Agricultural Systems xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Brief history of agricultural systems modeling

James W. Jones [a,*], John M. Antle [b], Bruno O. Basso [c], Kenneth J. Boote [a], Richard T. Conant [d], Ian Foster [e], H. Charles J. Godfray [f], Mario Herrero [g], Richard E. Howitt [h], Sander Janssen [i], Brian A. Keating [g], Rafael Munoz-Carpena [a], Cheryl H. Porter [a], Cynthia Rosenzweig [j], Tim R. Wheeler [k]

[a] University of Florida, Agricultural and Biological Engineering Department, Museum Road, Gainesville, FL 32611, USA
[b] Oregon State University, USA
[c] Michigan State University, USA
[d] Colorado State University, USA
[e] University of Chicago, USA
[f] Oxford Martin Programme on the Future of Food, University of Oxford, Department of Zoology, South Parks Rd., Oxford OX1 3PS, UK
[g] CSIRO, Australia
[h] University of California-Davis, USA
[i] Wageningen University, Netherlands
[j] NASA, Columbia University, USA
[k] University of Reading, UK

ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form 18 May 2016
Accepted 20 May 2016
Available online xxxx

Keywords:
Agricultural systems
Models
Next generation
Data
History

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. A number of past events combined with overall technological progress in other fields have strongly contributed to the evolution of agricultural system modeling, including development of process-based bio-physical models of crops and livestock, statistical models based on historical observations, and economic optimization and simulation models at household and regional to global scales. Characteristics of agricultural systems models have varied widely depending on the systems involved, their scales, and the wide range of purposes that motivated their development and use by researchers in different disciplines. Recent trends in broader collaboration across institutions, across disciplines, and between the public and private sectors suggest that the stage is set for the major advances in agricultural systems science that are needed for the next generation of models, databases, knowledge products and decision support systems. The lessons from history should be considered to help avoid roadblocks and pitfalls as the community develops this next generation of agricultural systems models.

1. 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 (e.g., Wheeler and von Braun, 2013). 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

* Corresponding author at: University of Florida, Gainesville, FL 32611, USA.
E-mail address: jimj@ufl.edu (J.W. Jones).

http://dx.doi.org/10.1016/j.agsy.2016.05.014
0308-521X/© 2016 Published by Elsevier Ltd.

necessarily sufficient to draw conclusions about an overall system by studying components in isolation (Hieronymi, 2013). 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 increasing 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 (e.g., see Wallach et al., 2014). 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 collection 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 consider 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 agro-ecological 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 (e.g., Teng and Penning de Vries, 1992). 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 information 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 (Michalski et al., 1985; Beck et al., 1989), farm financial planning (Boggess and Moss, 1989; Herrero et al., 1999), management of livestock enterprises (e.g., Herrero et al., 1998; Stuth and Stafford-Smith, 1993), and general crop and land management (Plant, 1989; Basso et al., 2013). DSS software packages have mainly been used by farm advisors and other specialists who work with farmers and policymakers (e.g. Nelson et al., 2002; Fraisse et al., 2015), although some may be used directly by farmers. In addition to this type of farm-level decision making support, agricultural system models are increasingly being used for various types of landscape-scale, national and global modeling and analysis that provides information to the general public, to inform research and development investment decisions, and informs specific public policy design and implementation.

In this paper, we provide a critical overview of past agricultural systems modeling followed by a discussion of the characteristics of this history relative to lessons learned that may help guide future progress. We discuss the state of agricultural system science relative to current and future needs for models, methods and data that are required across a range of public and private stakeholders. We start with an overview of major events that happened during the last 50+ years that led to an increased emphasis on agricultural systems modeling. This timeline identifies key drivers that led to the increasing interest and investments in agricultural system models, demonstrates the complexities of many of the issues, and illustrates a range of purposes. This is followed by an overview of the characteristics of agricultural systems models and the wide range of purposes that various researchers in different disciplines have had when developing and using them. We also discuss the key messages from this history that should help guide efforts to develop the next generation of models, databases, and knowledge-based tools.

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 (Heady, 1957; Heady and Dillon, 1964). This early work during the 1950s through the 1970s inspired additional economic modeling. Dent and Blackie (1979) 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 forward-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 (Worthington, 1975; Van Dyne and Anway, 1976).

The IBP initiative brought together scientists from different countries, different types of government, and different attitudes toward science (Breymeyer, 1980). 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 (Coleman et al., 2004).

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 (Duncan et al., 1967) 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 Duncan, 1972). His work and the work by de Wit (1958); also see Bouman and Rabbinge (1996) 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 (Stapleton et al., 1973), 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