Introduction to Crop Modeling Papers from Eastern Europe and the Former Soviet Union

John M. Baker*

At the 1994 ASA–CSSA–SSSA annual meetings in Seattle, WA, ASA Division A-3 sponsored a symposium entitled, “Use and Abuse of Crop Simulation Models.” The four speakers (Tom Sinclair, Ken Boote, John Pasioura, and John Monteith) presented such an entertaining and provocative picture of the state of the science that there were a number of suggestions afterwards for a written product. Accordingly, the editorial board of *Agronomy Journal* was approached and agreed to publish a set of papers, provided that they were subject to full peer review. Those papers appeared in print in 1996 (Agron. J. 88:689–716) and in turn elicited considerable interest among scientists in eastern Europe and the countries of the former Soviet Union where crop simulation modeling had a long parallel history, which was not well known elsewhere in the world due to political constraints on the professional interaction that most of us take for granted. Dr. Vitalij Denisov, of Klaipeda University in Lithuania, proposed a second set of papers to provide a view of the philosophy and status of crop modeling in these countries. The editorial board of *Agronomy Journal* agreed to the concept, subject to peer review, and the resulting papers are presented here. They are not intended to provide a comprehensive picture, but rather a snapshot of some of the crop modeling efforts undertaken in eastern Europe and the former Soviet Union as well as a vision of the potential role of such research in the future.

Crop Modeling: Advances and Problems

Oleg D. Sirotenko*

**ABSTRACT**

A brief history of crop modeling activities in the former USSR is presented, and the author’s view on the problems and perspectives of further developments is delineated. The paper is an analytical review of a detailed report on the issue of advances and problems in crop modeling that was recently published by the author. Although both theoretical and applied crop models are subjects of this review, the main emphasis is placed on the explanatory and behavioral features of existing and future crop models.

**ADVANCES IN CROP MODELING**

Recently I was given an opportunity to express my view on advances and problems in crop modeling (Sirotenko, 1996). The history of crop simulation in the former USSR is not tedious and monotonous. It started with the almost simultaneous development of two competitive versions (radiation and CO₂) of a quantitative theory of plant canopy photosynthesis. The first approach had been developed by Budagovsky et al. (1964), and the second one was presented by Budyko (1964) and Budyko and Gandin (1964). Young researchers were delighted with these works; however, the leading specialists rejected them as mathematical games only. Still, an informal society called Weather–Yield–Mathematics (WYM) was established in 1968 to develop these new ideas under the leadership of Professor Juhan Ross. During the subsequent 30 yr, extensive and rather effective activities on developing crop simulation models in the former USSR have been carried out within the framework of WYM. As a result, more than 20 monographs and some hundred papers were published. Unfortunately, the information contained in the vast majority of these publications remains unknown to the Western scientific community. The following are examples of some of the most important works that have apparently never been cited by English-speaking scientists: Tooming, 1977; Bikhele et al., 1980; Galyamin, 1980; Sirotenko, 1981; Palagin, 1981; Bondarenko et al., 1982; Tooming, 1984; Poluektov, 1991; Kan, 1992; and Boyko, 1993.

The WYM society has suffered from the economic crisis caused by the disintegration of the USSR. The optimism of its participants has changed to deep disappointment associated with lack of progress on the application of mathematical models and computers in agronomy. Activities in this field practically stopped for some years and only recently have shown some signs of reanimation. What conclusions can be drawn from an analysis of the experience gained in crop modeling in the former USSR?

**Abbreviations:** IDA, irradiation density of adaptation; WYM, Weather–Yield–Mathematics.
considered a dynamically developing open system—a green machine that absorbs solar radiation, CO₂, and other necessary substrates from the environment and produces organic substances. A system of differential equations and boundary conditions describing the green machine has been developed, and integration of this system of equations allows calculation of final agroecosystem productivity, depending on conditions in the physical environment at its boundaries. Thus, the problem of calculating agroecosystem productivity is formulated as a boundary value problem of mathematical physics. All known crop simulation models can be treated as simplifications (parameterizations) of this basic control system (for details see Sirotenko, 1996). The development of a theory is equivalent to possession of a network of good roads through which any advances in different fields (e.g., simulation of stomata resistance or mineralization of soil organic matter) can be easily built into a common system of equations and used to solve the principal problem, i.e., calculation of final agroecosystem productivity.

The applied crop simulation models that were developed during last two decades, despite all of their limitations, have extended our potential chances to solve such problems as crop development, yield forecast, assessment of soil and climate resources, and assessment of climate change consequences. It is especially evident from the problem of assessing the global greenhouse impact on agriculture. It gave rise to the development of simulation models themselves and, at the same time, methods of their application (Sirotenko et al., 1997; Baier and Bootsma, 1999). Nevertheless, the practical value of these opportunities has not yet been completely realized.

**LIMITATIONS OF MATHEMATIZATION**

The present day status of crop modeling cannot be recognized as satisfactory. There are many weeds, i.e., models that are half-finished products or partially modified versions of previous, known models. Quite often it is unknown what experimental data were used for parameter estimation; therefore, it is difficult to determine if a truly independent data set was used for their verification. In such a situation, questions arise regarding how to specify a set of satisfactory models and how to compare their performance. It is clear that there are overcomplicated, oversimplified, and conceptually wrong models, but the reference points and criteria for progress in crop modeling can easily become lost.

One of the main reasons for stagnation is unsatisfactory experimental support for activities related to agroecosystem modeling and an inability to make use of extremely scarce experimental data. The theory of identification of dynamic systems states that a balance should be rigorously maintained between a priori information included in model structure and the information contained in model parameters, whose values are estimated from the observations of a certain object. Hydrologists realized this problem when developing models of river runoff (Kuchment, 1972). Unfortunately, when agroecosystems are modeled, the problem cannot be solved by simply maintaining a definite ratio between the number of model parameters to be estimated and the sample size. The amount of information contained in \( n \) summer series of observations of crop yield formation can vary tremendously (Sirotenko and Varcheva, 1992; Sirotenko, 1996) depending on meteorological conditions. The more contrast that exists among years (in terms of meteorological conditions) contained in a data set, the better the plan. The mean efficiency of D-optimum plans varies in the Russian Plain territory by a factor of 5 or more, depending on climate conditions. The analysis of random-sample optimization with the D-criterion used by different researchers can explain why apparently good crop models may perform poorly in practice. We must agree with Poluektov (1991) that experimental support was and remains a major factor limiting developments in mathematical modeling. It should be added that, according to our calculations (Sirotenko and Varcheva, 1992), the proper use of the theory of experiment design can significantly decrease expenses for long-term field experiments and reduce the cost of optimizing their location in space and time with respect to the climate conditions and partial regulation of some factors (water regime and mineral nutrition).

The conclusion about stagnation observed in crop modeling is confirmed by the fact that many of the problems to be solved 20 yr ago still remain unsolved. For example, there is no marked progress in the development of methods for calculating turbulence in plant canopies, evaporation from dry soil, or the rates of water and mineral absorption by plant root systems.

Criticism of simulation models of crop production may be summed up as follows: Most existing models lack either the necessary originality to make the theory interesting or the specificity necessary for them to be useful in practical applications. Einstein’s quotation is well known: “the experiment is a decisive criterion of physical suitability of a mathematical construction but the creative beginning belongs to mathematics. Human reason initially has to construct, independently, the required forms before we will be able to find them in nature.” In crop modeling, it is not often that mathematics plays the role of creative beginning. Frequently, the models proposed are just an impoverished formalization of ideas put forward by biologists a long time ago and well described in textbooks.

Nevertheless, some examples can be given for which the initial hypothesis may be attributed to the ideas originating from mathematics. The most impressive example is the principle of maximum productivity of a photosynthesizing system, according to which plant adaptation in the plant community is aimed at achieving the maximum potential CO₂ gas exchange under the given ambient conditions. Proceeding from this principle, Tooming (1984) suggested the notion of irradiation density of adaptation (IDA), which determines competitive interactions in plant communities. The introduction of IDA stimulated physiologists to conduct corresponding experiments. It was shown that a low IDA level is a prerequisite for both photosynthesis and plant growth...
in community, whereas at high IDA, plant communities would not be likely to appear on Earth. The spectrum of ideas whose starting point was the problem of potential productivity of plant communities stimulated the development of a new line of investigations.

Another argument worth mention in discussing the significance of crop modeling is the explanation of the Issyk-Kul phenomenon. In the area of the Prezewalski cultivar testing grounds near Lake Issyk-Kul, 1718 m above the sea level, record-breaking cereal yields (about 11–12 t ha\(^{-1}\)) have been common. A variety of possible reasons were suggested for this phenomenon, including higher natural radiation and local soil composition. In 1986, spring wheat (\textit{Triticum aestivum} L.) yield was 8.5 t ha\(^{-1}\), whereas the simulated yield computed using the Crop–Weather model (which had not been adjusted or calibrated for the site) was 7.8 t ha\(^{-1}\). This is a very good agreement, particularly when one considers that before this case, the simulated yields at other locations (even for optimum soil moisture and mineral supply conditions) had not exceeded 5.5 t ha\(^{-1}\). The high yields in this area thus may be accounted for by purely meteorological reasons: suitable temperatures, high solar radiation, and a long growing period. With the unlimited soil water supply for the same 1986 year, the calculated yield was 12 t ha\(^{-1}\), which constitutes a record-breaking result.

**ONWARD TO THE NEXT GENERATION OF MODELS**

Let us first state the main unsolved problems found in the physical aspects of crop simulation. They include: the well-known problem of closing the set of hydrodynamic equations describing canopy turbulence; the problem of correct representation of soil internal evaporation and water uptake of roots; and the problem of assigning internal boundary conditions for the integrated energy and mass exchange of a plant community.

It is safe to say, however, that biological aspects, rather than physical ones, limit the further development of mathematical crop simulation models. In general, all of the biological problems can be related to the performance of the plant community as a kind of primitive biochemical reactor. The primacy of metabolism kinetics is abandoned only when attempting to simulate plant development morphology, which in no way proceeds from the crop biomass dynamics. The laws of nature do not fit into a rigid scheme—the faster the metabolic rate, the faster the developmental morphology and plant development rates. The hypothesis that new plant organs are initiated as soon as a simulated concentration reaches some critical value may be more flexible. However, both this assumption and the concept of a reserve pool cannot embrace all of the diversity of the plant autoregulation system. Therefore, of fundamental importance for further development in crop simulation seems to be the efforts to describe the operation of a second, metabolically independent program in plants—the developmental morphology, ontogenesis program, or both (see Mokronosov, 1983). It may be possible that calculating regulatory functions of plant hormones will provide an additional basis for the ontogenesis program in the next generation of models.

Interesting conceptual suggestions about plant growth and development were made by Dobrachev (1982), Kan (1989), Gulyaev (1983), Moldau (1984), and others. In these studies, the use of the optimum principle appears to be promising (its origin may be traced back to Darwin’s theory of natural selection). However, in practice, this principle has only been applied to local optimization procedures. For example, according to Tarko and Sudulaev (1984), newly formed biomass is partitioned among the leaves, stems, and roots of cotton (\textit{Gossypium hirsutum} L.) so that the maximum biomass accretion rate should be guaranteed at the next time step, provided that there have been no changes in the surrounding environment. It is our opinion, however, that optimum behavior should not be simulated by fitting such local procedures into a model; it should instead be simulated by formalizing a hypothesis that would embody the behavioral mechanism.

One more promising direction comes from the work of Kan (1992), who showed that nonhomogeneity of plant populations and other microecological aspects were significant for simulation of crop production. These aspects introduce stochastic principles, and thus open new vistas for agroecosystem studies. Currently, it seems impossible to foretell the shape of mathematical structures in which plant growth and development programs will be implemented in the next generation of models. It suffices to state only that future models will look as different from present models as mammals from reptiles. Due to the inclusion of adaptive aspects of plant growth and development, model behavior will become much more complex, but presumably it will be achieved without unnecessarily complicating the models themselves.

Drawing an analogy with the development of modern physics, the most impressive event in crop simulation must be the large unification of soil fertility models and the production of vitally important crops. It will be aimed at establishing computerized systems, which will continuously simulate the behavior of agronomic systems for as much as one to two decades or more ahead for different cropping patterns, land amelioration, and chemical application strategies, taking into account future changes in climate and chemical composition of the atmosphere.

Finally, I would like to touch on a particular but rather attractive and important problem involved in crop modeling. It is an old discussion on whether long-term crop yield variations contain deterministic cyclic components and whether the long-term crop yield forecast on this basis is possible. It has been shown (Naidenov and Shveikina, 1997) that a set of nonlinear differential equations, describing the dynamics of water reserves in a river basin and its sink, can have auto-oscillatory solutions even at constant external effects, i.e., precipitation. If so, the productivity of agroecosystems and ecosystems, depending on a soil moisture regime, must also undergo certain oscillations under constant external effects. Preliminary analysis of the set of three equations
Crop Modeling: Nostalgia about Present or Reminiscence about Future

Ratmir A. Poluektov* and Alexandre G. Topaj

ABSTRACT

During the last two decades, computer simulation models have become powerful tools for investigating agricultural crop dynamics and solving practical problems. Many models have been developed in various countries, which permits exploration of the influence of weather conditions and agricultural strategies on the fate of a crop. However, some fundamental problems related to the description of agricultural plant growth and development remain unsolved. These primarily concern the totality of biological processes such as ontogenetic development and morphogenesis due partly to the lack of knowledge in plant physiology and the absence of realistic ideas about the origin of plant life. These circumstances have forced modelers to use quite sophisticated heuristic approaches rather than biologically sound descriptions. This paper represents the authors' vision of this situation.

*Corresponding author (las_arl@vt4142.spb.edu)