The Role of Crop Systems Simulation in Agriculture and Environment

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ABSTRACT

Simulation of crop systems has evolved from a neophyte science into a robust and increasingly accepted discipline. Our vision is that crop systems simulation can serve important roles in agriculture and environment. Important roles and uses of crop systems simulation are in five primary areas: 1) basic research synthesis and integration, where simulation is used to synthesize our understanding of physiology, genetics, soil characteristics, management, and weather effects, 2) strategic tools for planning and policy to evaluate strategies and consequences of genetic improvement or resource management, 3) applications for management purposes, where crop systems simulations are used to evaluate impacts of weather and management on production, water use, nutrient use, nutrient leaching, and economics, 4) real time decision support to assist in management decisions (irrigation, fertilization, sowing date, harvest, yield forecast, pest management), and 5) education in class rooms and farms, to explain how crop systems function and are managed.

Keywords: *Decision Model, Dynamic Data Model, Ecological Modeling, Environmental Modeling, Input/Output Models, Knowledge Utilization, System*

INTRODUCTION

Simulation of crop systems has advanced greatly over the past 30 to 40 years. From a neophyte science with inadequate computing power, the field has evolved into a robust and increasingly accepted science supported by improved software, languages, development tools, and computer capabilities, but the foundation continues to be scientific insights from plant physiology, soil science, agroclimatology, and related fields. Crop system simulators contain mathematical equations describing basic flow and conversion processes of carbon, water, and nitrogen balance that are integrated daily or hourly by the computer program to predict the time course of crop growth, nutrient uptake, and water use, as well as to predict final yield and

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other plant traits and outputs. The goal of this paper is to give our vision on how crop systems simulation can serve important future roles in agriculture and environment and suggests how to prioritize research to better support these roles. The paper leads off with an historical overview describing how crop system models began, then discusses five primary roles and uses of crop systems simulation in agriculture and environment, concludes with a challenge for potential linkage of crop models with molecular biology-genetics, and suggests the need for continued improvement of the science in crop system models.

AN HISTORICAL OVERVIEW

The use of crop system models and simulation had its start in crop physiology, soil physics, and soil-crop-water processes. Early models focused mainly on the crop carbon (C) balance under optimum conditions, where only solar radiation and temperature were the driving variables. Simulation of crop canopy photosynthesis from leaf-level parameters was a primary focus (DeWit, 1965; Duncan, 1971), along with predicting crop development as described through their growth stages and examining strategies for increasing reproductive yield. These patriarchs of crop modeling soon advanced to developing simple whole crop models. Concurrently, the early agricultural engineers and soil physicists were developing soil-plant-water balance models that predicted daily crop evapotranspiration, crop water uptake, and water flow processes in soils (Whisler et al., 1986). See Whisler et al. (1986) for an overview and history of crop simulation models up to the mid-1980s, including typical processes considered, data required, model testing, and applications. The crop aspects of many of the early soil-water-balance models were often fairly simple, estimating daily growth from light-interception and radiation-use-efficiency. The soil water balance models vary from tipping bucket one-dimensional water balance (Ritchie, 1985, 1998) to more complex Darcy-driven water flow with two dimensional flow such as 2-DSOIL (Ahuja, Ma, & Timlin, 2006) and RZWQM (Ma et al., 2003). The next improvement in crop system models came with the simulation of soil nitrogen (N) balance with a simple tipping bucket plug-flow of nitrate N to allow simulation of N leaching, but success was limited until improvement in two major components had occurred: first, the crop C balance routines needed to estimate crop N demand accurately and second, accurate routines to estimate soil organic matter mineralization are needed to estimate the supply of soil mineral N beyond that coming from applied fertilizer N. There are many published soil organic matter models (e.g., see Smith et al., 1997, who compared nine different soil organic matter models). The most frequently cited organic matter models are CENTURY (Parton, Stewart, & Cole, 1988) and ROTHC (Jenkinson & Rayner, 1977), and these models often serve as reference models for many studies (Traore, Bostick, Jones, Koo, Goita, & Bado, 2008). Each of these models has shortcomings, and there are many difficulties correctly simulating soil organic matter dynamics, even after 20-30 years of progress, because soils are so variable and soil organic matter is complex.

Over the past 10 to 20 years, crop system model developers have succeeded in linking good crop C balance (N demand) with good soil water balance and good soil-crop N balance. The DSSAT V3.5 models (Hoogenboom, Wilkens, Porter, Batchelor, & Hunt, 1999; Jones et al., 1998) were among the early models to succeed in this full linkage, but APSIM (Keating et al., 2003; McCown, Hammer, Hargreaves, Holzworth, & Freebairn, 1996) and other models are also at this stage of development. The DSSAT-CSM V4.0 model (Hoogenboom et al., 2004; Jones et al., 2003) was a further improvement, in its use of a land-unit module, which is the interface of crop-soil-weather, where the soil organic matter module used can be the CENTURY model (Gijsman, Hoogenboom, Parton, & Kerridge, 2002) or the older Godwin soil organic matter model (Godwin & Jones, 1991; Godwin & Singh, 1998). Table 1 lists five current crop system models, APSIM, CROPSYST, CSM-CERES, CSM-CROPGRO, and EPIC, all of which have capabilities of simulating cropping sequences.

More modular systems of crop model development evolved over the 1990s and 2000s that allowed components of the crop models to separate along scientific disciplinary lines, and allowed smaller groups of modelers to improve those modules or to replace them with new modules or to add new modules (Jones, Keating, & Porter, 20001; Keating et al. 2003; Van Kraalingen, Rappoldt, & van Laar, 2003). This modular development was a natural evolution of the models, but progress had to build upon the first comprehensive models because one needed the rest of the model to properly predict most of the important driving variables of the soil-plant-atmosphere system, even while improving any particular module. APSIM (Keating et al., 2003; McCown et al., 1996) was one of the first modeling groups to develop modular crop models, with modules that could "plug and play" into the main simulation engine. Crop modules could be pulled out and replaced by alternate crop modules. The DSSAT-CSM (V4.0) was another of the early models to emphasize this modularity (Jones et al., 2001; Jones et al., 2003), with a single soil water module, two soil organic matter modules possible, a weather module, a management inputs module, and a crop template module with common source code, but one that allowed simulating different crops by defining species input files. The other modules operated around a soil-plant-atmosphere module that handled the competition for water, light, among soil, plant, and atmosphere. This modular approach built on early developments in the 1990s with the CROPGRO model, which showed the value of using a common source code for many crops, but with all species, ecotype, and cultivar coefficients pulled out of the code, and placed in read-in files (Boote, Jones, & Hoogenboom, 1998; Boote, Jones, Hoogenboom, & Pickering, 1998; Hoogenboom et al., 1994; Hoogenboom et al., 1999). This modular approach with one common source code facilitated development of additional models for other crop species such as faba bean (Boote, Mínguez, & Sau, 2002).

Model applications are a logical outcome of desires of scientists to develop crop simulation models for a broad range of uses, depending

Table 1. Examples of crop systems simulators, simple description, and background references on selected crop system models

Name	Crops	Description	Reference Describing the Model
APSIM	Maize, sorghum, wheat, barley, and many others	Radiation use efficiency. Daily time step. Allows cropping sequences.	Keating et al., 2003; McCown et al., 1996.
CropSyst	Barley, maize, sorghum, soybean, wheat, and others	Radiation use efficiency. Daily time step. Allows cropping sequences.	Stockle, Donatelli, & Nelson, 2003; Stockle, Martin, & Campbell, 1994.
CSM-CERES	Barley, maize, millet, sorghum, and wheat	Radiation use efficiency. Daily time step. Allows cropping sequences.	Jones et al., 2003; Hoogenboom et al., 2004.
CSM-CROP-GRO	Common bean, faba bean, peanut, soybean,, cotton, and others	Farquhar-type photosynthesis on an hourly basis with hedge-row light interception. Considers growth and maintenance respiration. Allows cropping sequences.	Boote, Jones, & Hoogenboom, 1998, Boote, Jones, Hoogenboom, & Pickering, 1998; Hoogenboom et al., 2004; Jones et al., 2003.
EPIC	Maize, millet, rice, sorghum, soybean, wheat, and others	Radiation use efficiency. Allows cropping sequences and can model effects of tillage and soil erosion.	Williams, Jones, Kiniry, & Spanel, 1989.

on individual scientist interest and interpreted need of farmers and policy specialists. Whisler et al. (1986) reviewed a range of applications attempted up to the mid-1980s. Boote, Jones, and Pickering (1996) in their paper reviewed potential uses and limitations of crop models, discussing a wide range of applications in a number of areas. Now, about 10 years later, we in the current paper, review important roles and uses of crop systems simulation models in the following five areas, which surprisingly, differ little from those visualized previously by Whisler et al. (1986) and Boote et al. (1996).

RESEARCH SYNTHESIS: MODELS ENCOURAGE INTERDISCIPLINARY COLLABORATION AMONG RESEARCHERS

Much of the first 30 years of crop systems simulation emphasized improving basic research synthesis and integration of our understanding in physiology, genetics, soil fertility, soil-water-traits, and ecology. Systems simulation provided an important tool, by which the research was done to understand the system and how the components interacted. Then this understanding was integrated or written, however imperfectly, into the code of models, to allow predicting the behavior of a system for given conditions. If the behavior was sufficiently well predicted over many conditions, then the optimistic goal was for the model predictions to be used to manage or control the system. Along the historical path of crop system model development, the crop modeling community learned some important lessons. We began to appreciate how crop system model development required a holistic effort involving scientists in many different disciplines, working together, to share their knowledge and data, in a continuing process whereby code was written and simulations tested, to help understand the relationships, to help synthesize and integrate the relationships and knowledge of crop physiology, genetics, soil physics, soil nutrients, and weather impacts. Crop simulation models have the potential to integrate the processes of your favorite discipline into crop system models, to allow you to see how the whole system works, and to see just how important a given process, enzyme, or genetic trait may be. Systems simulation provides a good focal point for engaging scientists in different disciplines as they work together on a given weather-crop-soil-water-N situation: the scientists get to see how their component processes fit, and ideally those scientists can provide help putting their processes into the models the way they think they should. One lesson is that crop systems simulation, for a given actual field situation, cannot just ignore certain aspects, but it must consider all processes and forcing factors that influence the crop C balance, soil-crop N balance, and soil-crop water balance. This encourages researchers to consider the broader context of cropping systems, and consider driving processes they might otherwise ignore. This process often forces one to consider other disciplines. So far, our discussion has focused on the biophysical; however as the models are improved and are increasingly used as decision support tools in industry and government, it has become evident that there is a need to include economists, social scientists, and political scientists in this interdisciplinary discussion.

The value of synthesis and integration should not to be underestimated, in an era where researchers have gone progressively deeper and more detailed in their individual laboratory investigations, to the point where researchers may lose sight of the importance of their individual contribution. Too often, and with understandable pride, these researchers may point to major potential production improvements possible with their particular findings, but where these findings are not sufficiently tested in field situations. This is particularly true with plant genomics scientists or plant physiologists who do not get into the field, and those who study processes in test tubes, or study plants such as *Arabidopsis* grown in artificial soil media in un-bordered pots in low-light growth chambers. There is a need to test the effects of given genetics or fertility or management treatments of crops in whole stands on problem soils under normal weather variability. In many cases, the phenotype is more determined by environment than by genotype.

We will give several examples of how optimistic promises from plant physiology, were scaled back in reality, when considered at the whole crop level and considering the whole system of inputs and outputs. After the advent of good infrared gas analyzers and the discovery of the C-4 vs. C-3 photosynthetic pathways, there was a major push during the 1970s and 1980s to select for higher single leaf photosynthesis. Researchers such as Dornhoff and Shibles (1970) found variation for increased single leaf light-saturated photosynthesis (A_{max}) that was associated with increased specific leaf weight (SLW) among soybean cultivars. This genetic variation was as much as 48% on a leaf area basis, but only 17% on a leaf mass basis. However, the yield of cultivars with higher leaf rate is not increased in proportion to the increase in single leaf rate. When the higher leaf photosynthesis is scaled up in model simulation of leaf-to-canopy assimilation and then to crop yield, the response is much less. With no coupling of A_{max} to SLW, a 10% higher leaf rate gives a 4 to 5% increase in canopy assimilation (but only for high light times of day). Therefore, the degree of benefit is scaled back considerably. The more realistic case is that the increased A_{max} is actually coupled or linked to increased SLW (this can be considered as a pleiotropic effect that causes the greater leaf rate). In this case, the simulated increase in canopy assimilation is much less, about 2 to 3%, because growing thicker leaves results in lower LAI (from the same leaf mass) and gives lower light interception (Boote & Tollenaar, 1994; Boote, Jones, Batchelor, Nafziger & Myers, 2003). Thus, the promised large benefit at leaf photosynthesis level is diminished greatly going to whole crop stands and on to final grain yield. There are other ways, via systems analysis of the whole crop, to envision a way to capitalize on the higher leaf A_{max}, but that requires a higher sowing density and narrow row spacing to push up the LAI to re-gain the light capture given up by thick leaves. Not surprisingly over the past 30 to 40 years, soybean producers have evolved toward using narrow row spacing and higher density sowing, such that some of the benefit is partially realized in current soybean cultivars (Boote et al., 2003). This example shows the need to synthesize and integrate an individual discipline finding into a whole crop systems simulation to see what the yield and economic value might be. This will be particularly important as molecular biologists propose improvements resulting from single genes that affect yield processes, in contrast to the current efforts on genes for herbicide tolerance, pest resistance, or crop composition.

Another example of the benefit of simulating crop C balance and energy cost, is that of genetically altering the composition of harvested products. A key concern is that there are differential energetic costs for producing different compounds. Simulations by Boote and Tollenaar (1994) showed that soybean yield was reduced almost 1% for each 1% increase in protein or 1% increase in oil, because proteins and oils require more energy to synthesize than starchy compounds. These simulations dispel the dream of plant breeders to just genetically “break” the observed negative linkage of high protein with lower yield potential. The problem here is one of limiting energy (or limited C or limited reduced N) that can be used to synthesize tissue, but it is not a genetics problem. The so-called genetic linkage is actually a physiological C:N:energy balance linkage. Indeed, if you were to give soybean a maize-seed composition, you could increase soybean yield by 32 to 41% (Boote & Tollenaar, 1994).

There have been major promises made for genes related to drought tolerance and water-use-efficiency. Crop systems simulations that consider energy balance, must trade (exchange) CO_2 gain for water vapor loss, because the pathway is the same. If stomata are partly closed to slow water loss rates, then the plant must decrease its CO_2 gain, and also endure higher foliage temperature. The physics of gradients for CO_2 in, and water vapor out, depend on relative humidity, leaf temperature, and light intensity (to drive CO_2-sink strength of leaf). The ratio of leaf internal CO_2 to external CO_2, appears to be highly regulated (Pearcy & Bjorkman, 1983) in crop plants (C-3 at 0.7 and C-4 at 0.4). There are only minor ways to modify the system. Thicker leaves and higher leaf protein concentration can decrease the intercellular CO_2 (C_i) of these species, thus providing a very minor improvement in WUE. Otherwise, there is little opportunity for improvement, despite promises in the literature. The concept of crop tolerance to desiccation, which is promoted by molecular genetics scientists, is almost irrelevant to annual seed-producing crops, because you do not want plants to enter a dormant state and stop producing economic yield, or you have already lost too much yield potential. However, survival under extended drought may have application to sustain stands of perennials used for grazing or forage, to avoid the necessity to re-plant the crop after extended drought.

Our future vision is that using models to integrate and synthesize research across disciplines will become more important into the future. Current funding agencies are also moving in this direction, by requiring participation of multiple disciplines to be represented in the development of grant proposals. There are now fairly accurate and well-tested mechanistic crop system simulation models that broadly consider all the external driving forces that can be found in field conditions, including the soil and weather environment and crop management inputs. These models can be used as platforms to allow the detail specialists to improve the crop models for depth and mechanism in their discipline area and then to test at the levels of what they understand to be intermediate test measurement outcomes, such as tissue nutrient concentrations or canopy transpiration, for example. But importantly, final growth and yield outcomes of those detail processes will also be available.

MODELS AS STRATEGIC TOOLS FOR RESEARCH PLANNING AND POLICY

There are many possible applications of crop system models that relate to making policy and strategy decisions at national, state, and local levels, where the use is not necessarily for real-time decisions. Government policy makers, agri-genetics firms (plant breeders), agrichemical companies, agricultural equipment companies, and research organizations can use crop system simulations as tools to evaluate strategies to plan for investments in research toward crop genetic improvement, crop management, and product development. This tool use differs from using models for integrating and synthesizing research, although it will require intelligent users and economic or political motivation. For example, a plant breeding company or a university plant breeder could use the model as a tool to evaluate aspects of genetic improvement versus germplasm that they hope to improve. A company selling fertilizer, fungicide, or herbicides could do the same to determine efficacy of a product.

Impacts of potential climate change on crop production, water use, nutrient leaching, and regional or national economics can be projected or hypothesized for future climate change scenarios, using crop system simulators along with other spatial and economics tools. This requires that the crop models be robust and correct for their response to elevated CO_2, temperature, rainfall, and solar radiation, and respond correctly to sowing dates, N fertility, and cultivar variation. Such tool use also requires the availability of reliable soils information, weather data, and knowledge of cropping practices (sowing date, cultivar, and fertilization) for the regions of interest. Various government agencies, universities, World Bank, and international centers such as International Food Policy Research Institute are interested in such applications. Potential uses include: to predict crop production/food security under a range of projected climate scenarios, to subsequently compute the economic consequences of the altered production, to compute the water use (irrigation required) and fertilizer use involved, to hypothesize possible adaptation/mitigation strategies under climate change such as shifted sowing dates, alternate crops/cultivars, genetic improvement for climatic stress (Boote, Jones, & Hoogenboom, 2008).

At regional and state levels with the same models, soils, and weather data availability over spatial regions, the crop system simulators could be used: 1) to project the consequences of N fertilization on production and N leaching over small to large watersheds for a given season or over long term weather, 2) to project crop water use (irrigation demand) for given watersheds for a given year or over long term weather, and 3) to hypothesize consequences of land use change to produce alternative crops, such as a biofuel crop, with the goal of understanding the water and fertilization requirements as well as the environmental and economic impact of shifting from one crop or land use to another. This could be particularly relevant in the current discussion of whether to produce biofuel crops rather than food crops, as it would allow evaluating overall economic, water, and resource use requirements. In order to take a good look at the options, one must have available good crop system models for forests, sugarcane, sweet sorghum, switchgrass, corn, and other food crop commodities.

For the state of Florida, Jones and Boote adapted and tested the DSSAT crop models with the goal of developing a best management practice (BMP) tool to maximize N use efficiency and to minimize N leaching. This required testing the models for correct uptake of N and correct tissue N concentrations, with the strategy that this would assist in predicting potential N leaching. Generally data on N leaching are scarce which limits model testing. The interest of the state of Florida, however, is to scale up and extend predictions of N use, N uptake, and N leaching over large-scale watersheds. In this particular case, the crop model is planned to be placed as one component within a watershed model.

Crop models have potential uses to evaluate possible "yield gap" causing reduced growth and yield, especially in under-developed country situations. For this purpose, the models must be developed and calibrated for potential growth in fields that do not have limiting factors of water, nutrients, or pests. In other words, the model response is primarily to temperature, solar radiation, and day length, along with genetic traits and crop management. If the same model over-predicts the slope of dry matter gain and/or final yield in a new field with the same basic weather, then one can suspect limiting factors such as soil fertility or pest limitations. This "yield gap" simulation approach was followed by Naab, Singh, Boote, Jones, & Marfo (2004) who determined that peanut yield in the rainy savannah of Ghana, was only partially limited by rainfall and soil water. Foliar diseases proved to be the main limitation and soil infertility was a minor additional contributing factor. The CROPGRO model in the DSSAT V3.5 and later DSSAT V4.0 is programmed to accept scouting inputs of pest damage (such as percent defoliation and percent necrosis), which are coupled to the model to create simulated reduction in leaf area index and simulated reduction in photosynthesis and eventually reduced growth and yield (Batchelor, Jones, Boote, & Pinnschmidt, 1993; Boote, Batchelor, Jones, & Pinnschmidt, 1993).

REAL-TIME DECISION SUPPORT TOOLS FOR MANAGEMENT DECISIONS

For many years, agricultural engineers and extension specialists have worked toward and anticipated the use of crop system simulation to assist with management decisions, both strategic pre-season as well as in-season, for a given field. The management decisions could include irrigation, N fertilization, sowing date, projected harvest, yield forecast, and pest management.

The realization of this dream has been slow and sporadic in its development, for several reasons. The first requirement is for crop models with sufficient ability to respond to these desired management practices as well as to the soils and weather experienced. Good spatial soils data are a second requirement because soils vary across a region and even within a given field. The third requirement is availability of long-term weather records (which allow a strategic pre-season evaluation of practices). A fourth requirement is for continuous access to current weather data to allow updating the simulations and projecting the crop growth and yield to the current date. Most of the limitations of these types of applications relate to access to accurate and local weather data (Hoogenboom, 2000). Typically, the models are additionally configured to run the remainder of the season with multiple “run-out” seasons of weather, to evaluate the range and probabilities of possible outcomes, depending on whether one irrigated or fertilized the crop today (or not), or otherwise manipulated the crop. Linkage to concurrently running pest simulators or input of scouting crop damage is another aspect that was attempted or envisioned. Prediction of growth stage for application of herbicides or growth regulators is a further use of in-season simulation.

The GOSSYM-COMAX system for cotton was one of the first simulators to attempt real-time field decision making, but a number of difficulties limited sustainable use of this system (McKinion & Baker, 1989). We attempted this use with the CROPGRO-Soybean model in a United Soybean Board (USB) project. The USB asked that the technology be transferred to a commercial firm as soon as possible, and the tool called PC-Yield (Welch, Jones, Brennan, Reeder, & Jacobson, 2002) was available for several years from a company named EMERGE which also sold weather services. However, the company went out of business in 2001, and the tool no longer is supported. One important lesson from the project, was the need to ensure ready access to data bases on cultivar coefficients, soils profiles, typical production practices, and the weather data. Lastly, a convenient simple interface with farmer/producers was very important. In order to develop this interface and what decision to offer a producer, we needed to have a good understanding of how the producers made their actual decisions.

Current versions of real-time decision support are being developed to provide producers with current weather data, a future 3-6 month expected climate projection (based on ENSO signal), and predicted crop performance. This approach has been successful with the Southeastern Climate Consortium (SCC) where the delivered product is primarily the past climate, along with simple computations such as chilling days, growing degree days, and pest favorability ratings (Fraisse et al., 2006; Paz et al., 2007). The SCC and other weather delivery service agencies are now examining how to provide available crop model simulations that run with the weather data for given locations, but this effort is proceeding slowly, so as not to overload the users. The agrometeorological weather service in India is actively moving in this direction (Boote et al., 2008). Issues to be resolved include learning what information the farmers and stakeholders really want, and how to develop their confidence in the information being delivered (Crane, Roncoli, Paz, Breuer, Broad, & Hoogenboom, 2009; Roncoli, Paz, Breuer, Ingram, Hoogenboom, & Broad, 2006). Again, we see the valuable role of socio-economic scientists in understanding how farmers make their decisions.

CROP SYSTEM SIMULATORS AS EDUCATIONAL TOOLS

Crop simulation models are valuable tools for the class room, to teach students and scientists the importance of considering and integrating all the driving variables that affect crop growth and yield in a given production situation. The first crop modeling courses were primarily to teach students about how to use the crop models, but increasingly the crop models are now being used in more general undergraduate/graduate classes to teach students about the integrational aspects of agriculture. Crop modeling courses (on how to model) were first offered by the Dutch modeling group in 1981 (K. Boote was an attendee). The next group to offer a crop modeling course, were Jones and Boote in 1984 at the University of Florida. About that time (1983-1984), the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) group was formed, and these scientists developed the Decision Support System for Agrotechnology Transfer (DSSAT) models, and began to conduct crop modeling workshops (Tsuji, Hoogenboom, & Thorton, 1998). This DSSAT modeling group of mostly the same scientists, over the next 20 years conducted crop modeling course every 1 to 2 years to present, for U.S. and international scientists. The DSSAT scientists now operate under a new umbrella, International Consortium for Agricultural Systems Applications (ICASA). The number of courses offered and the number of scientists taking the courses has increased over time, until in 2008, the DSSAT course was offered to 55 persons at one time. Most of the attendees have been scientists with PhDs and MSs with backgrounds in agronomy, agricultural engineering, agricultural economics, entomology, pathology, and information systems. Maybe a third of the attendees were actually graduate students at the time of taking the course, so most attendees were actually already in academia, government, and industry positions. G. Hoogenboom estimates that a total of 500 persons have taken the DSSAT course training and over 2,500 scientists have obtained a copy of the software through the International Consortium for Agricultural Systems Applications (ICASA, http://www.ICASA.net). J. W. Jones and K. J. Boote have offered essentially the same course as a University of Florida course annually or biannually since 2000. The crop modeling courses have been quite valuable to train individuals how to use the DSSAT software, but more importantly, to train the scientists to think about the whole systems function, to learn about the particular processes involved and how they are linked to the crop, and to learn how the systems models synthesize and link all the processes.

A FUTURE CHALLENGE: MODELING AND GENETICS/ MOLECULAR BIOLOGY

Advances in plant molecular biology are providing opportunities for crop modelers to improve the characterization of cultivar effects in models and to refine descriptions of plant processes. Although gene-based characterization of cultivars was first used in the 1990s (Messina, Jones, Boote, & Vallejos, 2006; White & Hoogenboom, 1996), broader application has been limited by the number of physiological gene loci described for any crop and the difficulty of obtaining genotype data for individual cultivars. Molecular biology is both increasing the list of major loci and providing low cost services for genotyping. Where information on specific loci is lacking, quantitative trait loci (QTLs) have been used. Again with decreasing costs of molecular characterizations, one option is to parameterize cultivar differences using QTLs. Even without QTL information, Mavromatis, Boote, Jones, Irmak, Shinde, and Hoogenboom (2001) and Mavromatis, Boote, Jones, Wilkerson, and Hoogenboom (2002) demonstrated that reliable genetic coefficients for simulating different cultivars could be derived from field performance trials on soybean with sufficient precision for crop model prediction under field conditions. With such genetic coefficients, crop models have already been used to evaluate genetic yield potential (Boote, Kropff, & Bindraban, 2001; Boote et al., 2003), especially over multi-environment test sites and yield testing procedures relative to genetic traits of crops such as peanut (Anothai, Pathanothai, Pannangpetch, Jogloy, Boote, & Hoogenboom, 2009; Putto, Pathanothai, Jogloy, Pannangpetch, Boote, & Hoogenboom, 2009).

Plant biology has also recognized the value of simulation modeling for synthesizing and integrating information, a process that can be viewed as a renewal of the interests of physiologists that fueled early simulation modeling (Loomis, Rabbinge, & Ng, 1979). Thus, simulation models are being developed for specific processes such as floral induction (Welch, Roe, Das, Dong, He, & Kirkham, 2005) and photosynthesis (Zhu, Portis, & Long, 2004). The iPlant Collaborative www.iplantcollaborative.org), a major project supported by the U.S. National Science Foundation, has recognized the need to develop an integrated cyberinfrastructure to facilitate modeling from the gene network level up to whole plant or crop system levels.

FUTURE NEEDS: MORE SCIENCE IN THE MODELS AND MODEL IMPROVEMENT

An important question is whether the crop models and their applications are data-limited or whether they are science-limited. Certainly, many of us have seen applications moving rather quickly in certain cases, and possibly ahead of the science. This is inevitable, considering the desire for users to promote novel applications (usually driven by grant funding), even before the crop modeling tools are full developed and tested. Funding is generally for applications, whereas funding for tool (crop model) development is rarer. In some cases, the science is already substantially developed (i.e., has the answers), but the crop model developers have too much inertia or are too busy, and basically delay making these changes because the changes may be too much work.

In answer to the above question, we believe that models are science-limited and are not being improved fast enough from the scientific knowledge that is already known, in part because the past emphases has been on software interfaces and other topics. Thus, we suggest several areas where we feel there is a need for more discipline-science-focused contribution to crop system model improvement: 1) description of root growth and nutrient uptake, especially for P and K, 2) coupling of foliar disease models (rusts or leafspots) to crop models to predict damage, 3) full coupling of energy balance to improve simulation of water-use-efficiency and responses to climate change, 4) full integration of crop models with global circulation models and regional circulation models, which may require the same energy balance as above, 5) addition of nutrient balance in models for nutrients beyond N and P, and 6) incorporation of information from genetics and molecular biology.

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J.W. White is a plant physiologist (PhD, UC Berkeley, 1981) who emphasizes use of ecophysiological models and geospatial tools to understand how crops respond to environment. His early research on common bean, conducted at CIAT near Cali, Colombia, sought to understand the physiological and genetic basis of cultivar differences in yield potential, adaptation to water deficits, and responses to photoperiod and temperature. Moving to CIMMYT in 1995, he established the Center's first GIS and crop modeling laboratory. His group revised CIMMYT's mega-environment classifications for maize and wheat research, and they successfully promoted use of geospatial tools at national and regional scales such as for efforts to develop drought tolerant maize in eastern and southern Africa. In 2003, Dr. White joined USDA-ARS in Arizona, where he currently works on predicting crop response to global change, continuing his work with models and geospatial tools. His work on incorporating genetic information in models suggests new avenues for collaboration among plant sciences, ecophysiology and global change biology. He has also long advocated improved data management, most recently through the International Crop Information System (ICIS), the International Consortium for Agricultural Systems Analysis (ICASA) and the iPlant Collaboration. He has coauthored over 60 journal papers and supervised over 15 MSc and PhD theses.