FOOD PRODUCTION AND AGRICULTURAL MODELS: BASIC PRINCIPLES OF DEVELOPMENT

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Summary

The present-day industrial technologies of crop cultivation to obtain food products have reached their development limit and now are inconsistent with the problems of environmental preservation. Therefore, consideration of geophysical factors and improvement of management quality acquire great significance. Mathematical models presented in this paper are essential for solving this problem. Different approaches to model classification in agrobiology are considered. Much emphasis is placed on theoretical models, i.e. a mathematical description of photosynthesis and related processes providing for solar radiation utilization and CO_2 absorption and a description of processes specifying organic matter dynamics in soil, which close a biospheric carbon cycle.

Data are presented on the current complete models of productivity, such as EPIC,

CERES, CROPGRO, etc. (main theoretical principles, input and output information, peculiarities of application). The Decision Support System for Agrotechnology Transfer (DSSAT) and other computer systems of realizing information technologies in agriculture are considered. The problems of comprehensive dynamic models applied to diagnosing weather conditions, operative yield forecasting, production process management by regulating water regime, assessing soil and climate conditions are treated. Model application for assessing consequences of a global greenhouse effect on agriculture is analyzed in particular. Experimental support of mathematical simulation, application of mathematical theory of planning of many-year experiments in agrobiology, and their optimization taking account of hydrometeorological data are treated.

1. Introduction

The present-day industrial technologies of crop cultivation to obtain food products have reached the saturation limits in the following aspects:

- ecological (environmental contamination and suppression of its self-regulation mechanisms);
- energetic (exponential growth of consumption of irreplaceable (non-renewable) energy per each extra production unit);
- productive (further increase of nitrogenous fertilizer doses and irrigation standards results in the suppression of growth and development of cultivated crops and microorganisms, decreases the agrocenosis stability to abiotic and biotic stresses).

Therefore, for a steady growth of agricultural food production the external environment factors (solar radiation income, active temperature sums, air drought, frosts and etc.) acquire great significance; optimization of these factors by technogenic means is impossible and economically not viable. The positions are strengthened of those who believe that the intensification process of crop production should be finally directed to realization of the main role of cultivated crops, i.e. utilization of solar energy and other inexhaustible sources of the external environment with a view to achieve sustainable crop growth without losing quality as well as increase humus content specifying energy potential of soil fertility.

In this case the strategies of Nature (increase in the total primary productivity) and of sustainable agriculture development aimed both at the increase in a pure ecosystem productivity and the organic matter accumulation in soil are not in conflict; on the contrary they are in mutual harmony. So, the simulation of two natural processes is of great fundamental concern for agronomy:

- photosynthesis and the associated physiological processes in green plants which contribute to utilization of the radiant solar energy, absorb carbon dioxide from the atmosphere and mineral nutrition elements from soil, and synthesize the organic substances, i.e. the base for the whole life pyramid on the Earth;
- organic matter destruction processes in soil and on its surface, which close the biospheric cycle of carbon, release the mineral substances necessary for plants and characterize the level of soil fertility.

The dialectic unity of the two global opposite processes (photosynthesis and mineralization) actuates the biological cycle of not only carbon, but also of other biogenic elements (nitrogen, phosphorus and etc.). The models of these interrelated mechanisms behind biosphere stability support can be conventionally called as the "green" and "brown" machines. Let us consider the principles of model classification.

2. Classification of Agricultural Models

There is a lot of ways for classifying the diverse mathematical models in various fields of knowledge. Consider the main principles used in their development without preference to any of them.

2.1. Empirical and Mechanistic Models

The main objective of empirical models is to describe and the main objective of mechanistic simulation is to explain the described one. The developer of an empirical model always remains within a single level (say, *i*-th level) of organizational hierarchy, where he/she derives the equations connecting parameters inherent solely to a given subsystem level . The developer of a mechanistic model attempts to describe the behavior of the *i*-th level subsystem parameters using more intimate i –1 level subsystem parameters. In this case the description of level i – 1 subsystem can be purely empirical as well as mixed, i.e. empirical-mechanistic and hence, include the subsystem parameters of level i – 2 and lower. Finally, any mechanistic model is deeply rooted in empiricism. The sense of a concept of hierarchy level is explained by an example typical of agriculture:

Level	Description
i+1	Totality of organisms (crops, herd)
i	Organism (animal, plant)
i-1	Organs
.....	Tissues
.....	Cells

So, mechanistic models provide for the relationship between the subsystems at different levels and, hence, allow *a priori* information to be taken into account more fully than in case of an empirical (one level) approach. Not touching upon advantages and limitations of empirical and mechanistic approaches, it is to be noted that positive results are often reached in their judicious combination within a model.

2.2. Static and Dynamic, Deterministic and Stochastic Models

A static model is a mathematical construction obviously not involving a time variable. When simulating the impact of hydrometeorological conditions on crop formation a problem of multidimensionality arises. The crop response to weather conditions varies in the process of crop development. To take it into consideration, the vegetation period is divided into a large number of time intervals that increases the number of independent variables and, consequently, decreases the accuracy of model coefficient assessment.

In dynamic models the conventional form of representation is a differential equation such as $\frac{dy}{dt} = f$, where t is time, y is the system's characteristic (e.g. agrocenosis biomass) and f is some function of y, t and other parameters, such as hydrometeorological variables. The transition to dynamic models gives some advantages, e.g. it allows us to solve the problem of multidimensionality in developing "Weather-Yield" models.

A distinctive feature of a deterministic model lies in the fact that any forecast (yield, precipitation amount) is formulated as a number and not in the form of probability distribution. In some cases it is quite reasonable, however, when dealing with quantities, the values of which are hard to predict, a deterministic approach may happen to be unsatisfactory. The greater the uncertainty in system behavior, the more effective is a stochastic model. The stochastic elements are introduced to account for inhomogeneity in biological objects (e.g. plants in crops) as well as for spatial inhomogeneity of plant habitat (distribution of humus, soil moisture in a field and etc.). The stochastic elements are also introduced in deterministic models in certain cases, for example, to consider the uncertainties of weather forecast in forecasting yields and the uncertainties of climate change scenarios in assessing global greenhouse effect on agriculture. A quickly increasing complexity of realization is inherent to this type of formalization.

Finally, consider a specialized classification of crop growth and productivity models from Penning de Vries according to whom these models are divided into the following classes: preliminary, comprehensive and summary. It is assumed that during its development a model moves forward from one class to another. The preliminary models should be simple they are based on data which may neither be sufficiently complete nor accurate. Competing hypotheses are often used for their development and preliminary models allow for their assessment. A comprehensive model is a system model the most important relationships between elements of which are wholly understood and which includes most of the information about the system. Summary models are models of comprehensive models, i.e. the essential statements of comprehensive models are formulated in summary models with less detail than possible. Simplifications make these models more accessible to users.

Models corresponding to these three classes considered and at the same time at three stages of simulation, differ much in the degree of simplicity and applicability for training, forecasting and developing of scientific knowledge (Table 1).

	Predictive value	**Scientific** value	**Instructive** value	**Simplicity**
Preliminary model	+	+ + +	+ +	+ +
Comprehensive model	+ +	+ + +	+	+
Summary model	+ + +	+	+ + +	+ +

Table 1. The relative values of certain aspects of models in different stages of development (the number of plusses indicate the degree of value)

3. Typical Theoretical Models in Agriculture

Models of productive agrocenosis and soil fertility are considered to be of paramount importance for studies of plant growth. The models, referred to as deterministic, dynamic and preliminary ones according to the above classification, are considered in the following. Their main advantage is simplicity and clearness which are lost in transition to the comprehensive "portrait" models.

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Bibliography

Baier W., Bootsma A. (1999). *Climate input requirements of Soil-Crop-Weather Models for climate change assessments.* Eastern Cereal and Oilseed Research Centre. Agriculture and Agri-Food Canada, 33 pp. [Analytical review of mathematical model application for assessing expected climate change impacts on crop productivity].

France J., Thornley J.H.M. (1984) *Mathematical Models in Agriculture*. A Quantitative Approach to Problems in Agriculture and Related Sciences, 335 pp., Butterworths Co (Publishers) LTD. [Different problems of development and application of mathematical models in agriculture from deterministic dynamic models of crop productivity, pest development and diseases to the simulation of meat and egg production, firm planning and control].

Hoogenboom, Gerrit, Jones, J.W., Hunt, L.A., Thornton, P.K. and Tsuji, G.Y. (1994) *An integrated decision support system for crop model applications.* Paper No.94-3025, ASAE, 2950 Niles Rd., St.Joseph, MI 49085-9659, USA [Manual on DSSAT system application for a wide spectrum of agricultural and ecological problems].

Penning de Vries F.W.T. and H.H.Van Laar (Eds.) (1982) *Similation of plant growth and crop production*, Wageningen. Centre for Agricultural Publishing and Documentation, 308 pp. [Considered is the dynamic simulation of a plant production process under optimal conditions and carbon, water and nitrogen deficit. Analyzed are the energy and mass exchange processes in the surface air layer and in soil and the formation of radiation, water-heat and nitrogen regimes of plant habitat].

Poluektov R.A. (1991) *Dynamic models of agroecosystem*, 312 pp. Leningrad, Hydrometeoizdat, Russia.[Designing and application of simulation dynamic models of energy and mass exchange and productivity of anthropogenic eco-agroecosystems].

Sirotenko O.D. (1996). *Mathematical models in crop bioclimatology in the Former USSR (History, Achievements and Prospects)*. Advances in Bioclimatology V.4, p. 125-169. [A review of developing methods of mathematical simulation of energy and mass exchange in plant habitat and their impact on crop productivity].

Whisler F.D., Acock B., Baker D.N., Fye K.E., Hodges H.F., Lambert J.R., Lemmon H.E., McKinion J.M. and Reddy V.R. (1986). *Crop simulation models in Agronomic Systems*. Advances in Agronomy, V.40, p.141-208. [Analytical review of development and application of dynamical models of crop productivity, description, classification, and comparison of some models].

Williams J.R. (1995) The Epic model,. Computer models of watershed hydrology (Chapter 25). Water Resources Publications, Littlton, Colorado. pages 909-1000 in V.P.Singh (Ed) [Detailed description of

the model Soil-Plant-Environment EPIC, simulating energy and mass exchange processes in the soil-water-vegetation-atmosphere continuum].

Biographical Sketch

Professor Oleg D.Sirotenko is presently Head of Department of the All Russian Institute of Agricultural Meteorology. His main scientific interests include mathematical modeling of energy-mass exchange in the soil-plant-atmosphere system and the development of models, describing weather and climate influence on crop productivity, assessment of global climatic change and greenhoouse impact on agriculture.

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