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Technological Transformation in Agriculture: Resource Limitations and Environmental Consequences. A Status Report on the IIASA Research Program

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TECHNOLOGICAL TRANSFORMATION IN AGRICULTURE: RESOURCE LIMITATIONS AND ENVIRONMENTAL CONSEQUENCES.

A STATUS REPORT ON THE IIASA RESEARCH PROGRAM

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FOREWORD

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

As a part of the research activities investigations of alternative paths of technological transformation in agriculture in the context of resource limitations and long term environmental consequences are being investigated. The purpose is to identify production plans strategies which are sustainable. The general approach and methodology developed at IIASA for this investigation is being applied in several case studies on the regional level in different countries with the help of collaborating institutions. 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, all these case studies address certain specific questions so as to permit a comparative analysis.

This paper describes the status of the study.

Kirit S. Parikh
Program Leader
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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.

* 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.

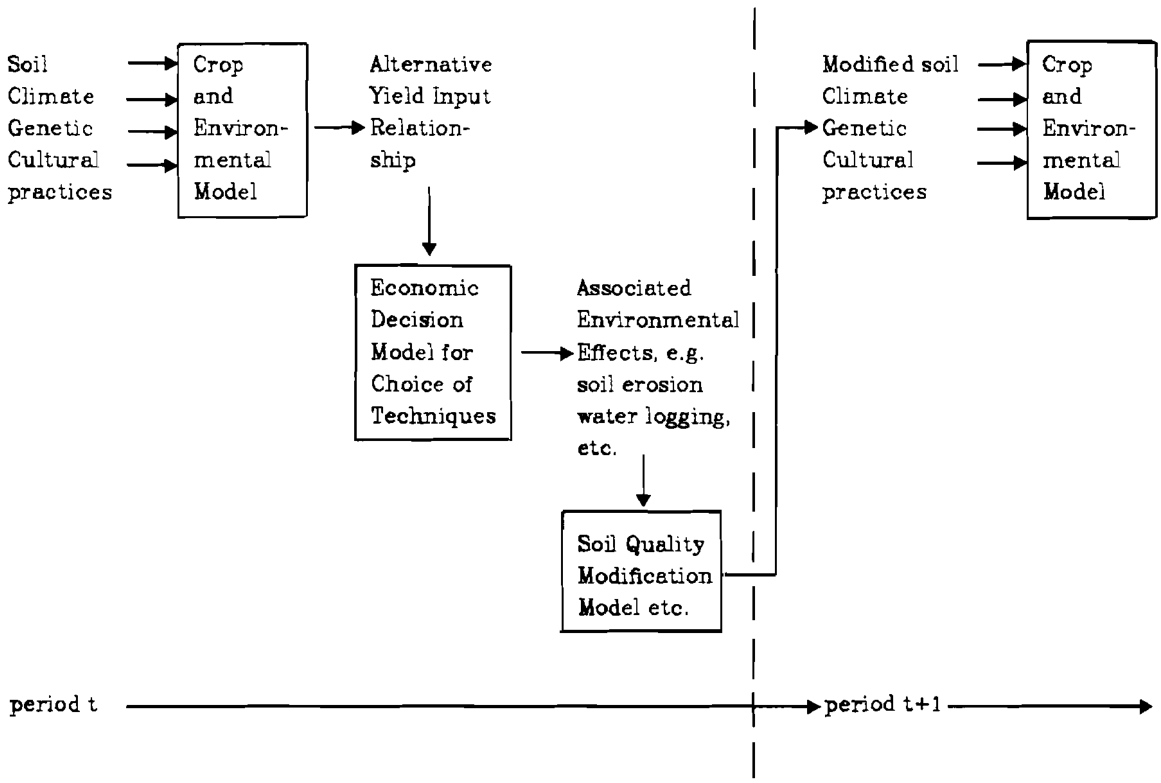

Figure 1. Schematic diagram of analytical elements

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

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	$\{Q_t\} = [u]\{x_t\}$
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

		Activities									
		soil 1							soil 2	...	soil s
	Inputs	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.

Operation	Constant σ_0	Soil 1 dummy σ_1	Soil 2 dummy σ_2	intensity of operation γ	vintage* of tractor β	tractor horse power α	DF	$\bar{R}^2$	F
	Coefficent of								
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 Operation	-4.892	-.199	-.066	-.017	.079	.561		0.69	70.6
	(-6.37)	(-4.43)	(-1.49)	(-.32)	(3.40)	(10.0)	151		
Precultivation Operations	-4.948	.466	.260	.256	.016	.889		0.64	38.4
	(-4.73)	(5.58)	(2.43)	(2.28)	(.81)	(8.17)	100		
Row Cultivation	-4.156	-.141	0.83	.330	.0056	1.14		0.53	24.0
	(-3.98)	(-1.49)	(-1.47)	(3.03)	(.31)	(6.79)	97		
Maize Harvesting	-6.03		-2.65	-.554	.040	.819		0.42	11.7
	(-4.62)		(-2.30)	(-1.73)	(.92)	(2.23)	55		

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

Values in ( ) are t-values

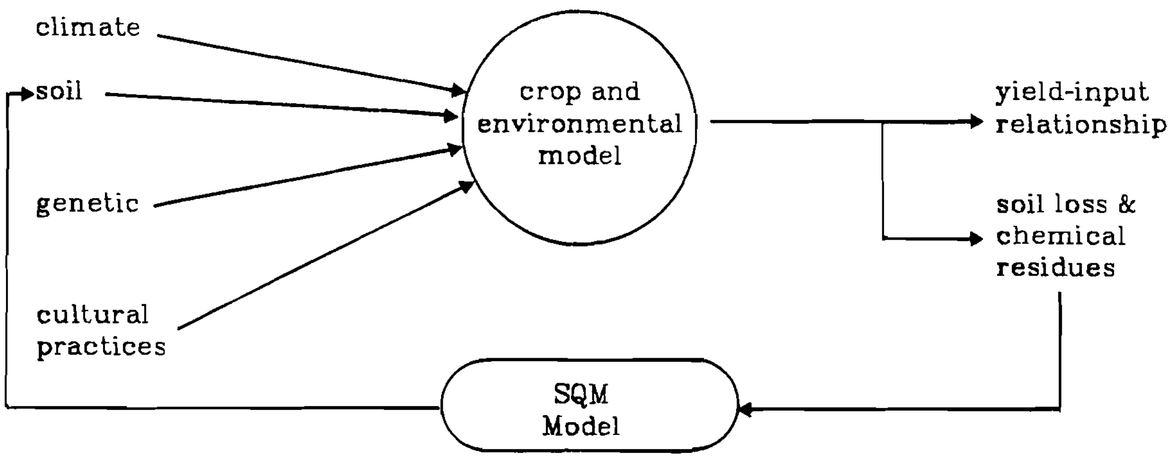

Figure 2. The Crop and Environmental Model in a dynamic context

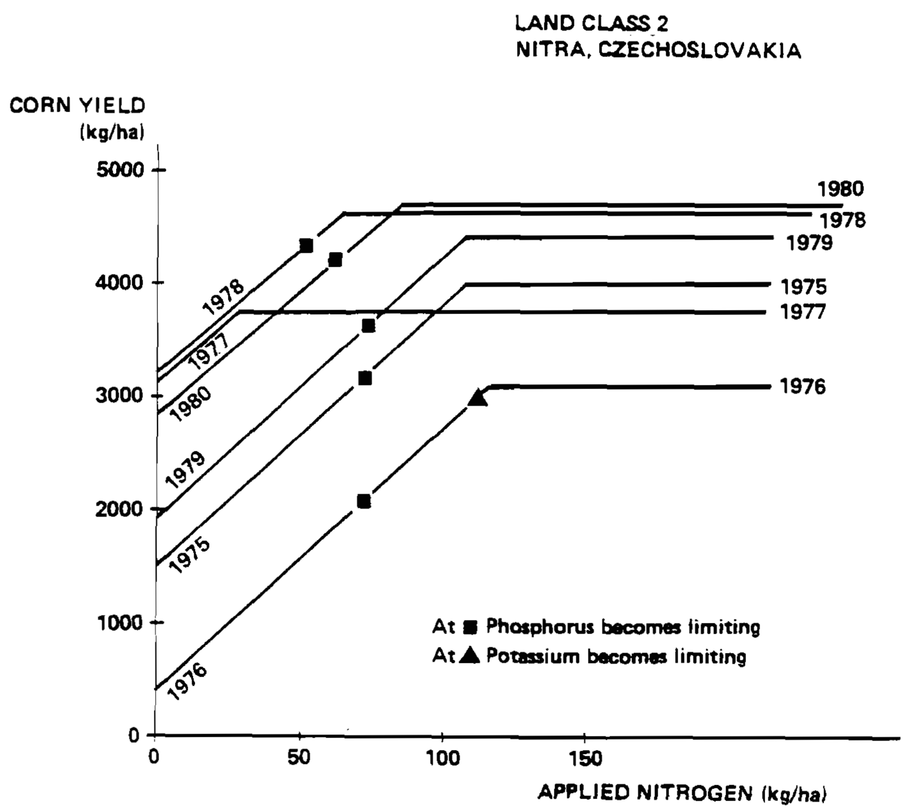

Figure 3a. Yield response to fertilizers of corn under climates of different years.

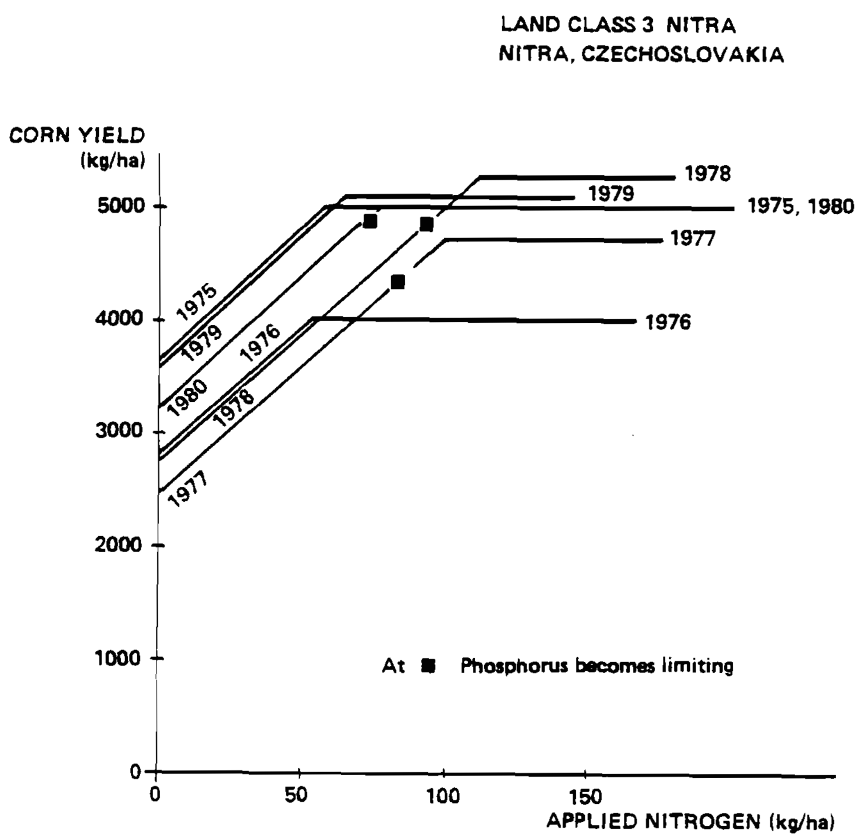

Figure 3b. Yield response to fertilizers of corn under climates of different years.

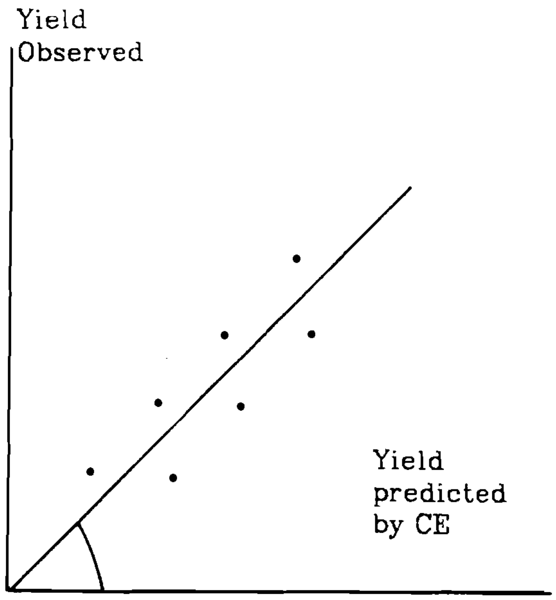

Figure 4. Validation of the crop and environmental model.

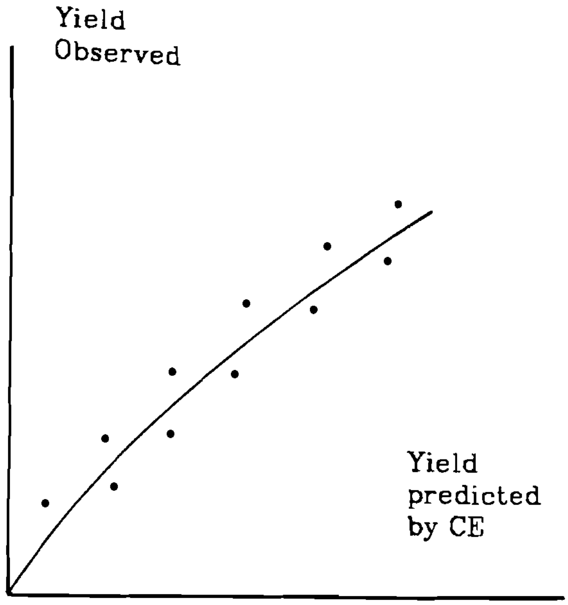

Figure 5. Calibration of the crop and environmental model.

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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