; |
| V, | infiltration rate. |

The depth of the root zone and leaf area index are preset for the growing season; the other data should be collected by the user when applying the model to a specific region with its typical soils.

The dry mass increment for each plant organ and per 10-day period "t" is obtained from the equation (1), where the real photosynthesis $\Phi^t$ is related to the potential photosynthesis $\Phi_0^t$ as follows:

$$\Phi^t = 0.68 \cdot \lambda(w^t, L/L_0) \cdot \Phi_0^t. \tag{9}$$

The curve that describes the λ-function has been shown in Figure 2. It follows from eqn.(9) that the real photosynthesis is proportional to λ which is the ratio of a real evapotranspiration TR to the potential evapotranspiration $TR_0$. This assumption is justified by the fact that both the $CO_2$ - and water vapor transport take place through the stomata. In the first rough approximation under conditions of adequate soil moisture content we can assume that:

$$\Phi^t \approx \frac{\text{Const}}{r_{st}} \cdot \Phi_0^t \text{ and } \quad TR^t \approx \frac{\text{Const}}{r_{st}} \cdot TR_0^t,$$

with the stomata resistance, $r_{st}$, depending to a considerable extent on soil moisture constant $w^t$. Hence

$$\lambda \approx \frac{\text{Const}}{r_{st}} \approx \frac{TR^t}{TR_0^t}.$$

Thus, the relationship between photosynthesis and soil water regime is described by empirical expressions that reflect the role of the regulation through the stomata.

In equation (2) we described the allocation of dry matter over the various plant organs. Among them we consider the most interesting part from an economical point of view (grain or tuber) in more detail. This value is denoted by $Y_0(w)$ and is regarded as a potential yield which can be reached under optimal conditions of nutrient supply. The potential yield becomes subject to reductions in case of sub-optimal nutrition is determined in the submodels for organic matter decay and nutrient availability.

During the allocation of the dry matter losses because of maintenance respiration take place. The rate of the losses is temperature dependent, the plant temperature is assumed to be equal to the air temperature. The respiration is plant type dependent, usually the higher the protein content the higher the maintenance respiration.

## 2.3. Available Plant Nutrients

### 2.3.1. Organic Sources

The module with the organic matter decomposition is rather complex. In view of limited knowledge the attempt to model the decay at a rather high level of aggregation has various subjective aspects. In this module the following five fractions in soil organic matter have been recognized: protein, hemicellulose, cellulose, lignine, and humus substances. Each fraction undergoes three stages of degradation, and the degradation of each fraction is independent of the others. Time increment for the estimations is equal to 1 day and is denoted by $\tau$.

Given the composition and decay rate of each fraction, one can determine the amount of N and C formed at any particular moment. Values for the rate of decay have so far been derived from literature (Personal Communication Driessen).

The module determines the amount of nitrogen lost, dependence on the properties of on the soil environment (soil moisture content, temperature, acidity, cation exchange capacity, etc.) and the uptake by plants. Two groups of nitrogen formed from nitrogenous fractions can be distinguished depending on their composition and degradation rate. One group is the source of the replenishment of inert humus substances, the other one is considered to be the source of available nitrogen.

No distinction during the transformation is made between the ammonification and the nitrification, so no matter whether it is ammonium or nitrate we deal only with nitrogen taken up by the plant.

The integrated approach for the description of the absorption processes of $NO_3^-$ and $NH_4^+$ by the root system is as follows. The description is based on the empirical potential nitrogen absorption curve 8(t). If N(t) is the amount of nitrogen absorbed during the whole period of plant growth, then:

$$8(t) = \frac{\Delta N(t)}{N(t)} \; .$$

In contrast with $\Delta N(t)$ and N(t) the 8 (t) -value is believed to be rather insensitive to the impact of divergent environmental conditions (this has been confirmed experimentally for the Stavropol Territory). The potential nitrogen uptake $NP^t$ for a 10-day period "t" can be described by:

$$NP^t = \chi(t) \cdot \frac{M_2 + M_3 + M_4}{s}$$

where $M_2, M_3, M_4$ are potential dry matter produced for resp. the leaves, the stems and reproductive organs that have been calculated by means of the equations (1) and (2). $M_2, M_3, M_4$ are calculated in the same way as $m_2, m_3, m_4$ (see eqn. 1) with soil moisture content ( $w^t$) non limiting ( $w^t > \beta$, figure 2). The coefficient "s" is equal to the total percentage of nitrogen in the leaves, stems and reproductive organs.

Actually absorbed nitrogen $NR^t$ and the transformations of nitrogenous fractions $\Delta_i^j$ are calculated based on the limiting factor principle:

$$\Delta_i^j(\tau) = \min \left[ \gamma_1(\psi^\tau), \gamma_2(T^\tau), \gamma_3(pH^\tau), \gamma_4((\frac{c}{N})^\tau) \right] \cdot \Delta_i^0 \cdot x_i^j \tag{10}$$

$$\tilde{NR}^{\tau} = \min\left[\gamma_5(\psi^{\tau}), \gamma_6(T^{\tau}), \gamma_7(pH^{\tau}), \gamma_4((\frac{C}{N})^{\tau})\right] \cdot NP^{\tau} \tag{11}$$

In the above expressions $\gamma_k$, ($k = 1, 2, \ldots, 7$ ) are soil environmental factors eventually limiting the process of decomposition of the fractions of soil organic matter $x_i^j(\tau)$ and nitrogen uptake $NP^{\tau}$ by the crop. $\Delta_i^0$ is the rate of decomposition under ideal conditions, that is when

$$\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 1$$

while "i" is the number of a fraction and "j" is the number of the stage of decomposition. The values of $\gamma_k$ lie between 0 to 1. It follows from (10) and (11) that in the given time interval, $\tau$, not all factors $\gamma_k$ are significant but only those minimizing the expressions (10) and (11). For instance, let us assume that in a certain time interval the soil moisture conditions are unfavorable, that is when soil moisture content $w^{\tau}$ as calculated by the water balance proved to be low. The water potential $\psi_{\tau}$ becomes:

$$\psi^{\tau} = e^{\sqrt{\frac{1}{\gamma}\ln\frac{w_p}{w^{\tau}}}} \tag{12}$$

where $w_p$ is soil porosity, $\gamma$ is a soil specific constant. This is followed by the calculation of the coefficient $\gamma_1(\psi^{\tau})$ which is described by the curve shown in Figure 3. Eqn. 12 shows that low soil moisture content values for $w^{\tau}$ correspond with high water tension values $\psi^{\tau}$. Figure 3 shows that at high as well as low soil moisture tension values $\gamma_1$ may become the most limiting factor. Besides $\gamma_1(\psi^{\tau})$ other $\gamma$ coefficients describing the soil environment may become limiting, like temperature $T^{\tau}$, soil acidity $pH^{\tau}$ or $(C/N)^{\tau}$ ratio, all possible in a similar way to that shown in Figure 3. This is followed by the determination of the minimum value of the given four $(\gamma_1, \gamma_2, \gamma_3, \gamma_4)$ for (10) and four ( $\gamma_5, \gamma_6, \gamma_7, \gamma_4$) for (11). A situation being typical for the Stavropol Territory is that $\gamma_1(\psi^{\tau})$ and $\gamma_5(\psi^{\tau})$ are the limiting coefficients. In that case the equations (10) and (11) can be written as follows:

$$\Delta_i^j \tau = \gamma_1(\psi^{\tau}) \cdot \Delta_i^0 \cdot x_i^j(\tau) \tag{13}$$

$$\tilde{NR}^{\tau} = \gamma_5(\psi^{\tau}) \cdot NP^{\tau} \ . \tag{14}$$

A characteristic feature of the processes described by the formulas (13) and (14) is that they are independent of the other non-limiting factors: $\gamma_2$, $\gamma_3$, $\gamma_4$, $\gamma_6$, $\gamma_7$ .

A question is whether the nitrogen absorption process as described by the formula (11) depends on the available nitrogen in the soil. The actual nitrogen $NR^{\tau}$ absorbed by the crop in the time interval $\tau$ is

$$NR^{\tau} = \min[\tilde{NR}^{\tau}, \max(0, \Delta N^{\tau})], \tag{15}$$

when $\Delta N^{\tau}$ is available nitrogen liberated from the decomposed fractions, taking losses because of leaching into consideration. The nitrogen absorbed by the crop over the whole growth period, NR, is

$$NR = \sum_{\tau} NR^{\tau}, \tag{16}$$

where the $NR^{\tau}$ values over all time intervals $\tau$ should be given. The values of $pH^{\tau}$ and $(C/N)^{\tau}$ are calculated based on empirical relationships.

Organic fertilizers and plant residues may play a role in the decomposition of organic matter and nitrogen uptake. Given the composition of the organic

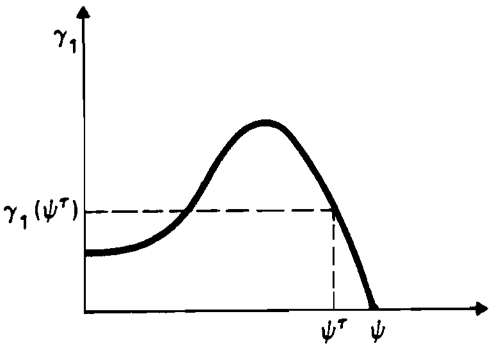


Figure 3. Factor $\gamma_1$ limiting the decomposition of organic matter as affected by soil water potential $\psi$.

fertilizers and the plant residues (total amount, fractions, N and C percentages for each fraction, etc.) the decay for each fraction can be calculated; at the time of application of the organic fertilizer and at harvest time an updating of the composition of all organic matter in the soil is carried out.

### 2.3.2. Inorganic Sources

Crop yield in response to various inorganic nutrients sources can be expressed as:

$$Y = \min_i \left[ \min \left[ S_i \cdot \frac{Y_0(w)}{V_i} + \frac{NR}{d_i} \cdot \alpha_i,\ Y_0(w) \right] + \beta_i \cdot \alpha_i \cdot 0.7 \cdot X_i \right], \qquad i = N, P, K \quad (17)$$

where

$Y_0(w)$ is the dry matter production with only water as a limiting factor (kg/ha);

$S_i$ is available nitrogen ($i = N$), phosphorus ($i = P$) and potassium ($i = K$) in soil at the beginning of the year with $S_N$ being always equal to 0;

$V_i$ is the yield of either of the three nutrients (N,P,K) assuming that the other two are abundantly available.

NR is the amount of nitrogen absorbed by the crop from organic sources during the growth period;

$d_i$ is the amount of P and K recovered from organic sources per one unit of N absorbed;

$\alpha_i$ is yield increment per N,P,K-unit absorbed;

$X_i$ is the amount of N,P,K fertilizers applied;

$\beta_i$ is the coefficients of the inorganic fertilizer's efficiency;

$\alpha_i'$ yield increment per N,P,K unit absorbed with

$$\alpha_N' = \alpha_N,\ \alpha_p' = \alpha_p/2.25, \alpha_K' = \alpha_K/1.2$$

The values of $Y_0(w)$ and NR have been estimated at an earlier stage of the program operation. Finally, the yield is obtained from the formula (17) as follows. The expression in square brackets for each $i$ = N, P, K after the substitution of the required values is effected, consists of two numbers. For each "i", the corresponding minimum is determined, followed by the computation of the magnitude of the expression in brackets. Thereby three results are obtained corresponding to $i$ = N, P, K. The final result is the minimum value out of the three "yields" determined, this is the minimum denoted as min {....}

In this publication no description of water erosion block and soil characteristics block is provided; these items were considered by N. Konijn (1984). Naturally, the present version of the model can be much criticized. However, the model structure and the diversity of the processes and factors described depend to a considerable extent on the objectives of modelling and its implications. In future the model is certain to be improved with corrections and modifications to be made.

## 3. Results of model experiments

The crop production model developed at IIASA has been installed and adapted on two home produced computers BESM-6 and ES-1060 at the Computing Center of the Academy of Sciences of the USSR. Extensive work has been done with regards to the collection and processing of meteorological, physiological, soil and agrochemical information. The input data covered a 12-year period of observations and research (1971-82). Soils of the Stavropol Territory were grouped into 15 land classes (Fig. 4); their distribution over districts and agricultural zones has been determined. Soils were grouped according to the distribution of soils over the different climatic zones in the Stavropol Territory.

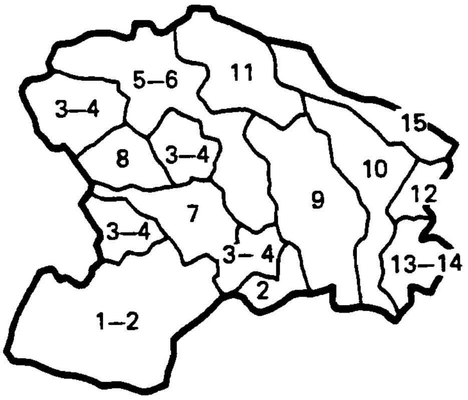


Figure 4. Soil classes of the Stavropol territory.

Based on the minimum and maximum yields obtained in field experiments, the corresponding fertilizer efficiency and its agrochemical parameters were determined. A number of the parameters necessary for the operation of the model were taken from literature and from results of experiments with similar models developed by other authors. This concerns those parameters that are not affected by the local conditions.

Not all necessary parameters are available, although various of them recently have been measured. For example, out of 15 soil classes that have been distinguished, 10 profiles have been sampled to a depth of 1 meter and have been analyzed on the fractional composition of soil organic matter. Furthermore analysis of the composition of plant residues and organic fertilizers have been carried out.

Other parameters that have been determined are the uptake coefficient $\alpha'$ that defines the amount of dry matter of grain or vegetative organs formed per unit of N, P, or K (Table 1). Obviously the coefficients vary with the crop.

Because of the specificness of the local varieties planted, the assumed values have to be checked. During the determination of the required parameters it might become obvious that alternatives exist, which might lead to a restructuring of the model. Therefore, the stage of parameter identification should be carried out in an early stage of the model development.

Table 1. Coefficient $\alpha'$ to be used for various crops being grown in the Stavropol territory

| Crop/ Plant Organ | Original Model Parameters $\alpha_N$ | $\alpha_P$ | $\alpha_K$ | Local Model Parameters $\alpha_N$ | $\alpha_P$ | $\alpha_K$ |
|---|---|---|---|---|---|---|
| Winter Wheat | | | | | | |
| grain | 37 | 223 | 244 | 40 | 250 | 234 |
| straw | 149 | 1429 | 86 | 222 | 1123 | 133 |
| Winter Barley | | | | | | |
| grain | 45 | 270 | 222 | 43 | 240 | 220 |
| straw | 161 | 2000 | 50 | 200 | 900 | 120 |
| Spring Barley | | | | | | |
| grain | 45 | 270 | 222 | 47 | 280 | 200 |
| straw | 161 | 2000 | 50 | 167 | 1125 | 120 |
| Maize for Grain | | | | | | |
| grain | 57 | 333 | 278 | 58 | 400 | 167 |
| vegetative mass | 93 | 1000 | 61 | 110 | 2500 | 140 |
| Peas | | | | | | |
| grain | 25 | 217 | 88 | 22 | 186 | 86 |
| vegetative mass | 48 | 417 | 77 | 42 | 320 | 71 |
| Soybean | | | | | | |
| grain | 14 | 152 | 56 | 17 | 210 | 95 |
| vegetative mass | 120 | 1167 | 179 | 83 | 450 | 730 |
| Sugarbeet | | | | | | |
| roots | 92 | 417 | 66 | 71 | 375 | 80 |
| tops | 42 | 455 | 17 | 33 | 410 | 228 |
| Sunflowers | | | | | | |
| seeds | 35 | 178 | 141 | 27 | 225 | 160 |
| vegetative mass | 250 | 1540 | 241 | 125 | 750 | 30 |
| Maize for silage | 85 | 900 | 100 | 60 | 560 | 120 |

### 3.1. Interannual results of model runs

The crop production model aims at generating yield data under various production circumstances. Finally this leads for a certain year to one or two crop yields. To show the estimations underlying these final crop yields a few more detailed output results of the model are shown.

These examples gives us an idea of how the model will respond to changes in the physical environment. The characteristics describing the physical environment are from Novoaloxandrovsky (Stavropol Territory) and oats (Avena sativa L.)is rather subjectively chosen as the crop.

Example 1. ***Photosynthetic dry matter production***

We show in Figure 5 the photosynthetic dry matter for two different years, respectively 1978 and 1979. Comparing the growing seasons for those two years we notice that there was more radiation during the first year. One would expect the year 1978 to receive less rainfall, however it is in the year 1979 that crops suffered here severely from water stress. So more radiation during the growing season does not necessarily mean less rainfall.

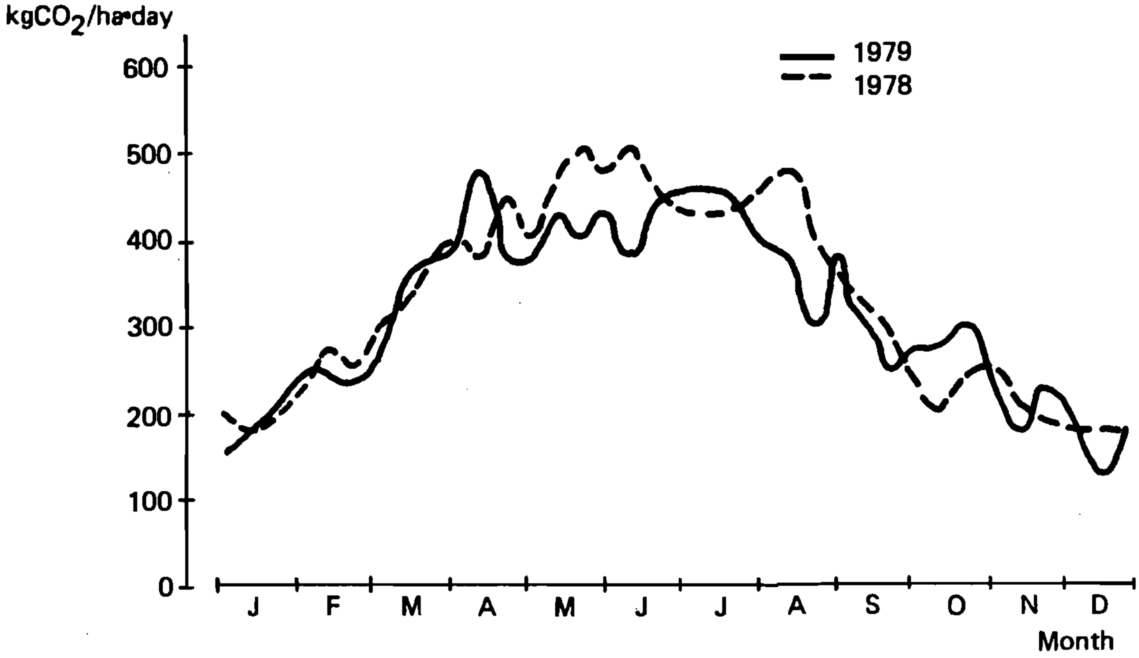
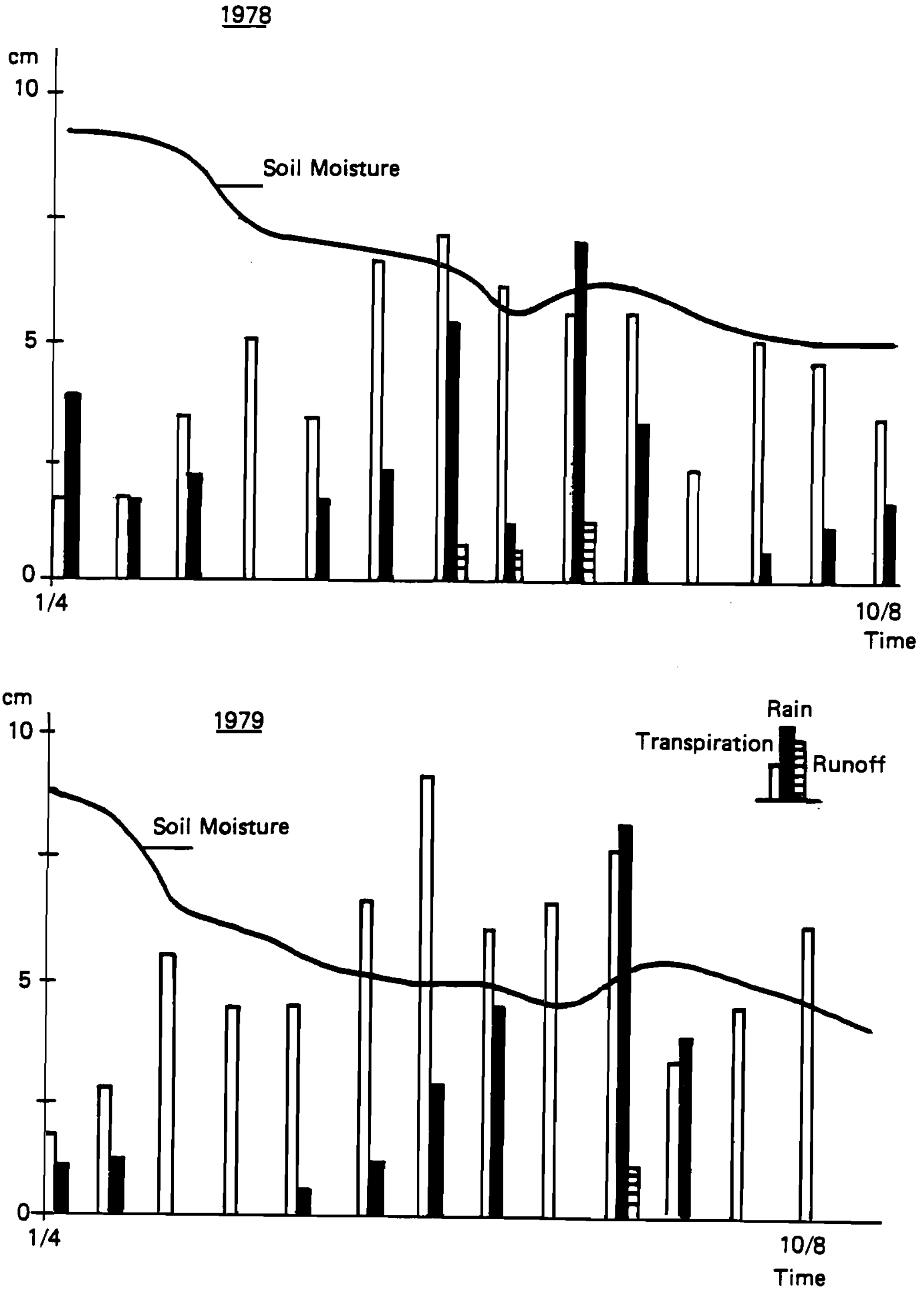


Figure 5. The photosynthetic dry matter production for two climatic year.

Example 2. *The water balance during the growing season*

Figure 6 presents the water balance for the years 1978 and 1979 of oats. Obviously, the soil moisture content decreases since the evapotranspiration is not compensated by sufficient rainfall. 1979 is a much drier year than 1978, which is shown by the course of the soil moisture content over the growing season.



All variables in cm, but soil moisture multiplied by 4 in %

Figure 6. The water balance for oats in Novo Alexandrovsky for two climatic years.

Example 3. *The effect of weather on dry matter allocation*

It is not merely the crop characteristics that determine the partitioning of dry matter produced over the various plant organs. The weather may play an important role as well. In Figure 7a and 7b we find the dry matter allocation for respectively 1978 and 1979, the latter being a much drier year. The harvest index, that is the ratio main yield over the residue, is lower in the drier year.

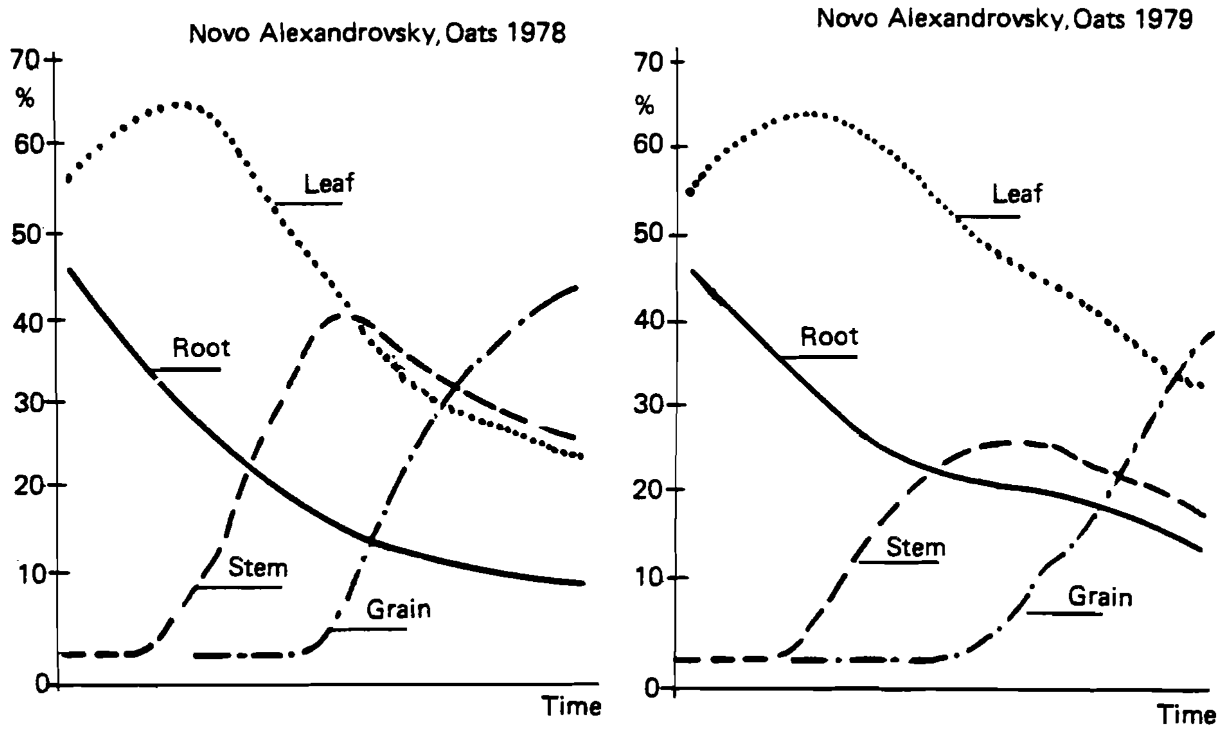
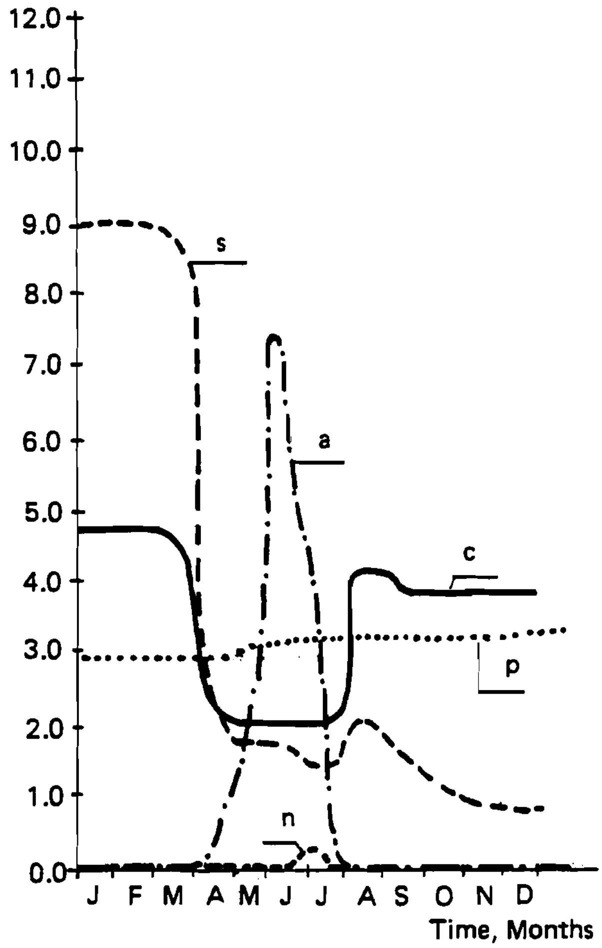


Figure 7. The partitioning among plant organs for two climatic years.

Example 4. *Decay of organic matter*

The decay of organic matter in Figure 8 looks quite impressive, however, one still has to take into consideration the deformation of the vertical scale, which is given at the bottom. The figure shows us that the decay of organic matter is important during the growing season, that is when the temperature is relatively high. Together with the changes in organic matter content, we notice changes in soil acidity and carbon/nitrogen ratio. The real uptake of nitrogen by the plant is for the year concerned rather low. In our example the residue is left on the field therefore we observe an increase in the amount of organic matter at the end of the growing season. This has its effect on the Carbon/Nitrogen-quotient as well.



One unit on the vertical scale is: resp. 4956 kgs org. matter per ha; 0.1 pH unit; 0.4 0/N-quotient unit pot. N uptake is 5 kgs per ha; real N uptake is 5 kgs per ha.

s = total organic matter multiply by 4956 and add 455902, to get the value in kgs per ha
p = soil acidity, divide by 10 and add 7 to get it as the neg. log. of the conc. in greq. per liter
c = C/N-quotient, divide by 2.5, and add 15 to get the real C/N-quotient
a = the potential N uptake, multiply by 5 to get kgs N uptake per hectare
n = the actual N uptake, multiply by 5 to get kgs N uptake per hectare

Figure 8. The decay of organic matter during the year.

### 3.2. A comparison between estimated and observed crop yields

With some numerical experiments we aimed at the comparison of yields estimated by the model with observed crop yields. The comparison was based on the soil, climatic and fertilizer conditions for the period 1971-82. Average yield data for the 10 to 13 major crops of the whole territory, individual regions, collective farms and experimental fields have been collected. The crops included winter wheat, winter barley, spring barley, maize for grain and silage, soybeans, pea, sugarbeet, sunflower, potato, annual grasses, alfalfa, sorghum. The results of some numerical experiments are shown in Figures 9, 10, 11 and 12.

The results obtained show a rather satisfactory quantitative determination of yield dynamics over the years by the model, at least based on the soil and climatic conditions. Still, for certain conditions the estimated yields proved to be 25 to 50% lower than the actual levels. This seems to be due to an insufficient adjustment of the model parameters to the conditions of the Stavropol Territory. Most of the unsatisfactory results are the consequence of the improper operation of the organic matter decay estimations. This part of the model predicts heavy soil nutrient deficiency which in reality is not the case. On the other side, the model provides a correct description of crop-mineral fertilizer relationships, i.e., it reflects the real crop response pattern.

The unsatisfactory performance of the organic matter decay module has considerable consequences for the process of updating of the soil properties from year to year, for the organic matter plays an important role in the updating.

Especially when we are interested in the realization of yield estimations with the model on crop rotations we need a proper estimation of the decay of organic matter. It is these rotations that should receive specific attention for the Stavropol Territory.

More numerical experiments will be carried out in the near future. The sensitivity of the model to certain parameters will certainly reduce considerably in future. Some further simplifications are expected to speed up the calculations. The calculations on various crop rotations have received more and more attention, finally that work should result into recommendations of the choice of crop rotation systems to be practiced soil-wise. Other experiments are under way aiming at yield estimations under various irrigation and cultural practices.

Finally it should be mentioned that the model has not covered all processes and factors of importance in the Stavropol Territory. Examples are the wind erosion, the over-wintering of plants and the utilization of winter precipitations.

Once the last mentioned processes and factors have been included, we have developed a model that can act as a reliable tool to describe not only the present agricultural situation, but which may show to be helpful in planning and further development of the agricultural production in the Stavropol Territory as well.

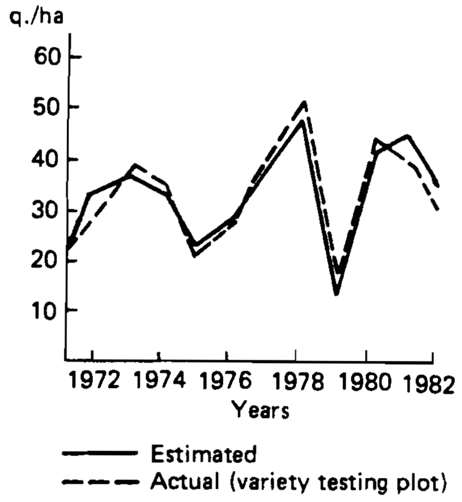


Figure 9.
Winter wheat yield on 4th class soils

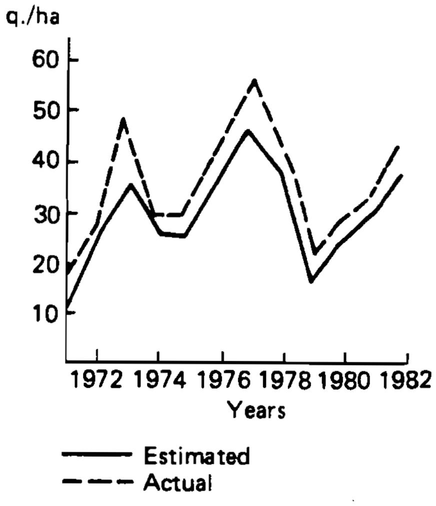


Figure 10.
Maize grain yield on 4th class soils

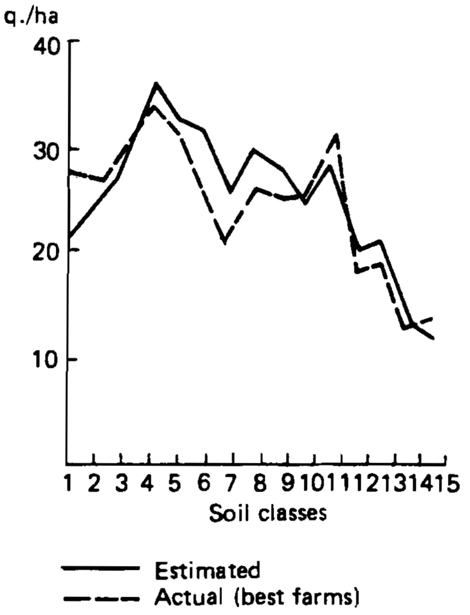


Figure 11.
Winter wheat yield as affected by soil classes

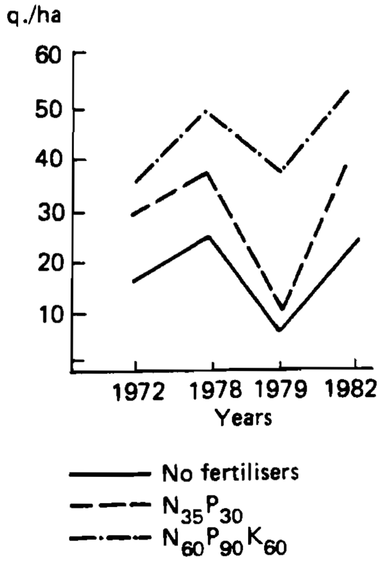


Figure 12.
Winter wheat yield as affected by fertilizer application

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

*F. Ereshko, V. Lebedev and K. Parikh*

## 1. Introduction

The Stavropol case study of Task 2 of FAP 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 large – and soon becomes impractical. 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' judgements. 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

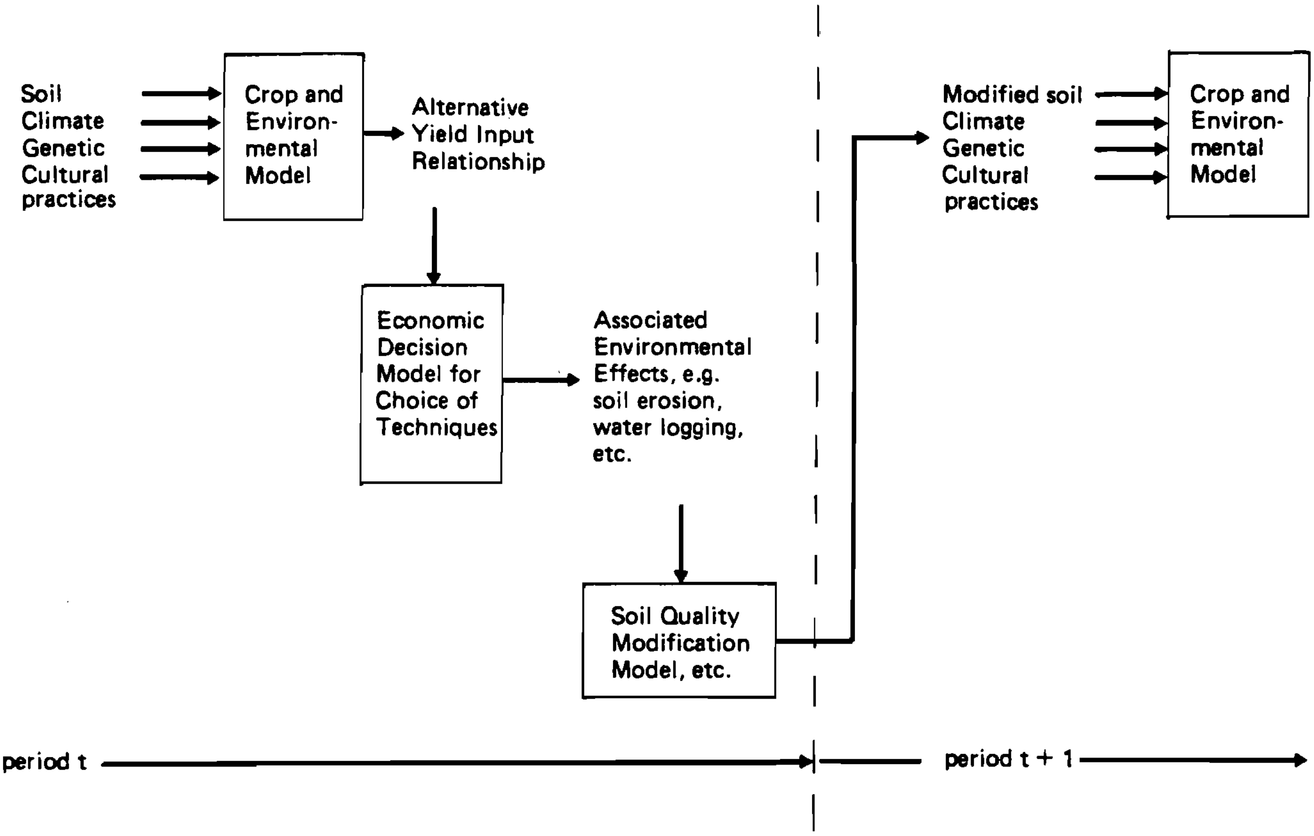

Figure 1. Schematic diagram of analytical elements

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 regarding use of resources implemented taking into account various economical considerations and environmental impacts from the implementation of those policies.

The plan of the paper is as follows: In Section 2 the physical crop production model, PCP, is described to briefly formalize its underlying structure. Section 3 outlines a simulation procedure which does not incorporate any economic rationale for decision making. Section 4 suggests a procedure to simplify the dimensionally exploding recursive dynamic computational problems underlying the substantive problems addressed here. Section 5 describes a further simplified model that was developed in the very initial stage.

## 2. PCP-Model

Based on agronomic and soil science principles, a model to quantify the longer-term yield effects of using alternative agricultural techniques is developed by N. Konijn (1982).

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.

N. Konijn (1982) has extended such a model to include the Soil Quality Modification (SQM) Model as was also shown in Figure 1.

Updating the input characteristics from year to year offers one 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 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 notion of 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
- cation exchange capacity for mineral components of soils

for each soil horizon

- 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 layers
- porosity of the layers
- density of the layers

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

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

- 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 layers):

- 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 layers. Thus the vector of state variables, $z^t$, has to the form

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

**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 applied
- 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 $\xi^t$ 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:

$$y^t = \Psi(z^{t-1},u^t,\xi^t,p) \tag{1}$$

where p is the vector of parameters defining the subregion.
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:

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

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

## 3. Simulation system

As is discussed in K. Parikh and 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 of 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 diversity of the soils in the region in terms of physical and chemical characteristics 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 will consist of the PCP-model and a production and resource accounting block, and is of the form:

**PCP-model**

$$z_l^t = F(z_l^{t-1},u_l^t,\xi_l^t,p_l)$$

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

(crop production from unit area in part l)

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

## Production and Resource Accounting

The crop production vector, $y^t$, is obtained simply by summing production in different subregions. Thus

$\sum_l s_l y_l^t = y^t$ - vector of production

The resources needed for production in the region are given by

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

where

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

K - set of indices of resources which are:

- electric energy
- fuel
- chemicals
- tractor services
- transport services
- grain harvesters services
- corn harvesters services
- beetroot harvesters services

For many agricultural systems livestock production is integrated with crop production. Thus accounting for livestock production is necessary. Denote by $d^{t,j}$ the fraction of the production $y^{t,j}$ used as feeds for animals. Then the production of feeds of type $\nu$ is given by

$$\sum_{j \in J} \beta_j^\nu d^{t,j} y^{t,j} = d^{t,\nu}$$

where the coefficients $\beta_j^\nu$ describe the amount of feed $\nu$ obtained from one unit of product j used to produce feed $\nu$. On the other hand, demand for feed is obtained as follows

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

where

$k_i^\nu$ - consumption per animal head of feed $\nu$

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

$\sum_i \alpha_{im} g_i^t = a^{tm}$ - product output of type m

where

$\alpha_{im}$ - output of product m from structural animal unit of type i

The difference between feed demand and supply to be imported from outside the region is given by

$$b^{t,\nu} - d^{t,\nu}$$

The production and resource accounting block together with the PCP-model constitute a description of a general simulation model, which we refer to as GM.

## Simulation experiments

The controls in the model are:

$$\text{set} L_{ch}^t, N_l^t, P_l^t, O_l^t, W_l^t, A_l^t, g_i^1$$

By specifying various scenarios by 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 $F^{1,t}$, $F^{2,t}$, $F^{3,t}$, $F^{4,t}$, $W^t$ as well as L are fixed at the beginning of the simulation run.

Such simulation experiments are useful in generating alternative production plans, the resources needed for meeting these plans and quantifying the associated environmental consequences of the plan. It does not, however, give any guidance about the economic desirability of the production plans generated. Not only one cannot say whether such a plan is optimum in terms of some given objective function, one cannot even say if the plan is economically efficient in the sense that with the resources used more could not be produced than indicated in the plan. Thus one needs to develop procedures for generating economically meaningful scenarios. 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. In the following sections we explore some alternatives.

## 4. Crop Rotations To Maintain Soil Quality

The computational difficulties imposed by the recursive dynamic nature of the system can be circumvented to some extent by decomposing the system. By conceiving of crop rotations that preserve soil quality and confining production alternatives to only such rotations, one can split the recursive dynamic computational procedure into two steps:

Step 1: Use the PCP model to identify for a given soil, alternative crop rotations that provide a stationary state for the soil (as defined below)

Step 2: Select a set of crop rotations that optimize the production plan given an objective function.

Though such a procedure is not fully globally optimal to the extent that the choice is confined to a subset of crop rotations, it does provide a much more meaningful subset of production strategies than can be obtained through pure simulations as described in the previous section. Moreover, crop rotations are widely used in agricultural practice and much expert knowledge can be brought to bear on the process of generating alternatives.

### 4.1. Stationary Crop Rotation

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

$$z_l^T = \bar{F}(z_l^0, z_l, \ldots, z_l^{T-1}, u_l^1, u_l^2, \ldots, u_l^T, \xi^*_l, \xi^*_l, \ldots, \xi^*_l, p_l) = z_l^0$$

We use this notion of stationarity 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,...,T is $z_l^{i-1}$ and 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 in Table 1, the actual state of subregion l remains the same as can be see from Table 1.

**Table 1.**

| Time<br>Subregion | t=1 | t=2 | ... | t=i | ... | t=T |
|---|---|---|---|---|---|---|
| 1 | $z_l^0$ | $z_l^1$ | ... | $z_e^{i-1}$ | ... | $z_l^{T-1}$ |
| 2 | $z_l^1$ | $z_l^2$ | ... | $z_l^i$ | ... | $z_l^1$ |
| . | . | . | . |  | . |  |
| . | . | . | . |  | . |  |
| . | . | . | . |  | . |  |
| T | $z_l^{T-1}$ | $z_l^0$ | ... | $z^{l^{i-2}}$ | ... | $z_l^{T-2}$ |

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 referred 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 $z_l^0$:

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

where n is the index of a crop rotation.

The production accounting relationships for the system can be described as follows:

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 with irrigation. Assume also that only one production technology is used for each crop rotation. Denote by $y_n^{1,l}$ the 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:

$$\sum_{l} k_l^{\nu} g_l = b^{\nu}$$

Animal production of type m:

$$\sum_{l} \alpha_{lm} g_l = a_m.$$

## 4.2. Decision-Making Problems Using Stationary Crop Rotations

In principle, the formulation of the crop rotation problem will be complete if the problem of choice of the decision variables is formulated.

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 imbalances 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 auxiliary 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' judgements with regard to the uncertainty in weather conditions. Table 2 illustrates the description of technologies for a crop rotation.

**Table 2. Description of technologies for a crop rotation.**

| | | | | |
|---|---|---|---|---|
| Production output | $y^1$ | $y^2$ | $\ldots y^t$ | $\ldots y^{T_n}$ |
| Crop index | $c_n^1$ | $c_n^2$ | $\ldots c_n^t$ | $\ldots c_n^{T_n}$ |
| Weather | $\xi^1$ | $\xi^2$ | $\ldots \xi^t$ | $\ldots \xi^{T_n}$ |
| Amount of fertilizers | $N^1$ | $N^2$ | $\ldots N^t$ | $\ldots N^{T_n}$ |
| Amount of fertilizers | $P^1$ | $P^2$ | $\ldots P^t$ | $\ldots P^{T_n}$ |
| Amount of fertilizers | $K^1$ | $K^2$ | $\ldots K^t$ | $\ldots K^{T_n}$ |
| Amount of fertilizers | $O^1$ | $O^2$ | $\ldots O^t$ | $\ldots O^{T_n}$ |
| Amount of fertilizers | $W^1$ | $W^2$ | $\ldots W^t$ | $\ldots W^{T_n}$ |
| State | $z^0$ | $z^1$ | $\ldots z^t$ | $\ldots z^{T_n-1}$ |
| Erosion | $e^0$ | $e^1$ | $\ldots e^t$ | $\ldots e^{T_n-1}$ |

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

$$f_n^1 = \frac{1}{T_n}\sum_t N^t, f_n^2 = \frac{1}{T_n}\sum_t P^t, f_n^3 = \frac{1}{T_n}\sum_t K^t,$$

$$f_n^4 = \frac{1}{T_n}\sum_t O^t, \upsilon_n \frac{1}{T_n}\sum_t W^t,$$

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:

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

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

Water demand:

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

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 the optimization problem.

Given production and environmental targets Y, A and E

$$\max_x \left[ \min \left( \min_{j \in J} \frac{y^j(1-d^j)}{Y^j}, \min_m \frac{\alpha^m}{A^m}, \frac{E-e}{E} \right) \right]$$

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

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

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

$$\max_x \rho \rightarrow$$

s.t.

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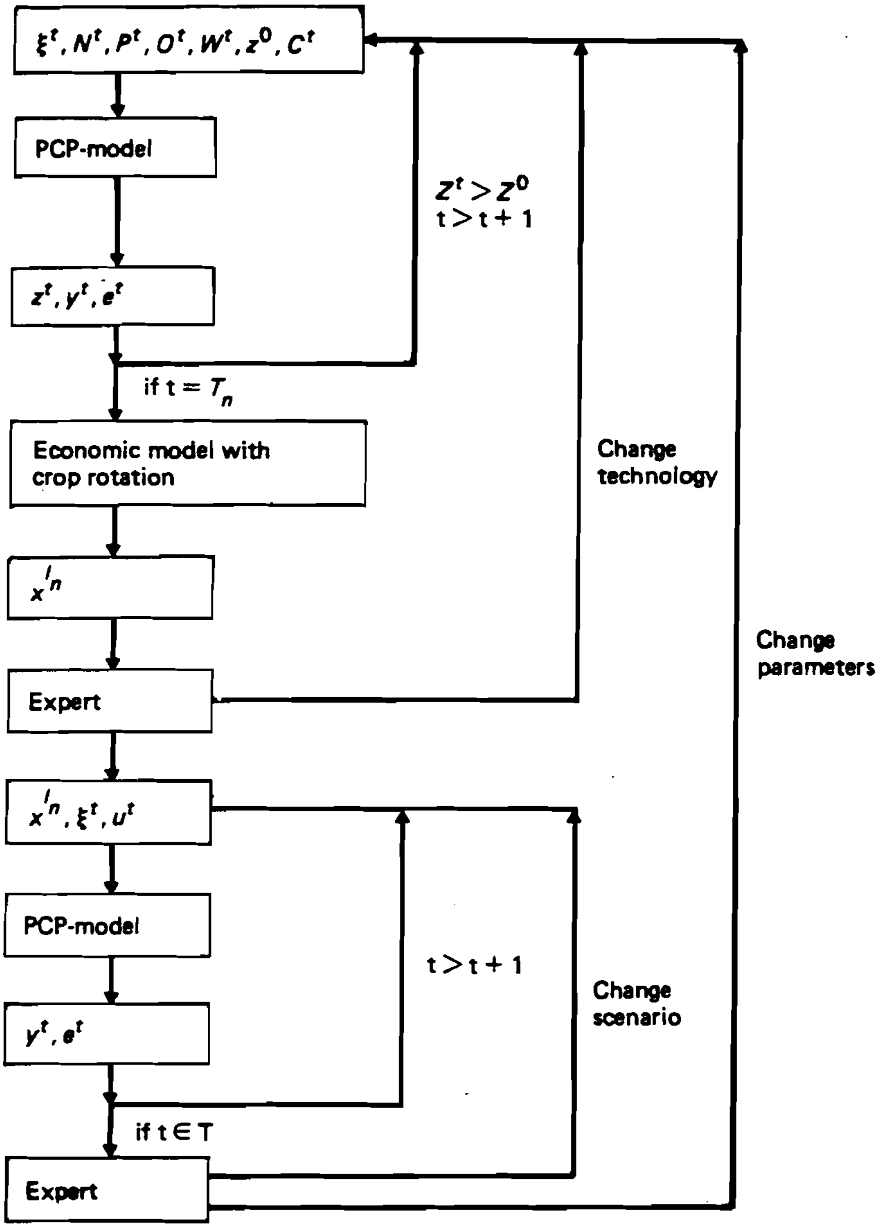
*Amounts of water may not be fixed, but obtained as water demands of crops.

$$y^j(1-d^j) \geq \rho Y^j, j \in J_1,$$
$$\alpha^m \geq \rho A^m, m=1,2,3,4;\ e \geq \rho E$$

plus constraints (6)-(8).

After having obtained the solution of the auxiliary crop rotation problem we should perform its evaluation. This can be achieved by solving the PCP model 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:



## 5. One Stage Monocrop Model – A Further Simplification as an Aid to Experts

The procedure outlined in the previous section is computationally feasible, but would require considerable inputs from experts into identifying, evaluating and assessing relevant crop rotations. In order to provide a feel to the experts on how the system actually functions, it was felt worthwhile to use the procedure for only one crop, rather than a crop rotation, for a number of years. This monocrop simplification thus differs from the basic recursive dynamic system in that in the recursive dynamic global optimal framework, the decisions regarding what crop to grow with which technology on which land, are taken every year. In the present simplification, it is assumed that the same crop will be grown on the land for T years. The choice of what crop to grow is done only for the entire period of T years as in the crop rotation model of the previous section.

Clearly, this is a much less realistic framework than the crop rotation approach. Yet such a simplification is easier to implement and 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 representative years $t \in T_1 = (t_1,\dots,t_\nu)$ together with the corresponding frequencies (probabilities) $p_p^t, q \in Q$ of their occurrence, representing experts' judgements with regard to the uncertainty in weather. The problem considered was that of allocating resources for 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:

$$\begin{aligned} z_l^1 &= F(z_l^0, u_l, \xi_l, p_l) \\ y_{l,ch} &= \Psi(z^{0_l}, N_l, P_l, K_l, O_l, W_l, c_h, \xi_l, p_l) \\ e_l &= \Phi(z^{0_l}, u_l, \xi_l, p_l) \end{aligned} \tag{9}$$

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:

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

for the average production for distribution q.

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

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

with $\{Y^j\}$ being a given vector of crop production, $\{A_m\}$ being a given vector of animal production, E being a given 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:

$$\sum_{h} s_{ch}^{1,l} \leq S^{1,l}$$

for subregion l:

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

for resources:

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

for fertilizers:

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

for water:

$$\sum_{ch} \nu_{ch} s_{ch}^{1,l} \leq W^{l}, l \in L,$$

$$\sum_{j \in J_1} \beta_j^{\nu} d^{t,j} + \sum_{j \in J_2} \gamma_j^{\nu} \sum_{l,c,h} (s_{ch}^{1,l} y_{l,ch}^{1,t,j} + s_{ch}^{2,l} y_{l,ch}^{2,t,j} \geq \sum_{i} k_i^{\nu} g_i, t \in T_1$$

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

This problem is reduced to the following linear programming problem:

$$\rho \rightarrow \max$$

$$y_q^j \geq \rho Y^j$$

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

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 this allocation pattern we can determine the corresponding allocation for crop rotations:

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

with $\alpha_c^n$ 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 would not be justified to make any conclusions with regard to the dynamics of the agricultural production and resource system as the choice set of cropping activities is seriously curtailed by assuming that the same crop will be grown for t years on a given piece of land.

The procedure for performing the analysis using the monocrop model can be

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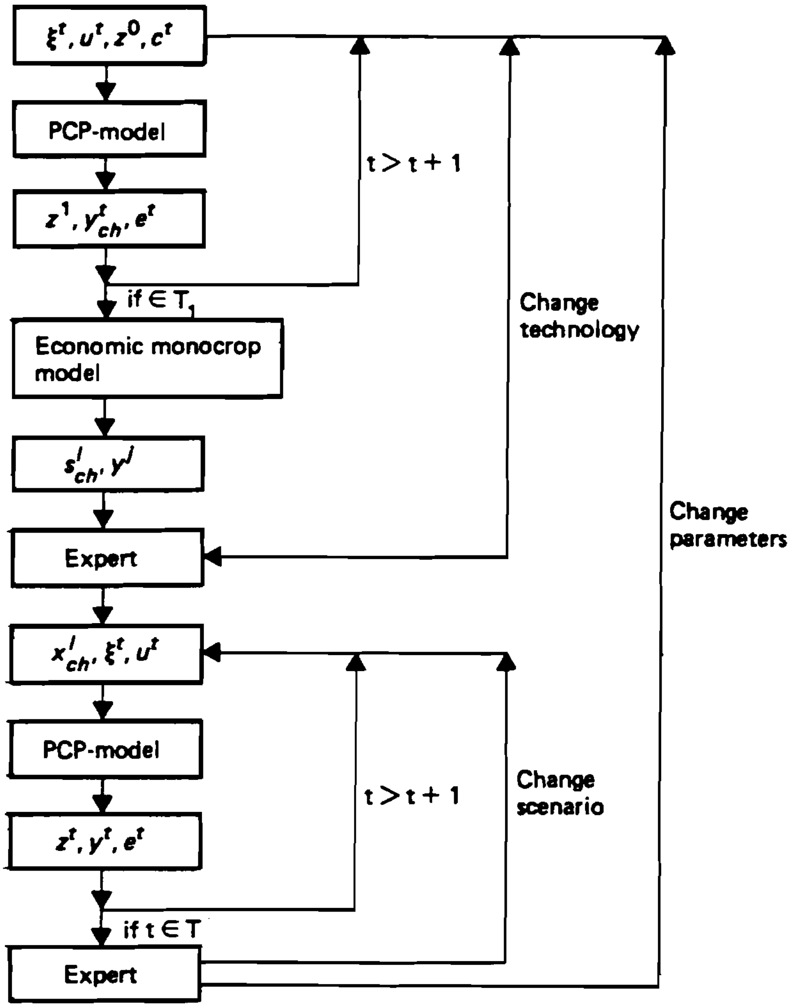
*Bounds SL and SU in constraints (10) are chosen to provide for the existence of a solution to this system.

depicted in the following form:



## 6. 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 section 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 irritation. 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.

## 7. Conclusions

We have described alternative ways to simplify the problem of finding optimal strategies for sustainable agriculture and make it computationally practicable. Though full optimality is sacrificed in the suggested procedures for exploring alternative strategies, the simplifications are done based on notions of agronomic realism of cropping patterns. Thus, one may expect that the loss of optimality may not be serious. This, however, is not established by us. One of the procedures searches for sustainable cropping patterns for each soil class separately in the first stage and an optimal cropping pattern for all the soil classes are selected in the second stage to meet economic objectives. Some of these procedures are applied in the Stavropol case study and have been found to be practicable.

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# THE REGION MACROMODELS: USE AND SOFTWARE

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Research workers at the Stavropol Research Institute of Agriculture and Computing Center of the USSR Academy of Sciences aim to elaborate the regional system of agricultural production in the Stavropol region, both present and prospective, as well as to provide concepts and methods of elaboration of agricultural production systems for different regions of the country. Finally, it is essential to work out a hierarchical system of aims, using systems analysis methods and by elaborating the system of models, methods of their use, and software for the realization of these aims.

The whole complex of existing macro- (economic) or micro- (physical) models may serve as a prototype of the system of models. Let us consider the block of macromodels, i.e. region-describing models. The possibility of stand-alone runs is one important requirement for developing separate blocks and models comprising the system. These models are developed by different groups of specialists at different times, which is why the off-line regime must be envisaged for blocks and separate models at the initial stages of investigation. Parameters and controls interconnecting a particular model or block with other models in the system are then evaluated by the experts judgements method. At this stage the models and initial data are debugged and the main features and qualitative characteristics of the model studied. Of particular interest is the possibility of obtaining important, though approximate, assessment at the initial stages of the object behavior by the off-line use of a model or several models. Thereby, the aims of the investigation, for which the models were intended, may be realized to a first approximation.

Our objectives in developing the system of macromodels were: the assessment of prospects for farm production development in the region; the determination of rational crop and animal production structures; the assessment of possible feed supply for livestock farming; the determination of a rational acreage of land under irrigation; the determination of a strategy for the use of material and natural resources; the determination of a rational distribution of agricultural production by different soil zones.

To attain the objectives mentioned above, we chose the linear, static model approach. It should be stressed that the object of study is a complex dynamic system with its own distinctive features, such as a multiattribute and hierarchic character, and the uncertain or stochastic nature of a number of main factors and parameters (crop yield capacity, precipitation, etc.). Therefore, the question of whether or not linear models are valid for describing the object is far from trivial.

There are two sorts of approaches to linear programming models. The first, expressed here in a slightly exaggerated manner, is that a decision made with the use of linear models is the ultimate truth, since the computer takes all the factors into consideration. The second is that linear models provide us with poor results and we must use these only because nothing better is available with the present level of software and data.

The first opinion is rather typical of economists who have just begun to use computers, while the second is expressed by some mathematicians. Our approach may be briefly described as follows. A single run of a linear model provides quite a limited amount of information. Only multiple, numerical experiments with the use of a system of models, conducted in an interactive mode under scenarios, enables a realistic study of properties of the object and of the main trends.

Studies with farm-production linear models, which are being undertaken at the Computing Center of the USSR Academy of Sciences concentrate on working out methodical concepts of linear model applications and on developing software in order to facilitate numerical experiments with a set of models. The experience gained has allowed for the realization of macromodels for the Stavropol region in a short period.

Three types of linear models of agricultural production allocation have been realized. The first model is intended for analyzing the expediency of application of different crop production technologies. In the model, technologies are characterized by sets of inputs (labor, electricity, fuel, fertilizers, herbicides, machinery working time) and by average crop yield capacities. The latter differ from different types of soil.

Among the basic relationships in the technology model are the constraints, in terms of crop area by type of soil, and resources used, as well as bilateral inequalities which set the upper and lower limits – each soil-type acreages for each crop. The latter deserve particular specification. First, they reflect the idea of rational land distribution by crops, and second, they account for crop rotations. Fields are allotted to crop rotations, not to individual crops; so there exist fairly complex relationships between acreages devoted to different crops. The problem of determining these relationships may be solved numerically – this requires a lot of computations, while the direct introduction of crop rotations into a technology model results in excessive model dimensions. Therefore, indirect descriptions are employed. In a technology model such a simplification is quite admissible, since the model is primarily intended to enable the choice of a set of preferable technologies that is rather stable with respect to changes in the model parameters.

The second model is a crop rotation model in which acreages according to different crop rotations are the variables. It is assumed that only one technology is employed for the cultivation of each crop on each soil type. The crop rotation model is intended to determine the best cropping pattern.

The third model is intended to assess the economic effectiveness of irrigation. The model, dealing with irrigated and nonirrigated land separately, sets limits in terms of the amounts of water available. The model envisages no choice of technologies, i.e., there are no alternatives. Crop rotations are taken into account implicitly, as in the first model. The third model is aggregated for a set of crops. It is of a rather small dimension, which enables it to be used for determining general trends in the development of a region.

Let us now consider the methodology of computer runs. This chapter deals only with general schemes for the use of linear static models in describing dynamic, multicriteria, and stochastic systems.

Usually the object is assessed by an expert who determines some general characteristics. Let us assume these characteristics to be represented by a linear aggregate of indices. Use of such a model may be conditionally divided into three stages. The first and the most protracted is the information debugging stage. At the second stage optimization and simulation runs are performed. The results of optimization is the determining of linear programming problem solutions corresponding to chosen criteria.

There are two methods for modeling the developing system. The first is to assess the production capacity with the increase in resources available. The second is the method of scenario experiments. In this case the analysis of some projects and measures result in altered model structures (new canals, processing plants, irrigation systems, etc., put into operation).

Assume that a specific year is chosen from the planning interval. Pareto-optimum surfaces for this year are constructed in the space of indices (a point in the space of indices is called a Pareto-optimum point if there exists no other point that is not inferior to this point in all indices values and superior to it in at least one index value). Relationships between indices are investigated with several sets of weather conditions. Assume that an expert or a decision maker finds such a point on the Pareto-optimum surface, which satisfies all the characteristics. Thus, he obtains a set of controls that provide the desired indices values under the given weather conditions. Now, with the aim of taking stochastics into account, this set of controls is run for different variants of weather conditions. The allocation is considered appropriate provided all the characteristics remain acceptable to the decision maker. If not, a new Pareto-optimum point must be found and the process repeated.

Finally, at the third stage of investigation, a decision maker employs his knowledge of the object, gained from the use of the models and from his instinct, to fine-tune the resultant set of controls and again investigates these controls in the simulation model for different weather conditions.

# USE OF MATHEMATICAL MODELS FOR ASSESSMENT OF THE IMPACT OF AGRICULTURE ON THE ENVIRONMENT

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Growth in the human population of the world and the demand for agricultural products has brought about an expansion and more intensive use of agricultural land. Intensification of agriculture involves the use of new technologies, erosion-preventive practices, and new methods of soil tillage. It also brings about complex problems of environmental impact, such as the pollution of water reservoirs with chemicals and fertilizers from agricultural fields, with the resultant deterioration in water quality, wind and water erosion of soil, increased salinity and waterlogging, and deterioration in soil structure and fertility.

As to the quantitative assessment of the impact of agriculture on the environment, mathematical models are an important tool for investigation. A good number of mathematical models are currently used outside the USSR for the quantitative assessment of findings of studies of the productivity of agricultural land. Haith [24] and Shvytov and Vasilyeva [52] have reviewed a number of such models. Problems of the interrelationships between agriculture and environment have been analyzed by Golubev et al. [21].

Some models are dealt with in this chapter. Mathematical models concerning the quantitative assessment of agricultural impacts on the environment have been extensively developed since the 1970s, many in the USA. It should be noted that problems of the interaction between agriculture and environment exist in all countries, and that they tend to gain in significance every year. Thus, intensification of agriculture leads to the activization of soil erosion, salinization, and waterlogging processes, which, in their turn, bring about degradation of the agricultural system and a decline in productivity.

The models differ in structure and aims of investigation, as well as in the degree of universality relative to input data and coefficients employed.

There are many possible ways of classifying the models. As a rule, classification is based on differences in the level of investments (local, regional, national, global), in the aims of investigation, which determine the model output characteristics, in the model structures, in the investigation time interval, and in the time step and mathematical tools. Many a model describe the local level (field level) of investigation [1, 4, 8, 9, 15, 16, 17, 18, 19, 22, 23, 24, 30, 31, 33, 34, 35, 40, 41, 47, 51, 56, 57, 58, 62]. Some models view the problem of crop yield from the viewpoint of agricultural impact on the environment at the "watershed" level (intermediate between field and region) [6, 7, 10, 26, 29, 36, 49, 55, 60, 63, 64]. Optimization processes with the use of linear and dynamic programming have been used for decision making at the regional and national levels. Attempts are currently being made by IIASA specialists to construct and unite national agricultural models [43].

Let us consider mathematical models of different levels, starting at the field level. The definition of an agricultural "field" is based on the notion of uniformity from the point of view of soil structure, uniform rainfall distribution in the area, type of cropping system, and crop production management. The field level models [4, 15, 16, 34, 35, 40, 41, 51, 62] have been constructed with the use of differential equations. Such an approach enables mathematical solutions in the analytical form. Six models [16, 33, 34, 35, 40, 51, 62] are used for the quantitative assessment of nitrates downflow or of the disappearance of phosphates from fields into the ground water. Model [4] deals with the joint migration of nitrates and phosphates, while two models [15, 41] deal with the same problem concerning pesticides. All models except for one, [16], demand the adjustment of parameters. Model [45] reflects the production of agricultural produce (plant biomass) as dependent on the concentration of nitrogen fertilizer. The model describes the mineralization of organic nitrogen, the nitrogen uptake by plant roots, and the biological growth of plants as being dependent on nitrogen content in the soil, mean air temperature, and moisture content in the soil. The processes of nitrogen transformation in the soil are dealt with in model [50]. Model [14] deals with the migration of nitrates into ground water at the "watershed" level. Problems of the migration of salts in the soil (at the "watershed" level) and of the process of salt transition from the soil into ground water are described in model [32]; model [38] deals with the joint migration of nitrates and other salts into ground water. The last two models require adjustment of the parameters.

Models [15, 16, 32, 40, 51, 62] present a comparison of model and estimated data. Models [1, 5, 8, 17, 18, 19, 22, 23, 31, 46, 47, 48, 56, 57, 58, 61, 66] are discrete simulation ones, seven of which describe the process of the migration of nitrates into ground water. Models [1, 22, 47] are notable for describing gently sloping fields. Model [1] is the only model that does not require adjustment of the parameters. Models [18, 58] are based on empirical equations and hence many of their parameters do not require adjustment. Models [18, 20, 57, 58] have not been tested in practice.

Model [57] includes the hydrological balance, but it does not account for the loss of nitrates with water runoff, accounting only for the penetration of nitrates into ground water. Model [19] is one of the first transport agricultural models. It has a hybrid structure, since the discrete simulation approach is employed in the model along with differential equations. Ten discrete simulation models have been constructed using a hydrological scenario as the basis, water being the basic component of the system under consideration. The hydrological component includes many physical processes, such as rainfall infiltration, soil saturation with water, formation of water flow on the field surface, water penetration into the root zone, and evaporation through soil and plants. The output data for the hydrological components determine water erosion processes, since exposure to rainfall results in a chipping of soil particles, and the rain flow on the field surface washes these particles from the field.

Model [59] consists of two components: hydrological and chemical. In addition to natural precipitation, the former takes into consideration irrigation, moisture penetration into the root zone, and water evaporation by plants and soil; the latter takes into account fertilizer application, nitrogen brought with precipitation, nitrogen disappearance with the harvested crop, and the leaching of nitrates.

Only four models [23, 24, 31, 56] include three system components: hydrological, erosion (sedimental), and chemical. Models [31, 56] have a more complex structure. The most complex is the CREAMS model (Chemical Runoff and Erosion from Agricultural Management Systems) developed by USDA specialists, in which the authors made extensive use of physical laws and regularities. In certain cases empirical correlations and coefficients determined on the basis of statistical data obtained from hundreds of observations were taken into account. Computations concerning soil erosion were conducted according to the Soil Loss Universal Equation, developed in the USA [68]. In the authors' opinion, the model does not require adjustment of the parameters. It should be noted that this model requires a great body of input data, and difficulties in obtaining these data partly impede its practical use, so the model has not yet been run using actual data.

The CREAMS model has been implemented on the IIASA computer and the researchers from Finland, FRG, Poland, Sweden, UK and USSR had operated this model to analyze an agricultural policy on the field level. The results of these investigations have been published [69].

Models describing the interactions between agriculture and environment in terms of the management options in the agrosystem belong to the third type [3, 5, 11, 25, 37, 39, 42, 44, 48, 54, 66, 67]. As a rule, such models deal with the agricultural production process from the viewpoint of economic return. Mechanisms of linear and dynamic programming are the basis for solving problems of the third type. Problems involving management of the impact of agriculture on the environment are described in the models by limitations imposed on the problem, which may manifest themselves as amounts of fertilizer and pesticides applied, soil erosion, salinization, water pollution, etc. Management (optimization) models cover extensive studies at different scales from field (a farm) to national level.

Nine models at the field level [12, 13, 25, 37, 39, 46, 53, 54, 65] analyze everyday, routine farmers' field work. Assessment of soil erosion processes using the Soil Loss Universal Equation is a feature common to these models. Only two models [12, 13] consider the process of field depletion of nutrients along with soil erosion. the authors of the last two models came to the conclusion that the processes of depletion and soil erosion are of a different nature, so methodically it would be wise to employ different equations for describing the control and management of these processes.

In model [65] variants of the development of 12 farms in the USA (Pennsylvania) have been simulated and analyzed to assess the impact of soil conservation programmes worked out by the Soil Conservation Service. Three variants have been run:

(1) Soil conservation

(2) Use of soils for agricultural purposes without any limitations

(3) Use of soils with limitations imposed on the loss of soil due to erosion.

The authors view the soil conservation programmes as ineffective.

Model [47] analyzes nitrogen-fertilizer application from the viewpoint of minimization of the potential water pollution by chemicals brought into water reservoirs by runoff from agricultural fields. Model [53] is based on a regression equation that contains experimental coefficients. The model offers an economic assessment for nitrogen-fertilizer application and the resultant chemical pollution.

The majority of nine models at the "watershed" level [3, 5, 11, 42, 44, 48, 61, 66, 67] view crop yields with regard to limitations imposed on soil erosion and the disappearance of sediments. In addition, model [42] includes the process of leaching of nitrates. In model [11] computations of soil erosion are related to nitrate contamination from the watershed. In this model the process of soil erosion is simulated, while the values of contamination with nitrates are derived by the multiplication of soil erosion quantitative values with a certain constant. For computations of the soil salinization process the mechanisms of dynamic programming is employed, models [5, 48].

The national and regional levels of investigation are represented by a number of models worked out in the USA, the most well-known being those developed under the leadership of the Director of the Agricultural Development Center, E.O. Heady [2, 27, 28]. They are extensively used in practice to verify the decision-making process at various levels, including governmental. In particular, these models are employed by the National Food Commission for the analysis of the USA agricultural policy. The National Water Resources Committee, Environment Protection Agency, National Water Use Commission, and other bodies in the USA used to employ the models, worked out by specialists of the Agricultural Development Center, for the elaboration and verification of certain agricultural strategies.

## Conclusion

The trend outside of the USSR to assess the environmental impacts of agriculture has been extensively developing in the last decade. All the existing models fall into two groups. The first one comprises the so-called "transport models", describing the removal of chemical elements from the fields; the second includes agricultural management (or optimization models, with the restraints imposed on the agrosystem taken into account.

In the first group three types can be distinguished. The first type describes primarily the downward migration of chemical elements. The solution may be expressed in an analytical form, but the majority of models call for model parameters to be adjusted, and hence their practical implication can encounter certain difficulties. Such models serve mainly methodological purposes and facilitate better understanding of the agricultural situations as a whole. The second type – discrete simulation models – are most common and are based on water balance and the balance of chemical elements. Some of them do not call for a great body of input information, with their value proven. However, in such cases it is desirable to verify the numerical model parameters prior to model implementation. The third type includes the so-called "functional" models based on empirical equations using the minimum amount of input data. They enjoy a widespread application due to the simplicity of computations. However, the coefficients and parameters used are determined by concrete data and in principle have to be verified for the given regions.

In management models falling into the second group, the components related to agricultural economic activities are better developed than those related to the environment. The latter are mainly confined to constraints on soil erosion and mineral fertilizer application. For the estimation of soil erosion at various levels the Soil Loss Universal Equation is widely used.

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