Systems Modeling for Soil and Water Research and Management: Current Status and Needs for the 21st Century

L. Ma, L. R. Ahuja, R. W. Malone

Abstract. *Quantitative system approaches, provided by process-based models of agricultural systems, are essential for optimizing the use of increasingly limited water and soil resources, guiding tactical management, and addressing the environmental concerns and global issues of the 21st century. Agricultural engineers have made significant contributions in the past to model development and applications in soil and water research, irrigation design, and water management, and they are uniquely capable of making the much-needed and exciting further model enhancements. In this brief review, we present: (1) the current status of system model development and applications in soil and water research and management, with examples from the USDA-ARS Root Zone Water Quality Model (RZWQM); (2) lessons learned from RZWQM development and applications; and (3) future needs and directions in system model enhancements and applications to make them more effective. We make a strong case for international collaborations among modelers and experimentalists and for a common development/applications protocol and platform for the future.*

Keywords. Agricultural management, Agricultural systems, Environmental quality, Model application, RZWQM.

In the 20th century, agricultural engineers made tremendous advances in soil and water research and applied the research results to manage soil and water resources around the global, which created major breakthroughs in management and technology for agricultural systems. Typical examples are efficient irrigation, subsurface tile drainage, soil erosion control, and water quality management technologies. However, as we enter the 21st century, agricultural research has more difficult and complex problems to solve. The quantity of fresh water available for agriculture is diminishing due to increased urban uses, and it is further affected by more frequent droughts and uneven rainfall distribution in recent years (Vörösmarty et al., 2000). The quality of groundwater and surface waters is seriously affected by excessive leaching and runoff of agricultural chemicals and salts in many places (Randall and Mulla, 2001; Dinnes et al., 2002). Wind and water erosion remain a problem in intensively farmed areas (Larson et al., 1983). The environmental concerns of the general public are challenging producers to modify farm management practices to protect water, soil, and air quality, while staying economically profitable in the new global market. The solution or mitigation of these problems requires more quantitative whole-system approaches to optimize the use of soil and water resources and assess the impacts of management practices on soil and water quality. Process-based agricultural system models provide this approach. Agricultural engineers need to work with scientists from other disciplines to further improve these models.

Agricultural engineers have been pioneers in developing and using system models for field research and design. Use of computer models in agriculture has been an interest among members of the ASABE since the 1960s (Smerdon, 1967). Major field-scale agricultural models published in *Transaction of the ASAE* (now *ASABE*) include CREAMS (Knisel et al., 1985), EPIC (Sabbagh et al., 1991a), DRAINMOD (Perry et al., 1990), GLEAMS (Reyes et al., 1993, 1995), CROPGRO (Irmak et al., 2005; Paz et al., 2001a, 2001b; Perry et al., 1990), CERES (Royce et al., 2001), WEPP (Reyes et al., 2004a), PRZM (Malone et al., 1999), and RZWQM (Ma et al., 2003; Bakhsh et al., 2004a, 2004b). Although some models initially emphasize selected components of a cropping system, not the whole system, hybrid models have been developed among these models to extend or enhance their applications. For example, the inclusion of water table and surface drainage in GLEAMS (GLEAMS-SWT) (Reyes et al., 2004b) and EPIC (Sabbagh et al., 1991a, 1991b), hybrid models between GLEAMS/CREAMS and DRAINMOD (Desmond et al., 1996; Saleh et al., 1994), the introduction of the SOYGRO plant growth model into DRAINMOD (Perry et al., 1990), linkage between EPIC and GLEAMS (Sabbagh et al., 1991b), the extension of RZWQM to simulate detailed crop canopy energy balance using components from SHAW (Flerchinger et al., 2000, Yu et al., 2007), and the addition of CERES and CROPGRO into RZWQM for better crop simulations (Ma et al., 2005; Ma et al., 2006).

Applications of the models have covered a variety of agricultural issues, such as climate impact on crop yield (Irmak et al., 2005), N loss due to drainage intensity (Skaggs et al., 2005) and irregularity (Northcott et al., 2001; Kurien et al., 1997), variable planting rate (Paz et al., 2001a) and planting

The authors are **Liwang Ma,** Soil Scientist, and **Lajpat R. Ahuja,** Soil Scientist, USDA-ARS Agricultural Systems Research Unit, Fort Collins, Colorado; and **Robert W. Malone, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS National Soil Tilth Lab, Ames, Iowa. **Corresponding author:** L. R. Ahuja, USDA-ARS Agricultural Systems Research Unit, 2150 Centre Ave. Building D, Fort Collins, CO 80526; phone: 970-492-7315; fax: 970-492-7310; e-mail: Laj.Ahuja@ars.usda. gov.

date (Saseendran et al., 2005a), tillage effects (Bakhsh and Kanwar, 2001), crop rotations (Ma et al., 2007a, 2007b), manure/fertilizer management (Edwards et al., 1994), precision farming (Irmak et al., 2001; Braga and Jones, 2004), pesticide management/transport (Sabbagh et al., 1991b), irrigation management (Ma et al., 2003), and soil erosion and runoff transport of applied manure and fertilizer (Edwards et al., 1994). Several of those models were also linked to GIS for spatial applications, such as RZWQM-GIS (Wang and Cui, 2004; Ascough et al., 2005), GLEAMS-GIS (Tucker et al., 2000), SWAT-GRASS (Rosenthal and Hoffman, 1999), and DSSAT-GIS (Lal et al., 1993).

Although applications of the models cannot replace the cutting-edge field studies, they do help us understand the complex interactions among different components and extend results beyond the experimental sites and years. The models can also be used to study phenomena that cannot be experimentally investigated, such as uncertainty analysis (Wang et al., 2005), climate impact (Irmak et al., 2005; Royce et al., 2001), risk/probability analysis (Saseendran et al., 2005b), optimization of management (Stulina et al., 2005), identification of limiting factors (Paz et al., 2001b), and regional scale analysis (Lal et al., 1993). Another important aspect of system models is their use as tools to investigate new knowledge gaps, such as water stress factors on plant growth (Kozak et al., 2006), surface residue structure effects on energy balance (Kozak et al., 2007a), scaling of infiltration and soil water across different soil types (Kozak and Ahuja, 2005; Kozak et al., 2005), rainfall interception by the plant canopy (Kozak et al., 2007b), pesticide adsorption mechanisms in soils (Sabbagh et al., 2007; Fox et al., 2007), and the role of macropore flow in chemical transport (Malone et al., 2001, 2003; Fox et al., 2004).

Since system models have much in common in their development and applications, we have selected the USDA-ARS RZWQM to demonstrate the evolution of a system model. Therefore, the objectives of this review are to present: (1) the current status of system model development and applications in soil and water research and management, with examples from the Root Zone Water Quality Model (RZWQM); (2) lessons learned from RZWQM development and applications; and (3) future needs and directions in system model enhancements and applications.

CURRENT STATUS OF SYSTEM MODEL DEVELOPMENT AND APPLICATIONS: RZWQM AS AN EXAMPLE

Many system models have been reported in the literature since the 1960s. Some of them are more widely used than others, and many have not been published in *Transactions of the ASABE*, such as Daisy (Hansen et al., 2001) and HERMES (Kersebaum and Beblik, 2001). The major directions in model development in the last 10 to 15 years have been: (1) to enhance an existing model to the whole-system level by including all possible agricultural processes (Kozak et al., 2006); (2) to extend the modeling process from one dimension to two or three dimensions (Wu et al., 2007); (3) to expand from field scale to landscape and watershed scales through linkage with GIS (Tucker et al., 2000; Ascough et al., 2005); and (4) to upgrade a model using better computer technology, such as better modularization and parameteriza-

tion tools (Jones et al., 2003; Ahuja et al., 2005). However, all the models share similar histories in their development and applications. Therefore, we use RZWQM as an example to illustrate the current status of system models. In addition, RZWQM uses state-of-the-science simulation of management effects on soil and water quality, which are critical to system modeling for agricultural applications.

In the fall of 1986, a group of USDA-ARS scientists met to identify the needs for modeling effects of agriculture on water quality. Based on the models available at that time, they concluded that there was a strong need for process-based quantification of chemical, physical, and biological reactions in the root zone as affected by management practices. The product from this workshop was the formation of a team from several USDA-ARS research units nationwide to build the Root Zone Water Quality Model (RZWQM). The team was to learn from existing models and incorporate additional features needed for simulating management impacts, such as chemical transport via macropores, tile drainage, detailed soil chemistry and nutrient transformations, improved pesticide dynamics, a comprehensive plant growth model, and major water-soil-plant management practices (Ahuja et al., 2000). The first version of RZWQM was released in 1992, and the development team immediately formed partnership with the scientists, especially agricultural engineers, in the MSEA (Management Systems Evaluation Areas) projects in the U.S. Midwest to evaluate the model. This integration of modeling with field research not only improved and enhanced RZWQM but also assisted field scientists in synthesizing and quantifying their field results.

In the last five years, a series of improvements have been implemented in RZWQM to meet the demands of its customers, including: (1) incorporation of the most widely used DSSAT crop growth modules (DSSAT3.5 first and DSSAT4.0 later) to provide state-of-the-science plant growth simulations (Ma et al., 2005, 2006); (2) linkage with SHAW to simulate surface energy balance and frozen soils (Flerchinger et al., 2000; Kozak et al., 2007a); (3) addition of the erosion component from GLEAMS; (4) extension of the soil profile to 30 m so that its simulation results can feed into a groundwater flow model to simulate management effects on groundwater contamination at the regional scale; (5) the capability of simulating tile flow under controlled drainage and subsurface lateral flow below the tile (Ma et al., 2007a, 2007b); 6) the flexibility of expressing a portion of pesticide directly into tile flow via a fraction of macropores (Fox et al., 2004, 2007); and (7) further improvement in the Windows user interface to facilitate model parameterization and post data analysis with experimental data. Efforts have been made to link RZWQM into GIS for watershed modeling (Wang and Cui, 2004; Ascough et al., 2005). Simulation results are also used to develop information database for decision support and economic analysis (Heilman et al., 2006).

Since its first release in 1992, RZWQM has been widely used to simulate various agricultural management effects on water quantity and quality, such as tillage, manure/fertilizer management, crop management, pesticide applications, and irrigation (Ma et al., 2000; Malone et al., 2004a, 2004b, 2004c, 2007; Ma et al., 2007a, 2007b). The following applications are from RZWQM to demonstrate a typical systems model's role in soil and water research. Information on how RZWQM simulates these management practices is available from Ahuja et al. (2000) and Ma et al. (2000).
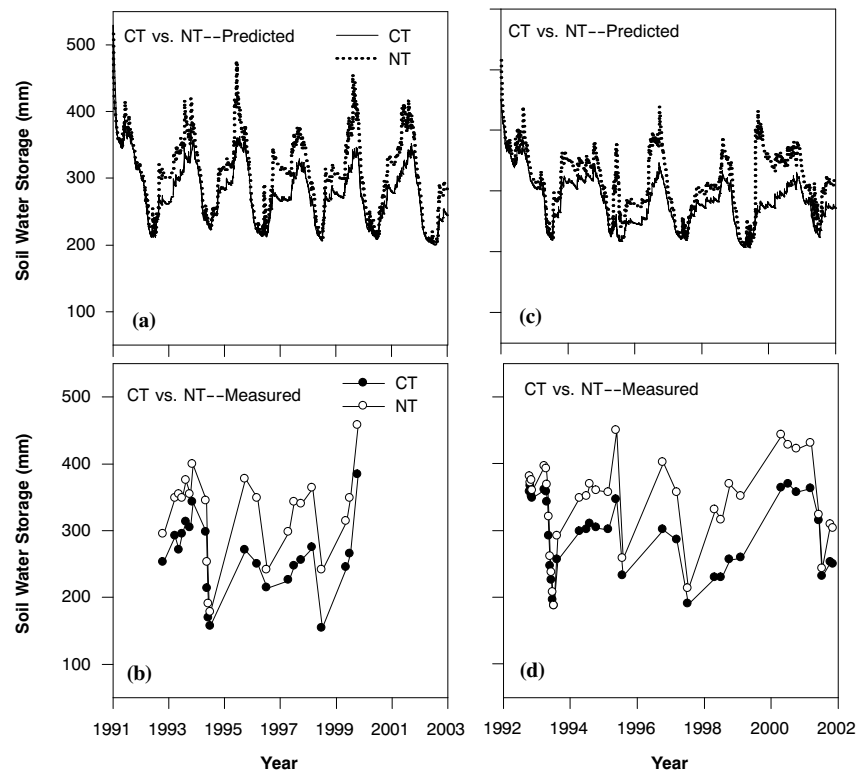
Figure 1. RZWQM-simulated and measured total soil water storage (180 cm) under (a and b) wheat-fallow and (c and d) fallow-wheat crop rotations under conventional tillage (CT) and no-till (NT) (Saseendran et al., 2005b).

TILLAGE PRACTICES

Reports of using RZWQM for simulating tillage effects on N loss and soil water content can be found in Saseendran et al. (2005b) and Ma et al. (2007a). As shown in Ma et al. (2007a) in their Nashua, Iowa, study, RZWQM adequately simulated tillage effects on yearly tile flow, flow-weighted N concentration in tile flow, and N losses in tile flow. However, the model failed to simulate tillage effects on crop yield. Further improvement in this area is warranted. Tillage effects on N loss in tile flow depended, as expected, on crop rotation and N management. In a separate study in eastern Colorado, Saseendran et al. (2005b) correctly simulated higher soil water storage under no-till than under conventional tillage in both phases of wheat-fallow rotations, although the simulated differences in soil water storage between tillage levels were not exactly the same as measured (fig. 1).

NITROGEN MANAGEMENT

RZWQM has been used extensively in simulating water, fertilizer, and manure management under tile-drained conditions (Ma et al., 2007a, 2007b; Malone et al., 2007; Bakhsh et al., 2004a, 2004b), in addition to the tillage effects noted above. Ma et al. (2007a) found that RZWQM was capable of simulating controlled drainage effects in Iowa by raising the tile outlet in the fall and winter to reduce N loss in tile flow. The model was also adequate in simulating tile flow amounts and N/pesticide loss in the tile flow and their responses to rainfall and manure/fertilizer management (Ma et al., 2007a, 2007b; Malone et al., 2007; Bakhsh et al., 2004a, 2004b). RZWQM was also used to evaluate crop yield and N leaching due to fertilizer applications under different rainfall conditions (Saseendran et al., 2004; Hu et al., 2006) and manure

management (Ma et al., 1998a, 1998b; Bakhsh et al., 1999). N loss in runoff was also simulated in several studies (Schwartz and Shuman, 2005). Figure 2 shows N losses in tile drainage with UAN (urea-ammonium-nitrate) and manure applications in a Nashua, Iowa, field study by Ma et al. (2007b). Both experimental and simulated results demonstrated high N loss in tile flow when UAN was applied. Fall manure application caused more N loss than spring manure application.

CROP ROTATION AND RESIDUE MANAGEMENT

RZWQM has been used to simulate several dryland crop rotations in Colorado for soil water use (Saseendran et al., 2005b) and corn-soybean and corn-corn rotations for water use and water quality in Iowa (Ma et al., 2007a, 2007b; Malone et al., 2007). Ma et al. (2007a) showed that RZWQM simulated the correct trend in crop rotation effects on tile drainage, flow-weighted yearly N concentration in tile flow, yearly N loss in tile flow, and crop yield. The calibrated model is being used for developing a database for decision support purpose. RZWQM was also successfully used to simulate residue decomposition (Ma et al., 1999), planting date management (Saseendran et al., 2005a), and winter cover crop effects on tile drainage and N leaching (Malone et al., 2007). The incorporation of SHAW into RZWQM enabled the simulation of crop management effects on surface energy balance (Kozak et al., 2007a) and extended RZWQM to frozen soils (Flerchinger et al., 2000).

IRRIGATION MANAGEMENT

Studies on applying RZWQM for irrigation management were focused on crop yield (Ma et al., 2003; Nielsen et al., 2002), N leaching (Ma et al., 1998a, 1998b), and pesticide
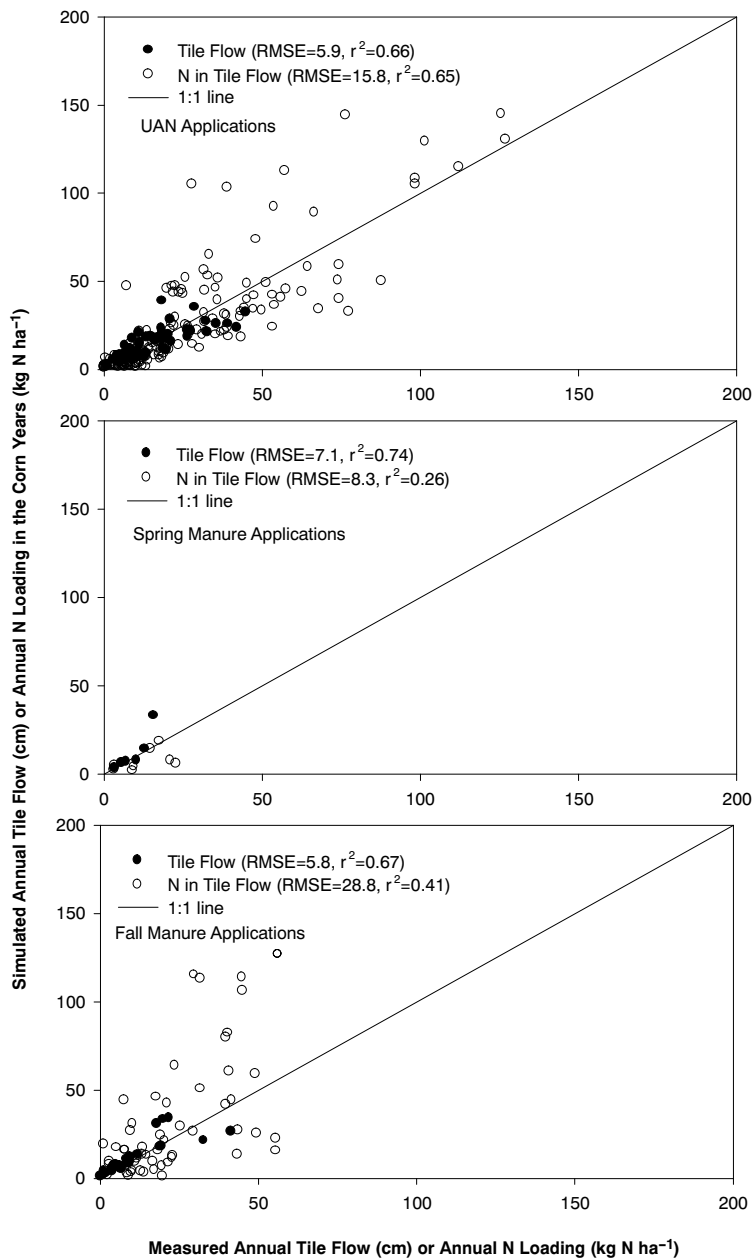
Figure 2. Simulated and measured annual tile flow and annual N loading in tile flow from a long-term study in Nashua, Iowa, for the corn years with UAN, spring manure, and fall manure applications (Ma et al., 2007b).

leaching (Ellerbroek et al., 1998; Azevedo et al., 2002). Figure 3 shows an example of RZWQM-simulated soybean yield under four irrigation scenarios in eastern Colorado (Ma et al., 2000). RZWQM provided better simulation results for both years (1985 and 1986), as compared to a regression equation based on evapotranspiration (Nielsen, 1990), which only provided reasonable results for 1986.

PESTICIDE MANAGEMENT

In RZWQM, we also allow express transport of pesticide into tile drains directly via a small fraction of macropores (Fox et al., 2004, 2007). Although there is a pesticide uptake routine in RZWQM, the uptake mechanism has not been fully tested (Sabbagh et al., 2007). Evaluation of RZWQM for pesticide management has been focused on residual soil pesticide (Ma et al., 1995), pesticide leaching (Ellerbroek et al., 1998), pesticide in runoff (Ma et al., 1996, 2004a), and pesti-

cide in tile flow (Bakhsh et al., 2004a). Recently, RZWQM has been used to simulate the fate and transport of pesticides and their metabolites from pesticide-treated seeds (Sabbagh et al., 2007; Fox et al., 2007) and under different tillage systems (Malone et al., 2003). Description of the pesticide components of RZWQM is available from Wauchope et al. (2004) along with several other applications and analyses (Ma et al., 2004a, 2004b; Malone et al., 2004a, 2004b, 2004c). However, simiulation of macropore dynamics is needed for pesticide transport in shrink-swollen soils.

OTHER APPLICATIONS

Coupling RZWQM with remotely sensed soil moisture was done by Mattikalli et al. (1998) to estimate soil hydraulic conductivities for spatially distributed soils. Heathman et al. (2003) was able to simulate surface soil moisture better when
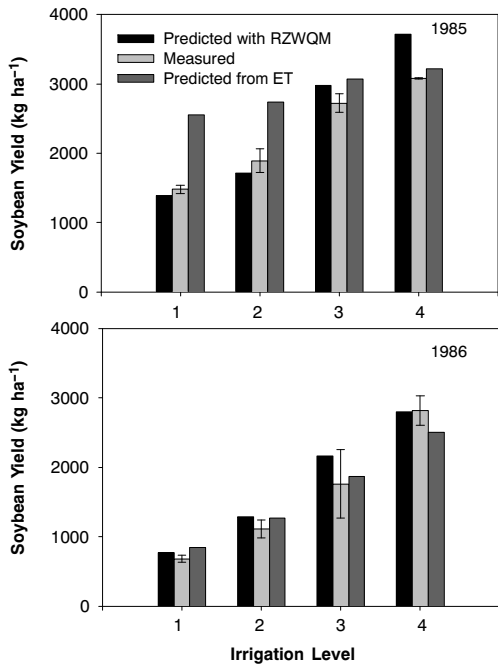
Figure 3. Measured and predicted soybean grain yield in 1985 and 1986 at four irrigation levels (from Ma et al., 2000). Seasonal irrigation for the four levels was 0.28, 3.38, 8.86, and 12.92 cm in 1985 and 1.15, 7.22, 17.11, and 24.98 cm in 1986. Regression equation to estimated soybean yield from ET was from Nielsen (1990).

remotely sensed data were used along with RZWQM. RZWQM was also used to evaluate alternative management practices (Ma et al., 2007a, 2007b; Malone et al., 2007; Saseendran et al., 2005b), to search for best management practices (Stulina et al., 2005) and to study the interactions between water and N management to recommend best management practices (Ma et al., 1998b; Hu et al., 2006). One important application of RZWQM was to help register a pesticide with the U.S. EPA when data collection in the field was incomplete (Fox et al., 2004). Other useful examples are the probability and risk analysis of crop production under different crop rotations and planting windows using historical weather data (Saseendran et al., 2004, 2005a, 2005b). Figure 4 shows the probabilities of obtaining break-even yield in eastern Colorado when corn was planted at different dates using historical weather data (Saseendran et al., 2005a).

LESSONS LEARNED FROM RZWQM DEVELOPMENT AND APPLICATIONS

As with other system models, RZWQM is constantly being enhanced to address new problems in agricultural systems. The lessons learned from RZWQM have general implications for the modeling community, especially as the RZWQM team is collaborating with system modelers worldwide. Valuable lessons include:

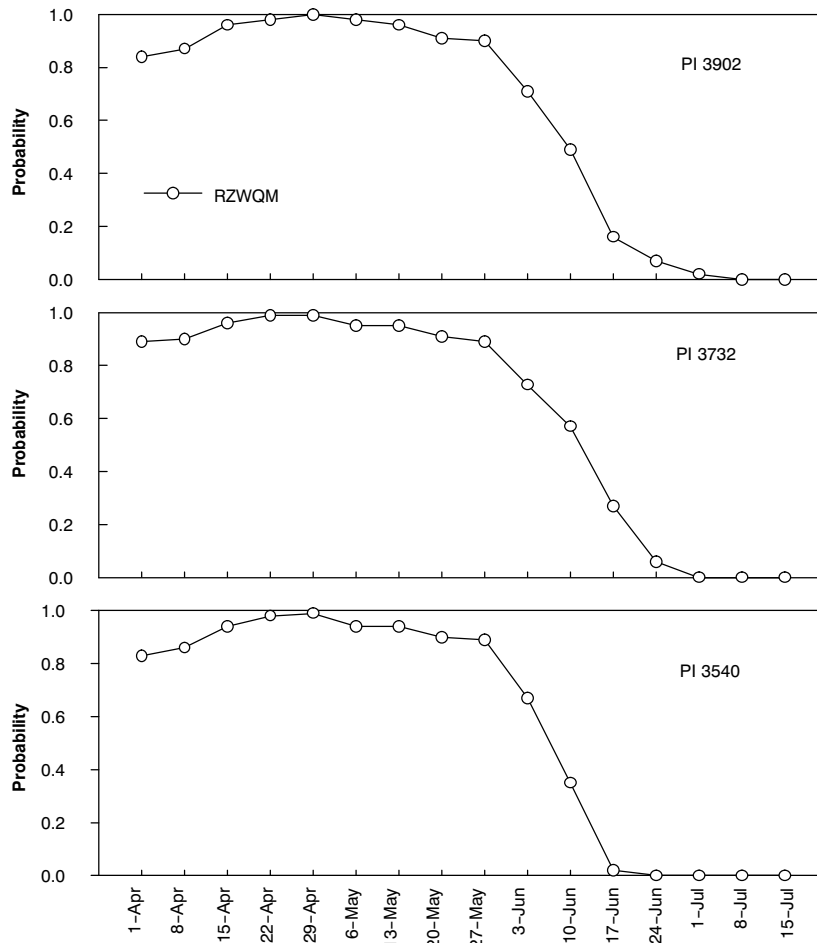**Figure 4. Probabilities of achieving break-even corn yield (7000 kg ha^{-1}) under irrigated conditions for plantings from 1 April through 15 July, derived from the long-term (1912-1999) simulations of hybrids PI 3902, PI 3732, and PI 3540 using RZWQM (Saseendran et al., 2005a).**

- It is important to understand the system to be simulated and to obtain first-hand information on the major system components and their interactions. For example, is runoff important? If it is, then rainfall intensities need to be accurate. Otherwise, the user does not need to work hard to find out exact rainfall intensity for each day. What are the major agronomic factors affecting plant growth and are they well represented in the model? Can we treat the whole field as a single simulation unit? If not, how many simulation units are needed and what are the interactions among them, or is a model at different scale needed? It is a constant challenge to define the physical-chemical-biological system being simulated, especially in terms of temporal and spatial variability.
- An easy-to-use interface is important for model users. When a Windows user interface was developed in 1998, use of RZWQM increased tremendously in the literature. From 1992 to 1998, the total number of peer-reviewed journal publications using RZWQM was 26; that increased to 68 from 1999 to 2006.
- It is important to provide standard scenarios of applications to be released with the model, so that users can be guided correctly in model parameterization and evaluation. It is equally important to provide a good help system (or user manual) and person-to-person technical support. A small unresolved problem can be a big hurdle for users and may discourage them. A frustrated or unhappy user also damages the reputation of a model.
- Correct parameterization and use of the model is fundamentally important. Misuse of models is inevitable if a component of the model is not correctly parameterized. Finding representative parameters for field research is a challenge (Ma et al., 2007c). Users have a tendency to pay more attention to the model components that they are more familiar with and rely on default parameters for others. It is also equally important to have balanced experimental measurements to make sure that all the system components are reasonably validated, including soil, water, nutrient, and plant variables (Ma et al., 2007a, 2007b).
- It is a challenge to balance simplicity of model use and complexity of model representation. On one hand, it is necessary to represent the processes in as much detail as possible for the model to be applicable to a wide range of conditions. On the other hand, it is equally important for a model to be not too complicated so as to discourage its use. It is necessary to find a compromise to meet both objectives, such as by building customized modules for specific purposes or locations from a library of stand-alone components.
- Simulating relative effects between management practices may be more important than matching exactly the absolute experimental measurements. Users are also more interested in simulation results with a confidence interval rather than a single number (Ma et al., 2007a, 2007b), just as with experimental data.
- Long-term and well balanced data are important in quantifying management effects. When RZWQM was applied to the Nashua, Iowa, study, tillage effects on tile flow and tile water quality could be different depending on the year and other management practices (Ma et al., 2007a, 2007b). Without long-term data, model evaluation can only be partially done, and model improvement based on partial data may be misleading. In addition, improvements to a model need to be evaluated using several different datasets to make sure that such improvements are valid under all the conditions. Therefore, it is advisable to preserve all the simulations of a model along with experimental data for future validation.
- It is a common practice to compare multiple models for the same set of experimental data to show which model is better in describing the data. However, the comparison may be biased unless the models are compared using large datasets across different management systems and soil/climate conditions. In addition, goodness of model performance varies depending on data type (e.g., soil water, soil N, yield, etc.) and resolution (daily, monthly, or yearly) (Chinkuyu et al., 2006).
- Development of hybrid models from existing models is a common practice in agricultural system studies because it saves time and brings in the best science from other disciplines. RZWQM-SHAW was developed to provide detailed surface energy balance simulation in RZWQM (Yu et al., 2007), and RZWQM-CERES and RZWQM-CROPGRO were developed to provide an option for plant growth in RZWQM (Ma et al., 2005, 2006). Caution should be taken when using a component from another model with a different level of complexity because the component may not function as expected in the new system environment (Smith et al., 1997).
- It is important that a model produce new knowledge that the experimentalists cannot otherwise obtain easily, so that the model is not just used to reproduce experimental results. Model applications need to go beyond the experiments and create new insight and knowledge about the system. This can be achieved by synthesizing the piecemeal information collected in the field experiments at different locations and times, and then extrapolating it to other locations and over longer time periods, and filling in information (knowledge gaps) on interactions among system components and missing data.
- When a model fails to perform for a particular field study, it is usually difficult to zoom in and find out which part of the model does not work correctly without adequate experimental data to verify each system component independently. This is especially true when multiple models are compared and only a few field measurements are used to verify their performance, which leaves a great deal of freedom in model parameterization to compensate for errors among system components.

FUTURE NEEDS AND DIRECTIONS IN SYSTEM MODEL EVALUATIONS AND APPLICATIONS

Ahuja et al. (2006, 2007) provide a good summary of future needs for enhancing applications and further enhancement of agricultural systems models:
- System models need to be more thoroughly tested and validated for scientific 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, parameterization, and evaluation. It is important to take into account spatial and temporal variability and the uncertainty of model parameters, and weather, to provide a confidence interval for simulation results.
- 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: improving quantification of agricultural management effects on soil-plant-atmosphere properties and processes; effects and dynamics of compaction, soil cracks, bio-channels, and root growth; plant response to water, nutrients, and temperature stresses and CO_2; and effects of natural hazards like hail, frost, insects, and diseases (see Ahuja et al., 2006 for more details).
- 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 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.

In summary, model developers need to work together 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. In addition, 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 them 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 agricultural research and technology to the next plateau. System modelers should take advantage of computer technology to advance agricultural science, rather than becoming lost or overwhelmed by chasing after this technology.

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