CHAPTER 8

The Co-Evolution of the Agricultural Production Systems Simulator (APSIM) and Its Use in Australian Dryland Cropping Research and Farm Management Intervention

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INTRODUCTION

Farmers, their advisors, and agricultural researchers face the challenge of understanding farms and the broader systems in which they reside well enough to make innovations appropriate to maintaining or improving system performance. In a complex, dynamic environment, "appropriate innovation" is a moving target as more efficient technology becomes available, prices shift, new knowledge about the state of the system emerges, market and environmental regulatory standards
and procedures evolve, etc. Although the ability to cope with these challenges is much of what has long constituted *expertise* in farm management, such complexities and uncertainties of modern farming have constituted much of the case for computer models and decision support systems (e.g., Wagner and Kuhlmann 1991; Ikeda 1991; Parker, 1999).

For nearly 20 years, champions of decision support systems have tended to explain low farmer adoption and use by the low ownership of computers in the farming community. But recent studies show that farmers are no longer lagging behind the general community in computer ownership. In 1999, computers were in use on approximately half of Australian farms and one in five were using the Internet — comparable usage to people in metropolitan areas (Australian Bureau of Statistics, 1999). Personal computers have become integral to farm business financial accounting and record keeping, and when connected to the Internet, by facilitating information gathering and diverse types of transactions. But this has not been accompanied by similar growth in the use of decision support systems (Hoag et al. 1999; Parker, 1999).

Because many agricultural decision support systems rely on an underlying simulation model of a production system, this has implications for model research and development. Since their origin in the late 1940s, these models of physical and biological processes in and around agricultural production have been integral to enormous progress in understanding of agricultural production processes and environment. Models have played significant roles in research problem setting and, occasionally, in applying scientific understanding to public policy. But expectation of eventual benefits to farmers of the decision support system has been a significant basis of financial support for modeling during the 1980s and into the 1990s. Although evidence is diffuse, our perception is that this support has faded since the mid-1990s with the failure of any significant market to emerge among farmers or their advisors.

More conspicuous has been the experience of ICASA (International Consortium for Agricultural Systems Applications), formed in 1995 to aggregate and position elite modeling groups to market a service to international agricultural research and development organizations (www.icasanet.org). Most observers would agree that there has been a disappointing level of financial support for ICASA among agencies expected to benefit from further development of models and applications in systems research.

In Australia, where demand for decision support systems has been no greater than elsewhere, significant support for modeling has been part of a major institutional shift away from research stations to research with a farming systems perspective and whose conduct involves farmers (Carberry, 2001). In addition to this driver of research reform, i.e., relevance to efficient farm management, there is the increasingly important driver of pressing environmental problems. On both fronts, the adequacy of traditional agricultural research approaches is being questioned, and there seems to be a new recognition by research stakeholders that simulation modeling, imbedded in the appropriate methodology, may be an important element of needed RD&E innovation.

This chapter summarizes the collective and ongoing experience of a group of researchers concerned with exploring how simulation may benefit the management of dryland farming systems in Australia. Over 15 years much change has taken place both in the models and in the ways in which researchers are using them. The primary aim here is to relate and reflect upon two intertwining threads of learning:

1. What capabilities in a simulator are important and feasible to develop and maintain?
2. In using simulation to aid farmers, and other system managers who influence or are influenced by farm production system performance, what are the keys to genuine usefulness that creates an ongoing demand for simulation?

Although major activities and learnings have not always been strictly sequential, it is convenient in telling the story here, to organize experience as phases. In the initial phase the team used what they judged at the time to be the most appropriate crop model for research aimed at contributing
to better farming practices in semiarid dryland farming systems. This was a period in which both
the power of dynamic simulation models in enhancing management research and the limits of the
existing models for dealing with important phenomena in such systems became apparent. This
phase was followed by one of rethinking and re-engineering models to overcome significant model
limits. Overlapping with this phase was one that focused on using models for aiding farm decision
making by working closely with farmers and their advisors on farms. What was learned in this
activity has led, in a current phase, to diversification of the way simulation models are used to
assist client managers and to new markets for simulation-aided services. In this ongoing phase,
simulator development continues in response to expanding diversity of crops and practices and
demand by users for features that aid effective and efficient data management, simulation, presenta-
tion, and Internet transmission. Demands from important “system analysis and design” activities
now compete with demands from “management discussion facilitating” and “farm management
consulting” activities as well.

FIRST PHASE: USING CROP MODELS TO DESIGN BETTER FARMING
PRACTICES AND DISCOVERING MODEL LIMITATIONS

Research on Semiarid Dryland Farming Systems

In the decade of the 1980s, simulation modeling became important to research on dryland
farming systems in semiarid, tropical regions of Australia and Kenya. Although very different
socioeconomic systems, they were similar in two important ways:

1. Economic feasibility of investment and intensification for greater production was made problematic
   by climatic risk.
2. Testing feasibility, either in practice or in an experimental research program, was problematic due
to high rainfall variability.

Feasibility of Cropping in Semiarid Northern Australia

Until recent years, the agricultural development potential of northern Australia has been uncer-
tain, and this uncertainty allowed rapid recovery of optimism following failed development ventures
(Chapman et al., 1996). A sufficient lapse of time, favorable economic conditions, and a conspicuous
run of good seasons seem to have been sufficient to conclude that earlier failures were due mainly
to factors other than an unsuitable climate. During the period 1978 to 1992, a significant research
effort was made to reevaluate the potential for cropping in the Australian semiarid tropics. Previous
failed initiatives had highlighted climatic risks, but there was disagreement about the importance
of low rainfall versus the affordability of adequate soil conservation measures and the importance
of these in relation to infrastructure constraints. Annual crops in this climate are at high risk
especially during establishment and anthesis due to highly variable rainfall and high radiation load
resulting in high evaporative demand and high soil and air temperatures (Abrecht and Bristow,
1996). The potentially arable soils are of low fertility, low water holding capacity and of poor
structural stability, and, under conventional tillage, highly vulnerable to serious water erosion
(Dilshad et al., 1996).

In the Northern Territory (NT), this research initially concentrated on soil management systems,
but later expanded to include climatic variability and production risk. In 1985, we undertook
simulation modeling to complement field research on the climatic and soil constraints to dryland
cropping and to develop and evaluate cropping practices that reduced risks and costs. This research
was in three key areas:
1. Quantifying the yield and economic returns from conventional dryland maize and sorghum enterprises (Muchow et al., 1991)

2. Testing the feasibility of a new dryland cropping system which centered on the use of no-tillage technology and the integration of livestock into the cropping system with the inclusion of pasture legumes as leys and intercrops (McCown et al., 1985)

3. Exploring the potential for a pulp and paper industry based on a totally new crop, kenaf (Hibiscus cannabinus L.) (Carberry et al., 1993a)

In addition, models developed in the NT were used to explore dryland cropping prospects on the dryer margins of established cropping regions in north Queensland (Carberry et al., 1991a).

Based on the criteria of being conceptually appropriate to the research issue, of having affordable input requirements, and capable of realistic simulation of performance, CERES-Maize (Jones and Kiniry, 1986) was initially selected in 1985 and tested for northern Australia (Carberry et al., 1989). After testing in this severe environment, CERES-Maize was modified to improve simulation of the effects of soil water deficit and extreme temperatures on crop establishment, phenology, leaf area development, grain set, and plant mortality (Carberry and Abrecht, 1991). The nitrogen supply routines were also modified with a number of improvements, principally to permit the simulation of surface residue dynamics (Dimes et al., 1996).

As part of this early phase of model evaluation and development, new models for sorghum (Birch et al., 1990; Carberry and Abrecht, 1991), kenaf (Carberry and Muchow, 1992), and Styllosanthes hamata (cv. Verano) (Carberry et al., 1992) were developed and validated for use in northern Australia. Together with the modified CERES-Maize, these enabled a systems analysis approach to evaluation of prospects for cropping in northern Australia. For maize and sorghum, these studies include the simulation of yields and assessment of risks to cropping at different locations, for different genotypes, for a range of planting times, and for different tillage strategies (Cogle et al., 1990; Carberry and Abrecht, 1991; Muchow and Carberry, 1991; Carberry et al., 1991b; Muchow et al., 1991). These evaluations provided a sobering picture of low expected economic returns. The prospects for intensive dryland cropping in semiarid northern Australia appeared bleak unless the cost–price situation for coarse grain crops changed dramatically.

But the hypothetical integrated crop-beef grazing system under evaluation recognized the viability of the existing local beef production system based on extensive natural pastures as well as the success of crop-sheep grazing systems based on legume pasture leys in Australia’s Mediterranean climatic regions. This hypothetical system for the Australian semiarid tropics (SAT) featured legume pastures grown in rotation with crops of maize and sorghum, which were used to fatten cattle (McCown et al. 1985). Crops were sown directly into chemically killed pastures that provided both protection from high soil temperatures and a source of mineralizable nitrogen. An understory of volunteer legume was permitted to establish from hard seed to form an intercrop with the grain crop. Cattle grazed native grass pastures on surrounding land during the wet season and were brought back to the cropland to graze crop residues and the volunteer legume pasture during the dry season. Although most aspects of the proposed integrated system were tested in agronomic experimentation over several years (McCown, 1996; Carberry et al., 1996a), the long-term potential under this system was also tested in simulation analyses (Carberry et al., 1993b, 1996b; Jones et al., 1996). Such analyses indicated that a combination of legume pasture and sorghum grain production was superior in terms of both gross margin returns and long-term soil fertility status compared with conventional coarse grain production.

Another regional development proposal has been for a pulp and paper industry based on the fiber crop, kenaf, but there has been uncertainty about effects of weather on long-term continuity of adequate supply of fiber to mills. A major feasibility study, funded by the NT government, was undertaken to assess the climatic risks to dryland kenaf production, using a simulation model of kenaf developed and validated for this task (Carberry et al., 1993a). The kenaf model was run, using long-term historical weather data, to determine optimal sowing strategies and expected yields
at four representative sites in the NT. A conflict existed between sowing early, with resulting long duration and high yield potential but high probability of plant mortality, and sowing later, with more reliable plant population but shorter duration and lower yields.

Since the late 1980s, *ex ante* analyses of the climatic risk to innovative production systems using locally specified and validated simulation models have contributed to development of policy both by government and private investors for dryland cropping industries in the semiarid tropics of northern Australia. The cautionary results of the analyses have complemented other cautionary information, and no such industries of national significance have yet been established (Chapman et al., 1996). The analyses have provided an enhanced understanding of the climatic realities, largely based on simulation with well-tested models (validated, in part, by failed commercial ventures). The models are a resource to assist future evaluations of new, inevitably risky, development propositions in the future.

**Feasibility of Purchased Fertilizer in Smallholder Crop Production in Kenya**

In 1985, in conjunction with the Australian Centre for International Agricultural Research (ACIAR), we began working with researchers from KARI (Kenya Agricultural Research Institute) on prospects for improvement in food security in semiarid eastern Kenya (McCown et al., 1992). The focus was on maize production strategies on smallholder farms where traditional soil fertility management systems had broken down due to population growth and farm fragmentation. Was there a place for commercial fertilizer inputs in these areas where the climatic risk was generally seen to preclude this option for soil fertility maintenance in a predominantly subsistence system? Over the next 6 years, we sought to answer this central question as well as explore a range of other management issues relevant to productivity in the maize-based farming systems of the region.

As we experienced the dominance of rainfall variability in this 500 to 700 mm bimodal rainfall environment (where two maize crops a year are attempted) on experimental results and the overall performance of different technologies, we realized that a maize model would be a valuable first step. The reasoning that had led to the selection of CERES-Maize (Jones and Kiniry 1986) for analysis of system performance in northern Australia appeared equally valid in Kenya. This model addressed a range of factors that were generally important in maize production (plant population, genotype characteristics, time of sowing, and water and nitrogen constraints), but a model of this type had not been "stretched" to mimic conditions in a smallholder agriculture setting in such a harsh environment before. In common with the work proceeding in parallel in northern Australia, the abiotic environment placed more severe constraints on crop growth and yield than was the case for high-input systems in temperate and humid tropical environments, which provided much of the basis for CERES-Maize initial development.

A major on-station experimental program over the 1985 to 1989 period resulted in many changes to CERES-Maize that improved its predictive performance in these semiarid, low-input environments (detailed in Keating et al., 1992a). Important changes included:

- Development of plant mortality routines to capture severely limiting water and nitrogen effects during vegetative growth
- Making the phenology model more sensitive to extreme water and nitrogen stress
- Making the grain number model better reflect yield response to plant population, and in particular the low plant populations that characterized resource-poor systems
- Redesign of the leaf area determination routines (Keating and Wafula, 1991) to improve performance over a diverse range of maize maturity classes
- Development of genotype parameter coefficients and related algorithms that were effective for the germplasm under consideration, which were generally outside the range then covered by CERES-Maize
The model that emerged from this testing and revision (referred to as CM-KEN to distinguish it from its parent CERES-Maize) provided a good overall predictive capability. Of special importance for our main objective of evaluating the economics of purchased fertilizer in this farming system was its competence in simulating the interactions between the management factors of plant population, water supply, and nitrogen supply. Over the period 1988 to 1992, this model proved to be a core tool in exploring implications of innovative management options, complicated by interactions between N fertilizer inputs and water climate. The first use of a simulation model to explore plant density effects under variable climates was reported by Keating et al. (1988), and the first application of this generation of simulation model to N fertilizer use studies in smallholder agriculture was reported by Keating et al. (1992b, 1991). This work showed that good long-term returns appeared to be possible, but the fact that N fertilizers were moderately high-risk in the season of fertilizer application was inescapable; and much depended on in-season management control in relation to an uncontrollable water supply.

A major part of the work in Kenya evaluated a tactical planning and fertilizing strategy called "response farming" as a means of reducing risk associated with crop production. This strategy involved adjusting plant populations and nitrogen fertilizer inputs in "response" to the timing and amount of early season rainfall. The concept had been developed earlier in this district (Stewart and Faught, 1984), and while intuitively appealing, there was no way of evaluating its efficacy in reducing risk without an adequate simulation capability. This required a maize model capable of processing complex management rules concerning events and actions in advance of crop planting, and subsequently imposing management actions such as thinning or fertilizer side dressing during early crop development. All these management actions needed to be conditional on the timing, pattern, and level of early season rainfall. CM-KEN and a visual and interactive version of CERES-Maize, CERES VI (Hargreaves and McCown, 1988) were elaborated to enable them to be used to explore the benefits and risks associated with response farming. Analysis of individual seasons showed important benefits from tactical adjustments in response to goodness of season. But if the time scale of analysis was extended to sequences of seasons, the most important benefit was from routine use of some N fertilizer (Wafula et al., 1992; McCown et al., 1991). The most important tactical benefit of response farming was the saving of costs by the withholding of fertilizer application in those seasons where indicated prospects were poor (Keating et al., 1992b).

Despite what appeared to be a desirable and feasible production strategy, researchers were increasingly conscious of the social, economic, institutional, and cultural factors that were likely to be inhibiting fertilizer usage in these systems (McCown et al., 1992). These realizations were important in shaping later work to include a much greater emphasis on the human side of the farming system, and to be more measured in our expectations for biophysical simulation modeling and decision support systems to underpin useful change in real-world practice (McCown et al., 1993). We return to this shift of emphasis after discussion of how this experience influenced simulation software development.

Lessons for Model Development

By 1990, a comprehensive crop modeling capability for the semiarid tropics had been developed. It was done cost effectively by appropriate modification of an established product, i.e., CERES Maize; however, coverage of the major crops was limited (maize, sorghum, kenaf, and the forage legume, *Stylosanthes hamata* cv. Verano), and we could not address key "systems issues" such as tillage, erosion, nutrients other than nitrogen, crop rotations, and competition between intercrops or crops and weeds.

These systems issues revealed inadequacies of the scope and architecture of the model of a crop. By the late 1980s, researchers became increasingly cognizant of the limitations of their
approach of continuously elaborating the code of a model of a crop to address systems issues. They were interested in interactions between crops sequentially and spatially and wanted to properly account for the effect cropping was having on the soil. In addition, they were increasingly ambitious in the conditional management strategies and tactics that they wanted to represent within the models. Their software was evolving in ways that made maintenance and further development awkward and costly. Adding each extra item of functionality caused ripples to go through the entire model code, necessitating an infeasible level of testing and repairs to ensure prior functionality was maintained. It was hard to see how continuation could deal with new needs, and by 1990, they opted for fundamental reengineering.

**PHASE OF SOFTWARE REDESIGN AND REDEVELOPMENT**

A major lesson from the efforts in Phase 1 was the discovery of the limitations of good crop simulation models when taken so far from the environmental and research domains in which they were developed. Research in Kenya and northern Australia provided grounds for key modifications. Modifications to CERES-Maize were sufficiently numerous and substantial to justify recognizing the derivative CM-Ken and CM-Sorghum (SAT) as distinct products (Keating et al., 1991; Carberry and Abrecht, 1991). A particularly important bridge to the subsequent phase of developing a cropping systems simulator, the early term used by Baker and Currie (1976), was the reengineering of CERES-Maize to enable interactive simulation. In Visual-Interactive (VI) CERES-Maize, events and trends of state variable are dynamically displayed and runs can be interrupted at any time in order to interrogate output files, change settings, etc. (Hargreaves and McCown, 1988). The experience using VI CERES-Maize to deal with complex management rules helped shape approaches in later manager modules.

Reengineering efforts progressed in the late 1980s to design a cropping systems simulator that overcame limits of existing available software. The assessment was that existing models fell into two distinct classes (McCown and Williams, 1989). One class was crop-oriented and aimed at accurate simulation of crop yields over a wide range of environmental conditions and genetic attributes, e.g., the CERES family of models.

The focus of the second class of software was on simulation of soil processes and management, e.g., EPIC (Williams, 1983) and NTRM (Shaffer et al., 1982). Between them, EPIC and NTRM simulated soil erosion and sedimentation, organic matter changes, nutrient dynamics, and they were actively expanding capabilities for dealing with other soil phenomena. The absence of such soil management orientation in our adapted CERES models was a severe limitation. A further attractive feature of both EPIC and NTRM was provision of a wide range of crops that could simulate diverse crop sequences. But the crucial deficiency was that this comprehensiveness and flexibility was achieved by use of simplified crop routines that did not have the degree of sensitivity to environmental extremes required for risk analysis in our climates (Williams et al., 1989; Steiner et al., 1987).

A peculiar need arose from the fact that, although analysis of risk in dryland cropping required high crop model sensitivity to environmental extremes, management of the risk to a crop generally involves actions or events that take place well prior to the planting of the crop, and indeed may be associated with the previous crop. (DSSAT later provided a framework for efficiently and flexibly accessing a suite of environmentally sensitive crop models as well as parameter and input data [Uehara and Tsuji, 1991], but failed to achieve the required 'systems' functionality of the soil-oriented simulators.) A simulator that combined the strengths of both classes of models was needed, and to get this, it appeared that the team had to make it.

McCown and Williams (1989) reported plans and progress concerning a design that featured three attributes:
1. Crop models with sufficient sensitivity to extremes of environmental inputs to predict realistic yield variation for risk analyses
2. Models to simulate trends in soil productivity as influenced by management, including crop sequences, intercropping, and crop residue management
3. Modular software that enables efficient evolution of the simulator by research teams

The core need was for an architecture that overcame the conflict between comprehensive system representation (agronomically important soil phenomena and a wide range of crops, as in EPIC and NTRM) and comprehensive treatment of crop physiology that conferred sensitive prediction of crop yield as in CERES. Because any given run configuration would require only a fraction of the total code, in the interest of minimizing run time the structure needed to be such that only required code would be processed. This was achieved by the concept of “plug-in, pull-out” modularity. The basic system being simulated is the soil profile as influenced by weather, crops, and management. Even when primary interest is in crop production, this architecture is advantageous because of the simplicity with which bare fallows, crop sequences, or crop mixtures can be configured by controlling only what crop modules are plugged in when. Multiple crop modules plugged in together compete for light, water, and nutrients using only the code for each crop behaving singularly and with access to resources regulated by a simple “arbiter.”

The formation of the Agricultural Production Systems Research Unit (APSRU) in 1991 brought together a CSIRO cropping systems team with a team at the Queensland Department of Primary Industries that had developed PERFECT (Littleboy et al., 1992). PERFECT combined a soil-oriented system with crop models sufficiently elaborate to have the desired sensitivity for risk analysis but, similar to CSIRO software, suffered a lack of good design and engineering process. The resultant and ongoing joint venture has produced APSIM (Agricultural Production System Simulato) (McCown et al., 1996).

APSIM v.1 was designed around the plug-in, pull-out modular concept, shown as a “hub–spoke” construct in Figure 8.1. All modules communicate with each other only by messages passed via the “engine” at the hub. Crops appear in the system as a consequence of management decisions, find the soil in some state, expire as a matter of course or are terminated by the manager, leave residues, and leave the soil in a different state. Using a standard interface protocol, this design enables easy removal, replacement, or exchange of modules without disruption to the overall operation of the system. It surpasses its predecessors in ease of representation of complex crop sequences or mixtures and dynamic simulation of the temporal and spatial interactions. From 1991 to 2001, and as a result of substantial investment, APSIM has developed in multiple directions. Space does not allow a historical account of these developments, but in a later section, an overview of APSIM as it stands in 2001 is provided.

**PHASE OF REENGINEERING MODEL-BASED DECISION SUPPORT FOR FARMERS**

In 1991, interest in decision support systems was at its zenith, and it was expected that a major focus of this new APSRU modeling team would be to produce appropriate decision support software for farmers. The starting point for this activity was a workshop with a group of elite farmers and extension experts. A surprising degree of skepticism and criticism expressed by farmers about the relevance of models to their management made this event a profoundly sobering experience. It appeared that the gap between farmers’ management techniques and scientists’ visions of the potential for simulation in management might be too wide to be bridged by mere talking. The stakes were too high to stop short of testing the hypothesis about the utility of simulation for farm management in real management situations.
The focus for this phase of research had shifted to the subtropical Darling Downs region of northeast Australia, characterized by intensive commercial dryland farming systems on productive self-mulching vertisols and in a highly variable rainfall regime. This trial was structured as a program of action research with the aim to find a way to use simulation in risky farm management — a methodical trial and error development of a methodology (in the manner of Checkland, 1981). The essential features of the situation were:

- Management dominated by uncertain rainfall
- An information technology with potential to alleviate this problem
- Weak farmer enthusiasm for the existing methodology for using this technology (the decision support system)
- Researcher conviction that a successful methodology was most likely if simulation modeling was researched in the context of farm management practice

Significantly, the activities did not initially feature simulation, but centered on reducing management uncertainty by enhanced monitoring of soil water and nitrogen (Dalglish and Foale, 1998). Measurements were often in the context of simple management experiments using treatment strips in commercial crops. This focus, besides capturing the farmers’ attention regarding matters of perceived importance and managerial deficiencies, provided researchers with data needed for subsequent simulation of specific farms and fields. The soil data often provided satisfying explanations of differences in crop performance. But the inevitable question of “What if we had done this last year?” highlighted the limitation of this approach and opened the door for answering the “What if?” question using simulation. The subsequent evolution of simulation-aided group discussions about farm management is the core element of a methodology that evolved over a period of several years, i.e., the FARMSCAPE approach (Farmers, Advisors, Researchers, Monitoring, Simulation, Communication, And Performance Evaluation) (Hochman et al., 2000).
Figure 8.2  A simplified model of the farm system, depicting management as normative, instrumental, and cybernetic. (After Soransen, J.T. and Kristensen, E.S., Global Appraisal of Livestock Farming Systems and Study on Their Organizational Levels: Concept, Methodology and Results, Commission of European Communities, Toulouse.)

The FARMSCAPE approach departs radically from the traditional concept of scientific decision support for farmer practice. Of operational significance, the simulator is “run” by an intermediary—a facilitator or service provider—not by the farmer. Departures of a conceptual nature can be seen with the aid of the representation of a farm system in Figure 8.2. Of the several subsystems that could be depicted as comprising a farm, only two are shown here. Agricultural science and simulation models are about the production system. Decision support is about what managers should do with regard to the production system, informed by scientific understanding. But in Figure 8.2, the operational emphasis is on the cybernetic relationships between the management system and the production system, characterized by actions to control production, feedback from the production system gained by monitoring in various ways, and further adjusting actions. The monitoring and site-specific simulations in the FARMSCAPE approach reflect the local and responsive nature of management and the need for simulation to capture this if it is to be seen by farmers as relevant to their management situations. The most significant learning by researchers from the FARMSCAPE experience concerns the importance to farmers of simulations being situated in their practice to be meaningful. An important aspect of this is specification of the simulator using local soil and climate data. Equally important is the origin of the simulation as an inquiry by a farmer seeking understanding or foresight. “Policies” in Figure 8.2 indicate the reality of a context of high order personal–household–cultural guides and constraints for management of production systems. Although well outside the boundaries of simulators of production systems and decision support systems, their influence in real decision making is implicit in the dynamics of the participatory “What if...? Analysis and Discussion” (WifAD) sessions.

For a simulation to be taken seriously by a farmer, it must be more than notionally relevant; it must be seen as significant for changed management action. But for this to happen, the action–outcome inferences must be credible. Every farmer with whom the scientists worked had to establish the simulator’s credibility before enthusiasm and strong demand for WifADs developed. In the main, this was achieved by demonstration of successful simulation either using special collaborative projects to collect the necessary data from relevant commercial crops (often overlaid by simple treatment
comparisons) or by simulations that matched with either farm records or memory of past crop yields (Carberry and Bange, 1998); however, with time, there appears to be an increasing readiness of farmers to accept as meaningful the validating experiences of respected farmer colleagues in their district.

The reluctance and skepticism of farmers to take simulations seriously and participate in their practice highlights deficiencies of the typical decision support system. For reasons of economy in the overall process, these are generally not designed to fit real situations, but only deal with the logic of situations (Checkland, 1981). Even if the scientific and economic logic of such products is sound, if farmers do not find treatments of issues locally meaningful, the products will not be used.

Finally, the FARMSCAPE approach represents a paradigm shift in interfaces between scientific knowledge and practical knowledge. The main process in a decision support system is intervention in farmer practice with a science-based recommendation for best practice. The main process in a WifAD is very different. If a production system simulator can be conditionally accepted as a substitute for a real production system in Figure 8.2, then management possibilities can be tested virtually very quickly and cheaply. Figure 8.2 can be seen as a learning cycle: starting on the left and moving counter-clockwise, actions as adjustments, or, alternatively, deeper structural changes, are taken. Production System consequences of the action are simulated, outcomes observed, overall implications deliberated in the management system, and a new priority for action constructed. This is similarly tested in the next cycle.

This use of a simulator in action learning has been described by Bakken et al. (1994), p. 246:

The goal of a learning laboratory is to provide an environment that will help enrich managers’ mental models using tools such as the management simulators. Learning laboratories help managers leverage their domain-rich knowledge by allowing them to play through simulated years, reflect on their actions, modify their mental models, then repeat the process. By compressing time and space, flight simulators can accelerate learning by enabling them to conduct many cycles of action and reflection.

Formal evaluation of participants' experiences in the FARMSCAPE research program has indicated farmers appreciate that this is the nature of WifADs (Coutts et al., 1998). This learning from the behavior of the production system (Figure 8.1) places great importance on simulated behavior being realistic, and prior investment in establishing this for the situation in question is indispensable. Researchers also found that farmers often benefit from analyses and discussions that make the functioning of the production system more intelligible. Just as stated by Bakken et al. (1994, p. 250):

The simulator also demands structural explanations of the “action → result” link that will force participants to search for a better understanding of the underlying forces that produce a given set of outcomes.

WifADs are free-flowing discussions that follow the directions of farmers' interests within the domains of the system represented in the simulator. Four functional types have been distinguished:

1. Yield benchmarking
2. Production decision support
3. Marketing decision support
4. Analysis of consequences of possible management change (Hochman et al., 2000)

These simulator applications address variously the two types of complexities (Senge, 1990). The contribution to yield benchmarking is reduction of detail complexity. This serves to aid insight (the reduction of detail that masks structure) that helps explain why the crop did what it did and what effects altered management actions could have made. In the last three types of WifADs, the function is reduction of dynamic complexity (Senge, 1990, p. 71) — complexity that includes variable outcomes from the same action taken repeatedly in the same circumstances. Instrumental to the contribution of simulation in reducing this complexity has been an emergent method in
climate forecasting based on the Southern Oscillation Index (Stone et al., 1996). Additional atmospheric pressure information, available for all years of weather records, provides a basis for identifying a set of "analog years" in which simulated outcomes for a specified action are more homogenous than for the entire population of years (Hammer et al., 2000).

Shifting from the notion of producing decision support systems for farmers to use of situated simulation in a FARMSCAPE approach is in line with a major paradigm shift in systems thinking from "hard" to "soft" (Checkland, 1981). It is also in line with a shift in cognitive science from using computers mainly to compensate for managers' cognitive deficiencies in their decision making to largely using computers to aid in constructing new understandings and new possibilities for future management (Clancey, 1997; Winograd and Flores, 1986). Such a shift to the FARMSCAPE approach has resulted in significant and demonstrable achievements in bringing benefits to farmers, broader agriindustries and the research community in northern Australia (Carberry, 2001).

Another general lesson that emerged in this phase of using and adapting existing models was the importance to the value of simulation in real farm management research that data for parameterization, initial conditions, and weather inputs are from the site. In contrast with much modeling in crop physiology research in which environmental settings can be abstracted to "scenarios," simulations were used primarily to virtually enlarge the sample size of years in which field monitoring and experimentation were conducted. There was recognition that efficient systems of weather monitoring, soil characterization, and soil monitoring needed to evolve together with simulation capability.

These developments in the use of the simulator to enable farmer education and management have placed a number of calls upon the model development effort. The demand for a comprehensive simulator, addressing the major crops and constraints in the farming system in realistic ways, is something that is needed in both management support and systems analysis and design applications. The reengineered approach to decision support that FARMSCAPE represents has placed additional demands on user interfaces, graphics tools, and database resources. The APSIM suite of tools contains a user-friendly interface, a flexible graphics tool, and a database tool for storing, manipulating and sharing soil properties data. These interface tools have much in common with the interface trappings of some decision support systems; however, because they are designed for a trained intermediary in the FARMSCAPE application instead of casual use by an untrained user, the interfaces can generally be more flexible and powerful.

THE CURRENT PHASE: MULTIPLE THEMES FOR ENHANCING SIMULATION OF PRODUCTION SYSTEMS

Since 1995, four themes have characterized CSIRO’s research and development:

1. Continued development of APSIM as software in response to needs arising from different applications, from opportunities and investment aimed at improving its science base and from growing experience in software engineering
2. Continued use of APSIM in R&D for functional design of potentially superior agricultural systems by identifying feasible or optimal strategies from a larger set of possibilities
3. Development of a delivery system for farm-situated simulations — FARMSCAPE training and accreditation for agricultural consultants
4. FARMSCAPE Online — Development of Internet video-conference interactions between researchers and farmer groups centered on "What if?" analysis and discussion for specific situations of farmer participants

APSIM Development: 1995 to 2000

By 2000, APSIM had reached version 1.6. Vegetation modules had been developed for barley, canola, chickpea, cowpea, fababean, mungbean, navy bean, hemp, wheat, lucerne, maize, peanut,
millet and pigeonpea (in association with ICRISAT), sorghum, sunflower, sugarcane, and cotton (the OZCOT model in association with CSIRO Plant Industry). A FOREST module has been used for Eucalyptus, Pinus, and other woody vegetation. A MICROMET module is available for treatment of energy and water fluxes in mixed canopy situations. Soil and related modules include models for soil water, nitrogen and phosphorus balance, soil surface residue decomposition, soil erosion and soil acidification. In some cases, alternative model representations are available as options. For instance, SOILWAT is a layered tipping bucket soil water balance model (Probert et al., 1997), and SWIM (in association with CSIRO Land and Water) is an implementation of Richard's Equation for water movement and the Convection–Dispersion Equation for solute movement (Verburg, 1996).

APSIM vegetation modules generally include water and nitrogen as limiting factors, with phosphorus limitation currently under development and, at present, only operational for maize. Powerful and flexible control of management in the simulation remains a feature in APSIM, with a pedigree that traces back to the Response Farming rules in CM-KEN and V1 CERES-Maize. The MANAGER module in APSIM utilizes a custom-built script language and compiler that enables users to comprehensively specify complex and conditional management rules for all aspects of a simulation.

Investment in software engineering process for the APSIM effort was stepped up in the mid-1990s. This was in recognition of the complexity of the task of managing a large software project that involved simultaneous development efforts by different programmer and modeling teams. A version control and regression testing system is central to the software engineering process. This system enables any past version of APSIM to be recreated and ensures code changes take place in an ordered way. Regression tests are automatically run every evening and reports provided on any changes in system performance. When unexpected or undesirable changes in performance are detected, action is taken immediately to investigate the causes. Other key aspects of APSIM software engineering process include formal documentation and peer review procedures, code analysis tools, code auto-documentation tools, as well as Web-based defect reporting and change request logging procedures. An APSIM support web site (www.APSIM-Help.tag.csiro.au) provides access to documentation and other support materials for users as well as restricted access to software engineering support materials for developers.

APSIM has been made available to individuals and groups via a license system that ensures and orderly development and support effort. As of February 2001, over 250 such licenses have been issued and the model has been used in all Australian States, and with national and international agencies in Africa and Asia.

Version 2 of APSIM was released in February 2001. The key new capability is support for the development of multipoint simulations, as the underlying software infrastructure can create multiple instances of any module. This new capability is starting to be applied to the simulation of multi-paddock crop-livestock systems and the simulation of agroforestry systems. APSIM v2 infrastructure is written in C++ and modules are contained within dynamic linked libraries (DLLs). These developments mean that modules written in different programming languages can generally be linked into the software system. The latter infrastructure developments are part of a joint effort with the GRAZPLAN/GrassGro developers in CSIRO Plant Industry (Donnelly et al., 1997) to develop a common modeling protocol to facilitate linkages between different modeling software entities. This protocol will be available on www.APSIM-Help.tag.csiro.au from June 2001.

**APSIM in Farming Systems Analysis and Design: 1995 to 2000**

As APSIM has developed from a limited single crop simulator to a comprehensive simulator of farming systems, the scope of the issues to which it has been applied has widened. All applications are characterized by an intent of system analysis to identify some feasible or optimal strategies or designs from a larger set of possibilities. This is policy research (Figure 8.3) and is quite different from the action research that characterizes the FARMSCAPE approach. Some key applications of APSIM in formal diagnosis and design are summarized in Table 8.1.
Knowing how to manage a situation

- **Action Research**: "The production of knowledge that guides practice, with the modification [in practice] of a given reality occurring as part of the research process". [Invention, improvisation]
- **Policy Research**: "The production of knowledge that guides practice, with the modification [in practice] of a given reality occurring subsequent to the research process". [Science-based design]
- **Applied Scientific Research**: [Science-based design]
- **Engineering Design**: Design of technology based on invention, applied research, and practical need.
- **Nomothetic Research**: "Attempts to explain and/or predict phenomena with regard to the external relations between a given phenomenon and one or several variables and constants". [Theory, model-making]
- **Descriptive Research**: "Delimits phenomena within typologies of facts and events". [Distinction-making]

**Knowing that something is the case, in principle**

Figure 8.3 Different ways to conduct research to achieve different types of knowledge. (The four-category typology is from Oquist, P., *Acta Sociologica*, 1978.)

This portfolio of applications continues to grow as new needs arise. The important finding is that, unlike our experience in the late 1980s, the integrity of the simulator software is maintained as additional capability is added. Software maintenance costs have not blown out as the model's scope has broadened. If anything, these costs have been reduced in recent years as the benefits of investment made in the mid-1990s in improved software engineering process have manifested throughout CSIRO's software development and maintenance activity.

**FARMSCAPE Training and Accreditation**

By 1998, over 230 farmers had engaged in FARMSCAPE research activities, the research had created a market demand by farmers for such interactions, and the systems research priority had shifted to development of a sustainable system for delivery of a customized service. It became necessary to scale up a FARMSCAPE service fast enough to prevent farmer disillusionment due to unmet high expectations, but at the expense of the quality of system simulation and human interactions necessary to retain the level of interest and confidence that created the demand.

Implicit in this mode of using simulation is a professional who is skilled in using the simulator and interpreting simulations of real farming situations, and who, generally, (but not necessarily) leads the "What-if?" discussions with farmer groups. Evolution in this direction has taken place in a farm service environment characterized by decline in publicly funded extension and increase in various forms of commercial consulting. Farmers who were enthusiastic about FARMSCAPE were prepared to pay for a service. In order to pilot the feasibility of provision of such a service, an in-business action research activity, analogous to earlier on-farm research with farmers was initiated. Researchers worked for a period within a commercial advisory firm that had an interest in gearing up to provide a FARMSCAPE service to farmers. The aim was for researchers and consultants to learn together in order to invent together feasible approaches for commercial service provision as well as training and support by researchers for service providers.
Table 8.1 Summary of Major Applications of APSIM to the Design or Enhanced Performance of Agricultural Systems

<table>
<thead>
<tr>
<th>Application</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of long term consequences of crop-pasture rotations, including</td>
<td>Carberry et al., 1996b</td>
</tr>
<tr>
<td>changes in soil C/N status</td>
<td></td>
</tr>
<tr>
<td>Assessment of long-term impacts of tillage and fertilizer management on</td>
<td>Probert et al., 1995</td>
</tr>
<tr>
<td>crop productivity and soil fertility</td>
<td></td>
</tr>
<tr>
<td>Assessment of management and climate on soil acidification</td>
<td>Hochman et al., 1998b</td>
</tr>
<tr>
<td>Assessment of long-term impacts of residue retention on sugarcane</td>
<td>Thorburn et al., 1999</td>
</tr>
<tr>
<td>productivity and soil organic matter dynamics</td>
<td></td>
</tr>
<tr>
<td>Identification of optimal crop management practice to minimize nitrate</td>
<td>Keating et al., 1997</td>
</tr>
<tr>
<td>leaching to groundwater from fertilizer in irrigated sugarcane production</td>
<td></td>
</tr>
<tr>
<td>systems</td>
<td></td>
</tr>
<tr>
<td>Assessing water balance of cereal-lucerne systems</td>
<td>Dunin et al., 1999</td>
</tr>
<tr>
<td>Design of strategies to address soil structure degradation in cereal–pasture</td>
<td>Connolly and Freebairn,</td>
</tr>
<tr>
<td>rotations</td>
<td>1996</td>
</tr>
<tr>
<td>Maize-weed interactions in relation to fertilizer effectiveness in small</td>
<td>Shamudzaria et al., 1999;</td>
</tr>
<tr>
<td>hoder systems in Zimbabwe</td>
<td>Keating et al., 1999</td>
</tr>
<tr>
<td>Optimizing irrigation inputs in sugarcane production systems</td>
<td>Muchow and Keating, 1998</td>
</tr>
<tr>
<td>Design of on-farm water storage in sugarcane production systems</td>
<td>Lisson et al., 2000</td>
</tr>
<tr>
<td>Assessment of nitrogen fertilizer strategies in sugarcane systems</td>
<td>Verburg et al., 1996</td>
</tr>
<tr>
<td>Design of effluent irrigation practices for sugarcane, pastures and tree</td>
<td>Snow et al., 1999</td>
</tr>
<tr>
<td>crop systems</td>
<td></td>
</tr>
<tr>
<td>Assessment of severity of drought for government policy implementation on</td>
<td>Keating and Meinke, 1998</td>
</tr>
<tr>
<td>assistance under exceptional circumstances</td>
<td></td>
</tr>
<tr>
<td>Evaluation of seasonal climate forecast systems</td>
<td>Meinke et al., 1996</td>
</tr>
<tr>
<td>Evaluation of cropping potential in new regions</td>
<td>Cogle et al., 1990</td>
</tr>
<tr>
<td>Assessing the benefits associated with intercropping systems</td>
<td>Carberry et al., 1998c</td>
</tr>
<tr>
<td>Design of farming systems to minimize deep drainage below root zones to</td>
<td>Paydar et al., 1999;</td>
</tr>
<tr>
<td>restrict development of dryland salinity</td>
<td>Ringrose-Voase et al., 1999;</td>
</tr>
<tr>
<td>Assessing the erosion and productivity impacts of maize/shrub legume</td>
<td>Asseng et al., 1998</td>
</tr>
<tr>
<td>hedges-row cropping in the Philippines</td>
<td>Nelson et al., 1988a,b</td>
</tr>
</tbody>
</table>

The outcome of deliberations on training and support was a plan to:

1. Establish a FARMSCAPE training, accreditation, and support program to provide both the scientific and technical training and on-going support for advisors to provide a service enhancement based on competent APSIM simulations.
2. In collaboration with accredited advisors, continue to learn and develop more cost-effective and sustainable mechanisms for delivery of the FARMSCAPE approach in assisting farmers’ learning, planning, and decision making.
3. Progress FARMSCAPE tools and methods to suit a range of industry users.
4. Evaluate the success of and learn from the FARMSCAPE approach to RD&E delivery and its impacts on management decisions.

Two aspects of commercial consultant situations strongly influenced the choice of methodology:

1. Trainees are already accomplished professionals in their businesses, and their inputs, drawing on their expertise and experience, were an important determinant of the adapted service product
2. Trainees are busy practitioners in a highly competitive environment.

The research approach that nicely maps onto these realities is that of action research (Figure 8.3), which features learning-in-action rather than being trained by instruction (Schon, 1983). Learning projects are collaboratively designed and conducted within the consultant’s practice, with the high degree of mentoring and support required initially declining over time. The research team treats each individual project as a case study, which is documented, evaluated, discussed, and compared
with others as a way of learning how FARMSCAPE suits consulting, what adaptations consultants make to the approach, and what changes might be needed in APSIM or in the training program.

After publicly advertising, four companies were selected from eight applicants to participate in the initial training and accreditation program now in progress, each with two participants. The training program and associated on-going support was designed to provide:

- A high level of expertise in the use of APSIM and a sound appreciation of the underlying science
- Internet access to weather data for regions of interest in the Australian cropping belt that is both long-term and updated regularly enough for yield forecasting
- Internet access to a GIS of measured soil properties needed for APSIM and the means to add significant locations to this database
- The ability to measure initial soil conditions cost-effectively

The training program consists of the following modules/competency areas.

1. Soil monitoring and data management — principles, techniques, and quality assurance
2. Weather monitoring and data management — principles, techniques, and quality assurance
3. APSIM — the program and the science
4. Simulation applications in farm management
5. Analysis of simulation results and quality assurance
6. Flexible representation of results and communication with decision makers

The core of the program consists of on-farm projects negotiated with trainees and built around trainees’ services to selected farmer clients. The initial project was the systematic monitoring of a crop or crops that enabled project participants to track soil water and nitrogen supply and crop growth through the season, providing the data needed to simulate the crop using APSIM and to test model performance. Procedural manuals and interactive coaching from APSRU staff, often through Internet video conferences, enabled trainees distributed over a large geographic area to carry out their projects with a high degree of success. This provided a practical, experience-producing framework within which the formal technical and theoretical training modules were flexibly presented to maximize practical relevance and significance. For the researchers pioneering a novel activity, it provided a valuable suite of case studies whose analysis will guide the program redesign for the next intake of trainees. Case data include logs of all soil monitoring advisory activity and APSIM simulations applied to clients’ problems. In addition, regular review of trainee logs aid the trainers in insuring that trainees get the required experience with FARMSCAPE tools and techniques, assist in assessing the progress of trainees, and to learn how they adapt the FARMSCAPE approach to their business situations.

At the time of this writing, the first trainees were halfway through the program. Key research findings included:

- Some individuals were experiencing periodic difficulties meeting the demands of training in competition with urgent demands from their clients.
- Trainees were generally demonstrating high levels of competence in assessing tasks and involving clients in them.
- Job mobility for trainees and changing company ownership has proved to be a challenge for retaining the same trainees through a prolonged training program.
- Both trainees and their employers reported high levels of satisfaction with the program.

A critical, but subtle, lesson was that, in order for training activities to compete for attention in a high pressure commercial environment, an ongoing need exists for nurturing and reinforcement of the early expectations of trainees and their managers regarding valuable new service to farmer clients.
FARMSCAPE Online

In parallel with training and accreditation of intermediaries, means of conducting FARMSCAPE interactions with farmers using Internet conferencing are being developed (Hargreaves et al., 2001). Importantly, the latter is not in competition with the training and accreditation of intermediaries, but, instead, exploration of a medium that may prove to be valuable to the trained intermediaries, as well as valuable for interactions by researchers with farmers on matters outside technical and business consulting. The key research question concerns the degree of loss in value of online WifADs relative to face-to-face meetings. The approach is one of action research in which researchers play the role of a commercial advisors.

As described previously, although the FARMSCAPE approach features simulation of production system behavior using abstract models, experience has shown that effective interactions begin with concrete management issues and actions whose treatment is later enhanced in interactions using simulation. The most common starting point involved practical means of reducing uncertainty about soil water and nitrogen supply. One of the challenges of the online project has been to provide this through a combination of a soil-monitoring workshop followed by support for soil and weather monitoring for a season.

Team involvement typically begins with researchers conducting a face-to-face soil workshop for farmers in a district. The workshops are a mixture of instruction about local landscape geo-history and hands-on activities in practical soil sampling, processing soil cores, and calculations and data processing. A central aim is to provide farmers with the opportunity to appreciate their soil resource in new ways. The cores allow participants to see soil properties at depths not often accessed and the utility of measurements beyond those made normally in their practice. Simply breaking cores sequentially down the profile to trace rooting depth and feeling the relative wetness or dryness throughout the profile is a start to new appreciations for many. Researchers report back on data in an online meeting at a later date and implications are discussed. Measurements are a combination of what is valuable in its own right for decision making and what enables specification of APSIM for the situation (Dalgliesh and Foale, 1998).

The aim is to engage farmers in a process of active learning. Evaluation shows that most farmers who attend these workshops have mental models of soil water congruent with the prevailing technique for measurement — the pushing of a pointed steel rod about a meter long into the soil as far as the farmer can push it. This measures the depth of wet, i.e., soft soil, following a rainfall event. The activity undertaken during the soil workshop provides the opportunity for farmers to evaluate an alternative to this representation of the soil water environment — one that features a “water budget” concept with water stored in the empty volume of the soil “sponge.” This concept leads logically to plant available water capacity (PAWC), which links with the way APSIM simulates soil water change. We have found that many farmers find the storage concept and the metaphor of the soil as a bucket, with a capacity and a content that varies from empty to full, is more useful than the depth of wet soil. “How big is the bucket?” is an increasingly common question in farmers’ discussions of their soils. (Probes, nevertheless, continue to be valuable for quick checks after a rainfall event.)

Evaluations undertaken after the half-day soil workshops reveal that many participants are motivated to increase monitoring activity. The team’s research program has followed this energy by providing support of a limited number of enthusiastic farmer groups for a cropping season in monitoring soil and weather, including access to a hydraulic soil-coring rig, an automatic weather station, and an electronic balance. Monitoring programs have been developed jointly with these farmers and are centered on issues of significance nominated by them. Issues suggested by farmers include evaluating the variables of row spacing, planting rate, nitrogen application, and planting date, as they relate to yield and gross margins, particularly via effects on the often scarce resource of soil water.
An online meeting using Microsoft NetMeeting\textsuperscript{TM} takes place between a group of farmers assembled around a host farmer's computer and a researcher at his or her office. This technology supports audio and video communication as well as computer screen sharing. Bandwidth limitations in rural Australia generally require the use of separate audio via a simultaneous telephone connection with hands-free speakers. The researcher shares graphs of field data using specifically designed Excel spreadsheets. Farmers discuss these, often in relation to their personal and practical experiences with a particular crop, soil state, and weather.

How severe is the loss in quality of experience in an online meeting relative to a face-to-face meeting? This has been posed in evaluation interviews as “If an online meeting was free, how much extra would you pay for a face-to-face meeting?” The characteristic answer has been “Why would I pay more when this is as good as?” This response has been somewhat surprising to the researchers, because some exercise of tolerance with technical problems and effort in repairing human communications is often required. But aside from early problems attributable to inexperience, all concerned expect that most problems will be solved by increased telecommunication bandwidth for rural areas in Australia in the future.

**DISCUSSION**

Most researchers would agree with the proposition that agricultural systems research is a distinctive form of agricultural science. But there would probably be less agreement on what makes systems knowledge distinctive. The simple dichotomous structure of human knowledge proposed by Ryle (1949) appeals to us as the basis for a significant distinction. Ryle distinguished between “knowing that something is the case in the world” and “knowing how to bring about, or maintain, a desired state in the world.”

The importance of both types of knowledge in a farm system can be discussed in terms of Figure 8.2. The analytical knowledge of agricultural science concerning the nature of the production system exemplifies “knowing that.” The focus of systems research is on “knowing how” to achieve and maintain the desired state of the production system. Although this distinction is useful, it is not absolute. There is interaction and overlap between the two in both research and farming practice. These days, the ways that high-performing farmers see and think about their production systems is strongly influenced by knowing that production systems are structured as science claims them to be. This theoretical knowledge augments the primary structure of management that is based on feedback linkages (monitoring and action in Figure 8.2) underpinned by know-how, based on the historical patterns of system behavior (Senge, 1990).

In their 15-year systems research experiment, the authors found simulation modeling can provide a unique bridge between the knowledge of agricultural science and the know-how of farming practice. Effective bridging depends on good science, embodied in good process models. But in this role, good systems practice requires good compromise of both comprehensiveness of process treatment and the practicalities of model specification and testing. This results in models that are more often functional than scientifically mechanistic (Simon, 1996). Practicalities also drive the need for adding value to models by imbedding them in simulators (Baker and Curry, 1976; Banks et al., 1991), which make data management, model reconfiguration, and simulation output reporting efficient and effective.

Simulators convert modeled relationships to meaningful, albeit virtual, histories of system behavior. Such artificial histories have proved of particular value in providing a sort of *artificial* experience to both professionals and farmers. Whereas a farmer has some cumulative *actual* experience of the nature and variability of his or her environment, creation of a simulated history can provide advisors and researchers seeking to service the farmer with a helpful substitute. In highly variable climates, patterns are hard to perceive and a sense of “how often” or rules of thumb
for action concerning weather tend to be weakly developed [a possible example of the Outcome-Irrelevant Learning Structure (OILS) of Einhorn (1982)]. Using a simulator and local climatic records, patterns in local histories are arguably more readily perceived than in real farming life, which is protracted and largely undocumented. Team members found that farmers value simulated histories, appropriately analyzed and graphed, as a means of evaluating the prospects of a contemplated management change (Hochman et al., 1998a).

In an entirely different arena, that of public policy, descriptions of problems and their backgrounds have been created that enable policy analysts to view certain simulated histories as relevant and, possibly, significant to actual futures, and expansion of this role for simulation is of high priority in our research on sustainable ecosystems (Table 8.1).

In real life, there is no substitute for experience gained through encounters with system behavior. Simulation can sometimes enhance this experience, through artificial experience, as described previously, but it can also enhance it by providing insight to deep structure — theory valuable in explaining behavior and in anticipating future behavior. When system simulation is providing a (partial) substitute for actual (risky) experience, a good simulator makes it easy to look inside to see how it works, and such understanding is often highly valued by farmers and advisors.

This involvement in human learning and planning practice is a long way from our starting points in crop and soil process research. How does simulation based on abstract models play these various roles in the representation of "knowing that," and in the construction of both of new knowledge and enhanced know-how? This is a systems question, but it is at a level of abstraction such that answers must be expected to be largely philosophical. Although an answer at this level has not proved to be essential prior to conduct of the research, it takes on greater significance as we try to make holistic sense of this new model-based research and justify it in a modeling community that is expecting something quite different. It involves both deeper understanding of the natures of both simulation and management or an actual family farm.

Although an instantiation of the production system in Figure 8.2 would refer ultimately to a set of soils, crops, etc., somewhere in the world as a framework for discussing models and simulation, its reference is more directly an abstract set of such objects and their relationships to one another (Kleene, 1952 quoted by Kliemt, 1996, p. 15):

By a system S of objects we mean a set D of objects among which are established certain relationships. The system is abstract if the objects of the system are known only through the relationships of the system. [...] what is established in this case is the structure of the system, and what the objects are, in any respects other than how they fit into the structure, is left unspecified. Moreover, any further specification of what the objects are gives a representation (or model) of the abstract system, i.e., a system of objects which satisfy the relationships of the abstract system and have some further status as well.

This construction of the theoretical structure of the system (creating subsets of objects identified only by parsimonious mathematical relationships) is the essence of nomothetic research (Oquist, 1978). This activity creates smaller, intelligible worlds, in part by abstracting away detail complexity (Senge 1990) to provide general structure, and, in part, by selecting only relevant objects and aspects to study (Schutz, 1963, quoted by Blaikie, 1993, p. 42).

It is up to the natural sciences to determine which sector of the universe of nature, which facts and events therein, and which aspects of such facts and events are... relevant to their specific purpose... Relevance is not inherent in nature as such; it is the result of the selective and interpretive activity of man [sic] within nature or observing nature....

Agricultural scientists seek to understand "what is the case" in production systems, focusing on "what is relevant to the activity of agriculture," in principle. Models of the production system
represent elements whose structural relationships, provided with Kleene’s "further status" by appropriate specification, are capable of mimicking relevant facts and events. This capability then provides a double-sided capability—to explain and to predict the behavior of the abstract system S, which represents, in principle, real production systems. The fact that a structural-functional model can be specified for local conditions provides a systems research tool for partially bridging the gap between scientific knowledge and the know-how in farming practice. In the typology of research of Oquist (1978), depicted as the gray portions of Figure 8.3, nomothetic research, which creates relevant abstract systems and models based on “knowing that,” contribute to policy research, applied scientific research, and engineering design. The latter two are aimed at contributing to the “knowing how” of practice. Whereas agricultural science is concerned with descriptive, nomothetic and applied research, systems research extends beyond these in the direction of management know-how.

According to Checkland (1981), “hard” systems research embraces engineering design and policy research aimed at optimizing the logic of human activity, or practice. As hard systems activities, operations research and decision support systems provide guides to practice that are structured by the underlying abstract models—logic for action based on theory about the nature of the external environment as constructed by science. Taylor and Evans (1985) termed this “potentially knowing how.” Recommendations for optimal action, explicit or implicit, so derived, are scientifically normative. They represent the best efforts of a scientific design approach to real world practice from outside the problem context, using the logic of the situation. But actual know-how has passed the filter of meaningful practical experience in the management situation. The profound nature of the gap between such external, potential know-how and internal, actual know-how is only becoming to be appreciated by hard systems researchers (McCown, 2001). Good science studies the local out of necessity, but uses clever techniques to move beyond the local to make general statements. But, perversely, this very abstraction contributes to the gap that is often lamented. The biologist and philosopher, Gregory Bateson, saw this as one of the most profound aspects of the distillation process of history as well as science: “...there is a deep gulf between statements about an identified individual and statements about a class. Such statements are of different logical type, and prediction from one to the other are always unsure” (Bateson, 1980).

The FARMSCAPE approach uses nomothetic research and the hard systems tool of production system simulation to deal realistically with the structure of the production system. But instead of using science to design optimal practice, the simulator is used to enable meaningful and adaptive experience of managers—a soft systems approach to construction of managers’ “knowing how” (but often with a by-product of “knowing that” insights by participants). The paradigm shift is epitomized by the fact that soft systems knowledge is structured, not by abstract biophysical relationships, but by the intentionality of the manager (Caws, 1988)—implicit in the policies portion of the management system of Figure 8.1. One of the main arguments for the superiority of the decision support system over previous operations research optimization for managers was that the former recognized that many management problems were less than fully structured and so could not be adequately modeled. This lack of structure referred to the degree to which managers’ policies included deviations from the striving for maximum profits—deviations that are important in farming practice (Frost, 2000).

Decision support systems in the hands of farmers notionally allowed other preferences to be exercised, guided by knowledge of structure as revealed in simulated events and patterns of events. Although this rationale was a step in situating models within the management system (Figure 8.2), our work with farmers in FARMSCAPE indicates that a central reason for the low use of decision support systems was the failure of simulations to be adequately situated in local practice physically or a lack of means for the user to test if this was the case. There is a substantial cost to specifying a model to simulate a real situation, and this cost has been considered by many to be prohibitive (e.g., Boote et al., 1996). Such costs include not only the demands of creating data of adequate quality but, generally, operating the model in this more open, flexible mode with acceptable risks of operator error. FARMSCAPE addresses this by having a flexible simulator operated by a
professional intermediary trained in its operation, pragmatic data requirements, and efficient field measurement systems. This investment in physical situatedness is complemented by socially situating simulations in WifADs. One aspect of this social situating is analysis and discussion of farmers’ perceived problems; another is the satisfaction of farmers’ needs for evidence that the simulated system performance conforms to their own experienced performance or performance records.

It is important that justifiable criticism of the logic of applying models to design of decision support systems for individuals not detract from the justified logic of using of models in nomothetic and policy research when the aim is general knowledge and public policy. This was the original logic of hard systems that grew out of a World War II need for more rational plans for responding to enemy air attacks. This was followed in peacetime by enormous contributions by operations research and systems engineering to design of better policies and physical systems in industry and government. This intellectual and technological movement diffused into agriculture in the late 1940s. (In an interview with the late Professor C.T. DeWit shortly before his death, the pioneer of modeling in agriculture said he was strongly influenced as a graduate student by a new professor who had come from Shell Oil — an expert in simulating petroleum distillation.) Enormous progress has been made in the past 50 years in the ability to simulate agricultural production systems, building on the experience from industrial systems. Competent models imbedded in efficient simulators will undoubtedly be even more important in the future to enable learning from virtual mistakes instead of costly real ones. But systems researchers face a public application context that has become increasingly complex and problematic.

This trend can be tracked by two successive books with the same title: Operational Research and the Social Sciences, which are proceedings of conferences that brought together operations researchers and social scientists — first, in 1964 (Lawrence, 1966) and again in 1989 (Jackson et al., 1989). At the time of the first conference, hard, scientific modeling efforts concerning important systems problems were attracting criticism for work that ignored or underestimated the social nature of most problems of importance. By the time of the second conference, it was noted by the editors that (Jackson et al., 1989, p. v):

Few, these days, regard OR [operational research] as being simply applied mathematics. The recognition that OR is a process of intervention in organizations and human affairs is now wider and more explicit. There has been a penetration and diffusion of ideas from the social sciences into OR, reflected most strongly in the body of writing about soft OR methods and soft systems thinking. Social and political skills are now recognized as critical to the success of OR practice and this is particularly so as operational researchers have sought to extend their client base outside that conventionally served. The rise of computer technology, embraced by OR, has required some thought to be given to its powerful impact on and consequences for organizations, people, and processes of decision. As a consequence, perhaps, of broadening its methodological base in attempting to extend its impact, OR has encountered the problem of competing “paradigms” — a condition long experienced by the social sciences.

Systems activities in agriculture have historically often lagged behind the main systems movement by a decade or two. During the past 10 years, CSIRO’s own hard systems team has become very cognizant of the soft paradigm, and its thinking about systems and research and intervention practices have changed significantly. Although the team experienced paradigm competition (Ridge and Cox, 2000; Woods et al., 1997), members are impressed with what might be called the paradigm cooperation of Mingers and Gill (1997), which offers, in the metaphor of Sellars (1963), “stereoscopic vision.” The aim is to use the best hard tools and methods science can provide in a “soft” philosophical and communication matrix that will enable appropriate response to the human setting of the problem and our inescapable inclusion in this setting.

The authors find that scientists commonly perceive their program of soft and hard systems approaches as an unconventional mix of research and extension. They assert it is more helpful to
see it as a way of doing research differently in an age when scientific knowledge is increasingly expected to be directly linked to, and justified by, relevant and significant new know-how in practice. The exciting new realization for us is that a simulator based on scientific knowledge can be instrumental in enabling and facilitating situated cooperative learning by practitioners and researchers.

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REFERENCES


Agricultural system models in field research and technology transfer
Edited by L.R. Ahuja, L. Ma, T.A. Howell

This volume is a collection of 16 expository review chapters, each on some aspect of crop modeling. Although not necessarily evident from the title, the book is almost exclusively devoted to crop simulation models: there is one chapter on forage models and virtually no mention outside of this chapter of animal physiological or behavior models. To quote from the first sentence of the Preface, the purpose of the book is “to present the state-of-science of applications of agricultural system models, and tremendous benefits to be derived from the use of these computer models in agriculture research and technology transfer in the 21st century.” The editors are all USDA-ARS scientists, and the Foreword, written by an ARS administrator, implies that the project of developing the book was conceived within that organization.

The editors have clearly made some effort to include a perspective from outside the USDA. Of the 16 chapters, five have no authors from either ARS or the ARS-associated IBSNAT modeling program. Two of these, however, represent the experience of users of models developed by USDA-ARS scientists, so that there are only three papers that have little or no ARS influence. Two are from the CSIRO modeling group in Australia, and one is from the group at the Center for Agricultural Landscape Research in Muencheberg, Germany. In part, this reflects the dominant role that ARS scientists have played over the last three decades in the development of successful crop models, that is, crop models that are useful and survive to be used by people outside the lab where the model was developed. There are, however, some notable absences. The scope of the book would have been much enhanced by the inclusion of chapters from the Wageningen school, as well as from the group associated with James Thornley, to name two examples. The primary focus of the volume is on models developed under the auspices of ARS (primarily EPIC, the CERES and CROPGRO models, and GOSSYM and GLYCIM). A good source of further information for those unfamiliar with crop model acronyms is the Register of Ecological Models, http://eco.wiz.uni-kassel.de/ecobas.html

After the introductory overview chapter written by the editors the remaining chapters are organized into a sequence of four thematic groups. The first group, Chapters 2 through 5, represent what may be loosely described as the developers’ perspective. These chapters describe the history and philosophy of the programs that produced FARMSCAPE, GOSSYM/COMAX, GLYSIM, and the DSSAT collection, which incorporates the CERES and CROPGO models. In each of these chapters the focus is not so much on the internal workings of the models as on the history of their development, the goals of the modelers, and how the model achieved...
these goals. None of the chapters contain a detailed description of how the model works; there are few flowcharts and virtually no equations. In each chapter there are a number of fairly detailed descriptions of successful applications of the model, both in research and in support of farm management or policy decisions.

Chapters 6 through 9 represent what might be considered the user perspective of these models. Chapter 6, written by scientists from the International Fertilizer Development Center, describes their experiences with models in various applications, both at the farm and the policy level, in Asia and Africa. Most of the discussion involves the DSSAT models but there is also some discussion of other models such as QUEFTS and COTONS. Chapter 7 provides a systematic and thorough comparison of the RZWQM, CROPGRO, and CERES-Maize models under a variety of applications. Chapter 8 describes the experiences of the authors in implementing models for decision support in Australia. Both this chapter and Chapter 6 detail some of the problems experienced in using models as on-farm decision support tools. This is a sufficiently important topic that I will devote a more lengthy discussion to it later in the review. Chapter 9 reviews a variety of models to a variety of applications in semi-arid regions.

Chapters 10 through 13 are devoted to the currently most active area of crop modeling research: the incorporation of spatial variability into simulation models through linkage with a geographic information system. Hartkamp et al. (1999) provides a review of this topic that contains a very useful structure for organizing and classifying the various ways to link a model with a GIS, and this paper is a good introduction to the subject before reading these chapters. As with single-plant crop simulation models such as those described in Chapters 2 through 5, some of the most prominent and successful farm and landscape scale models, such as ALMANAC and SWAT, have been developed under the auspices of USDA-ARS. Chapter 10 provides a description of these models and a demonstration of their use to various problems at different spatial scales. Chapter 11, which is one of two European contributions to the volume, describes the application of the HERMES simulation model to two questions involving spatially variable fertilizer application. Chapters 12 and 13 contain two relatively short discussions of linking a simulation model to a GIS to simulate spatial variability at the field level, and of the incorporation of topographic variability into a simulation, respectively.

Chapters 14 through 16 discuss various topics in crop simulation model research. Chapter 14 provides a systematic and useful review of the problem of parameter estimation and how to do it in a statistically consistent manner. Chapter 15 provides a description of the Object Modeling System (OMS) project currently under way at USDA-ARS. This is a laudable attempt to develop a common standard for object-oriented model development that, if implemented on a wide scale, would permit more efficient interchange of components of crop simulation models. Anyone who has ever waded through pages of FORTRAN code sprinkled with GO TO statements can only applaud this effort. Finally, Chapter 16 forecasts some future directions of research in crop simulation modeling.

The subtitle of the volume explicitly addresses the twin applications that have motivated the development of crop simulation models over the years, field research
and technology transfer (which prominently includes decision support). Not surprisingly, the conclusions of most individual chapters are largely upbeat. The two principal exceptions are in Chapters 6 and 8, which mention some of the difficulties associated with the use of crop models in on-farm decision support. On a personal level, my own experiences probably reflect those of many who have been involved with crop modeling. On the one hand, crop simulation models can provide a useful tool for developing precisely stated hypotheses that are subject to test in field experimentation. On the other hand, the international effort to develop farm-level decision support systems (DSS’s) based on crop models and expert systems (a form of model), which began in the late 1980’s with such high expectations, had by the end of the century been largely abandoned as a failure. The authors of Chapter 8 have themselves sponsored a collection of papers published in the journal *Agricultural Systems* that addresses the roots of this failure. In the introductory paper to this collection, McCown and Carberry (2002) develop a subtle and well-thought out analysis. At the risk of oversimplifying their work, I want to focus on one aspect of it.

McCown and Carberry (2002) note that the failure of DSS in agriculture reflects a more widespread failure of such systems observed throughout the discipline of operations research. One of their ascribed causes of this failure is the “Delphic” approach to DSS in which the flow of information is strictly in one direction: from the system to the user. Technology transfer workers in Australia have responded by developing a new paradigm, described in Chapter 8 of the reviewed volume, in which farmers and scientists participate in group exchanges of information, with the simulation model serving as a vehicle for enhancing discussion and understanding. This experience reflects my own and that of other researchers and I think may be generalized to other applications of simulation modeling.

In their insightful history of crop simulation Sinclair and Seligman (1996) make the case that those who benefit most from the development of a simulation model are the modelers themselves, through the use of the development effort as a vehicle for organizing one’s thoughts and synthesizing linkages between knowledge segments. (This paper is part of another special series of papers, entitled “Use and Abuse of Crop Simulation Models,” that should also be on the reading list of anyone interested in this subject.) Sinclair and Seligman present an unpublished argument of Imanuel Noy-Meyer that states that it is not necessary even to complete the development of an actual model to achieve the benefit. While this takes the argument perhaps to an extreme point, the combined experiences presented here indicate that successful use of a crop simulation model as a technology transfer tool requires a collaborative effort between farmers and scientists in which the model is used as a device to assist in organizing knowledge of the participants, rather than as a source of knowledge in itself. Similarly, a model can be best used as a research tool if individuals who understand its assumptions and limitations use it to propose experiments whose outcome can be interpreted within these limitations to test a well-formed hypothesis.

So where does that leave the subject of this book review? Obviously, all of us who have worked with models and decision support systems over the last 20 years or so...
have emerged with a few lessons learned, sometimes the hard way. With the exceptions already noted, the volume does not really offer much in the way of lessons learned through failure, and thus perhaps presents an overly optimistic view of the potential of crop models as research and decision support tools. There have been many successes, however, and crop models clearly have a significant place in the scientific toolbox, both in research and in technology transfer. Those who want to learn about crop modeling and are seeking an objective comparison of a wide variety of crop models developed around the world will likely be disappointed by this volume. Those who are seeking information on the many prominent crop simulation models developed under the auspices of, or in collaboration with, the USDA-ARS, and examples of highly successful applications of these models, are likely to find exactly what they are looking for. It is a tribute to the prominent role of the ARS in crop simulation modeling that there are sure to be a very large number of scientists who fall into this second category.

References


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