SUMMARY. In the 21st century, agricultural research has more difficult and complex problems to solve. The continued increase in population in the developing countries requires continued increases in agricultural production. However, the increased use of fertilizers, pesticides, and water required for the new higher yielding crop varieties has been causing environmental problems. Excessive leaching and runoff of agricultural chemicals are seriously affecting the quality of both the groundwater and surface waters. Increase in soil salinity, decline in soil organic matter, and increase in soil erosion remain the major problems in intensively farmed areas. Even the air quality is being affected. At the same time, market-based global competition is challenging the eco-
nomic viability of traditional agricultural systems. Global climate change will pose additional challenges. The solution or mitigation of these changing and multiple problems will require continual improvement or changes in management and selection of dynamic cropping systems using a whole-system approach. Therefore, synthesis and quantification of disciplinary knowledge at the whole-system level is essential to meeting these challenges. The process-based models of agricultural systems provide such a synthesis and quantification for evaluating the effects of varying management practices, crops, soils, water, and climate on both the production and the environment. These system models will greatly enhance the efficiency of field research for developing sustainable agricultural systems, serve as guides for planning and management, and help transfer new technologies to various conditions of developing countries. Current state of the system models and their applications for these purposes are reviewed, and advancements needed in models to improve and extend these applications are presented. doi:10.1300/J411v19n01_04 [Article copies available for a fee from The Haworth Document Delivery Service: 1-800-HAWORTH. E-mail address: <docdelivery@haworthpress.com> Website: <http://www.HaworthPress.com> © 2007 by The Haworth Press, Inc. All rights reserved.]

KEYWORDS. Synthesis of knowledge, synthesis across space and time, system approach, system models in research, decision support system, technology transfer

INTRODUCTION

Understanding real-world situations and solving significant agro-
nomic, engineering, and environmental problems require process-based synthesis and quantification of knowledge at the whole-system level. In the 20th Century, we made tremendous advances in discovering fundamental principles in different scientific disciplines using reduction methods, which created major breakthroughs in management and technology for agricultural systems. However, as we enter the 21st Century, agricultural research has more difficult and complex problems to solve. The environmental consciousness of the general public is challenging producers to modify farm management to protect water, air, and soil quality, while staying economically profitable. At the same time, market-based global competition in agricultural production and the global climate change are threatening economic viability of the traditional agricultural systems, and require the development of new and dynamic
production systems. Site-specific, optimal management of spatially variable soil, appropriately selected crops, and available water resources on the landscape can help achieve both environmental and production objectives. Fortunately, the new electronic technologies can provide a vast amount of real-time information about soil and crop conditions via remote sensing with satellites or ground-based instruments, which, combined with near-term weather, can be used to develop a whole new level of site-specific management. However, we need the means to assimilate this vast amount of data. A synthesis and quantification of disciplinary knowledge at the whole-system level, via process-based modeling of agricultural systems, are essential to develop such means and the management systems that can be adapted to continual change. Interactions among disciplinary components of the agricultural systems are generally very important. Models are the only way to find and understand these interactions in a system, integrate various experimental results and observations for different conditions, and extrapolate limited experimental results to other soil and climate conditions.

System modeling has been a vital step in many scientific disciplines. We would not have gone to the moon successfully without the combined use of good data and models. In designing of automobiles and airplanes, computer models of the system are increasingly replacing the scaled physical models of the past. Models have also been used extensively in designing and managing water resource reservoirs and distribution systems, and in analyzing waste disposal sites. Although a lot more work is needed to bring agricultural system models to the level of physics and hydraulic system models, the agricultural system models have matured enough (Ahuja et al., 2002; Matthews and Stephens, 2002; Struif Bontkes and Wopereis, 2003) that, with some good data to serve as reference, they can be used for many practical applications in research and management. These applications will expose knowledge or conceptual gaps in the models that will then be filled in time.

**HOW WILL MODELS BENEFIT FIELD RESEARCH?**

An agricultural system involves complex interactions among several different components and factors. Figure 1 illustrates some of these interactions of multiple factors operating through their connection to soil water. These interactions need interdisciplinary field research and quantification with the help of conceptual and process models.
FIGURE 1. An illustration of complexity of the agricultural systems via interactions among multiple components and factors through their connection to soil water.

Integration of system models with field research has the potential to significantly enhance efficiency of agricultural research and raise agricultural science and technology to the next higher level. The integration will benefit both field research and models in the following ways:

- Promote a systems approach to field research that examines all component interactions,
- Facilitate better understanding of the cause-and-effect relationships in and quantification of experimental results,
- Promote efficient and effective transfer of field research results to different soil and weather conditions, and to different cropping and management systems outside the experimental plots,
- Help field researchers focus on the identified fundamental knowledge gaps and make field research more efficient, and
- Provide the needed field test and improvement of the models before delivery to other potential users—agricultural consultants, farmers, ranchers, extension agencies, and action agencies (NRCS, EPA, and others).

Modeling of agricultural management effects on soil-plant-atmosphere properties and processes has to be a centerpiece of an agricul-
tural system model if it is to have useful applications in field research and management. An example is the ARS Root Zone Water Quality Model (RZWQM), a process level model built to simulate management effects on water quality and crop production (Figure 2; Ahuja et al., 2000). Most widely used crop models, such as the CERES and CROPGRO family, APSIM, GOSSYM, GLYCIM, EPIC/ALMANAC, need to be enhanced for simulating management effects on both production and environmental quality.

APPLICATIONS IN TECHNOLOGY TRANSFER AND MAKING MANAGEMENT AND POLICY DECISIONS

A field-tested model can be used to transfer the results of experimental research to other soil types, climates, and management conditions outside the experimental stations. It can also be used for extrapolating experimental results from a limited period of experimentation to variability in climatic conditions across longer periods (e.g., 25-100 years), and to extreme climatic conditions (e.g., droughts or flooding) not encountered during the study period. A validated model is an excellent tool for in-depth analysis of problems in management, environmental

FIGURE 2. Processes and time steps in RZWQM. Management practices are the centerpiece of this process-based cropping system model. (Adapted from Ahuja et al., 2000.)
quality, global climate change, and other new emerging issues. It can thus be a basis for national policies. Models can also be used to explore new ideas and strategies under different weather and climatic conditions before testing them in the field.

A field-tested model can also be used as a decision aid in choosing the best management practices for sustainable production over the long term (e.g., Andales et al., 2003), as well as to guide site-specific management on variable landscapes and within-season dynamic management in response to variable soil moisture and weather conditions (e.g., Ahuja and Ma, 2002). The new decision support systems (DSSs) have an agricultural system model at their core, but are supported by soil, climate, and management databases, environmental and economic analysis packages, user-friendly interfaces to check the default data and enter site-specific data, and a graphical visualization of results. An example is the design of USDA-ARS, GPFARM-DSS (Figure 3; Ascough et al., 1995; Andales et al., 2003). The GPFARM (Great Plains Framework for Agricultural Resource Management) is a whole-farm decision support system for strategic planning and evaluation of alternate cropping systems, range-livestock systems, and integrated crop-livestock farming options, for production, economics, and environmental impacts.

Currently, process level models may be difficult for agricultural consultants, extension field office personnel, and producers to use. A new approach toward a DSS is to create an integrated research-information database as a core of the DSS in place of a model. A system model, validated against available experimental data, is used to generate production and environmental impacts of different management practices for all major soil types, weather conditions, and cropping systems outside the experimental limits. This model-generated information is then combined with experimental data and the long-term experience of the farmers and field professionals to create a database (Rojas et al., 2000). The database can be combined with an economic analysis package. It may also be connected to a so-called “Multi-Objective DSS” for conducting a tradeoff analysis between conflicting objectives, such as economic return and environmental quality (Heilman et al., 2002). It is also very flexible in generating site-specific recommendations.

The most desirable vision for agricultural research and technology is to have a continual, two-way interaction among cutting-edge field research, conceptual and process-based models, and DSSs (Figure 4; Ahuja et al., 2002).
FIGURE 3: The design of GPFARM decision support system (DSS). (Adapted from Ascough et al., 1995 and Andailes et al., 2003.)
FIGURE 4. Interactions among field research, process-based system models, and decision support systems. (Adapted from Ahuja et al. 2002.)

EXAMPLES OF SYSTEM MODEL APPLICATIONS

In this section, we provide a broad sampling of applications of system models in research and strategic management. More comprehensive reviews of system-model applications are provided by Ahuja et al. (2002), Matthews and Stephens (2002), and Struif Bontkes and Wopereis (2003), among others. Several examples were taken from these three compilations while others were selected from the literature.

Enhanced Understanding of the Complexities in Experimental Data

The field experimental results are most often the outcome of the complex effects and interactions of several soil, climatic, and biological factors. As a consequence, the results vary from location to location and year to year. The cause-and-effect relationships in the data are extremely difficult to discern. The models are built upon the concepts and theories developed from the past hypothesis-based experimental research and include the various interactions to the extent of current knowledge. The models should account for the varying soils and climatic conditions for different locations and years for model simulations of the data to help explain variation of results and cause-and-effect relations in the results. When a model is tested against a good quality dataset and the model results deviate significantly from the experimental results, it may point to a possible knowledge gap in the model. Matthews and Stephens (1998) provided a good example of this. An ini-
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Model for tea (Camellia sinensis) showed that temperature alone could not be used to simulate a large peak in tea production in September of each year in Tanzania. A mechanism that could explain the peak was the assumption that the growth of dormant shoots was triggered at the time of winter solstice, allowing a large number of shoots to develop simultaneously and reach harvestable size at the same time. The proposed mechanism was based on the hypothesis that shoot dormancy was induced by declining photoperiod and released by increasing photoperiod. Additional research was needed to test this hypothesis more carefully, but the model did help enhance understanding of the mechanism.

Another example is provided in the area of chemical transport in soils. In certain soils, the distribution of a non-adsorbed chemical deviated from the Gaussian distribution that is theoretically expected and commonly found (Figure 5, top; Ahuja et al., 1995), in that the chemical seemed to be retained longer near the soil surface. Experiments and modeling in soil columns showed that when the surface soil layer consisted of stable aggregates, more chemical was retained near the soil surface (Figure 5, bottom; Ahuja et al., 1995).

Management of Crop Production

It is both difficult and impractical to conduct plot–or field–scale experiments that consider all possible management options across numerous environments. An obvious application of cropping system models is to simulate various management options in different environments to predict effects on crop production. Through careful interpretation of simulation results, researchers can identify the best management practices under the simulated conditions. In this section, applications of cropping-system models in studying the effects of various management practices on yield are highlighted.

Crop models have been used in yield-gap analyses to quantify potential yield compared with actual yield. Models can be used to estimate potential yields at multiple locations to determine effects of genotype and the environment (e.g., soils, climate, and day length). In one such example, Aggarwal et al. (1995) used the WTGROWS model to predict potential wheat yields across a latitude gradient in India. They determined that the yield gap was at least 2000 kg ha⁻¹, which indicated that much more could be done in wheat management to increase actual yields. A major finding in the study was that late sowing was contributing significantly to the yield gap.
Some crop-specific models can be used to simulate differences in yield among varieties. This is achieved by using the appropriate genetic coefficients in the model that characterize each variety. Dimes et al. (2003) used such an approach with the APSIM model in Zimbabwe. Using simulations of maize growth and yield, they demonstrated to local farmers the impact of changing from a short-duration variety commonly...
used in the area to a medium-duration variety. An 11-year simulation showed that this would have a detrimental effect on maize yields in most years, and local farmers clearly appreciated this information.

Oftentimes, there is interest in studying the interactions between variety and one or more management practices, such as planting date or nitrogen (N) fertilization. One example is the study by Dzotsi et al. (2003) using the Decision Support System for Agrotechnology Transfer (DSSAT) model to derive optimum combinations of cultivar and sowing dates for maize in Southern Togo. The study quantified the risks (standard deviations of yield) associated with combinations of varieties and planting dates. From the simulated data, informational leaflets were made and distributed to farmers as a guide in the selection of maize variety as a function of the preferred time of sowing.

Some crop models do not simulate all the major plant processes but rather focus on a single aspect or process, such as phenology. These models, as well as the more detailed models that simulate assimilation and allocation to plant parts, can be used to develop cropping calendars that give recommended dates for different operations. For example, the Rice Development (RIDEV) phenology model was used to simulate rice phenology for 30 years of historical weather data in Podor, Senegal to develop a cropping calendar (Wopereis et al., 2003). The cropping calendar included estimated dates for sowing, transplanting, split-applications of urea, last drainage, and harvest (Table 1).

A common application of crop models is the simulation of interactions between crop yield and levels of agricultural inputs such as irrigation water or nitrogen (N) fertilizer. Because models keep track of the water balance and N amounts in the soil profile as well as the estimated uptake by crops, the models can help estimate the proper amounts and timing of irrigation or N fertilization.

Saseendran et al. (2004) used RZWQM to quantify interactions between N level and wheat yield at Akron, Colorado (Figure 6). They found that the model was sensitive enough to simulate differences in biomass and grain yield among different N application rates. Thus, the model could potentially be used to determine N application rates, given soils and weather information.

Using data from the same location, Ma et al. (2000) used RZWQM to simulate soybean grain yield under different levels of irrigation (Figure 7). The study showed that the model had adequate sensitivity to correctly simulate the response of soybeans to various levels of water availability.
TABLE 1. RIDEV estimated cropping calendars using 7-day intervals for transplanted rice, cultivar Jaya, during the wet season in Podor, Senegal. (Based on simulations using 30 years of historical weather data.) (Modified from Wopereis et al., 2003.)

<table>
<thead>
<tr>
<th>Transplanting Date</th>
<th>First Urea Split</th>
<th>Second Urea Split</th>
<th>Third Urea Split</th>
<th>Date of Flowering</th>
<th>Date of Last Drainage</th>
<th>Harvest Date</th>
<th>Cropping Cycle (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 13</td>
<td>July 31</td>
<td>Aug 27</td>
<td>Sept 16</td>
<td>Sept 26</td>
<td>Oct 11</td>
<td>Oct 25</td>
<td>125</td>
</tr>
<tr>
<td>July 27</td>
<td>Aug 14</td>
<td>Sept 8</td>
<td>Sept 29</td>
<td>Oct 9</td>
<td>Oct 23</td>
<td>Nov 6</td>
<td>125</td>
</tr>
<tr>
<td>Aug 24</td>
<td>Sept 11</td>
<td>Oct 5</td>
<td>Oct 26</td>
<td>Nov 5</td>
<td>Nov 19</td>
<td>Dec 3</td>
<td>128</td>
</tr>
<tr>
<td>Aug 31</td>
<td>Sept 18</td>
<td>Oct 13</td>
<td>Nov 3</td>
<td>Nov 13</td>
<td>Nov 27</td>
<td>Dec 11</td>
<td>131</td>
</tr>
<tr>
<td>Sept 7</td>
<td>Sept 25</td>
<td>Oct 23</td>
<td>Nov 12</td>
<td>Nov 22</td>
<td>Dec 7</td>
<td>Dec 21</td>
<td>135</td>
</tr>
<tr>
<td>Sept 14</td>
<td>Oct 2</td>
<td>Nov 2</td>
<td>Nov 22</td>
<td>Dec 2</td>
<td>Dec 17</td>
<td>Dec 31</td>
<td>140</td>
</tr>
<tr>
<td>Sept 21</td>
<td>Oct 9</td>
<td>Nov 14</td>
<td>Dec 5</td>
<td>Dec 15</td>
<td>Dec 29</td>
<td>Jan 12</td>
<td>147</td>
</tr>
<tr>
<td>Sept 28</td>
<td>Oct 16</td>
<td>Nov 28</td>
<td>Dec 19</td>
<td>Dec 29</td>
<td>Jan 12</td>
<td>Jan 26</td>
<td>154</td>
</tr>
</tbody>
</table>

The CERES-Maize model was used in Malawi to perform modeling experiments to investigate the N fertilizer response on different soils (Singh et al., 2002). The complex interaction between soil moisture and nutrient rates across 25 seasons is shown in Figure 8.

Ahuja and Ma (2002) provided an example of using RZWQM to link irrigation timing and amount to soil water contents in the root zone. The model was used to simulate maize silage yields, N uptake by the crop, and N leaching at different irrigation amounts (Figure 9) at a site in eastern Colorado. The lower limit of available water to trigger irrigation was varied from 10% to 90%, and the upper limit to stop irrigation from 50% to 90%. The simulations showed that irrigations should be triggered when available water is about 20% and stopped when soil water storage is filled to about 50% to maximize N uptake and silage yield and minimize nitrate-N leached.

The model application described by Ma et al. (2000) is a good example of using RZWQM to determine the best time of nitrate-N application to optimize N uptake and silage yield while minimizing nitrate-N leaching (Figure 10). Their finding was that early-season was the best time to apply N.

Carberry et al. (2004) used simulation modeling in a novel way by combining a participatory research approach (direct interaction with
FIGURE 6. Field-measured and RZWQM model-predicted winter wheat grain and biomass yields during three crop seasons (1987-98, 1988-89 and 1989-90) under different N nutrient rates (0 kg N ha⁻¹ of 1987-88 was used for calibration of the model). Error bars represent one standard deviation of the measured grain yield from the mean.
FIGURE 7. Predicted soybean yields via RZWQM and a locally derived regression equation. Irrigation was applied with a gradient line-source system. 1985 irrigation (cm): (1) 0.28, (2) 3.38, (3) 8.86, and (4) 12.92. 1986 irrigation (cm): (1) 1.15, (2) 7.22, (3) 17.11, and (4) 24.98.

Farmers) with computer-based simulation modeling to engage smallholder farmers in Zimbabwe on issues of soil fertility management. One of their applications involved the simulation of different levels of manure application to answer a local farmer’s question about the value of applying manure. Through a combination of discussions with farmers and simulations with the APSIM cropping systems model, they demonstrated to the local farmers that the addition of low quality manure (Figure 11 b, C:N = 35:1) would have a detrimental effect on maize yield.
(because of N immobilization) but that the addition of higher-quality manure could increase maize yields (Figure 11 c and d).

A major concern in crop production is the sustainability of existing cropping systems and possibilities for improvement through introduction of alternate crops in a rotation. In a study of dry land cropping systems in eastern Colorado, Andales et al. (2003) used both GPFARM and experimental field data to show that cropping intensification more effectively utilized available soil moisture and increased overall system productivity compared with the prevalent wheat-fallow rotation (Figure 12).

In a simulation exercise using the Decision Support System for Agrotechnology Transfer (DSSAT) models in Brazil, Bowen et al. (1998) found that a continuous maize-fallow system with no inputs of fertilizer exhibited a gradual decline in maize yields across 50 years. On the other hand, a green manure-maize-fallow system was shown to maintain yields during the same period.
FIGURE 9. The responses of yearly average N uptake, maize silage yield, and nitrate-N leached to irrigation according to degree of root zone water depletion, as simulated by RZWQM.
The International Rice Research Institute is using rice crop models to help design morphological traits of the new plant types for yield and weed competition (Dingkuhn et al., 1991). Similarly the Pioneer Hi-Bred Company is exploring the use of models for developing new maize hybrids (personal communication).

Some examples of the commercial use of models to guide tactical management are (Matthews and Stephens, 2002):
1. SIRATAC for insecticide applications in cotton in Australia, 1981-89.
2. EMPIRE for control of diseases and pests in winter wheat in Europe, 1980s.
3. PUTU for irrigation scheduling in S. Africa, 1980s.

The models are also being used in teaching in several different countries.

**Water Quality**

An important requirement for the sustainability of current agricultural systems is the mitigation of adverse environmental effects. Intensive crop production has been recognized as a significant non-point source of water contaminants. A major concern is the movement of nitrate (NO$_3$-N), phosphorus, and agricultural chemicals (e.g., pesticides, herbicides) from agricultural fields into surface and ground water bodies. Agricultural system models that have the capability to simulate transformations and movement of agricultural chemicals have been used to assess the interactions between water quality and crop production management.

The Root Zone Water Quality Model (RZWQM) has been applied to various investigations of nitrate movement in the root zone and subsurface drains. Singh (1994) used the model to predict NO$_3$-N concentrations in the soil profile under different tillage practices in Iowa (Figures 13 and 14). He showed that the model could accurately differentiate among four alternative tillage practices and that NO$_3$-N concentration in the soil profile was a function of the degree of soil disturbance by tillage (e.g., no-till exhibited the least NO$_3$-N concentrations). In the same study, the NO$_3$-N concentrations in tile flow (sub-surface drainage) were also simulated (Figure 15).

Chemical transport in agricultural soils is greatly influenced by soil texture and structure. For example, the presence of surface aggregates and macropores (e.g., worm holes, channels left by decayed roots, cracks in drying soil) can result in preferential flow (i.e., by-passing of the soil matrix) and transport of pollutants to groundwater. The RZWQM was successfully used to simulate the flow of bromide in soil columns of varying combinations of surface aggregation and presence of macropores (Ahuja et al., 1995). The concentrations of
FIGURE 11. (a) Baseline simulation, using climate data for Tsholotsho for 11 years (1991-2001), was for maize cultivar sc501 grown on ipane soil with no applications of manure or inorganic fertilizer; and the changes in maize yields (bags acre$^{-1}$); (b) for the application of low quality manure; (c) for the application of high quality manure; and (d) for the application of high quality manure concentrated on a smaller area (0.5 acre). (Carberry et al., 2004. Reproduced by permission of ACIAR.)
FIGURE 12. Annualized yields at Sterling, CO (1989-1993) for different crop rotations (WF = wheat-fallow, WCF = wheat-corn-fallow, WCMF = wheat-corn-millet-fallow), observed and simulated by GPFARM.

FIGURE 13. Observed (points) vs. RZWQM simulated (lines) NO$_3$-N concentration for soil profile for day 150 in 1990. CP-Chisel Plow, MP-Moldboard Plow. (Modified from Singh, 1994.)
FIGURE 14. Observed (points) vs. RZWQM simulated (lines) NO$_3$-N concentration for soil profile for day 150 in 1990. NT-No Tillage, RT-Reduced Tillage. (Modified from Singh, 1994.)

FIGURE 15. Water and nitrate movement into tile drains (Nashua, IA). Simulations were done with RZWQM. (Modified from Singh, 1994.)
bromide, which is a surrogate for non-absorbed chemicals such as NO\textsubscript{3}-N, were adequately simulated in the soil columns (Figures 16 and 17). This provided some evidence that RZWQM can be used to predict transport of non-absorbed chemicals in soils exhibiting preferential flow.

In a field application of the RZWQM in Georgia, Ma et al. (1995) simulated atrazine (herbicide) transport in runoff. A strong correlation between simulated and measured atrazine in runoff (Figure 18) sug-

FIGURE 16. Bromide concentrations in soil water observed (solid curve) and simulated with RZWQM (dashed curve) with no surface aggregates.

![Bromide concentration in soil water observed and simulated](image1)

FIGURE 17. Bromide concentration in soil water as influenced by macropores and a 1 cm layer of surface aggregates observed (solid curve) and simulated with RZWQM (dashed curve).

![Bromide concentration in soil water with surface aggregates](image2)
gested that the model effectively simulated movement of atrazine from the field.

**Climate Change Effects on Crop Production**

At the close of the 20th Century, widespread concern grew about climate change brought about by anthropogenic pollution. In the agricultural sector, the main concern is the effect of climate change (e.g., increased atmospheric CO$_2$, elevated air temperature) on crop production. Agricultural system models have been used to investigate the possible impacts of climate change on yield. Practically, system modeling is the only feasible approach to the study of this global phenomenon as it is impossible to completely understand the interactions between climate change and crop production based on limited plot-scale experiments or controlled-environment studies. With system models, investigators can simulate crop production under various scenarios of climate change.

The GOSSYM cotton model was used in a 30-year simulation study and showed that increased CO$_2$ had a positive effect on cotton production in Mississippi (Figure 19; Reddy et al., 2002). Various climate scenarios

were investigated based on possible combinations of CO₂ concentration and weather patterns (Figure 20; Reddy et al., 2002).

In a study of climate change effects on rice yields in India, Aggarwal and Mall (2002) looked at the interactions among uncertainties in climate change scenarios, crop models, and nitrogen management (Figure 21). There was considerable difference in the impact of climate change on rice yields calculated by the ORYZA1N and CERES-Rice crop models (see differences between lines 1 and 2; lines 3 and 4 in Figure 21). This example shows the potential for arriving at different conclusions, mainly due to differences in assumptions built into different crop models.

A good example of a large-scale application of crop modeling in climate change studies is the investigation by Matthews et al. (1995) funded by the U.S. Environmental Protection Agency. The ORYZA1 model was used to predict changes in rice production for the major rice-producing countries in Asia under three general circulation model (GCM) scenarios. In general, an increase in CO₂ level was found to increase rice yields, whereas yields were reduced with increases in temperature.
FIGURE 20. Simulated cotton yields for different years with varying weather patterns. (Reddy et al., 2002. Copyright 2002 from Agricultural System Models in Field Research and Technology Transfer by L.R. Ahuja, L. Ma, and T.A. Howell (Eds.). Reproduced by permission of Routledge/Taylor & Francis Group, LLC.)

Not only does climate change affect crop production, but also contributes to further climate change via production of greenhouse gases. Methane (CH$_4$) is a greenhouse gas that is emitted from rice fields in significant amounts because of the anaerobic soil conditions under which rice is grown. Matthews et al. (2000) used the MERES (Methane Emissions from Rice EcoSystems) model to upscale experimental field data of CH$_4$ emissions to the national level and to evaluate potential mitigation strategies. The model predictions showed that field drainage to minimize anaerobic conditions could potentially decrease CH$_4$ emissions by an average of 13% across five countries, viz., China, India, Indonesia, Philippines, and Thailand.

COLLABORATIONS FOR FURTHER DEVELOPMENTS

The collective experiences of model developers and users show that, even though they are not perfect, the agricultural system models can be
FIGURE 21. Response of irrigated rice yields (% change in yield in climate change over the control yield) in northern India to different levels of N availability for the Intergovernmental Panel on Climate Change's (IPCC) optimistic and pessimistic scenarios of climate change for 2010 and 2070. The simulations were done using two crop models–CERES-rice and ORYZA1N. The difference between lines 1 and 2 and between lines 3 and 4 refers to uncertainties in impact assessment due to climate change scenarios as simulated by ORYZA1N and CERES-rice, respectively. The difference between the top and bottom lines in each figure refers to the total uncertainties due to crop models and climate change scenarios. (Aggarwal and Mall, 2002. Reproduced by permission of Springer Science and Business Media.)

very useful in field research, technology transfer, and management decision-making as demonstrated in this paper. These experiences also show a number of problems or issues that should be addressed to improve the models and their applications. The most important issues are:

- System models need to be more thoroughly tested and validated for science defensibility under a variety of soil, climate, and management conditions, with experimental data of high resolution in time and space.
- There is a need to build comprehensive and common shared experimental databases based on existing standard experimental protocols, and relate measured values to modeling variables, so that conceptual model parameters can be experimentally verified.
- There is a need for better methods of determining parameters for different spatial and temporal scales, and for aggregating simulation results from plots to fields and larger scales.
• There is a need for better communication and coordination among model developers in the areas of model development, model parameterization, and model evaluation.

• There is a need for better collaboration between model developers and field scientists for appropriate experimental data collection and for evaluation and application of models. Many times the involvement of field scientists in modeling exercises is limited to providing experimental data for model testing. Instead, field scientists should be involved in model development from the beginning.

• There is an urgent need for filling the most important knowledge gaps: agricultural management effects on soil-plant-atmosphere properties and processes; plant response to water, nutrients, and temperature stresses; and effects of natural hazards like hail, frost, insects, and diseases.

• And finally we need to improve upon the methods and structure of model building so that: (1) the models are modular, with each model component (module) clearly defined, documented, and assigned a degree of uncertainty; (2) each model component can be independently tested and improved, and can be easily substituted; (3) the whole world community can contribute to developing, testing, and improving components; (4) the components may vary with the scale of application; (5) hierarchical parameter estimation from varying degrees of input information is a component of the model; (6) the assembled models of the system are kept compact and easy to use by customizing them to agro-ecosystem regions; (7) a user-friendly interface is provided for easy input of data and output of results; and (8) a well-illustrated user manual is provided to illustrate a step-by-step procedure for running the model and some examples of model application that demonstrate the benefits of using the model as well as the uncertainty in results.

To address the last issue stated above, a cross-agency (USDA-ARS, NRCS, USGS) project is underway to develop a modular modeling computer framework that will consist of a library of alternate modules (or subroutines) for different sub-processes of science, associated databases, and the logic to facilitate the assembly of appropriate modules into a modeling package (David et al., 2002; Ahuja et al., 2005). The modeling package can be tailored or customized to a problem, data constraints, and scale of application. The framework will: (1) enable the use of best science for all components of a model; (2) allow quick updates or replacement of science or database modules as new knowledge
becomes available; (3) eliminate duplication of work by modelers; (4) provide a common platform and standards for development and implementation; (5) serve as a reference and coordination mechanism for future research and development; and (6) make collaboration much easier among modelers by sharing science modules/components and experimental/simulated databases, so that specialties of each individual modeling group can be maximally utilized.

In the future, model developers need to work together among themselves to address the seven problem areas described above, and then train and work with field scientists to improve model visibility and applicability in solving real-world problems. Also, there is a need to better document system models and simulated processes so that field scientists will be able to understand these processes without too much difficulty. We also need to document good case studies on model applications to serve as guides for field users. Any improvements to an existing model could be checked against these documented cases to see if these improvements are applicable to all situations. Since most field data are not collected for the purpose of evaluating with a system model, some good system-oriented experiments may be needed. International efforts are needed to coordinate system modeling and to encourage model developers and field scientists to work on identified knowledge gaps and research priorities. The above actions will prepare the models for their important roles in the 21st Century, and take the agricultural research and technology to the next higher plateau.

**CONCLUSIONS**

This article describes the tremendous potential benefits of the agricultural system models for field research and as management guides. It provides some examples of model applications in research and management from the worldwide literature. It also brings out the limitations and knowledge gaps in the current models where further improvements must be made.

Where do we go from here? In order to gradually realize the potential benefits of the models and further improve the models, we believe the most important first step is to fully integrate system models with field research. Modelers must work collaboratively with field scientists in various areas from several different locations. Even with current shortcomings of the models, the models can be very useful in synthesizing and quantifying experimental results across different climates, soils,
and agricultural systems at different locations. This synthesis will enhance understanding of the diversity of results and point toward different management practices. For example, system models should be used to synthesize results for different crop rotations, water quality, and greenhouse gas emissions across a region or a country. The models should also be used to evaluate sustainability of current agricultural systems over longer periods of time, with current climate and with projected climate changes. This will lead to information for devising management strategies to mitigate adverse effects of climate change. The major new findings from the regional or national evaluations and from long-term system analysis could be provided to the end users and policy makers in simple spreadsheet and graphical forms.

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