# Crop growth models for decision support systems

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Jame, Y. W. and Cutforth, H. W. 1996. Crop growth models for decision support systems. Can. J. Plant Sci. 76: 9–19. Studies on crop production are traditionally carried out by using conventional experience-based agronomic research, in which crop production functions were derived from statistical analysis without referring to the underlying biological or physical principles involved. The weaknesses and disadvantages of this approach and the need for greater in-depth analysis have long been recognized. Recently, application of the knowledge-based systems approach to agricultural management has been gaining popularity because of our expanding knowledge of processes that are involved in the growth of plants, coupled with the availability of inexpensive and powerful computers. The systems approach makes use of dynamic simulation models of crop growth and of cropping systems. In the most satisfactory crop growth models, current knowledge of plant growth and development from various disciplines, such as crop physiology, agrometeorology, soil science and agronomy, is integrated in a consistent, quantitative and process-oriented manner. After proper validation, the models are used to predict crop responses to different environments that are either the result of global change or induced by agricultural management and to test alternative crop management options.

Computerized decision support systems for field-level crop management are now available. The decision support systems for agrotechnology transfer (DSSAT) allows users to combine the technical knowledge contained in crop growth models with economic considerations and environmental impact evaluations to facilitate economic analysis and risk assessment of farming enterprises. Thus, DSSAT is a valuable tool to aid the development of a viable and sustainable agricultural industry. The development and validation of crop models can improve our understanding of the underlying processes, pinpoint where our understanding is inadequate, and, hence, support strategic agricultural research. The knowledge-based systems approach offers great potential to expand our ability to make good agricultural management decisions, not only for the current climatic variability, but for the anticipated climatic changes of the future.

Key words: Simulation, crop growth, development, management strategy

Jame, Y. W. et Cutforth, H. W. 1996. Modèles de croissance des cultures pour les systèmes de soutien aux prises de décision. Can. J. Plant Sci. 76: 9-19. Les études sur la production des cultures utilisent le plus souvent les méthodes conventionnelles de recherches agroéconomiques fondées sur l'expérience, dans lesquelles les fonctions de production des cultures sont dérivées de l'analyse statistique, sans égard aucun aux principes biologiques ou physiques sous-jacents. Les lacunes et les inconvénients d'une telle démarche et la nécessitée d'une analyse plus en profondeur sont reconnus depuis longtemps. Depuis quelques années, l'application au domaine de la gestion agricole de systèmes basés sur les connaissances gagne en popularité, en raison de la meilleure connaissance dont nous disposons sur les mécanismes intervenant dans la croissance des végétaux et de la disponibilité d'ordinateurs à la fois puissants et à prix abordables. La démarche systèmes utilise des modèles en simulation dynamiques de la croissance des cultures, ainsi que des systèmes culturaux. Les modèles de croissance des cultures les plus satisfaisants, qui incorporent les connaissances physiologiques, agrologiques et agrométéorologiques actuelles sur la croissance et sur le développement des cultures sont intégrés dans un protocole quantitatif fonctionnel cohérent. Dûment validés, les modèles peuvent alors servir à prédire les comportement des cultures dans diverses situations environnementales crées résultant de modifications à l'échelle planétaire ou des techniques agronomiques. On peut s'en servir aussi pour tester des nouvelles méthodes agronomiques. On dispose aujourd'hui de systèmes informatisés de soutien décisionnel dans le domaine de la gestion agronomique au niveau de la parcelle. Les systèmes de soutien décisionnel pour le transfert de la technologie agricole (DSSAT) permettent à l'usager de combiner les connaissances techniques contenues dans les modèles de croissance des cultures avec des considérations économiques et des évaluations environnementales. Ils facilitent ainsi l'analyse économique et l'évaluation des risques liés aux diverses orientations technico-économiques des exploitations. Ainsi le DSSAT est un auxiliaire précieux pour la mise en place d'un secteur agricole viable et durable. La mise au point et la validation des modèles culturaux peut améliorer notre compréhension des mécanismes sous-jacents, mettre en évidence les zones d'ombre à éclaircir et, partant, appuyer les recherches agricoles stratégiques. La demande de systèmes fondés sur les connaissances offre de merveilleuses possibilités d'élargir notre aptitude à prendre des décisions de gestion agricole sages, non seulement dans le contexte et de variabilité climatique actuelle mais dans l'éventualité de futurs changements climatiques à l'échelle planétaire.

Mots clés: Simulation, croissance, développement, stratégie de gestion

On the Canadian Prairies, risk related to erratic and unpredictable weather is a serious impediment to profitable and stable agriculture. Because decision makers have no control over weather, risk is an important factor in the decisionmaking process. To help the agricultural industry thrive on the Canadian Prairies, scientists need to provide useful tools Abbreviations: COMAX, cotton management expert; DSSAT, decision support systems for agrotechnology transfer; GCTE, global change and terrestrial ecosystems; GIS, geographic information system; IBSNAT, International Benchmark Sites Network for Agrotechnology Transfer; IGBP, International Geosphere-Biosphere Programme for agricultural producers and policy makers to better quantify weather risk associated with crop production, as well as developing crop and soil management practices that reduce the risk to acceptable levels for the decision maker.

Traditionally, crop production functions that are used in agricultural decision making were derived from conventional experienced-based agronomic research, in which crop yields were related to some defined variables based on correlation and regression analysis. Crop yields were expressed as polynomial or exponential mathematical functions of the defined variables, with regression coefficients obtained through linear or nonlinear curve-fitting procedures based on observed values; usually there was little consideration given to the physical and physiological processes involved. For example, a large number of studies have been carried out on the Canadian Prairies to obtain production functions of wheat yield and water use. Derived yield-water use functions ranged from simple linear (Fig. 1), quadratic (Fig. 2) and cubic relationships (Fig. 2) to multifactorial relationships (UMA 1982) employing several combinations of water use factors to estimate yield. Several other functions have been developed for use on the Canadian Prairies to describe crop yield response to water and nutrient supply (Bole and Pittman 1980; Kulshreshtha et al. 1991) as well as other site- and soil-specific variables (Williams et al. 1975).

The application of correlation and regression analysis has provided some qualitative understanding of the variables and their interactions that were involved in cropping systems and has contributed to the progress of agricultural science. However, the quantitative information obtained from this type of analysis is very site specific. The information obtained can only be reliably applied to other sites where climate, important soil parameters and crop management are similar to those used in developing the original functions. Thus, the quantitative applicability of regressionbased crop yield models for decision making is severely limited. In addition, because of the unavoidable variability associated with weather on the Canadian Prairies, more than 10 yr is required to develop statistical relationships that are useful in agricultural decision making. Statistical evidence based on long-term studies generally show that more than 40% of the total variation is usually associated with experimental error. An example of the relationship between wheat yield and total water use, along with five prediction equations commonly used in southern Saskatchewan, is given in Fig. 1. There is tremendous scatter about the regression curves, but despite the imprecision and uncertainty, these types of production functions are widely used to estimate yields on the Canadian Prairies.

The major weakness associated with correlation and regression analysis is that the technique only results in a statistical average. This approach offers decision makers opportunities to make comparisons between the means of alternative strategies only; it does not provide the full probability information that is needed to assess risk. Nix (1980) referred to the conventional agronomic research which focuses on treatment means, as "white-peg agronomy." Good and Bell (1980) discussed the time-consuming, trialand-error nature of current research methods for improving crop production and concluded that only to the extent that we can describe productivity in terms of the mechanisms that control the processes of plant growth and development can we bring productivity out of the dark ages of pure empiricism. In his annual presidential address to the Royal Meteorological Society, Monteith (1981) said "The statistical blunderbuss is a very clumsy weapon for attacking the problem of crop-weather relations; but it is also very uninstructive because it ignores the interaction of physical and physiological mechanisms." He stressed that some of these mechanisms are well understood and can be described by simple, explicit mathematical functions and that models of this type had been appearing in the literature for more than 30 yr.

In the past, the main focus of agronomic research has been on crop production. Recently, in addition to profitable crop production, the quality of the environment has become an important issue that agricultural producers must address. Agricultural managers require strategies for optimizing the profitability of crop production while maintaining soil quality and minimizing environmental degradation. Solutions to this new challenge require consideration of how numerous components interact to effect plant growth. To achieve this goal, future agricultural research will require considerably more effort and resources than present research activity.

Indeed, plant and soil systems are very complex, with numerous factors influencing any desired end result. However, advances in computer technology have made possible the consideration of the combined influence of several factors in various interactions. As a result, it is possible to quantitatively combine the soil, plant, and climatic systems to more accurately predict crop yield. Thus, with the availability of inexpensive and powerful computers and with the growing popularity of the application of integrated systems to agricultural practices, a new era of agricultural research and development is emerging (Jones 1993).

The systems approach makes use of dynamic simulation models of crop growth and of cropping systems. In crop growth models, current knowledge of plant growth and development from various disciplines, such as crop physiology, agrometeorology, soil science and agronomy, is integrated in a consistent, quantitative and process-oriented manner. After proper validation, the models may be used to predict the effects of changes in environment and management on crop yield.

Computerized decision support systems that allow users to combine technical knowledge contained in crop growth models with economic considerations and environmental impact evaluations are now available. The system DSSAT (Tsuji et al. 1994) is an excellent example of a management tool that enables individual farmers to match the biological requirement of a crop to the physical characteristics of the land to obtain specified objectives.

## **CROP GROWTH SIMULATION MODELS**

A model is a set of mathematical equations describing a physical system (in our case, soil-plant-atmosphere). The



Fig. 1. The relationships between wheat yield and water use in southern Saskatchewan. Observed data were collected in 1982–1986 from Brown and Dark Brown soil zones on Topographic Class 3 soil under the innovative Acres Research and Development project (Rennie and de Jong 1989).



Fig. 2. The quadratic (left, for stubble-seeded wheat) and cubic (right, for fallow-seeded wheat) relationships between yield and water use (after Campbell et al. 1988).

model simulates or imitates the behaviour of a real crop by predicting the growth of its components, such as leaves, roots, stems and grains. Thus, a crop growth simulation model not only predicts the final state of total biomass or harvestable yield, but also contains quantitative information about major processes involved in the growth and development of a plant.

The development of crop growth simulation models has been a natural progression of scientific research. Jame (1992) reviewed the history of attempts to quantify the relationships between crop yield and water use from the early work on simple water-balance models in the 1960s to the development of crop growth simulation models in the 1980s. Two decades ago, it was not certain whether the complex physical, physiological and morphological processes involved in the growth of a plant could be described mathematically, except perhaps in some controlled environments. Thus, the relevance of crop growth simulation models in crop agronomy was challenged (Passioura 1973). However, during the past 20 yr, crop growth modelling has changed dramatically from something akin to alchemy to a highly professional activity (Grable 1987). At present, there are many teams around the world building crop growth simulation models for crops of major importance. The recent release of DSSAT version 3 (Tsuji et al. 1994) includes models for the following crops: wheat (Triticum eastivum L.), rice (Oryza sativa L.), maize (Zea mays L.), barley (Hordeum vulgare L.), sorghum (Sorghum bicolor L.), millet (Pennisetum americanum L.), dry bean (Phaseolus vulgaris L.), soybean [Glycine max (L.) Merr.], peanut (Arachis hypogea L.), potato (Solanum tuberosum L.), cassava (Manihot esculenta L.) and aroids [Colocasia esculenta L. (taro) and Xanthosoma sagittifolium L. (tannier)].

A major difference between empirical crop production functions based on regression analysis and the simulation approach is the reduction in the time interval involved, e.g., from a growing season to a day or less. Most crop models employ a daily time step to calculate growth and development; a few models require hourly time steps to execute the more detailed processes that can only be described with more precise solutions. A typical crop growth model, such as the CERES-Wheat model (Godwin and Vlek 1985) (Fig. 3), normally includes the following major processes governing growth and development: phenologic development, canopy development, organ formation, photosynthesis, assimilate allocation, and carbon, water and nitrogen dynamics in the soil and in the plant. Thus, a sophisticated



Fig. 3. The system diagram of CERES-Wheat model (after Godwin and Vlek 1985.

crop model can simulate the effects of weather, soil water, and nitrogen dynamics in the soil on growth and yield for the specified cultivar.

The minimum weather data needed to run a crop model include daily values of incoming solar radiation, maximum and minimum air temperature, and precipitation. Optional data include humidity and wind speed. Soil input data for the soil water submodels that are based on a simple water balance normally include albedo, upper flux limit of the first stage of soil evaporation, drainage coefficient, runoff curve number, and, for each soil layer, information on the lower soil water content limit for plant growth, the drained upper soil water content limit, the field-saturated soil water content, and the relative distribution for root growth. For more detailed soil water submodels that calculate water flow in the soil based on numerical solutions of Richard's equation, the hydraulic conductivity for each soil layer is required. If the actual data are unavailable, a general description of the physical and chemical characteristics of the soil is sufficient to estimate the parameters required for the model.

Crop genetic coefficients are also required by many crop models to simulate the difference in performance among varieties. Examples of genetic coefficients are the thermal time (°C–d) required by a crop to reach a particular growth stage, sensitivity to vernerlization and photoperiod, maximum kernel filling rate, and kernel number per stem weight for cereal crops or maximum number of seeds per shell for legume crops. On a personal computer equipped with a math co-processor — for example, a PC486 DX2/66 — a crop growth model running on a daily time step requires only a few seconds to simulate a whole growing season. The outputs from the model normally include phenological events, growth details, soil temperatures, and water and nitrogen dynamics in the soil and in the plant on a daily basis.

Because there are many levels of detail to which a crop model can be developed, a number of crop growth models are presently available. Some of them were listed by Whisler et al. (1986) and Ritchie (1991). These lists are not all inclusive because new crop models are being developed almost monthly. For wheat alone, more than 70 simulation models are already in existence (McMaster et al. 1992). Some crop models are based mainly on a broad collection of empirical functions for processes involved in the growth of a plant, for example, the EPIC crop growth model (Williams et al. 1989). Recent advances in crop modelling have incorporated the increased understanding of plant physiological mechanisms in the simulation. Examples of this type of model are CERES-Wheat (Ritchie and Schulthes 1994), ARFCWHEAT (Porter 1994), SWheat (van Keulen 1994), SPIKEGRO (McMaster et al. 1992), and ECOSYS (Grant 1994).

Two main reasons for building crop growth models are (1) to better understand the processes involved in crop production; and (2) to use the model as a tool for managing agricultural systems. Agriculture involves very complex systems. At present, even the most advanced crop models are still small imitations of reality, i.e., all models have their limitations. Thus, using crop models as a tool for agricultural management requires knowledge of systems research, of the objective and structure of the model, of the extent to which the model has been validated and calibrated, and of the problems related to the quality of the soil, crop and climatic parameters within the model. Running models without insight is counterproductive.

#### **Empirical and Mechanistic Models**

A crop growth model is normally compartmentalized into submodels, each involved with specific processes related to the growth of the plant. The complexity of the submodels depends on the objective of the model. In some cases, simple empirical functions can be used satisfactorily to describe the relationships among the variables involved in the process. On the other hand, mechanistic equations may be used to express the known or hypothesized theory that relates the variables and attempts to explain their observed behaviour. Thus, crop models may range from strictly empirical models that use only a few variables and involve only a few processes to predict crop yield, to very complex models that include detailed biochemical simulation of guard-cell control of stomatal opening and the influence this has on the photosynthetic process.

Although the distinction between empirical and mechanistic models is useful, most crop growth models contain a mixture of empiricism and mechanism. All models become empirical at some level. For example, a mechanistic model describing crop growth and development at the plant and organ levels would be considered empirical by scientists who work at the cellular level. An ultimate crop model would be one that physically and physiologically defines all relations between variables the model reproduces and universally real-world behaviour. This model cannot be developed because the biological system is too complex and many processes involved in the system are not fully understood. Even if an ideal crop model could be produced, the collection of the highly precise system parameters and of the input data for the crop environment would be a formidable task in itself. Thus, the level of detail involved in a crop model is closely linked to the end use of the model and the precision required.

#### **Research and Application Models**

Many crop models have been developed to help scientists understand the operation of various processes within the agronomic cropping system, e.g., soil water flow, photosynthesis, and nutrient balance. Such models strongly reflect the interests and strengths of the scientists who develop them and will often be weak in the areas of less interest. For example, LEACHM (Wagenet and Hutson 1987) is a process-based model of water and solute movement, transformations, and chemical reactions in the unsaturated soil zone. Thus, the model has very comprehensive descriptions of water movement, as well as the basic physics and chemistry of salt, nitrogen or pesticide transport and transformation in agricultural soils. On the other hand, the plant growth submodel in LEACHM is very simple, using a set of empirical equations that predict crop cover as a function of time and root density as a function both time and depth. The effects of water and nitrogen stress on plant growth are not considered in the model.

Crop models can also be used as tools for assessing agricultural management strategies and their interaction with climatic risk. In this case, the models are used to generate a large set of possible outcomes. Outputs of this information become the inputs for other analyses related to economics and policy. Unlike research models that are developed to study some specific processes of a cropping system, an application model requires a balanced analysis of the whole system, with major processes being treated at approximately the same level of detail. A model that is strong in one process but weak in another is no better than information contained in the weakest part, if the weak part is an important process of the system.

Thus, a model for research on cropping systems can be comprehensive, with increasing amounts of mechanism incorporated into the model; but for most practical applications, we need a model that is balanced and simple to use. Simplicity in use is generally achieved by (1) the use of empirical equations or a summary model derived from a comprehensive model; and (2) the use of a user-friendly interface. The model's user friendliness can eliminate the frustration often experienced by novice computer users and can greatly increase the usability and utility of a model. For example, most crop models are written in the FORTRAN computer language for ease in integrating many variables and submodels, but many of these models have a specially designed user-friendly interface (Hoogenboon et al. 1994) written in BASIC, PASCAL or C computer language, providing an easy method of running the model, a simplified data entry format, and graphical analysis of the model output.

Summary models have proven to be effective tools for many applications and predictive purposes. They combine the advantages of simplicity, such as a reduced parameter set, with explanations and reasonable accuracy. For instance, plant biomass accumulation involves three

fundamental processes: (1) carbon fixation through photosynthesis, (2) maintenance respiration, and (3) growth respiration. In more mechanistic models, these three processes are all included in the simulation (van Keulen and Seligman 1987; Grant 1989; Hoogenboon et al. 1994). In some crop growth models, e.g., CERES-Wheat (Ritchie and Schulthes 1994) and EPIC (Williams et al. 1989), the total amount of dry matter produced by a crop is estimated as the product of the radiation absorbed or intercepted by the canopy and an energy conversion factor called radiation use efficiency. This approach assumes that respiration is proportional to gross photosynthesis. Hence, the three components are simplified and combined into one calculation. This simple calculation was used by Monteith (1977) to evaluate the effects of climate on crop production in Britain. Since then, numerous workers have used this approach, or some modification of it, with relatively good success (Norman and Arkebauer 1991)

The simplified approach to crop growth simulation is reasonable and can be considered in the context of good science (Ritchie 1991). For example, the use of thermal time to predict plant development and the use of potential evaporation to predict actual water evaporation from the plant and the soil are all proven concepts when the appropriate information for their application is available. Simplicity reduces the number of system parameters and input data requirement, permitting faster adoption by scientists and producers.

#### Level of Simplicity for an Application Model

What level of simplicity is optimal for an application model? The decision is generally based on the pragmatic tradeoff between precision, affordable data requirements, and computing power. As the level of mechanism in a crop model increases, so does the requirement for more input data and system parameters and for more detailed experimental data. Such data are often unavailable and may be difficult to obtain experimentally. Thus, the main determinant of the level of model simplicity is data availability for running the model. For example, with our present knowledge, it is feasible to include very detailed simulations of the processes of infiltration, surface detention, runoff, soil moisture redistribution, evaporation, and deep drainage in a crop model by using numerical solutions of Richard's water-flow equation. However, if only daily total rainfall values are available, then we are limited to using a simple water-balance model rather than the detailed numerical analysis technique that depends on rainfall intensities and amount and on precise soil hydraulic properties.

The introduction of more mechanism into a crop model also implies the use of smaller time steps, requiring more time to run the model. For practical applications, most crop models use a daily time step. In these models, the rate of water uptake by the plant is generally related to the leaf area index, climatic conditions and soil moisture content. Affordable microcomputers are sufficiently powerful to run such models through a fully simulated growing season in a few seconds. Some more comprehensive models include leaf water potential and stomatal resistance in the transpiration process. Because of the plant's smaller capacity to store water, compared with the much larger capacity of the soil, these detailed models are run with very small time steps (hours or even seconds) and may require several hours to complete a given crop growth cycle.

Generally, simple models trade parameter-related inaccuracy for structure-related inaccuracy. To illustrate, models for predicting crop growth over a narrow temperature range are much simpler to develop than models dealing with a wide temperature range. However, models that are too simple are site specific and of interest to only a small group of users. An ideal way to develop an application model is to simplify a comprehensive model, with a specific target in mind, and then calibrate the model with proper field trials.

## **Model Calibration**

Calibration is adjustment of the system parameters so that simulated results reach a predetermined level, usually that of an observation. For empirical models, calibration is the only way that system coefficients can be determined. Although calibration is against the principle of explanatory crop modelling, it is necessary when adapting an existing application model to a new environment. This procedure is avoidable only when a perfect crop model is produced. Calibration should be conducted using a few well-defined experiments in which the soil and climatic conditions are carefully monitored and the crop growth details are duly recorded; otherwise, much time is wasted in the trial-anderror type of specific curve fitting. Generally, data sets collected previously from conventional agronomic research for regression models are insufficiently precise and detailed and so are of little use for calibrating process-based crop growth models.

The accuracy of yield prediction from a crop model depends on having an adequate model structure, precise system parameters, and accurate environmental data. Both the comprehensive and simplified crop models have technical problems, but they generally can provide reasonably good predictions, especially when the model is properly calibrated for a region.

### **Model Validation**

Since all practical crop models are limited imitations of the real system, they all need extensive field validation to assess whether they are structurally sound and, as well, to assess the extent and limitations of their validity. A practical model should be rigorously validated under widely differing environmental conditions to evaluate its accuracy on overall yield predictions, as well as the performance of major processes in the model. Normally, the results from the validation process are used to refine the model or to guide modellers to further experiments that will produce a better model. Only after extensive experimental validation (and, no doubt, after numerous modifications) can a crop model become an actual working tool capable of providing guidance on the practical management of agricultural systems.

About a decade ago, the literature in agricultural science was replete with many empirical crop production functions not based on explicit theory, and their seemingly contradictory results often could not be reconciled because of the absence of a unifying concept. Now it seems that the opposite problem has appeared, namely, numerous theoretical crop models — a consequence of recent advances in computer technology capable of handling complex systems. Most models are virtually untested or poorly tested, and hence their usefulness is unproven. Indeed, it is easier to formulate models than to validate them.

Many agronomists have been confused by the situation. They are discouraged by the complexity of the models, the lack of model testing, and the inevitable inaccuracies that arise when such testing is done. Consequently, they have seriously doubted the useability of crop models in agronomy. Unfortunately, this confusion is caused partly by those who are naively optimistic that crop modelling is the panacea for agricultural problems and apply crop models indiscriminantly. Because most agronomists do not fully understand the concept of crop growth modelling and systems-approach research, training in this area is needed.

## **DECISION SUPPORT SYSTEMS**

After a crop model has been properly validated, the uses for the model in agricultural management are numerous. Crop growth models have been used as a management tool to estimate potential crop yield in a new location (Aggarwal and Penning de Vries 1989), to assess the adaptation of a new cultivar to a region (Muchow et al. 1991), to estimate sensitivity of crop production to climatic change (Williams et al. 1988), to forecast yields before harvest (Duchon 1986), and to evaluate improved management options (van Keulen and Wolf 1986). Whisler et al. (1986) demonstrated the usefulness of crop models in breeding programs, as well as in studies to assess the effects of soil erosion impact, insect damage, and herbicide injury on crop production.

Agricultural decision makers at all levels need an increasing amount of information to better understand the possible outcomes of their decisions and to assist them in developing plans and policies that meet their goals. The first integration of an expert system with a crop growth simulation model for daily use in farm management was the GOSSYM/COMAX system (McKinion et al. 1989). GOSSYM is a computer model that simulates the growth of the cotton plant (Baker et al. 1983). The project was developed over 12 yr with contributions from 10 scientists and four institutions in two countries (Lemmon 1986). When linked with a stochastic weather generator (Richardson and Wright 1984), GOSSYM is capable of assessing crop productivity and the associated risk before harvest by using the actual recorded weather data from planting to the current date and stochastically generated weather data for the remainder of the growing season. An expert system, COMAX, was developed and integrated with GOSSYM. This new system determined the best strategy for scheduling (timing and amounts) irrigations, nitrogen applications, and seeding dates to optimize yields and economic returns. COMAX hypothesized a scenario for fertilizing and irrigating and then tested the impacts of the scenario by running the crop model with the hypothesized values. A set of rules was used to improve on the first approximations by optimizing them, using optimization techniques from operations research.

Decision makers may differ on what constitutes the best management strategy. For instance, a farmer may choose to add nitrogen fertilizer to maximize net profit while a policy maker may choose to minimize nitrate contamination of ground water. In 1982, the IBSNAT project was established. The purpose of IBSNAT was to assemble and distribute a computerized decision support system that enables individual users to match the biological requirements of the crop to the physical characteristics of the land to attain specified objectives. To achieve its goals, IBSNAT chose to use crop growth models and adopted the systems-analysis approach. In principle, the technique employed is to represent the biological system as a simulation model, modify it in various ways to represent management options, and run it with various sequences of weather data. By optimizing the outcomes in terms of the economic benefit within the constraints of soil and environmental qualities, the best management strategy can be determined from various management options (Fig. 4).

Under IBSNAT, an international team of scientists composed DSSAT to assess yield, resource use, and risk associated with different crop production practices (Tsuji et al. 1994). DSSAT relies heavily on crop growth simulation models to predict the performance of crops for making a wide range of decisions. Thus, DSSAT is essentially a set of computer programs designed to accommodate standardized crop models. It allows users to (1) input, organize, and store crop, soil, and weather data; (2) calibrate and validate crop growth models; and (3) evaluate different management practices at a site. The programs to perform these functions are written in various computer languages. A shell program (Fig. 5) using pop-up menus provides easy access to the specific tasks to be performed; thus, users are not involved with the details of submodel execution.

The real power of DSSAT for decision making lies in its ability to analyze many different management strategies. When a user is convinced that the crop model can accurately simulate local behaviour, a more comprehensive analysis of crop performance can be conducted for different soil types, cultivars, planting dates, plant densities, and irrigation and fertilization strategies to determine those practices that are the most promising and the least risky. The analysis program within DSSAT can establish the desired combinations of management practices, run the crop model with historical weather data or multiple years of weather data generated by a weather generator, and analyze and present the results to the user. DSSAT assists users in evaluating the relative merits of the simulated strategies with respect to crop yield, net return, water use, nitrogen uptake, nitrogen leached, etc. and identifies the best strategy. DSSAT is also able to sequentially operate models to simulate crop rotations and the longterm effects of cropping systems on soil N, organic matter, and P availability. Cumulative probability functions are graphically presented to help users select a strategy with the desired mean and variabiality characteristics.

At the field level, the decision maker may use DSSAT to select, first, the crop and then the cultivar, the planting date,



Fig. 4. The field-level agricultural decision support system.

cultural practices, and water, nutrient, and pest management practices. Many of the problems faced by agricultural decision makers extend beyond the boundaries of individual fields. At the farm level, decision making would consist of field-level plans for all fields that meet the goals of the farmer within the constraints of his or her resources. At the regional level, agricultural production alternatives would involve the combination of land use, soil types, weather, and field-scale management for each unit of land in the region. At both farm and regional levels, there will be additional uncertainties, such as spatial variability of soil and weather and uncertainties in the selection of crops and agronomic practices.

To consider spatial variability in risk, further coupling of the field-level DSSAT to databases of soil attributes, weather data and crop management procedures via a GIS is required. GIS can overlay one or more data sets on geographic coordinates. Such systems are needed for archiving, editing, aggregating, and integrating the vast amount of information available from remote sensing, soil surveys, weather networks, topographic maps, groundwater surveys, and other data sets required by resource managers. Thornton (1991) discussed a regional-level decision support system that allows users to query the databases for information or to specify proposed plans, practices, and restrictions for the simulation of regional responses. A prototype that integrates DSSAT with GIS to form the regional decision support system has been developed (Calixte et al. 1991).

DSSAT is a management tool that can substantially improve the quality, number, and timeliness of decisions made by agricultural producers and policy makers. In a few minutes, computers enable DSSAT to generate information to facilitate decision making that would have otherwise required a lifetime of work for an agronomist. Decisions can be made, not only to obtain profitable crop production, but also to deal with such issues as climate change, regional adaptation of new crops or cultivars, environmental degradation, and agriculture sustainability.

## DIRECTIONS FOR FUTURE RESEARCH AND DEVELOPMENT

The possibility and potential value of the crop-model-based decision support system have been described. However, for this new system to be successfully accepted as a tool for



Fig. 5. Pop-up menus on the shell program of the DSSAT for easy access to specific tasks to be performed.

agricultural resource management, the user's distrust of computer-generated information must be overcome. One effective way to gain user confidence is to demonstrate the predicting power of crop models to local audiences. The demonstration can also serve as site validation for the crop model. Such demonstrations are integral to systems development.

The greatest limitations to DSSAT applications are related to limitations in the crop models. Simulation models for the major crops are being developed, but they require careful calibration and validation for local use. Recently, International Crop Networks were organized by Focus 3 of GCTE, a core project of IGBP. The networks will develop and validate crop models that are robust for a wide range of possible global change scenarios. The initial emphasis of this project has been on the establishment of worldwide research networks on wheat and rice. The network approach facilitates adequate cross comparison of different models and maximizes collaborative utilization of field data for testing the models.

Thirteen wheat models with 31 testing sites around the world were included in the International GCTE Wheat Network (GCTE 1994). In November 1993, scientists from the network gathered at Lunteren, The Netherlands, to interchange data and models and to run all models in the network for two typical climatic conditions: one in North America and one in western Europe. Contrary to expectations, the variation in the model results was enormous. For the North American data, crop yields varied from 2500 to 8000 kg ha<sup>-1</sup>. The simulated results were slightly less variable for the European data, differing by a factor of two, from 5400 to 10 300 kg ha<sup>-1</sup>. The accuracy of crop models depends on our current understanding of physiological processes and their interactions. The discrepancies among the models clearly indicates that this understanding is by no means complete. Thus, an emphasis of agronomic research should be to further our understanding so that improved functions can be incorporated into the crop models. The improvement will facilitate the development of fewer models, generic in performance. Generic models allow users to have more uniform procedures for calibration and validation.

Crop models are in an infant stage of development. Most models only simulate the major factors that affect crop performance, e.g., weather, water, and soil nitrogen availability. Missing are components to predict the effects of tillage, pests, weeds, salinity, excess water, and other factors on crop performance. To use crop models and the systems approach for more effective resource management, simulation models for all the major crops incorporated into cropping rotations for that region are needed.

Many crop models use genetic coefficients to simulate crop growth and development. Employing cultivar-specific characteristics generally improves model performance and enables the model to analyze cultivar adaptation to diverse environments. In the past, these coefficients were usually not adequately determined. To prevent the unavailability of these coefficients from becoming the bottleneck in model applications, support for determining crop-specific coefficients is needed. The desired outcome would be having the proper genetic coefficients available when new cultivars are released so that the suitability of a new cultivar for a region can be quickly evaluated.

Improvements in the technology and accuracy of crop modelling have convinced many scientists that the routine use of crop models for agricultural decision making is a desirable goal. Thus, knowledge-based systems-approach research will gradually increase in importance relative to experience-based conventional agronomic research. Crop models will become an important mechanism for synthesizing the existing knowledge about plants and resources and for updating this knowledge as we learn more about complex agricultural systems. Eventually, the systems model will become the primary agent for technology transfer, replacing the traditional extension short courses and handbooks.

#### CONCLUSIONS

Agricultural systems are very complex. If we hope to manage our scarce agricultural resources or to estimate the effects of future climatic change on agriculture, we first need to develop an integrated tool that will simulate observed crop growth in a wide variety of environments and under a wide variety of management practices. Fortunately, recent advances in computer technology have made it possible to represent the soil-plant-climate system quantitatively. This has convinced scientists that the use of processoriented crop models and the systems approach to research is a worthwhile and important goal.

The principle of crop growth modelling and its application to decision making are based on the understanding of natural processes and using this understanding to describe agricultural systems performance through systems analysis. The reliability of this approach depends on how well we understand the physical and physiological processes involved in the growth of a crop. This understanding is by no means complete. Thus, research projects need to be focused on further efforts toward increasing our knowledge and improving our understanding of soil-plant-atmosphere interactions, rather than on developing strictly empirical relationships. Calibration and validation of crop models can improve our understanding of the underlying processes and their interactions, pinpoint where our understanding is inadequate and, hence, support strategic agricultural research. However, many agronomists do not understand the concept of crop growth modelling and systems research. Proper training and demonstration of systems analysis and crop growth modelling are required.

The development and validation of crop growth and agricultural systems models requires an integrated research approach. Agricultural systems research units working on concise objectives, directed toward producing useable, integrated, and complete data for decision makers, will significantly contribute to developing sustainable agriculture that meets the world's needs for food and fibre.

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