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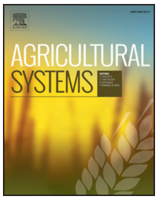

Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science

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ABSTRACT

We review the current state of agricultural systems science, focusing in particular on the capabilities and limitations of agricultural systems models. We discuss the state of models relative to five different Use Cases spanning field, farm, landscape, regional, and global spatial scales and engaging questions in past, current, and future time periods. Contributions from multiple disciplines have made major advances relevant to a wide range of agricultural system model applications at various spatial and temporal scales. Although current agricultural systems models have features that are needed for the Use Cases, we found that all of them have limitations and need to be improved. We identified common limitations across all Use Cases, namely 1) a scarcity of data for developing, evaluating, and applying agricultural system models and 2) inadequate knowledge systems that effectively communicate model results to society. We argue that these limitations are greater obstacles to progress than gaps in conceptual theory or available methods for using system models. New initiatives on open data show promise for addressing the data problem, but there also needs to be a cultural change among agricultural researchers to ensure that data for addressing the range of Use Cases are available for future model improvements and applications. We conclude that multiple platforms and multiple models are needed for model applications for different purposes. The Use Cases provide a useful framework for considering capabilities and limitations of existing models and data.

1. Introduction

Agricultural systems science as we know it today has evolved over the last 50 or more years with contributions from a wide range of disciplines (Jones et al., this issue). Generally during this same time period, appreciation for and acceptance of agricultural systems science has increased as more scientists, engineers, and economists graduate from universities with training in systems modeling, analytical approaches, and information technology (IT) tools. Over this time period, there has also been a corresponding increase in demands for agricultural systems science to address questions faced by society that transcend agriculture. Relevant questions range from how to better manage systems for higher and more efficient production, what changes are needed in a farming system for higher profitability without harming the environment, what policies are needed to help farming systems evolve to meet broader societal goals, and what systems are needed to adapt to the continual changes that agriculture faces, including climate change, changes in demand for agricultural products, volatile energy prices, and limitations of land, water, and other natural resources. Agricultural systems models are being challenged to move beyond just including economic and sustainability issues. There is a strong agenda of new Sustainable Development Goals (e.g., FAO, 2016), which will require models of nutritional quality of food beyond bulk yields and multifunctional

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landscape models for policy analyses. Sustainable solutions that address multiple goals will likely benefit from a convergence of science and technologies that make use of information and cognitive sciences (Scott et al., 2015; Wolfe et al., 2016).

In order to analyze these different dimensions of agriculture and food systems, ideally we would have a virtual laboratory containing models, data, analytical tools and IT tools to conduct studies that evaluate outcomes and tradeoffs among alternative technologies, policies, or scenarios. The virtual laboratory would allow users to define scenarios, specify analyses covering different social, political, and resource situations and different spatial and temporal scales, and produce outputs suitable for interpretation and use by decision makers. Clearly, that virtual laboratory does not exist. But where are we currently relative to this ideal situation? The purpose of this paper is to address that question by reviewing the state of agricultural systems science and its capabilities for the Use Cases described by Antle, Jones and Rosenzweig (this issue) that represent two important areas of agricultural systems model applications: for smallholder agriculture in developing countries and for commercial agriculture in industrialized countries. This paper builds on earlier reviews of specific components. In the concluding article of this Special Issue, Antle, Jones and Rosenzweig (this issue) discuss the implications of NextGen for global change research, another major area of agricultural systems model applications.

2. Component agricultural system models

Here, we address models as components of integrated agricultural systems models, focusing on applicability of models for selected Use Cases. Janssen et al. (this issue) discuss the capabilities and limitations of various data and information tools for the different Use Cases as well as what is needed for the next generation of models and knowledge systems.

2.1. Cropping system and grassland models

Several crop modeling review papers have recently been published (e.g., Holzworth et al., 2015; Boote et al., 2013; Basso et al., 2016), summarizing model capabilities and uses. For example, Rivington and Koo (2010) surveyed crop model developers and users to assess the state of crop models for use in research and decision making related to climate change. They emphasized the need for additional model development as well as the need for more and better quality data. Ewert et al. (2014) reviewed crop models relative to their adequacy in performing integrated assessments of climate change impacts, and pointed out important limitations in most crop models. Holzworth et al. (2015) discussed advances in capabilities and applications over time. Basso et al. (2016) reviewed the performance of CERES maize (Ritchie, 1986), wheat (Otter and Ritchie, 1985) and rice models (Ritchie et al., 1986a) compared to measured data over the last 30 years in 43 countries. They reported that model performance, using site-specific inputs, was outstanding for the variables compared (e.g., average relative error for grain yield of 13%).

Models of cropping and grassland systems share the same fundament characteristics: both describe crop or grassland agro-ecosystem growth and yield responses to climate, soil, plant species characteristics, and management. However, several aspects of grassland/rangeland modeling present unique challenges. Many of these challenges stem from the requirement that grassland models represent several interacting species, including perennial and woody species of grasses. Persistence of plants over multiple years forces the models to consider residual effects over time. Dependency on soil-derived nutrients or human-induced disturbances like fire reinforce the longer-term perspective needed for grassland modeling. Thus, although most biophysical processes are similar (e.g., relative to photosynthesis, growth, water and nutrient uptake from soil, etc.) additional factors are considered when modeling grasslands.

2.1.1. Model-simulated responses of interest to users

The most common response variable modeled for cropping systems is yield, whether of grain, tuber, or forage biomass yield. This yield is harvested at a single point in time for determinate annual crops, while indeterminate crops and grasslands may be harvested multiple times. Although statistical models may be useful for predicting these biological yields in response to some combination of weather conditions, nutrient levels, irrigation amounts, etc. (e.g., Schlenker and Lobell, 2010; Lobell et al., 2011), they do not predict responses to nonlinearities and threshold effects outside the range of conditions in data used to develop them.

In contrast, dynamic cropping and grassland system models may simulate these biological yields and other responses important to analysts, such as crop water use, nitrogen uptake, nitrate leaching, soil erosion, soil carbon, greenhouse gas emissions, and residual soil nutrients. Dynamic models can also be used to estimate responses in places and for time periods and conditions for which there are no prior experiments. They can be used to simulate experiments and estimate responses that allow users to evaluate economic and environmental tradeoffs among alternative systems. Simulation experiments can predict responses to various climate and soil conditions, genetics, and management factors that are represented in the model. "Hybrid" agricultural system models that combine dynamic crop simulations with appropriate economic models can simulate policy-relevant "treatment effects" in an experimental design of climate impact and adaptation (Antle and Stockle, 2015).

2.1.2. Factors to which cropping and grassland systems respond

Many factors affect crop growth and yield in agricultural fields and pastures. One innovation of early crop modeling pioneers was to categorize the crop production situation being modeled to narrow down the many factors that are needed by crop models (Bouman et al., 1996; van Ittersum et al., 2003). Fig. 1 summarizes three crop production levels and factors that influence each. Potential production is defined as crop production that is determined completely by defining factors of CO_2, radiation, temperature, and crop characteristics (e.g., genetic control of physiology and canopy architecture). Potential production models also include partitioning of biomass growth into grain and other plant parts, with defining factors modeled to affect these

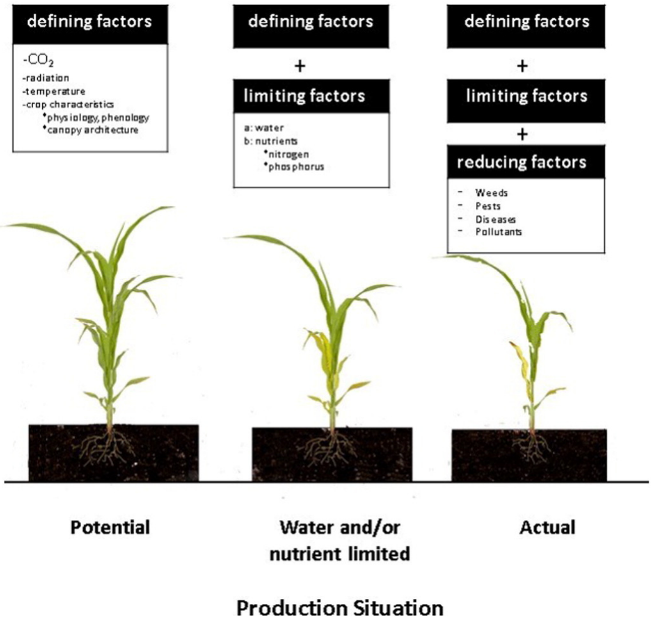

Fig. 1. Diagram of production situation used to characterize factors included and excluded from cropping system models to help guide their development and inform users of their applicability to address different questions.
Adapted from van Ittersum et al. (2003).

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