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Review Article

Brief History of Agricultural Systems Modeling

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ABSTRACT

Agricultural systems science generates knowledge that allows researchers to consider complex problems or take informed agricultural decisions. The rich history of this science exemplifies the diversity of systems and scales over which they operate and have been studied. Modeling, an essential tool in agricultural systems science, has been accomplished by scientists from a wide range of disciplines, who have contributed concepts and tools over more than six decades. As agricultural scientists now consider the "next generation" models, data, and knowledge products needed to meet the increasingly complex systems problems faced by society, it is important to take stock of this history and its lessons to ensure that we avoid re-invention and strive to consider all dimensions of associated challenges. To this end, we summarize here the history of agricultural systems modeling and identify lessons learned that can help guide the design and development of next generation of agricultural system tools and methods.

Keywords: *Next generation, Earth's natural resources, Decision Support Systems (DSSs)*

INTRODUCTION

The world has become more complex in recent years due to many factors, including our growing population and its demands for more food, water, and energy, the limited arable land for expanding food production, and increasing pressures on natural resources. These factors are further compounded by climate change that will lead to many changes in the world as we have known it. How can science help address these complexities? On the one hand, there is a continuing explosion in the amount of published information and data contributions from every field of science. On the other hand, the problem of managing all of this knowledge and underpinning data becomes more difficult and risks information overload. The information explosion is leading to greater recognition of the interconnectedness of what may have been treated earlier as independent components and processes. We now know that interactions among components can have major influences on responses of systems, hence it is not necessarily sufficient to draw conclusions about an overall system by studying components in isolation.

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These interactions transcend traditional disciplinary boundaries. Although there continues to be a strong emphasis on disciplinary science that leads to greater understanding of components and individual processes, there is also an in- creasing emphasis on systems science.

Systems science is the study of real world "systems" that consist of components defined by specialists. These components interact with one another and with their environment to determine overall system behavior. These interacting components are exposed to an external environment that may influence the behavior of system components but the environment itself may not be affected by the changes that take place within the system boundary. Although systems are abstractions of the real world defined for specific purposes, they are highly useful in science and engineering across all fields, including agriculture. An agricultural system, or agro-ecosystem, is a col- lection of components that has as its overall purpose the production of crops and raising livestock to produce food, fiber, and energy from the Earth's natural resources. Such systems may also cause undesired effects on the environment.

Agricultural systems science is an interdisciplinary field that studies the behavior of complex agricultural systems. Although it is useful to study agricultural systems in nature using data collected that characterize how a particular system behaves under specific circumstances, it is impossible or impractical to do this in many situations. Scientific study of an agro-ecosystem requires a system model of components and their interactions considering agricultural production, natural resources, and human factors. Thus, models are necessary for understanding and predicting overall agro-ecosystem performance, for specific purposes. Data are needed to develop, evaluate, and run models so that when a system is studied, inferences about the real system can be simulated by conducting model-based "experiments." When we consider the "state of agricultural systems science," it is thus important to con- sider the state of agricultural system models, the data needed to develop and use them, and all of the supporting tools and information used to interpret and communicate results of agricultural systems analyses for guiding decisions and policies.

Agricultural system models play increasingly important roles in the development of sustainable land management across diverse agroecological and socioeconomic conditions because field and farm experiments require large amounts of resources and may still not provide sufficient information in space and time to identify appropriate and effective management practices. Models can help identify management options for maximizing sustainability goals to land managers and policymakers across space and time as long as the needed soil, management, climate, and socioeconomic in- formation are available. They can help screen for potential risk areas where more detailed field studies can be carried out. Decision Support Systems (DSSs) are computer software programs that make use of models and other information to make site-specific recommendations for pest management, farm financial planning, management of livestock enterprises, and general crop and land management. DSS software packages have mainly been used by farm advisors and other specialists who work with farmers and policymakers.

2. A brief history

The history of agricultural system modeling is characterized by a number of key events and drivers that led scientists from different disciplines to develop and use models for different purposes (Fig. 1). Some of the earliest agricultural systems modeling (Table 1) were done by Earl Heady and his students to optimize decisions at a farm scale and evaluate the effects of policies on the economic benefits of rural development. This early work during the 1950s through the 1970s inspired additional economic modeling. included models of farming systems with economic and biological components; their book provided an important source for different disciplines to learn about agricultural systems modeling. Soon after agricultural economists started modeling farm systems, the International Biological Program (IBP) was created. This led to the development of various ecological models, including models of grasslands during the late 1960s and early 1970s, which were also used for studying grazing by livestock. The IBP was inspired by for-ward-looking ecological scientists to create research tools that would allow them to study the complex behavior of ecosystems as affected by a range of environmental drivers.

The IBP initiative brought together scientists from different countries, different types of government, and different attitudes toward science. Before this program, systems modeling and analysis were not practiced in scientific efforts to understand complex natural systems. IBP left a legacy of thinking and conceptual and mathematical modeling that contributed strongly to the evolution of systems approaches for studying natural systems and their interactions with other components of more comprehensive, managed systems.

Models of agricultural production systems were first conceived of in the 1960s. One of the pioneers of agricultural system modeling was a physicist, C. T. de Wit of Wageningen University, who, in the mid-1960s, believed that agricultural systems could be modeled by combining physical and biological principles. Another pioneer was a chemical engineer, W. G. Duncan, who had made a fortune in the fertilizer industry and returned to graduate school to obtain his PhD degree in Agronomy at age 58. His paper on modeling canopy photosynthesis is an enduring development that has been cited and used by many crop modeling groups since its publication. After his PhD degree, he began creating some of the first crop-specific simulation models (for corn, cotton, and peanut, see. His work and the work by intrigued many scientists and engineers who started developing and using crop models. In 1969, a regional research project was initiated in the USA to develop and use production system models for improving cotton production, building on the ideas of de Wit, Duncan, and Herb Stapleton, an agricultural engineer in Arizona. Thus, some of the first crop models were curiosity-driven with scientists and engineers from different disciplines developing new ways of studying agricultural systems that differed from traditional reductionist approaches, and inspiring others to get involved in a new, risky research approach. During this early time period, most agricultural scientists were highly skeptical of the value of quantitative, systems approaches and models.

In 1972, the development of crop models received a major boost after the US government was surprised by large purchases of wheat by the Soviet Union, causing major price increases and global wheat shortages. New research programs were funded to create crop models that would allow the USA to use them with newly- available remote sensing information to predict the production of major crops that were grown anywhere in the world and traded inter- nationally. This led to the development of the CERES-Wheat and CERES-Maize crop models by Joe Ritchie and his colleagues in Texas. These two models have continually evolved and are now contained in the DSSAT suite of crop models.

During much of the time since the 1960s, only small fractions of agricultural research funding were used to support agricultural system models, although the Dutch modeling group of C. T. de Wit was a notable exception. Thus, most of those who were modeling cropping systems, for example, struggled to obtain financial support for the experimental and modeling research needed to develop new models or to evaluate and improve existing ones. In- stead, there were other "crisis" events or realizations of key needs fueling model development (Table 1), each typically leading to infusion of additional financial support over short durations of time for model development or uses.

2001–2003	European Society Agronomy meeting hosts special session on modeling cropping systems. Published as Volume 18 European Journal Agronomy
2006	Representation of CO2 effects in crop model simulations challenged
2005–2009	European Union funding of the System for Environmental and Agricultural Modeling: Linking European Science and Society (SEAMLESS)
2005–2010	Development of Earth system models, components of general circulation models (GCMs)
2006	FAO Livestock's Long Shadow report
Mid 2005s on wards	Development of global livestock models
2005; FAO, 2013,	
2010	Creation of the Agricultural Model Intercomparison and Improvement Project (AgMIP), a global program and community of agricultural scientists
2010s	Increasing interests by the private sector in agricultural system models
2010s	With the food price shock of 2008/2010, a realization of the need to increase food production to meet needs of 10 billion by 2050, including challenges of climate change and sustainable natural resources

This meeting led to a special issue of *European Journal of Agronomy* (vol 18) in which comprehensive papers on the major modeling systems, namely DSSAT, APSIM, CROPSYST, STICS, Wageningen models. Over 2000 citations for models in this publication.

Opened a debate between plant experimenters and modelers on the skill of crop models for yield prediction in future climates; prompted interest in more evaluations of CO_2 effects interacting with temperature, other factors This led to major collaboration across Europe for developing models for use across scales, from field to farm, country, and EU levels.

Led to new methods for coupling crop simulation models to land surface schemes of numerical climate models.

Demonstrated the large environmental footprint of livestock leading to programs for assessing and reducing the environmental impacts of livestock. Most of this work was done through modeling.

Global integrated assessment of livestock systems now possible at high resolution including land use, emissions, economics, biomass use and others and their links to other sectors (crops, forestry, energy, etc.)
This initiative led to model comparisons and initiatives for improving models, capturing the imagination and interest of agricultural modelers worldwide.

Some companies create their own crop modeling teams, others start working in public-private collaborations.

This realization is leading to greater interest in use of new ICT developments (e.g., cloud computing, smart phones, app stores, mobile computing, use of UAVs for agricultural management) and agricultural system models to help guide investments and development and to greater interest by the private sector.

Another innovation in computer software development is noteworthy. In 1998, the concept of open source software was developed. As the agricultural systems science community is evolving, there is consider- able interest in creating open-source agricultural system models, with modular components and with interfaces to common databases. Al- ready, at least two cropping system models are being offered as modified open source (APSIM, https://www.apsim.info/AboutUs.aspx; and DSSAT, Cropping System Model, http://dssat.net/downloads/dssat- v46). These two crop modeling systems allow free access to model source code to enable community-based development of model components for possible inclusion in official model versions.

In parallel to funded initiatives, scientists started creating consortia and networks to enhance collaboration for specific purposes. One Other events have contributed to development of specific agricultural models in different countries. We do not attempt to create a comprehensive list of all such events, but instead to highlight those that played major roles in getting this work started in addition to those that had major implications globally. Between events in Table 1, model development and use has proceeded, but overall progress has been slow at times. The continued dedication to develop reliable models has been one of the main features of many agricultural modeling efforts for cropping systems, livestock, and economics (e.g., DSSAT, EPIC, APSIM, STICS, WOFOST, ORYZA, CROPSYST, RZWQM, TOA, IMPACT, SWAP, and GTAP).

3.: Characteristics of agricultural system models

Although many factors have motivated the development of agricultural system models, there are three characteristics that stand out among them: 1) intended use of models, 2) approaches taken to develop the models, and 3) their target scales. Here, we present these important characteristics with examples for each.

3.1: Purposes for model development

There are two broad categories that motivate agricultural model development; scientific understanding, and decision/policy support. The first of these motivations is to increase basic scientific un- derstanding of components of agricultural systems or understanding of interactions that lead to overall responses of those systems. referred to models with this purpose as explanatory. Models developed to increase scientific understanding tend to be mechanistic models as they are usually based on known or hypothesized control of physical, chemical, and biological processes occurring in crop or animal production systems. Examples are mechanistic models of photosynthesis and water movement in soils (e.g., model implementation of the equation.

At the basic science level, models developed to increase understanding are used as tools to address research questions about control of processes, magnitudes of responses, and interactions. Modeled outputs are compared with observations that are measured in laboratories or in fields for testing the understanding that is embedded in the model. For example, transport of water or mineral N through a soil involves many processes that affect the correct balance of water.

3.2: Approaches for modeling agricultural systems

Several dimensions are needed to describe the types of models that have been developed in the past for use in improving decisions and policies. Here we discuss the major types of models that produce response outputs that are of interest to decision/policy makers. First, statistical models have been developed using historical data sets on system responses, such as crop yield, milk production, and prices of commodities. For example, statistical models — fitting a function to predict crop yield using observed weather variables and crop regional yield statistics over multiple years — were the first crop models used for large-scale yield estimations. Average regional yields were regressed on weather and time to reveal a general trend in crop yields. It is assumed that the data used to create statistical models are samples of a population such that the model can be used to predict regional yields in new years with different weather patterns.

In most cases, results of statistical models cannot be extrapolated "out of sample" because data used for parameter estimation do not rep- resent the soil, management, weather and other conditions encountered elsewhere. Furthermore, they are poorly suited to estimate climate change impacts in the future because they cannot represent un- observed changes in management (adaptation), soil properties, pests and diseases, and the influence of increasing atmospheric CO_2 concentrations (beyond the range of historical data). Despite these limitations, statistical models can be useful. When sufficient data are available to develop such models, they can provide insights about historical influences on past yields and inform other kinds of models. They also can be coupled with process-based models to predict out-of-sample responses.

3.3.: Spatial and temporal scales of agricultural system models

Users of models or information derived from them and the models themselves vary considerably across spatial and temporal scales. Similarly, the scope of the system being modeled and managed varies depending on the questions being asked and the decisions and policies that are being studied. Users in Fig. 2 are not necessarily those who run the models; instead, they are those who want information about responses of the systems to different ways of managing them in whatever physical, biological, and socioeconomic climate conditions are involved.

DISCUSSION

The history of agricultural systems modeling shows that major contributions have been made by different disciplines, addressing different production systems from field to farm, landscape, and beyond. In addition, there are excellent examples in which component models from different disciplines have been combined in different ways to produce more comprehensive system models that consider biophysical, socio- economic, and environmental responses. There are many examples where crop, livestock, and economic models have been combined to study farming systems as well as to analyze national and global impacts of climate change, policies, or alternative technologies, as shown in the companion paper on the state of agricultural system science (Jones et al. 1990). This history also shows that the development of agricultural system models is still evolving through efforts of an increasing number of research organizations worldwide and through various glob- al efforts, demonstrating that researchers in these institutions are increasingly interested in contributing to communities of science (e.g., via the global AgMIP, 2014 effort (www.agmip.org), various CGIAR-led programs, e.g., such as the IFPRI-led Global Futures and Harvest Choice projects (www.ifpri.org/) and the CIAT-led CCAFS project (ccafs.cgiar. org/)), the new CIMSANS Center www.ilsi.org/ResearchFoundation/CIMSANS/Pages/HomePage.aspx, and various global initiatives that aim for more harmonized and open databases for agriculture.

This history demonstrates that a minimum set of component models are needed to develop agricultural system models that are more or less common across various applications. These include crop models that combine weather, soil, genetic, and management components to simulate yield, resource use, and outputs of nutrients and chemicals to surrounding water, air, and ecological systems. These crop models need to take into account weed, pest and disease pressures, and predict performance to a range of inputs and practices that represent subsistence to highly controlled, intensive production technologies and new varieties. Similarly, livestock models are needed that account for climate, herd management, feed sources, and breeds. Farming system models are needed that integrate the various livestock and cropping systems, including their interactions, taking into account the socioeconomic and landscape characteristics of specific farms and a population of farms to address questions by individual farmers, agribusiness, and policy makers at community to subnational, national, and global scales. Similarly, this commonality should provide incentive for the efforts at creating harmonized and open databases to ensure that these basic needs for data will address future needs. The history also led us to conclude that different platforms for combining models and data for specific purposes will be necessary, and that the design of next generation models and data should account for this need over a range of platforms for applying the models and providing outputs needed for the various use cases that exist, as illustrated by those presented in the introduction to this special issue (Antle et al., in this issuea).

Several key lessons and important messages emerge from this history. These lessons should be considered by those who want to create an enabling environment for development of next generation agricultural system models and to help the community of developers avoid road- blocks and pitfalls. Here we summarize these key lessons.

Technological advances**:** A strong lesson from the past is the influence of technological advances, including mainframe computers, the PC, and the Internet. New technologies and knowledge should be embraced by those who are developing next generation of agricultural systems models, data, and knowledge systems. Contemporary technology examples include smart phones and telecommunications, apps and video games, molecular biology, remote sensing, open source software tools, cloud computing as a means of enabling broad access to powerful tools, and high-performance parallel computers for large parameter sweeps, model comparisons, and gridded crop model simulations.

Through the review of existing initiatives and discussions among the authors involved in this special issue, it is clear that there is a need for a more focused effort to connect these various agricultural systems modeling, database, harmonization and open-access data, and DSS efforts together, so that the scientific resources being invested in these different initiatives will contribute to compatible set of models, data, and platforms to ensure global public goods. This is critically important, considering that these tools are increasingly needed to ensure that agriculture will meet the food demands of the next 50 to 100 years and will be sustainable environmentally and economically.

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