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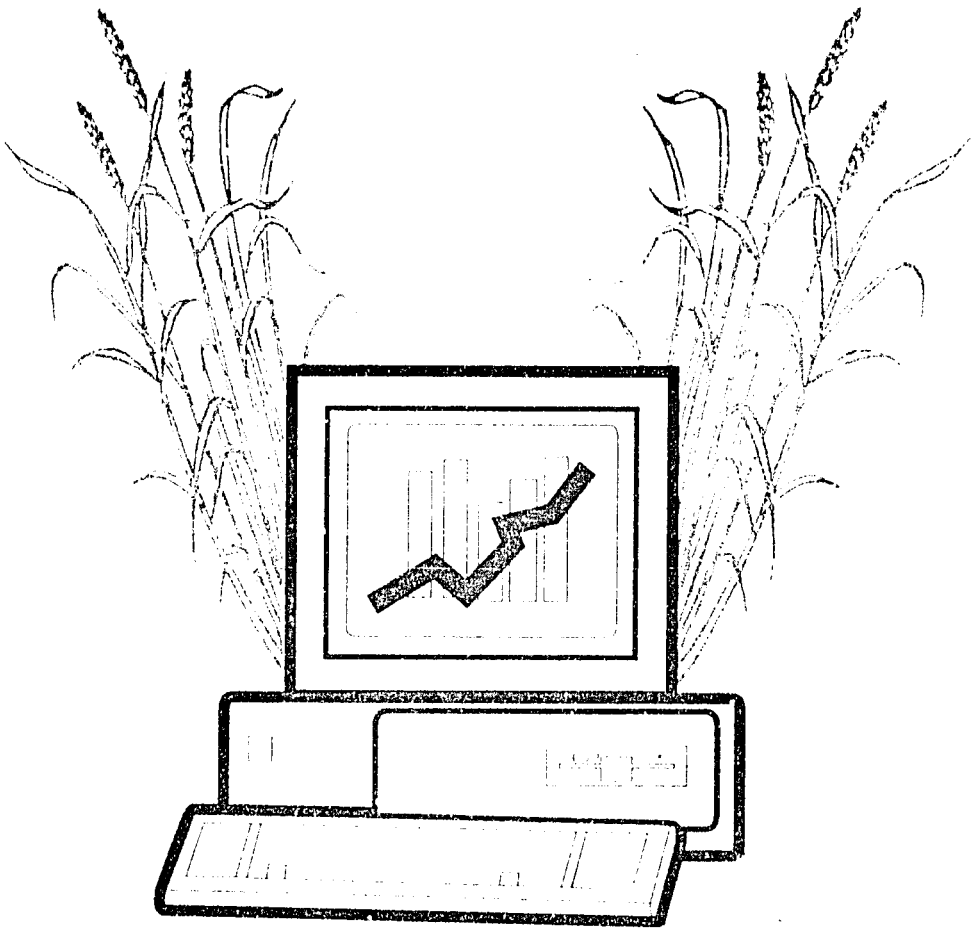
# Applying Crop Models and Decision Support Systems



International Consortium for Agricultural Systems Applications
University of Florida
International Fertilizer Development Center

# Applying Crop Models and Decision Support Systems

*Summaries*

*Training Program on Computer Simulation of Crop Growth and Management Responses*
*University of Florida*
*Gainesville, Florida, U.S.A.*
*August 8-19, 1994*

*Edited by*

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# Preface

A series of annual training courses was initiated in 1988 under the auspices of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project, an initiative funded by the United States Agency for International Development (USAID) and based at the University of Hawaii. A course has been held each year since, the venue usually alternating between the University of Florida and the International Fertilizer Development Center (IFDC). The training course in 1994, "Computer Simulation of Crop Growth and Management Responses," was held at the University of Florida, Gainesville, Florida, August 8-19. It attracted 34 participants from the following 17 countries: Albania, Brazil, Canada, Germany, Italy, Kenya, Malaysia, Mexico, the Netherlands, Norway, Portugal, South Africa, Thailand, Trinidad, the United Kingdom, the United States, and Venezuela. Nine persons from the United States, the United Kingdom, Canada, and the Netherlands formed the faculty.

Participants came with a wide range of experience and expertise in modeling and computers, but all had very specific ideas for using crop models in their own particular areas of work. In order to document this breadth of interest and application, all participants and resource persons were asked to contribute a maximum of two pages outlining current or future applications of crop modeling techniques in their own research programs. These have been collected for this volume.

The summaries appear in alphabetical order by first author, except for two introductory summaries: an outline of ICASA, the umbrella consortium of model developers and users that has grown out of IBSNAT, and an outline of the Decision Support System for Agrotechnology Transfer (DSSAT), the modeling software that was used for much of the training course.

All the summaries should serve as a reminder of two facts: first, that training scientists in the use and application of modeling is no less crucial than model development, model testing, and model documentation; and second, that modeling is not an end in itself but a means to solving real-world problems that are often of considerable urgency.

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## Abbreviations

| | |
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| DSSAT | Decision Support System for Agrotechnology Transfer |
| GIS | Geographic Information System |
| IARC | International Agricultural Research Center |
| IBSNAT | International Benchmark Sites Network for Agrotechnology Transfer |
| ICASA | International Consortium for Agricultural Systems Applications |
| IFDC | International Fertilizer Development Center |
| NARC | National Agricultural Research Center |
| NOAA | National Oceanic and Atmospheric Administration |
| SARP | Simulation and Systems Analysis for Rice Production |
| USAID | United States Agency for International Development |
| USDA | United States Department of Agriculture |

# The International Consortium for Agricultural Systems Applications (ICASA)

A new international consortium has been formed to bring together expertise from various organizations for more effective and efficient development and application of systems approaches to agricultural production systems, resource management, and rural development. Organizers of the consortium were previously contributors to the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) and SARP (Simulation and Systems Analysis for Rice Production) projects. The IBSNAT project had headquarters at the University of Hawaii; major contributors were at the University of Edinburgh in Scotland, the University of Guelph in Canada, and the International Fertilizer Development Center, Michigan State University, the University of Georgia, and the University of Florida in the United States. The main goal of this project was to improve methods for technology transfer using models of crops and soils and analysis tools to compare alternative management practices at sites where weather and soil data were available. A major emphasis was on collecting a minimum set of data for evaluating the models. The Decision Support System for Agrotechnology Transfer (DSSAT) was conceptualized, designed, and developed by scientists cooperating on this project. Many researchers have acquired this package, which is described in another summary in this document, and a number of workshops and training programs have been organized around the DSSAT. The SARP project, funded by the Dutch government, was also a highly successful research program in which a systems approach was taken, including the use of a rice crop model. This project was led by scientists from the Wageningen Agricultural University, Production Ecology and Agrobiology Research units, which also have had outstanding successes in developing agricultural models, publishing books and training material on this subject, and applying the models to regions around the world. Teams of researchers were established throughout Asia and trained on the concepts of systems analysis and crop modeling, and in particular on how to apply rice models to research in their institutions.

As both projects evolved, more or less independently, it became clear that cooperation would facilitate a more effective use of the models and other tools that had been developed and were being developed. Some rather simple issues, such as the use of different data formats, prevented the effective comparisons of models and approaches. In many cases it was noted that duplication of effort could be reduced by cooperating. In addition, various national and international research centers became increasingly interested in the application of models and systems tools in their research programs. Therefore, ICASA was born. It is an official non-profit entity, with headquarters at the University of Hawaii, and with a Board of Directors chaired by Professor Rudy Rabbinge of Wageningen Agricultural University and co-chaired by Professor Joe T Ritchie of Michigan State University.

The main objectives of ICASA are to provide national agricultural research centers (NARCs) and international agricultural research centers (IARCs) with system-analytical tools for integrated research and analyses and for practical applications aimed at optimal and sustainable agricultural production systems, resource management, and rural

development. There is a growing demand for food from sustainable agriculture, competition between agriculture and other sectors for limited resources, land degradation, and possibly changes in climate. Determining the best strategies to solve these problems is not possible by traditional experimentation alone. Plans are to meet the objectives by participating in research and technology transfer projects with international ICASA partners and by developing training materials and holding training courses and workshops to teach others the effective use of this technology. Standards will be developed for data formats and methods for model application at different levels to facilitate model evaluation and minimize duplication and wasted efforts. Application-oriented software shells will be developed to allow evaluation of different models so that they can be improved as we learn more about agricultural systems.

Initially, the data formats defined and documented for the DSSAT v3.0 have been adopted by ICASA. Efforts are underway to make the SARP rice model and other crop models from Wageningen compatible with these formats. Considerable progress has already been made toward this goal. Thus, different models will be able to run under DSSAT v3.0, although plans are to improve the common data formats and structures as time progresses, and an ICASA shell will ultimately replace the DSSAT v3.0 shell. Efforts will be made to make future upgrades in the data structures and application shells backward compatible so that current users can evolve smoothly into the new ICASA systems. Furthermore, we expect a number of user-oriented shells to evolve, each of which will adhere to the common data structures so that the building blocks, such as crop models, soil models, weather generators, and analysis software, can be readily adopted to different applications. The DSSAT v3.0 is but one of several application packages expected. For example, the Agricultural and Environmental Geographic Information System software forms the basis for a land evaluation package that can be adopted to different regions, a yield forecasting shell has been developed by ICASA members at IFDC, and a farming system analysis shell is being developed at the University of Florida.

ICASA has just been formalized, and procedures are being worked out for methods of cooperation between the two groups associated with the IBSNAT and SARP projects and for a much broader group, including researchers at national and international research centers and universities. Additional training programs are already scheduled and others are being planned. Several specific research proposals have been drafted to work with IARCs and NARCs. Membership in ICASA will not be exclusive, and details are being worked out as to how to expand current membership, which originally consisted of SARP and IBSNAT network members. Anyone interested in ICASA activities should contact Dr. Gordon Tsuji, ICASA Office, Department of Agronomy and Soils, University of Hawaii, Honolulu, HI 96822, U.S.A. (gordont@uhunix.uhcc.hawaii.edu).

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# The Decision Support System for Agrotechnology Transfer (DSSAT) Version 3.0

The DSSAT is the major product of a multiple institute, multidisciplinary research and development project funded by the United States Agency for International Development (USAID) from 1983 to 1993. Based at the University of Hawaii, the project involved several universities and research institutes in the United States and elsewhere. This was the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project, consisting of networks of model developers, testers, and users. The DSSAT represents a very large investment of time, resources, and expertise on the part of many people. IBSNAT's rationale for crop modeling activities was that the provision of information with which to make decisions is a critical bottleneck in the development process and that suitable models can help to provide decision makers with the type of information they need to make better, more informed decisions.

DSSAT was first released as Version 2.1 in 1989. Over 300 copies were distributed to institutes and individuals around the world for use in training and research. Although funding for IBSNAT finished in 1993, the networks are continuing under the aegis of a new consortium involving the former IBSNAT and Dutch modeling groups, the International Consortium for Agricultural Systems Applications (ICASA).

DSSAT v3.0 has new input-output structures, improved models, and better data handling capabilities, and it allows crop rotations to be simulated and analyzed. The software consists of a set of computer programs accessible under a shell designed to enter, store, and manipulate weather, soil, and crop data; run crop simulation models; and analyze crop model outputs. There are 10 crop models in v3.0: maize, wheat, rice, barley, sorghum, millet, soybean, peanut, phaseolus bean, and cassava. Potato, taro and tanier, sugar cane, and tomato will be added in the near future. All crop models share a common input-output format, and they are similar in level of detail. They operate on a daily time step and are based on an understanding of biophysical processes. Model capabilities are continually being improved.

The crop models can be run in a number of ways in the DSSAT:

* Validation mode, to compare simulation output with real-world field trial results to assess model performance in an environment.

* Sensitivity analysis mode, to answer "what if ..." questions; for example, what happens to yield response if I grow another variety of wheat or apply more fertilizer?

* Strategy analysis mode, where replicated seasonal or rotation experiments can be simulated and weather and economic risk assessed.

The DSSAT is being used as a teaching and training tool; as a research tool, to derive recommendations concerning crop management and to investigate environmental and sustainability issues; as a business tool, to enhance profitability and improve input marketing; and as a policy tool, for yield and area forecasting and land use planning.

The crop models are being linked to other software tools such as Geographic Information Systems (GIS), to allow regional analyses to be carried out, and multiple-objective mathematical programming models, to help solve resource use issues that impinge on various sections of society with different goals.

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# Soil Site-Specific Management: Using Soil Spatial Variability as a Tool for Land Management Practices

In traditional agricultural practices, land management is usually homogeneous within one field, although differences may occur with respect to soil types, landscape, or elevation. The combination of homogeneous management and variable soils produces different patterns of crop growth or leaching of agro-chemicals. For example, fertilizer recommendations are often based on the average plant-nutrient content in a field, thus resulting in some locations within a field receiving too much fertilizer while others receive too little. The result is inefficient use of fertilizers and possible pollution of ground or surface water. Soil site-specific management or precision agriculture focuses on the use of variability assessments for soil management purposes with the aim of developing agricultural systems that are economically beneficial and can function within environmental legislation.

Precision Agriculture requires additional tools for farmers, including farm management decision tools as well as operational technical tools such as global positioning systems. The objective of the Department of Soil Science and Geology with respect to precision agriculture is to provide a knowledge-based decision support system that can help farmers to apply precision agriculture at the farm level, taking into account both economic and environmental management objectives. To achieve this objective, several research projects have been, or are being, conducted. These projects can be grouped into three main categories:

1. The development of soil survey techniques, including geostatistical analysis, to develop a soil database which can be used within the knowledge-based decision support system.

2. Measurement and prediction of environmental hazards in agroecological systems. Monitoring of critical soil and water parameters is combined with field-scale scenario studies using simulation models.

3. The use of remote-sensing techniques as tools for monitoring plant status, especially with respect to drought or nutrient stress. Adequate monitoring of plant stress provides the possibility of adjusting farm management practices such as local fertilizer or pesticide applications.

All these research projects are being carried out on an experimental farm in the northwest of the Netherlands. The results obtained so far deal mainly with the development of operational procedures to adequately describe soil spatial variability and to combine these procedures with the results of simulation studies. For example, this combination permits the production of maps showing the probability of exceeding threshold values of critical nitrate concentration at the field or farm level, thus allowing the adjustment of local fertilizer applications. Monte-Carlo simulation procedures were applied to take into account

variability of model parameters and to study model sensitivity. In combination with othe statistical techniques, this Monte-Carlo procedure was also used to calibrate mod parameters on field-measured data series.

In the near future we will construct a database containing information for the decisio support system. Pedotransfer functions to derive difficult-to-measure soil properties fro commonly measured soil properties will be developed. The methodology will be teste within the case studies mentioned above, and data will be used in databases and GI applications to support decision making.

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# Using CROPGRO to Evaluate Grain Legume Response to Climatic Factors

CROPGRO is a new concept, a generic crop model that simulates growth of soybean, peanut, and dry bean. The code is modular and will simulate all three legumes with one common set of FORTRAN code. Species attributes are input from "species" files. In addition there are cultivar attributes. CROPGRO has been substantially modified and is more mechanistic than its predecessor models. The model includes leaf-level photosynthesis, hedgerow canopy light interception, soil nitrogen balance, nitrogen uptake, $N_2$ fixation, additional energy-balance options, improved crop development routines, and pest-coupling approaches. Simulated soil-plant nitrogen balance includes nitrogen uptake, $N_2$ fixation, and nitrogen deficiency effects on vegetative and seed growth processes. Carbohydrate dynamics are modeled and respond to N deficiency. Leaf-level photosynthesis in an hourly hedgerow canopy assimilation loop improves response to row spacing, allows more mechanistic response to climatic factors, and allows the analysis of the effects of varying plant physiological traits. Several evapotranspiration options are available, including Priestley-Taylor and FAO-Penman. The phenology simulation uses newly optimized coefficients and a more flexible approach that allows development during various growth phases to be differentially sensitive to temperature, photoperiod, water deficit, and nitrogen stresses.

Because CROPGRO is a substantially modified model, we analyzed the model's sensitivity to climate change and management factors such as $CO_2$, temperature, irradiance, planting date, and row spacing. Model response to $CO_2$ is asymptotic as expected: daily assimilation and seed yield of soybean are increased 29 and 30% with a doubling of $CO_2$ from 350 to 700 ppm. Modeled canopy assimilation and dry matter accumulation have a broad temperature optimum centered in the range 28-33°C despite increase in leaf rate to 36°C. By contrast, modeled seed growth and yield have a clear optimum at 20, 22, and 24°C mean temperature for bean, soybean, and peanut, respectively, and yield declines at higher or lower temperatures. The temperature optimum for seed yield is a complex result of the temperature that is nearly optimal for seed growth, nearly optimal for assimilation, and somewhat below the optimum for development to give slower life cycle progress. Planting date simulations illustrate optimal planting dates for yield that depend on rainfall and crop response to photoperiod and temperature. Predicted optimal planting date for soybean at Gainesville is late April to early May. The response of simulated dry bean yield to planting date was complex; yield was lower for late spring plantings because the single seed growth rate and partitioning to seed are depressed by elevated temperatures in mid-summer. The CROPGRO model is part of the DSSAT v3.0 software, which facilitates sensitivity analyses.

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# Some Potential Applications of Simulation Models for Cropping Systems in Italy

In Italy, as in many other countries, the priority of agricultural activities and the related research effort have moved from the single goal of raising yield levels to the multiple target of producing stable incomes, maintaining soil fertility, and avoiding negative effects on the environment. As a result, research activities must be oriented towards the development of decision tools to help evaluate agricultural management options at both the farm and watershed levels.

Crop management in most regions of Italy typically relies on high inputs. Consequently there is great concern about groundwater quality. There is a need to quantify variables of environmental interest such as crop water use, water percolation, runoff, nitrate leaching, soil organic matter, soil erosion, and fate of pesticide. Experimental data are usually derived for only a limited combination of specific factors, and so results cannot be extrapolated to all the possible cropping systems and management options. In addition, the impact of weather variability on the cropping systems tested cannot be adequately addressed in short-duration field experiments. In response to such problems, a national research project called PANDA (Sequi, 1994) is underway in Italy to study the effects of agricultural management on the environment. Three objectives of the project have been defined: (a) calibration and validation of cropping system simulation models, (b) use of the models to study cropping systems at a number of sites in Italy, and (c) development of a modeling environment to build modular system models.

Major activities are as follows:

1. The cropping system models are being calibrated and validated at ISA-Modena, focusing on the EPIC and CropSyst models. DSSAT v3.0 models will also be tested.
2. A preliminary simulation study on the comparison of cropping systems at two locations was made using the EPIC model, and some of the results of management and rotation effects on leaching estimates are now being tested in experimental trials. Simulation studies of this type will be carried out to determine the environmental impact of both standard and low-input cropping systems at representative sites in Italy.
3. A modeling environment is being developed using the programming languages Clipper and C++ for the user interface and VisualBasic for model code.

Preliminary results of model testing are encouraging (Ceotto et al., 1993a; Ceotto et al., 1993b; Donatelli et al., 1995; Spallacci et al., 1995); however, further testing, using more detailed data sets from different sites in Italy, will be carried out. To summarize:

* General trends for soil water content in the soil profile were correctly simulated for a number of crops, although some discrepancies suggest the need to investigate the effect of soil cracking on clay soils.
* Soil nitrate content over time is estimated better on clay soils than on loam soils with low organic matter content; calibration did not improve model performance.
* Growth of winter cereals was often not simulated adequately.
* The model used did not allow an estimate of the effect of tillage on water infiltration; tillage effects are known to be substantial on clay soils which are common in Italy.

* Water table effects cannot be simulated satisfactorily with the current versions of EPIC and CropSyst; thus, these models cannot be used in areas with a perched water table.

A preliminary study (Donatelli et al., 1995) evaluated the risks associated with high-nitrogen-input fertilization and residue management as well as the risk of nitrate leaching associated with different crop sequences. In areas where soil water is not completely refilled in all years, the accumulation of nitrate in the soil can result in substantial leaching. Extension of this type of study to different combinations of soil and weather will allow an evaluation of the risks associated with a given crop sequence and nitrogen fertilizer management system.

The modeling environment under development (Donatelli et al., 1994) allows the user to edit input files and change their structure and to implement a submodel for process simulation by writing the relevant VisualBasic code. A system model can be created by selecting submodels to include in the daily loop of the system model frame. Cropping system simulations can then be run and sensitivity analyses performed. The user may also define data output formats. This environment will eventually enable us to assemble different models for cropping systems in Italian conditions using a variety of approaches already implemented in various models.

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## Crop Growth Simulation in Potchefstroom, South Africa

South Africa is a country with limited agricultural resources, and thus considerable emphasis has been placed on the use of mechanistic (functional) models. The Summer Grain Centre has been active in maize growth simulation for almost two decades, and an empirical maize model developed by the Centre has been widely used in practice. More recently a research program aimed at modifying CERES-Maize for South Africa's maize production areas has been initiated. Trials are being conducted to address simulation shortcomings in the model.

The South African summer rainfall production area has a low and variable rainfall, and maize production may range from 3 to 12 million tonnes per annum. Production practices, therefore, have to be adapted to optimize moisture utilization so as to minimize yield variation. Models could be used to solve this problem. The operational success of maize growth simulation models in South Africa will determine how farmers accept other crop models in South Africa.

Several key research objectives were identified to help utilize CERES-Maize in South African maize yield prediction:

* To structure research to improve CERES-Maize.
* To stringently test CERES-Maize under a wide range of water stress scenarios, plant populations, and row widths.
* To determine the genetic parameters of South Africa's commercial cultivars.
* To test CERES-Maize over a wide range of climate-soil combinations.
* To provide access to weather and soil databases for most of South Africa's maize production areas.
* To adapt CERES-Maize for South Africa's unique climate and maize production practices.

All these objectives are currently receiving attention by local scientists and are at different stages of fulfillment. When these objectives have been attained, South Africa will be one of the few countries with the relevant input data to use crop models operationally. Unrealistic demands on accuracy (± 5%) could delay the models' operational use.

To determine the simulation shortfalls in CERES-Maize, the model is tested against historical data. Trials are then developed to address these shortfalls. Some farmers have historical yield, rainfall, and management data records. These data can be used in field validation of CERES-Maize. The absence of measured initial soil water content at planting could be minimized by the ability of DSSAT v3.0 to do sequential simulation runs. To compile weather files from historical data sets, the DSSAT v3.0 program "Weatherman" is of considerable value.

The success of DSSAT v3.0 is closely correlated with the accuracy of the crop growth models. Sequence analysis will make the models more applicable for crop rotation trials. In a project where soil inputs were determined for the major maize producing areas of South Africa, "Weatherman" was used to generate a weather file that filled the profile to saturation followed by no rain for the rest of the season. First stage evapotranspiration was set at a very low value. A drainage curve was thus simulated and compared with the real curve. Preliminary results showed substantial differences between actual and predicted values. These differences could be reduced by changing the soil water content. Empirical functions to determine the drained upper limit and lower limit gave different values. In this exercise, tables in the soil file in DSSAT v3.0 were also used for these determinations.

The confusion around the empirical determination of drained upper level and lower level needs to be clarified. In a country where water shortage is the major problem, accurate soil input data are very important.

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# IRDDESS: Irrigation District Decision Support System

Irrigated agriculture plays a key role in sustaining national and regional food and fiber production. It is destined to play a greater role as world population continues to escalate. The rather poor performance of irrigation systems in many parts of the world (in terms of yield and sustainability) when compared with design intentions and investment expectations raises concerns about the ability of irrigated agriculture to face this challenge (World Bank, 1989). Water management considerations are required in all phases of irrigation development. In Texas, for example, recent Water Conservation Plan regulations require many irrigation districts to submit water conservation and drought contingency plans.

Managing irrigation systems involves collecting, storing, and processing large amounts of data on climatology, hydrology, pedology, agriculture, and administration. The widespread availability of computer technology and advances in crop modeling provide the opportunity to take advantage of such complex data sets. Modeling allows systematic analysis of all parts of the crop production system, including the prediction of spatial and temporal crop performance.

The goal is to improve the capabilities of irrigation districts in water conservation planning and optimization of water delivery, leading towards sustainable use of irrigation water.

The objective is to develop computer software that integrates a generic crop model with water routing routines to simulate the spatial and temporal variability in crop productivity and to simulate water use from the farm level up to the point of diversion in an irrigation district.

IRDDESS was developed to meet the overall goal and objective. IRDDESS is a menu-driven personal computer program composed of three modules: simulation, routing, and utility. The simulation module uses a generic crop model similar to the family of models represented by WOFOST (Driessen and Konijn, 1992) to analyze crop production for an individual field with and without water stress. Nutrient supply is assumed to be optimal, and control of weeds, pests, and diseases is assumed. The crop model is repeatedly used in two other submodules to analyze potential production under any combination of irrigation schedules and weather.

IRDDESS considers field-level water management as critical in improving overall district performance. The routing module is made up of seven submodules to track the daily water needs of a group of fields served by the same lateral in the conveyance system. Three levels of conveyance are considered: primary, secondary, and tertiary. Tertiaries supply canals or pipes which irrigate the fields directly. Secondaries supply a group of

tertiaries. The primary is the main artery of the system and supplies the secondaries. The first routing submodule uses the crop model.

The utility module performs three functions if necessary. Potential evaporation and evapotranspiration are calculated with a modified Penman equation. Weather data provided by the National Oceanic and Atmospheric Administration (NOAA) are changed to metric units. Daily weather data, except for rainfall, is generated from monthly mean data by simple interpolation.

The IBSNAT project, through its product DSSAT, has successfully demonstrated the use of crop models for many applications, including short- and long-term irrigation studies (IBSNAT, 1993; Hoogenboom and Gresham, 1993). IRDDESS tailors physically based crop modeling to real-time irrigation district management needs and assessment. Because of the variability in soils, crops, and weather conditions, modeling real-time irrigation district water management can be complex. IRDDESS uses a generic crop model to reduce complexity in programming, data collection, and input. The crop model is being tested for maize, cotton, and wheat. IRDDESS also takes a broader definition of an irrigation district. Any irrigation system that has a layout that fits its analytic capability can be modeled. Future work will link IRDDESS with a GIS, which provides a framework for capturing, storing, updating, analyzing, and outputting spatial and temporal data.

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# Expert-N: A Prototype Building Block System for Nitrogen Simulation Models

Reducing pollution of natural resources caused by agriculture and increasing the efficiency of crop husbandry are important goals of research. Over the last few years, many researchers have worked on understanding the processes within the soil-plant-climate system, for which simulation models are increasingly being developed and used. Because of the importance of the plant nutrient nitrogen in crop husbandry and its impact on the environment, many research projects are dealing with the description of nitrogen dynamics in agroecosystems. A comparative analysis of existing simulation models (Engel et al., 1993) shows that many models describe the major processes involved in a similar way. Differences between the models are usually associated with the number of processes that are taken into consideration and the kind and values of the parameters used.

Expert-N is a research project sponsored by the German Federal Ministry of Research and Technology. The objective is the development of a building block system of nitrogen models. This model system will contain a collection of different modules for important processes of the nitrogen cycle in soil-crop systems such as nitrogen transformations and movement, water and heat balance, and crop growth and nitrogen uptake. It is designed as a tool to compare various models and model approaches and to study their effects in the entire system. The modular structure and the standardized model units allow easy exchange of the different algorithms to describe single processes. In this way it is possible to fit the model to the user's specific purpose (research, management) and conditions of the site (crop, soil, available input parameters). Expert-N is thus a highly flexible nitrogen simulation model itself.

A feature of Expert-N is its ability to be run on different computer systems such as a personal computer, workstation, or mainframe. The code of Expert-N, written in C, is contained in a C library, which has only to be extended by a user interface for the available computer system.

Currently a prototype is available with a graphical user interface for IBM-compatible personal computers. The prototype runs in MS-Windows 3.1 and has the following characteristics:

* An easy-to-use program to feed data into the computer with estimation of missing input data.
* Storage of data using Btrieve database files.
* An ASCII interface between input and simulation program.
* A building block system with the algorithms and model approaches of the complex deterministic model LEACHN (Hutson and Wagenet, 1991) and the simpler empirical models N-SIM (Engel, 1991), CERES-Wheat (Ritchie, 1991), CERES-Barley, and CERES-Maize.
* Different hydraulic functions and mathematical algorithms to solve the partial differential equations involved.

* The possibility to program new functions and integrate these as dynamic link libraries.
* Extensive graphical screen and printer outputs.

A user of Expert-N may compare simulation results of different models such as LEACHN and CERES, create "new" simulation models by combining different model components, add original modules to the building block system, and search for the best agreement between measurements and simulation for a specific site. A comparison of the models LEACHN and CERES using Expert-N shows large differences with respect to required input data and computer performance. Simulation results are quite different, especially in terms of water transport and the crop growth.

The next step of the project will be to compare the simulation results with measurements to find out which model or model combination performs best for a specific site. Additionally it is necessary to program interfaces to existing weather and soil databases in Germany to facilitate data supply to the system. The link to a GIS will improve the site-specific presentation of the simulation results. To make the system compatible with other systems, an interface to the DSSAT v3.0 data format will be constructed. This will allow for easy exchange of input data and simulation results with other modelers and modeling groups. Currently only a German language prototype is available, but an English version of Expert-N is planned.

In summary, Expert-N is a flexible tool for comparing nitrogen models and modeling approaches, for analyzing N-transformation processes, and for fitting models to a specific site. In future the system will be used as a tool to support the farmer in his management decisions, particularly with respect to optimal fertilization from an economic as well as ecological point of view.

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# Application of Soybean Crop Models in Brazil

The soybean crop occupies a very important position in the Brazilian economy, and this justifies the search for new information aimed at optimizing its cultivation as well as reducing the risk of losses. Quantitative analysis of climate-plant interrelations has many practical uses in agricultural activities. Charts and maps of results from different models may be used for land use planning and agricultural zoning. The models are excellent tools for characterizing the duration of crop cycles, allowing the correct planning of sowings and the monitoring of harvest periods (thus reducing the risks of climatic adversities) as well as the estimation of production based on the effects of weather. Models can also be used to estimate the need for irrigation and disease management in studies of the feasibility of introducing crops or cultivars into new areas. These charts and maps are also useful in studies of crop and cultivar behavior in different conditions with respect to temperature, water availability, photoperiod, and $CO_2$ concentration.

Our institute started working with models in 1990 with SOYGRO v5.42. Since then, field experiments with and without irrigation have been carried out in order to calibrate this model for Brazilian cultivars. In a preliminary evaluation of the SOYGRO model for these cultivars, results showed a strong tendency for the model to underestimate the occurrence of the main phenological phases of the soybean crop as well as the weight of dry matter. With regard to estimates of yield and its components, there were significant differences between observed and simulated values. After several adjustments, simulated values were very close to the observed values. Estimates of crop phenology were very similar to the values observed in the field, but the tendency to underestimate these variables was still evident. Dry weight and yield data were also similar to those observed in the field. Because the data were from field plots with and without irrigation, it was possible to observe that the model simulates water availability in the soil quite well. Despite the satisfactory results obtained after calibration, many adjustments are still necessary, especially those related to estimates of phenological periods.

There are two serious problems involving the soybean crop in Brazil:

* Yield variability arising because of the occurrence of pronounced water deficits, which are frequent in the southern parts of the country.

* The expansion of the soybean crop to northern Brazil (low latitude areas), with associated problems of adaptation of genotypes that are insensitive to photoperiod.

In the National Soybean Research Center (EMBRAPA-CNPSo) we are working with four basic research lines related to soybean ecophysiology:

1. Agronomic and physiological responses of soybean to environmental stresses, mainly water deficit.

2. Characterization of the thermophotoperiodic needs (sensitivities) of cultivars with a long juvenile period.

3. Adaptation of cultivars to different environments.

4. Strategy evaluation and economic analysis of different management practices and farm systems.

In all these research areas the models can be tools of great value, allowing a better understanding of the processes involved in crop production under different crop management and environmental conditions. The results obtained will provide fundamental information for zoning and agricultural planning activities, allowing expansion of the soybean crop to new areas and identification of planting dates that are less susceptible to crop failure owing to climatic adversity. The results will also contribute guidelines to rural credit and insurance institutions concerning the levels of economic risk associated with conditions in each area.

In many training programs and extension activities, these models will be used to demonstrate to extensionists and farmers the effect of the environment, as well as the effects of adoption of different soil and crop management practices, on crop behavior and economic profitability.

We intend, as soon as possible, to study the behavior of Brazilian cultivars under different conditions with respect to temperature, water availability, photoperiods, and $CO_2$ concentration, to obtain information on crop behavior under future possible climatic change. This activity should lead to more rational crop research strategies as well as to increases in soybean production and productivity, with associated benefits for society and the economy in Brazil.

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# Testing and Application of Simulation Models in Bean-Based Farming Systems in Guatemala

A project, funded through a grant of the USAID Program in Science and Technology Cooperation, is being undertaken as a case study to test the hypothesis that simulation models have a role to play in enhancing the efficiency of both agricultural field experimentation and the identification of promising technologies in developing countries. Other studies have shown promising results with application of models in tropical regions (White et al., 1995). This project seeks to refine and apply methodologies that are applicable in other locations, that help to reduce costly and time-consuming agricultural experimentation, that help to avoid duplication of effort, and that enhance the efficiency of development, through the identification, testing, and dissemination of more appropriate technology for resource-poor farmers in the tropics.

The specific objectives are the following:

* To assemble resource databases for the region of Jutiapa in southeast Guatemala concerning soils, weather, and broad farming system descriptors that can be linked to crop simulation models.
* To calibrate and validate existing simulation models for beans and maize through a program of on-farm and on-station field experimentation.
* To develop a methodology for identifying efficiently the most promising genetic lines of the study crops that will produce high and stable yields in monoculture and in maize-bean associations, thereby decreasing the time between first selection and release to farmers.
* To identify ways of increasing and diversifying production, and raising household income, through the screening of agricultural production alternatives with reference to the biological and economic sustainability of farming systems.

Automated weather stations have been installed on three farms and at two experiment stations, Jutiapa and Cuyuta in the coastal region. These record daily maximum and minimum temperature, solar radiation, and precipitation. Additional long-term weather data have been obtained from the national weather service in Guatemala to establish a climatological database for crop model applications. Soil data are being collected at each site where experiments are conducted. Trials are being conducted at the experimental station in Jutiapa and in several farmers' fields. Crop development data are being collected at least twice a week, and growth analyses are performed at one- to two-week intervals. A wide range of cultivars, including several advanced lines, are being grown at Jutiapa with different levels of irrigation.

The crop models CERES-Maize (Tsuji et al., 1994) and BEANGRO (Hoogenboom et al., 1994) are being calibrated with the experimental data collected in the experiments described previously. The Decision Support System for Agrotechnology Transfer v2.1 (IBSNAT, 1989) has been installed on computers of the bean program at the headquarters of the Instituto de Ciencia y Tecnología Agrícolas, and at the experiment station in Jutiapa.

Field data have been entered into the computer, and several technicians have learned to use the DSSAT V2.1 software through hands-on experience. Translation of several of the Technical Reports into Spanish also has facilitated the rapid adaptation of these systems analysis and modeling technologies.

The model application phase will involve using the validated models to investigate a variety of problems. For instance, promising genetic lines can be identified for particular areas of the study region using the crop models. Long-term simulations will be run and the performance of cultivars compared in different locations. Promising lines could then enter field testing in farmers' plots. In addition, the performance of theoretical lines can be simulated, to help identify cultivars that are drought resistant because of early maturity, for example, and that can be produced or selected by the breeder through different crossing combinations.

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# Evaluation and Application of the Dry Bean and Soybean Models

## Dry Bean Project

The State of Santa Catarina, in southern Brazil, is characterized by its irregular topography, four climatic seasons, and small but diversified farms Maize, dry bean, soybean, cassava, tobacco, hogs, chickens, and dairy cattle are the major activities. There are also some specific areas with apples, plums, peaches, grapes, kiwi, oranges, beef cattle, onions, garlic, and vegetables.

Dry bean is a staple food in Brazil. Yields are low and variable, because the crop is rainfed. Therefore, planting date is critical to avoid water stress in some phenological phases. The use of irrigation could be an alternative, but it is expensive and viable only in a few areas. Potential yield increases due to irrigation, as well as its economic evaluation, must be determined before recommending this practice. Such analyses can be performed using the crop simulation models and the strategy analyses built into DSSAT.

The first step will be the collection, organization, and filtering of weather, soil, and crop data already available. In order to obtain a good calibration, further data will be needed. Some cultivar test experiments, carried out annually in specific bean production areas, could be used to obtain an adequate data set (soil characterization, crop growth, and development measurements) for model calibration. The assembling of databases and model calibration is expected to take 2 years. After calibration, simulations will be performed over time (using real weather data) in order to determine the best planting dates for the main dry bean cultivars. Seasonal analysis in the DSSAT will then be used to evaluate alternative strategies with respect to risk reduction and economic factors.

## Soybean Project

A data set from Taiwan, collected from field experiments conducted at the Asian Vegetable Research and Development Center, will be used for calibration and validation of the soybean simulation model in DSSAT v3.0. Experimental data for four cultivars and five soil types are available. In total, there were 20 experiments planted at different times of the year: autumn planting (3), spring planting (9), and summer planting (8). Soil, weather, and crop input files have already been created. However, soils still need better characterization.

Spring and autumn planting experiments will be used for model calibration. Summer experiments (high temperatures during the growing season) will be used for model validation. The variables to be considered are anthesis, first seed, and physiological maturity dates; grain, stem, and biomass weights; leaf area index; and harvest index.

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# An Object-Oriented Process-Level Farming System Simulator

An object-oriented, discrete-event, whole-farm simulation model was developed as a tool for examining the future viability of crop-based farming systems. The farm model calls process-level crop simulation models using information from a standard IBSNAT experiment file. The crop models then output a schedule of field operations with their associated material resource balances. The farm model matches operations to requirements for timed resources such as labor and equipment. A queue stores events as polymorphic objects. After the crop models have simulated all fields, the event queue executes stored field operations and performs monthly events that update fixed costs, debt servicing, and household consumption. For seven classes of resources – consumable, credit, timed, capital, machine, seasonal, and aggregate – the farm model includes methods for checking their availability, updating their fixed costs, charging variable costs, and "buying" from or "selling" to other resources when storage constraints are exceeded. Fixed and variable costs associated with a particular resource are represented as links to other resources, with price inputs determining exchange rates between resources. Scenarios can be replicated with inputs of weather and prices sampled from stochastic time-series models. The object-oriented structure provides both an intuitive representation of the farm and flexibility in defining and simulating farming scenarios; it also simplifies extension of the model.

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# Integration of Crop Simulation Models and Geographic Information Systems for Farm-Level Applications

Crop models can be an effective tool in simulating growth and development of a particular crop as a function of environmental conditions and management scenarios. Using either different planting dates or different weather years as input, the IBSNAT crop models can simulate very well the effect of temporal variability of weather conditions and the effect of management conditions on growth, development, and yield of crops (IBSNAT, 1989). However, the models can only predict yield for the actual location where the experiment was conducted or for which the input conditions are known. Apart from temporal variability, environmental factors are also characterized by spatial variability. Both weather and soil conditions vary across space; this variability is normally ignored, however, especially at small scales.

One of the computer tools that can handle spatial variability is a Geographic Information System, which consists of databases with spatial attributes. A GIS allows the user to digitize a map and store all the information of the map in digital form. Linking a GIS with crop simulation models gives the user the capability to address both the spatial and temporal variation of environmental variables and the effect of such variation on crop production. The Agricultural and Environmental Geographic Information System (AEGIS) was one of the first crop model-GIS packages to be developed (Lal et al., 1993), and several versions of the system have been used to address different regional productivity issues (Papajorgji et al., 1994).

A study is being conducted to look at spatial variability on a farm scale rather than at a regional scale. Although the concepts of model linkage with GIS are similar, the applications are different. The main objective is to investigate the effect of soil variability on yield as a function of different land use practices.

The soils map of the Bledsoe farm of the Georgia Agricultural Experiment Stations (GAES) was digitized according to the maps published by Perkins et al. (1985). In addition to having detailed plot and field use information available for these research farms, detailed environmental variables are also being collected. As part of this study, most of the research farms of the GAES will be digitized to represent the different climatic regions of Georgia (Wei et al., 1994). For each unique soil type, the soil parameters required as input for the crop models were calculated using the programs provided with DSSAT V2.1 (IBSNAT, 1989) and the soil profile data published by Perkins et al. (1985). It was assumed that the weather conditions were the same for all fields of Bledsoe Farm. An automated weather station has been in operation at this site since 1988. The GIS system used was PC-ARC/INFO (ESRI, 1988). A new interface was developed to allow the user to select a specific area of the farm for which to apply the simulation and to select different crop management scenarios. The DSSAT V2.1 crop models were linked into this system.

Initial results showed that this Interactive AEGIS was able to predict spatial yield variability as a function of soil variability for rainfed conditions (Hoogenboom et al.,

1993). When irrigation was applied, yield was largely uniform across the entire farm, but the irrigation required to reach this yield level varied as a function of soil conditions. The Interactive AEGIS has been ported to a Unix environment (Wei et al., 1994) to study the possible effects of climate change at the farm level.

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# WIMOVAC: Windows Intuitive Model of Vegetation Response to Atmosphere and Climate Change

The ability to predict net carbon exchange and production of vegetation in response to predicted atmospheric and climate change is critical to assessing the potential impacts of these changes. Mathematical models provide an important tool in the study of whole plant, canopy, and ecosystem responses to global environmental change. Because this requires prediction beyond experience, mechanistic rather than empirical models are needed. The uniformity and strong understanding of the photosynthetic process, which is the primary point of response of plant production to global atmospheric change, provide a basis for such an approach. Existing modeling systems have been developed primarily for expert modelers and have not been easily accessible to experimentalists, managers, and students. WIMOVAC (Windows Intuitive Model of Vegetation Response to Atmosphere and Climate Change) is a mechanistic, modular modeling system operating within Windows which provides user-friendly access to modeling of various aspects of plant photosynthesis with particular emphasis on the effects of global climate change. WIMOVAC has been designed to run on IBM PC compatible computers running Microsoft Windows. The package allows the sophisticated control of the simulation processes for photosynthesis through a standardized Windows user interface and provides automatically formatted results as either tabulated data or as a range of customizable graphs. WIMOVAC has been written in Microsoft VisualBasic, to facilitate the rapid development of user-friendly modules within the familiar Windows framework, while allowing a structured development. The highly interactive nature of controls adopted by WIMOVAC makes it suitable for research, management, and educational purposes.

WIMOVAC currently gives a firm foundation for future modeling work at the level of leaf and canopy photosynthesis. Further work on model dialogs is indicated, however, for a more detailed treatment of soil processes including decomposition, nitrogen cycling, and mineralization. Attention to herbivory and refinement of links between ecophysical and ecosystem processes is also required. The DSSAT modeling system is a widely used and validated empirical modeling system which incorporates many of the soil and physical processes required in WIMOVAC. The empirical nature of core equations for dry matter accumulation in DSSAT may, however, weaken its predictive power for photosynthetic processes in global environmental change scenarios. It was our intention to use the soil and physical process models and the scaling mechanisms presented in DSSAT within WIMOVAC and to compare and validate empirical and mechanistic observations from the two systems. A modified version of DSSAT, currently under construction, will have parameters for sweet sorghum and will be recompiled to form a dynamic link library directly compatible with a Windows interface and the WIMOVAC modeling system.

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# Development of a Simulation Model for Evaluating Hypotheses Concerning the Functioning of Wheat Crop Systems

More than 70 models of wheat have been developed during the past 20 years (McMaster, 1993). Not all of these models have been based on the physiological processes of the crop, however, and the number of process-oriented models developed lies somewhere between 10 and 20. Prominent examples of such models, reflecting a variety of approaches to the representation of wheat growth and development, but all being usable on personal computers, are CERES (Ritchie and Otter, 1984), Simtag (Stapper, 1984), AFRCWHEAT2 (Porter, 1993), Swheat and Sucros (van Keulen and Seligman, 1987), and the models developed by Amir and Sinclair (1991) and Sinclair and Amir (1992). The number of wheat simulation models available suggests that it should be possible to use them as tools to aid the evaluation and interpretation of field experiments undertaken to test hypotheses concerning the functioning of the wheat crop system. Unfortunately, most available models are not set up to facilitate comparison of model outputs with experimental data, modification for new cultivars, and incorporation of new functional relationships, as is often necessary when attempting to evaluate a new hypothesis. New data standards to facilitate the handling of experimental data and the comparison of model outputs with measured data have recently been elaborated (Hunt et al., 1994), and software to simplify the computation of genotype specific characteristics has also been released (Hunt et al., 1993).

The objective is to develop a model of the wheat crop system that both conforms to the recently developed DSSAT v3.0 standards and allows the functional relationships embedded in the computer code of the model to be changed easily.

The Cropsim-wheat model (Hunt and Pararajasingham, 1994; Hunt, 1994) will be used as the starting point. The model will be embedded in a "shell" program that not only facilitates running the model and examining outputs, but also facilitates editing the computer code of the different subroutines, compiling and linking the edited sections, and re-examining model outputs and field data.

The model is being applied in a hypothesis testing mode even though the shell program to facilitate editing, compiling, and linking has not yet been developed. As an example, one application has been concerned with the factors that determine response to planting date in spring wheat in a northern North American environment. The initial working hypothesis was that, in the absence of severe water, nutrient, and disease stresses, response to planting date would be determined by canopy dry weight around the time of anthesis, this being the single aspect thought to determine the number of grains set. Simulations based on this understanding did not match well with the pattern of change recorded in field work in Minnesota (cooperation with Dr. J. Wiersma, North West Agricultural Experiment Station, University of Minnesota, Crookston, MN 56716), particularly for early plantings. Incorporation of a function in which grain set was made dependent on both canopy weight and solar radiation around the time of anthesis considerably improved the quality of fit, particularly for early plantings. This suggests that a hypothesis in which

grain set is dependent on both canopy weight and solar radiation about the time of anthesis is closer to reality than one in which grain set is dependent solely on canopy weight; there is a need, however, for further experimentation to clarify the situation.

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# Development of a Decision Support System for Nitrogen Fertilizer Management for Grain and Groundwater Qualities

Grain protein concentration in wheat is an important nutritional and industrial quality parameter. In general it is positively related to the amount of nitrogen fertilizer applied (Fernandez and Laird, 1959; Nass et al., 1976; Bruckner and Morey, 1988). Nitrogen applications for optimum grain quality, however, may not correspond with those required for optimum yield. There is thus a need to optimize N fertilizer management for both protein concentration and grain yield. The optimum N rate for grain quality and yield often varies significantly from year to year due to variations in growing conditions and management practices. Excess N fertilizer may be applied in some years, with part of the excess moving beyond the root zone into the groundwater, thus contributing to groundwater degradation (Environment Canada, 1990). Agricultural professionals must, therefore, develop N management systems that will achieve target grain protein concentrations, allow appropriate yield expression, and minimize groundwater contamination. We are working to help meet this goal by producing a software package that can help to make appropriate N management decisions across Canada, but with specific reference to the province of Ontario. The objectives of the project are as follows:

1. To evaluate the accuracy and precision of the Cropsim-wheat model. The Cropsim model contains a section that describes soil N transformations following fertilizer N addition, N losses and N uptake, and N movement to the grain. It has been examined using a limited number of data sets in which various N fertilizer regimes have been utilized, but it requires further evaluation and possible modification through comparison of simulated data with experimental results. The first objective, therefore, is to evaluate the N components of Cropsim and to modify the model by incorporating additional detail if the precision of predictions is found to be unacceptable.

2. To develop a strategic planning tool for N management. While the accuracy of Cropsim is being evaluated, the model will be packaged for use in strategic decision making relative to various fertilizer management options. This will be achieved by developing a software package that includes the model, historic weather data spanning more than 20 years for all wheat growing regions in Canada, soil data, and programs for (a) interpolating weather data for specified locations, (b) running the model for computer experiments involving various combinations of cultivar, fertilizer source, timing, application rate and placement, and planting time, and (c) presenting the outputs in an acceptable manner for decision making.

3. To develop a tactical management tool for N management. The third objective will be to package the model for tactical decision making through the life of the crop. A software package will be developed that couples real-time simulation and simulation using generated weather data to harvest. Generated data on harvest protein concentrations and soil N budget components would serve as "early warning" indicators for growers. The earlier it can be indicated that there is a high probability of a particular crop failing to achieve a desired target grain quality, the more time there is for the application of a corrective measure.

To meet objective 1, outputs from the Cropsim-wheat model (Hunt and Pararajasingham, 1995; Hunt, 1994) will be compared with field measurements obtained from experiments with both winter and spring wheat located throughout Canada, but with emphasis on Ontario's wheat producing area. The time course of accumulated inorganic N present in the soil will be estimated by periodically sampling the soil profile.

Packaging the model to meet objective 2 will be accomplished through the development of a "shell" program that would allow a user to select a particular site, to specify crop management options, to run a series of simulations using either historical weather data or generated weather data, and to present the data in a form that simplifies decision making but emphasizes probability aspects. Databases of daily weather information and soils will be assembled for all wheat growing regions of the country.

For objective 3, system development for tactical N fertilizer management will proceed on lines similar to those adopted for the strategic planning system. The shell in this case would facilitate the running of the model with both the current season's weather data and generated data, runs being repeated several times so that a probability envelope for final grain N concentration and soil N balance components can be constructed.

The final outcome will be a decision support tool that producers, agricultural consultants, extension personnel, and policy makers can use to help in the management of N fertilizer applications for specific field and market situations. Use of the tool would avoid fertilizer waste and thus not only improve farm returns but also reduce $NO_3^-$ contamination of groundwater.

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# A Systems Research Approach Using Crop Models in Albania

The liberalization of state controls, the distribution of land for private cultivation, and the establishment of private sector dealers for agricultural inputs are leading to the creation of a dynamic agricultural system in Albania. To perform efficiently, participants in this process must have access to information that is relevant, accurate, and timely. The types of information needed range from improved production technologies that are economically and environmentally sound to reliable reports on market conditions. Presently, however, the public infrastructure and other components needed to generate and to provide such information in Albania are either lacking or in need of revitalization. As it attempts to correct these deficiencies and assist Albanians in taking advantage of new economic opportunities, the Ministry of Agriculture and Food needs access to the latest information technology tools. These tools, developed from advances in computer technology and information science, include crop growth simulation models, models of social and economic systems, geographic information systems, and database management systems. When integrated into a system used to aid decision makers in analyzing complex issues, these computer-based tools are often labeled decision support systems or management information systems.

Crop growth simulation models can significantly enhance the efficiency of the research, development, and extension processes by allowing extrapolation of field trial results to other locations in other weather years. Once set within the framework of a comprehensive management information system, the crop models can facilitate the effective analysis of issues related to agricultural production, resource allocation, risk, environmental quality, and land use.

The goal of this project is the development of a decision support system for Albania that incorporates knowledge of soil resources, climatic variability, and crop growth potential. Specific objectives include the assembling of quantitative descriptions of the major agricultural soils, construction of an historical weather database, incorporation of both soil and weather information into a GIS, and the validation of the CERES wheat and maize models.

In collaboration with the World Soil Resources division of the United States Department of Agriculture (USDA), a GIS database is being constructed for the major agricultural soils. Initial information was obtained for a scale of 1:200,000 and will be refined to a larger scale (such as 1:50,000) as time and resources permit. Automated weather stations that record daily rainfall, solar radiation, and minimum and maximum temperature have been set up at two locations where field trials are being conducted to validate the models. To the extent possible, field data from earlier experiments are also being used to calibrate and test the models. Training programs will be used to introduce the systems approach and simulation tools to professionals in Albania.

Winter wheat and maize experiments were conducted in Lushnja and Kamza during 1993-1994 to collect data for testing the capability of the model to simulate response to nitrogen fertilizer. Data from these experiments were used in a two-week training program held at the Agricultural University of Tirana for 23 Albanian professionals from various public and private institutions. The systems research approach using simulation tools has proven beneficial to Albanian scientists by providing a framework for making recommendations to farmers even as support for further experimental work has been decreasing. As restructuring of the agricultural sector in Albania proceeds, the institutionalization of data collection techniques and simulation analysis capabilities will be an important prerequisite to the productive management of information.

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# Relating Environmental Variables to Crop Growth and Development

Studies of crop production on the Canadian prairies traditionally involved conventional agronomic research, in which crop yields were related to the defined environmental variables through correlation and regression analysis without referring to any underlying biological or physical principles that exist between crop yields and those variables. The relationships obtained from one site were then applied to other locations with similar environments. Given the large number of crops, new cultivars, soil types, weather patterns, and management options that occur across time and space over the Canadian prairies, it is practically impossible to define optimal tactics and strategies of crop production by this type of experience-based agronomic research. Furthermore, results obtained from regression analysis provide only a statistical average. This technique offers decision makers opportunities to make comparisons between the means of alternative strategies; it does not provide the probabilistic information that is needed to assess risk.

Since 1987, we have adopted the knowledge-based systems approach to research to replace the conventional agronomic research. The systems approach makes use of dynamic simulation models of crops and cropping systems. In crop growth models, current knowledge of plant growth and development from differing disciplines such as crop physiology, agrometeorology, soil science, and agronomy are integrated in a consistent, quantitative, and process-oriented way. After proper validation, the crop growth models are used to predict the effect of changes in various environmental conditions and to test the alternative crop management options.

Presently, the goals of our research project "Relating Environmental Variables to Crop Growth and Development" are as follows:

* To develop and validate crop growth models that can predict the effect of changes in climate as well as agricultural management on crop production under Canadian prairie conditions.

* To design and undertake experiments to provide improved mechanistic understanding of crop growth and development to aid model development.

Eventually, the models developed will be included in a decision support system to do the following:

* Guide prairie producers in making proper on-farm decisions with respect to water and nitrogen management.
* Assess the adaptation of new cultivars.
* Evaluate alternative cropping and management strategies for achieving sustainable farming on the Canadian prairies.

The initial phase of our project (1987-1995) was focused on developing and validating a cereal growth model for spring wheat and spring barley grown on the Canadian prairies. Our effort in tailoring the existing cereal growth model to meet important constraints under prairie conditions started with the CERES model and followed a natural progression of changes needed to deal with important phenomena. The CERES model was tested, not merely for its overall predictions, but also for its component processes under a wide range of environmental conditions to assess the model structure as well as the extent and limitations of its validity. Thus, in this project, environmental variables are properly monitored and crop growth details duly recorded in well-defined experiments (both in the field and in controlled environments) for facilitating model calibration and validation. Data sets from several existing long-term cropping systems experiments on the Canadian prairies were also prepared for model validation. The activity on testing the wheat growth model of this project is part of the International Wheat Network under Focus 3 of Global Change and Terrestrial Ecosystems, a core project of the International Geosphere-Biosphere Program. All experimental data were documented in the DSSAT format.

Our work has revealed that some modifications to the CERES-Wheat model are needed for its practical applications on the Canadian prairies. For example, some genetic coefficients that are used as inputs to run the model are not constants that depend solely on genotype. Modifications of the CERES model for use on the Canadian prairies are presently being undertaken. We believe that only after extensive experimental validation can a crop growth model eventually become (no doubt after numerous modifications) a working tool capable of providing guidance in the practical management of agricultural systems. After proper validation, crop growth models will be included in the DSSAT for use in managing agricultural resources and also to support strategic agricultural research. The DSSAT will provide necessary information for assessing complex management systems from the standpoint of productivity and profitability as well as organic matter maintenance and nutrient losses, both for the short-term and for several decades.

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# Developing and Testing the CANEGRO Model in Thailand

Sugarcane is an important economic crop in Thailand, with annual sugar production on 1 million ha reported in 1992. The majority of sugarcane production is in the Central Plain and the Northeast areas. Thailand exported about 3.5 million t of sugar in 1992.

The industry is faced with an important and fundamental problem of how to estimate the annual sugarcane production in different regions of the country based on historical records and field observations. The current practice is based on simple linear regression and personal experience of a few experts in the country. The 1993 crop year estimate was overestimated by more than 20% in term of total production, i.e., 47 million t was estimated, whereas 32 million t was produced.

Advances in computer technology in recent years offer opportunities to overcome the problem. Remote sensing provides an excellent tool to estimate the sugarcane production area. A process-oriented model can provide a good estimate of sugarcane growth and yield. A functional model of sugarcane was developed based on the CERES-Maize model (Inman-Bamber, 1991). The model was designed to simulate growth and yield of different sugarcane cultivars under different cultural practices, following Ritchie's approach in calculating soil water balance. The project will be able to build on the already existing sugarcane model.

Three broad objectives were developed for this project:

1. To develop, calibrate, and validate a process-oriented sugarcane crop growth model in Thailand.
2. To develop a practical estimation method for sugarcane production areas, using remote sensing data.
3. To develop a decision support system that will facilitate estimation of sugarcane production on a regional basis.

To accomplish the project objectives, a number of activities are associated with each objective. A small group discussion was organized to establish interest among sugarcane researchers in Thailand. An international workshop on crop growth and fertilizer management response in Gainesville, Florida was attended by three project staff during May 1994. A common field experiment, which will be carried out by collaborators in Thailand, will be designed to generate necessary data for model development and validation. The isoenzymes method will be carried out to differentiate different sugarcane cultivars.

A practical method for LANDSAT data image processing will be developed under the IDRISI GIS software package. Sugarcane production areas will be estimated and a sugarcane land use map will be produced.

An interface will be developed to allow users interactive access to weather and soil data as well as the sugarcane model. Workshops will be conducted to demonstrate the system to general users in Thailand.

It is expected that the proposed research will result in substantial benefits. The Chiang Mai University team has a close relationship with the IBSNAT network of modelers and has considerable experience and expertise in this area. Remote sensing data are readily available from the National Science Research Council, and a process-based sugarcane model will be developed.

The following benefits can be identified from this project:

* A validated process-oriented sugarcane model for Thailand.
* A decision support system shell, which will allow users to interact with the model and analytical tools.
* An organized resource database for sugarcane yield estimation on a regional basis including climate, soil, and crop inputs that will benefit future studies in Thailand.
* Training materials for workshops.

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# Best Management Practice Decision Support System for Soybean

Management alternatives are needed that will allow farmers to reach their profitability goals while considering environmental quality regulations. A 2-year project was approved by the United Soybean Board in June, 1994, to develop "best management practices" for improving soybean profitability and reducing risks of environmental effects by providing information and computer models to analyze management alternatives. The project seeks to develop a decision support system to aid soybean farmers in improving production efficiencies and adapting best management practices. Researchers have been developing soybean crop models and testing their abilities to predict growth and yield, both in research plots and in farmers' fields. Similarly, researchers have developed models to estimate nutrient and pesticide losses and soil erosion from fields to help determine practices that reduce potential degradation of the environment. This project will integrate these two efforts with information on production systems, weather, soil, weeds, and costs for supporting soybean farmers' decisions. The approach will allow farmers to simulate different field management practices on the computer to compare yield, profit, and nutrient and pesticide losses and will provide information to aid in selecting practices that best meet their goals.

This soybean decision support system will have the capabilities to (a) analyze combinations of proposed soybean production plans under various weather, soil, weed, economic, environment, and regulation scenarios posed by farmers or consultants who advise them, (b) propose best management practices using criteria based on differences in productivity, profit, soil degradation, and environmental quality, taking into account existing and proposed regulations, and (c) answer questions to help farmers make decisions concerning production plans, with a "friendly" interface to ensure ease of use. With this tool, farmers will become more efficient in producing and profiting from soybeans and be more proactive regarding environmental quality issues. They could also react more quickly to determine options for improving profitability when extreme weather events occur, such as the 1993 floods in the Midwest, drought in the eastern United States, and cool temperatures in 1992. This system will be used as a planning tool to address production options, such as planting date, variety selection, subsoil moisture, fertilizer timing and amount, weed control, precision farming, row spacing, field rotations, forecasting harvest date and yields, and possible reactions to unusual weather years and changes in economic conditions. The system can also be used to analyze the progress of a soybean crop during a growing season to determine the best timing of practices, such as irrigation. Investigators are implementing the system next summer on a few farms in five states to help develop and test it. Researchers from twelve states and the Agricultural Research Service of USDA are cooperating on this project.

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# The ORYZA1 Model for Potential Production of Rice

The IRRI-Wageningen model ORYZA1 simulates potential growth of a rice crop based on detailed physiological calculations of $CO_2$ assimilation and respiration. The model has been documented by Kropff et al. (1994). Under potential growth conditions, the main factors determining the growth rate of the crop on a specific day are light, temperature, and the varietal characteristics for phenological, morphological, and physiological processes. The model follows a calculation scheme for the rates of daily dry matter production of the plant organs, the rate of leaf area development, and the rate of phenological development. By integrating these rates over time, dry matter production of the crop is simulated throughout the growing season.

The total daily rate of canopy $CO_2$ assimilation is calculated from the daily incoming radiation, temperature, and leaf area index. The model contains subroutines that calculate the daily rate of canopy $CO_2$ assimilation by integrating instantaneous rates of leaf $CO_2$ assimilation. The calculation is based on an assumed sinusoidal time course of radiation over the day and the exponential light profile within the canopy. On the basis of the photosynthesis characteristics of single leaves, which depend upon the nitrogen concentration, the photosynthesis profile in the canopy is obtained. Integration over the leaf area index of the canopy and over the day gives the daily $CO_2$ assimilation rate. After subtraction of respiration requirements, the net daily growth rate in kilograms dry matter per hectare per day is obtained. In contrast to the other models, ORYZA1 simulates light use efficiency from photosynthesis and respiration. The dry matter produced is partitioned among the various plant organs following a partitioning pattern that is determined by the developmental stage of the crop.

Phenological development rate is tracked in the model as a function of ambient daily average temperature and photoperiod. When the canopy is not yet closed, leaf area increment is calculated from daily average temperature (sink limited) because carbohydrate production does not limit leaf expansion. When the canopy closes, the increase in leaf area is obtained from the increase in leaf weight (source limited). Integration of daily growth rates of the organs and leaf area results in dry weight increment during the growing season.

The model simulates the formation of spikelets as a function of the total growth between panicle initiation and flowering. A simple procedure was built into the model to simulate sink limitation as a result of spikelet sterility at high or low temperatures.

The model has been evaluated using data from IRRI (Kropff et al., 1994) and from the SARP project, in which Wageningen, IRRI and 16 NARCs from 9 Asian countries collaborate. Total potential above-ground biomass (ranging from 11.5 to 17.8 t $ha^{-1}$ in wet and dry seasons at IRRI, respectively) as well as panicle dry matter (ranging from 5.7 to 9.8 t $ha^{-1}$) was simulated accurately by the model for a wide range of data sets, using parameters that were derived from the highest yielding dry season experiment at IRRI (development rates, partitioning coefficients, leaf nitrogen content, and relative growth rate of the leaf area). Recently, Australian scientists obtained rice yields of about 15 t $ha^{-1}$ by combining improved management with new plant type breeding to overcome low-temperature stress

(Williams and Lewin, personal communication). The ORYZA1 model was also evaluated with data from these experiments. Measured and simulated total biomass was 28.9 and 27.3 t $ha^{-1}$, respectively, and measured and simulated yields were 14.7 and 14.3 t $ha^{-1}$ (panicle dry weight), respectively, for an experiment conducted in 1991. The differences in yield potential between the IRRI wet season (6 t $ha^{-1}$) and Yanco, Australia (15 t $ha^{-1}$) were the result of low temperature, which caused a long duration of grain filling and increased intercepted radiation, resulting in high yields. In the tropics, the duration is short as a result of the high temperature, but the high radiation in the dry season allows a higher yield than in the wet season.

Several applications of the model have been indicated by Kropff et al., 1994), such as data input requirements. The model can also be used as a tool for the following:

* Prediction of yield potential of a variety in a particular environment as defined by radiation and temperature during the growing season. This is an essential step in defining the yield gap in farmers' fields.
* Extrapolation of experimental results to other environments.
* Detailed analysis of data from field experiments.
* Analysis of physiological requirements for increased yield potential.
* Estimation of the effect of climatic change on rice yield potential.

The model can also be used as a framework for studies that focus on specific agronomic problems. In such studies, submodel development is integrated with experimental work. New quantitative physiological insight into processes that are not yet included will often be required, and the model may help to guide the direction of physiological research.

Two extensions of the basic model have been developed so far: ORYZA_W for water-limited situations and ORYZA_N for nitrogen-limited situations.

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## Potential Applications of Crop Models and Decision Support Systems by the Soil Conservation Service

The USDA-Soil Conservation Service (SCS) has a long history of developing decision support tools to help land users make resource management decisions. Such tools as the Universal Soil Loss Equation and the Wind Erosion Equation have long been used to help educate farmers about the hazards of soil erosion and to help them design management systems to minimize their erosion problems.

About 5 years ago, SCS began a major effort to automate field office operations and to develop information systems that would facilitate the use of decision support tools. The current Field Office Computing System (FOCS) is a software package that integrates land user information, such as farm and field acreage, land use, cropping systems, and information on planned and applied conservation systems. This information is stored in a relational database with the SCS Soils Database. In addition to standard record keeping modules, the Revised Universal Soil Loss Equation, an automated version of the Wind Erosion Equation, and the Grazing Lands Applications modules are currently available in FOCS. These decision support tools speed the process of designing erosion control systems and grazing systems on cropland and rangeland.

The current plans for FOCS call for several more integrated modules, many of which are under development. These include a screening tool that will help determine the potential for pesticide losses to surface or ground water, a screening tool that will help determine the potential for nitrogen or phosphorus losses to surface or ground water, a plant/crop database, a module to help design animal waste management systems, a module that will help develop water budgets for a field, and others.

Long-term plans call for a nutrient management module, a more sophisticated hydrology model, a pesticide management module, a more sophisticated erosion prediction model, and a water quality planning module. All of these will need some type of crop growth simulation to give realistic results. The crop growth models must be robust enough to work with a large number of crops in a wide variety of growing conditions.

We plan to explore the possibility of integrating the crop growth models in the DSSAT package into the SCS suite of decision support tools, particularly those dealing with nutrient management, pesticide management, and water management. We realize that the DSSAT models as they currently exist may not be entirely suitable for our needs or that our simulations may not need the level of detail that is in these models. If that is the case, we hope to work with the crop growth model developers in adapting these models to meet our needs, or possibly incorporating only certain parts of the models into our decision support tools to refine our simulations.

If we are successful in integrating crop growth models with our nutrient management, pesticide management, erosion control, and hydrology modules, we will be able to

offer land users a sophisticated decision support tool to help them better manage their resources. The simulations performed by this suite of tools would help farmers compare the effects of various management systems on soil and water quality and facilitate the selection of an integrated system that best meets their needs. This would be an invaluable tool to farmers as the pressures to maintain or improve soil and water quality increase.

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# Irrigated Crop Management in Portugal

In a masters program in crop production at the Universidade Tecnica de Lisboa, which was concluded in October 1994, I was involved in adapting and validating a potato growth model developed in the United States to Portuguese conditions; some of the subroutines, as well as the user interface, were rebuilt. At present the agricultural department (Instituto Superior de Agronomia, Universidade Tecnica de Lisboa) has a research project related to potato modeling, and we are developing computer applications in agricultural production systems analysis and farm advisory packages. I am also involved with Ph.D. studies in the area of agricultural systems, as a split program between the University of Reading in the United Kingdom and the Instituto Superior de Agronomia that includes a research component in Portugal. The specific objectives are the analysis and modeling of irrigated production systems in order to estimate potential crop yields and associated water needs.

Interest in this research field will certainly increase over the next few years in Portugal because of Alqueva, an irrigation project in the south that will give rise to some 200,000 ha of newly irrigated land. This project is part of the recently approved PRAXIS XXI program, a European Union initiative to improve Portuguese research and development in science and technology.

The agroecological zoning and land use planning of the newly irrigated areas can be divided into three sequential stages:

1. Implementation of a geographic information system with databases on soil, climate, and current land use.

2. Application of agrometeorological models to estimate yields and irrigation needs for current and potential new crops.

3. Development of a decision support system to be used in the selection of newly irrigated areas.

The proposed plan for the Ph.D. study is related to the second stage. It does not depend on either of the other two stages, but could benefit enormously from the databases and information generated from the first stage. The study will involve the following components:

* Reviewing and summarizing field trials with irrigated crops under similar soil and weather conditions during the last 15 to 20 years.

* Using this information to validate, calibrate, and adapt existing agro-meteorological models.

* Applying these models in order to estimate crop productivity and irrigation needs using GIS.

* Using the predictions to determine global water needs and evaluate potential land use.

This methodology could serve as a support for the technical and economic analysis of irrigated cropping systems. The potential for the introduction of new crops, the establishment of different crop rotations, the effect of inputs such as water on yield, and the impact of irrigation on the environment (through soil erosion or nitrate accumulation, for instance) are some of the questions that can be efficiently studied through the integration of systems analysis and modeling.

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# Assessing the Adaptability of Durum Wheat Genotypes to Italian Growing Areas Using Crop Simulation Models

Italian growing areas for durum wheat are very different from north to south in regards to climate, soil, and nutrients. Since 1975, trials have been conducted in about 60 environments each year to test the behavior of new varieties of durum wheat. On the basis of yield response of each variety in each environment, we have tried to classify growing areas and to identify varieties having general or specific adaptability. The application of computer simulation models, allowing us to vary the characteristics of soil, climate, and nutrients, will be useful for a better understanding of both environmental characteristics and variety adaptability to different growing areas. Crop models will be applied to the agronomic results of trials conducted over many years and locations, together with weather data collected in the same locations. We also intend to use the CERES-Wheat model to generate genetic coefficients for Italian durum wheat varieties to increase the efficiency of breeding programs. The breeding results can be enhanced by linking the knowledge of growing area classification with the measures of genotype-environment interaction.

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# Using Crop Simulation Models to Support Agricultural Research Planning in Mexico

In Mexico, one of the main concerns of agriculture is related to the generation and utilization of technologies that not only promote increased crop productivity but also take advantage, in a rational way, of natural resources such as water and soil so that gains in productivity are sustainable.

At the National Institute for Forestry, Agricultural and Livestock Research (INIFAP), a radical change in the methods and the approach of research is occurring. Up to now, projects and problems were defined with respect to a reductionist and disciplinary vision of reality. Now, efforts are being made with the intention of designing strategic plans of research with ecological input and great emphasis on the integration of interdisciplinary teams.

This change was implemented to increase the capacity of the researchers to predict the effects of the technology generated with respect to productivity and natural resources in the long term. As a part of this change, in 1994 a project called "Diagnostic of potential production limitations and simulation of crops production" was approved to support the planning of agricultural research at INIFAP, through the construction and utilization of crop simulation models. In this project, the use of a systems approach as a manner of viewing and understanding reality, coupled with systems modeling and simulation as the main tools to analyze the relevant processes, has been emphasized since the beginning.

The general objectives identified in this project are:

* To form an interdisciplinary team of researchers to integrate the knowledge of different processes involved in crop production.

* To construct and utilize crop simulation models in order to understand and optimize the process of production, considering the different management, soil, and climate resources of the country.

In 1989, the same group of researchers that now work in this project began to develop a simulation model of potential production for rainfed maize in the State of Guanajuato, Mexico. On the basis of that experience, there have been advances in the construction of simulation models for potential production of maize, wheat, sorghum, and potato. In the same year, validation of the maize model began. In the coming years, we hope to make similar progress with the models of wheat, sorghum, and potato. At the same time, the generated crop growth data will be used to estimate the genetic coefficients required to calibrate the DSSAT v3.0 models.

Although some applications such as irrigation and nitrogen optimization could be more easily performed using available models in the literature, other research questions,

such as pest and disease management, will require the development of specific models matched to local conditions. Furthermore, the acquisition of the skills required to construct dynamic models is considered a very important feature in researcher training and will facilitate the understanding and operation of other models. The simulation languages used for this purpose are DYNAMO and FORTRAN.

Utilizing the capabilities of systems such as DSSAT v3.0 and EPIC is also being considered, as well as the possibility of cooperative participation of scientists at international development institutions. The interaction with the group of INIFAP researchers devoted to the development of soil and climate databases within a GIS is an essential element for the success of this project.

Three principal levels are contemplated at which agricultural research planning and decision making may be supported:

* At the cropping systems level, simulation models can be utilized in combination with GIS to determine potential zones for crop production. Additionally, systems analysis can be used to identify the main limiting factors of production in each region and to quantify the difference between actual and potential production.

* At the farming systems level, the outputs of simulation exercises involving different crops and management options can be utilized to identify, through linear programming analysis, optimal production options for producers.

* At the regional or agroecosystem level, simulation models can be utilized to create scenarios assuming different economic and technological trends. This can lead to insight into the different approaches in which both a higher and sustainable productivity could be reached, without degradation or exhaustion of natural resources.

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# Potential Application of Crop Models and Decision Support Systems: Providing Agrometeorological Services in Trinidad and Tobago

Trinidad is a small Caribbean Island lying within the tropics. During the dry season from December to April, agricultural crops must often be irrigated. The wet season, from May to November, brings the rains – sometimes too much, causing water-logging, and sometimes not enough when needed, resulting in unseasonal drought. With the rains come many fungal and bacterial plant diseases. The main crops grown are rice, maize, sugarcane, legumes, vegetables, tropical fruits, cocoa, coffee, and root crops such as cassava. Agricultural methods are traditional and old-fashioned; they lack vital agrometeorological inputs. Farmers try to compensate by depending heavily on chemicals and fertilizers. Trinidad's Meteorological Services has sought a solution. It has almost completed its program of establishing a network of eight automated weather stations in the main agricultural areas across the country. This is the first step towards providing an agrometeorological service.

The main objectives are to provide farmers with crop calendars, moisture-drought indices, irrigation scheduling advice, and pest-disease warnings, for example, and to impress upon them the benefits of proper planning. Farmers are also to be made aware of the services available.

It is proposed that a committee be set up to diagnose agricultural problems and offer solutions. This group would consist of an agricultural extension officer, an entomologist, an agronomist, a soil scientist, and a meteorologist.

The automated weather stations could provide a database that could be accessed by crop models. The results of crop model simulations would provide the basis for the management of crops (rice and maize in the first instance). Validation of the models for these crops will need to be carried out. Continuous monitoring of the weather stations would provide timely indicators of possible drought or disease conditions.

It is expected that farmers would benefit from the agrometeorological services provided and that their management techniques would improve.

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# Possibilities for Yield Increase and Sustainability of Cropping Systems in Tanzania

Tanzania's economy is dependent on the agricultural sector, which contributes more than 50% of the gross domestic product and more than 80% of the export earnings and accounts for about 90% of rural employment. However, this contribution has been uneven for the past 25 to 30 years. The quality and availability of agricultural land have declined because of increasing human and livestock pressures. exacerbated by inadequate soil and water conservation measures (Ministry of Agriculture and Livestock Development, 1991).

In Tanzania, six major agroecological zones have been identified, each with a few dominant cropping systems (Rwamugira, 1991). Problems associated with the current cropping systems include soil mining, erosion losses, and deforestation. In densely populated areas of the country, crop residues are transferred from field to homestead to be fed to livestock because extensive grazing cannot be practiced. Soil erosion is caused in part by farmers who cultivate hilly areas and mountain slopes without using soil conservation technologies. Deforestation is evident because of the demands for fodder, fuelwood, and expansion of land for cultivation. In the valley bottoms and other areas of potentially high productivity, continuous cultivation is practiced without additional fertilizer materials. The problem is compounded by the fact that most of the tropical African soils are highly weathered, have low organic matter content, and are susceptible to erosion. Such problems have contributed to the decline of agricultural production in the country (Lal, 1987; Matlon and Spencer, 1984; Stoorvogel and Smaling, 1990).

The overall goal is to re-examine the dominant cropping systems in selected agroecological zones and assess their sustainability. Specific objectives are (a) to establish potential and actual yield trends of the selected systems, (b) to study the management practices and nutrient balances in the systems, (c) to establish relationships between changes in these parameters and yield over time, (d) to predict productivity and sustainability of such systems on a long-term basis, and (e) to explore potential management practices that would either maintain or improve soil nitrogen, organic matter, and available phosphorus.

In accordance with the goals and objectives of study, analysis of the cropping systems will be on a long-term basis. Therefore the approach will involve selecting the study areas, identifying their main cropping systems, and collecting background data with respect to management practices, cropping calendars, soil, climate, and yields. After acquiring these data, we will use models and other tools to analyze and predict the productivity, stability, and sustainability of the selected cropping systems over long periods of time.

In such a study, it is not possible to use a single technique or model; thus, the following models may be used: DSSAT, QUEFTS (Quantitative Evaluation of Fertility of Tropical Soils), Century, and the Tropical Soil Productivity Calculator (which is still under development at the Agricultural University of Norway).

This study is sponsored by the Center for Sustainable Development, Agricultural University of Norway, under the project "Ecology and Development in Tanzania." The results obtained from this study will be input to the economic part of the project. The integrated results will form a basis for recommendations and advice to policy makers concerning the direction of the agricultural sector.

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# Development of Decision Support Systems for Weed Management

Integrated weed management (IWM) is designed to implement soil conservation practices and reduce the amount of herbicide introduced into the environment. To encourage agricultural producers to implement IWM, we must provide information that can allow them to minimize costs and risks and maximize benefits. We plan to examine the effects of soil moisture and temperature on a factor that accounts for much of crop yield losses, i.e., the emergence patterns of weeds relative to crops. This will allow us to construct models of weed emergence that may be applied under field conditions and enable producers to determine the optimum time for implementation of weed control. This information will be incorporated into a more comprehensive mechanistic model of ragweed and white bean growth. The economic period threshold will be calculated under varying weed management options and commodity prices, the main program providing the necessary yield loss estimates.

Objectives are as follows:

1. To examine the effects of soil moisture and temperature on emergence patterns of ragweed and lamb's-quarters, and test whether models of weed emergence may be applied under field conditions.

2. To use the information obtained from objective 1 and from previous studies to construct a mechanistic model of ragweed growth. In conjunction with a mechanistic model of white bean growth (Chikoye et al., 1995), the mechanistic model of ragweed growth will contribute to calculation of weed economic thresholds for ragweed in white beans in Ontario.

The time of weed seedling emergence influences both amount and variation of crop yield loss from weed competition (Kropff et al., 1992). Predictions of weed emergence are confounded by genetic and/or environmental variation (Forcella, 1993; Mohler, 1993; Weaver et al., 1992). As influenced by management practice, environmental variation causes soil moisture and temperature to vary; these are the factors most critical to seed germination and seedling emergence. Because most emergence models have failed to account for interactions of these variables, their predictive power has been limited. Further, previous emergence models were developed for conventional tillage and may not be valid for conservation tillage systems. The ability to predict the time of weed emergence relative to the crop affects the critical periods, the time interval when it is essential to maintain a weed-free environment to prevent yield loss (Hall et al., 1992; Swanton and Weise, 1991). Producers only apply herbicides during the critical period if an economic threshold has been reached (where the yield loss avoided is greater than the cost of application). Critical periods thus indicate the length of time that a crop can tolerate weed competition at varying degrees of weed infestation before yield losses exceed the cost of control (the weed economic period threshold). Models of weed economic thresholds predict a tolerable number of weeds escaping control, thereby predicting if additional control measures are

needed. This promotes cost-effective weed management and reduces unnecessary use of control measures.

Although there is a public demand for more environmentally acceptable agricultural practices, the economic risks to agricultural producers require that alternative management strategies be applied efficiently and predictably. Our proposal thus uses a comprehensive approach. We plan to account for differences in agricultural practices and conditions (tillage, species composition, location, and environmental variation) and to predict future weed problems. We will provide a comprehensive method of making cost-effective decisions for weed control applicable throughout Canada. By promoting our research early, often, and effectively, we believe that our IWM program may be implemented by Canadian producers as early as 1998, immediately following the project's conclusion. This will provide a means for producers to become more cost-effective and adaptable in implementing weed control management strategies. It is difficult to predict the savings in terms of increased yield and reduced management costs to producers. However, in that weeds resulted in annual production losses of $62 million (1985-89) in corn, soybeans, and white beans, the potential savings from successful application of these tools may be in the tens of millions of dollars.

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# An Integrated Approach to Assessing Soil Fertility and Climatic Interactions in Pilot Maize-Producing Areas of Kenya

Soil fertility is the major constraint to small-scale maize production in Kenya. Yields are modest, yet soils are still being mined of the essential nutrients. Integrated approaches to soil fertility management, involving the use of inorganic fertilizers as well as manures and composts, for example, will have to be developed and adopted if soil fertility levels are to be maintained or improved (Blackie, 1994). A major requirement for such work is a framework that allows the extrapolation of biophysical performance of the crop across time and space in response to environmental and management inputs. We propose to add a potentially powerful tool to existing integrated databases that can address the issue of extrapolation directly: detailed crop simulation models. For a number of pilot sites in Kenya, the models will be tested with existing field data, validated, and linked via GIS to existing databases that describe maize production systems and practices, soils, and weather.

Project objectives are to define and assess variation in yield potential across pilot maize growing areas arising as a function of soil and weather conditions and management; to develop location- and season-specific baskets of soil fertility management options that can be presented to farmers to try, adopt, or reject as they see fit; and to further develop within KARI a modeling group with increased capability for using crop simulation models and information technology tools.

The project will provide a framework for assessing maize production in a specified environment in a particular farming system. The project will tap into existing comprehensive databases that describe the biophysical and socio-cultural features of maize production systems around the country. Once the maize crop model has been linked to these databases, we will develop an atlas of production potentials under various management options that would cover much of Kenya, building on KARI's previous experience in crop modeling (Keating et al., 1993) and other experience with maize modeling in the region (Thornton et al., 1995).

Project outputs will include refined information on the nature and spatial and temporal variability of the yield gap; a tool for extrapolating the response of maize to management and soil fertility interventions across space and time; and a group of KARI scientists well-acquainted with the models and the tools used. The project also will have regional implications: it could subsequently be developed further for other areas of Kenya, or other areas of Eastern Africa as appropriate. It should also be of help in relating farming system physical inputs to physical outputs in the development of a commodity-based research prioritization framework.

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# Effects of Predicted Minimum and Maximum Temperature Changes on Wheat Yields in the Great Plains of the United States: A Simulation Study

While global-mean surface air temperatures have increased by about 0.5°C in the past century (IPCC, 1990; Hansen and Lebedeff, 1987), recent observations over a large portion of the earth's land area for the period 1951-1990 suggest that minimum temperatures might have increased about three times as much as the corresponding maxima (Karl et al., 1993). If the projected future warming continues to follow this asymmetric pattern of temperature change, crop yields might be differentially affected, for example, by a modification of heat stress during the day and respiration rates at night (Ryan, 1991; Rosenzweig and Hillel, 1993). A recent multiple-regression study of corn yields in the southern United States for the last 50 years stressed the importance of minimum/maximum temperature asymmetries in determining directions and magnitudes of yield change (Stooksbury and Michaels, 1994).

In a limited simulation study of Canadian spring wheat, we found that increasing minimum temperatures more than maximum temperatures significantly reduced the potential negative effects of mean temperature increase on grain yield (Tubiello et al., 1995). In that study, a modified version of the CERES-Wheat model (Otter-Näcke et al., 1986) was developed in order to simulate the physiological effects of temperature and $CO_2$ on canopy photosynthesis. We intend to use the same modified CERES-Wheat model to assess the importance of asymmetric temperature changes on wheat yields in the Great Plains of the United States.

Wheat growth is being simulated at four locations along a north-south transect of the Great Plains: Fargo, North Dakota; North Platte, Nebraska; Dodge City, Kansas; and San Antonio, Texas, using weather data for the 30-year period 1951-1980. A base case scenario (no temperature change, representing current conditions) and four mean temperature increases (1°C to 4°C) will be analyzed. For each mean temperature increase, we consider two cases. In scenario A, daytime maxima and nighttime minima are increased by an equal amount; in scenario B, minima are raised three times as much as the corresponding maxima. In addition, simulations will be run under two atmospheric $CO_2$ concentrations: ambient (330 ppm) and "doubled" (550 ppm), roughly corresponding to the above temperature increases once the forcing effects of other anthropogenic greenhouse gases ($CH_4$, CFCs, $NO_2$) are included (Hansen et al., 1988).

We found from preliminary runs that the main mechanisms controlling the simulated wheat responses to temperature are direct and indirect temperature effects on wheat phasic development. In the north-central Great Plains, higher temperatures tend to shorten the growth cycle; in the southern Great Plains, they increase the length of the vegetative phase through reduced vernalization, delaying the other growth phases. Both effects reduce the time available for grain filling, thus limiting potential yield. Within each mean

temperature change, increasing the minima three times as much as the maxima led, at all sites, to higher yields than were obtained with an equal increase of minima and maxima.

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# Using Models to Improve Bean (*Phaseolus Vulgaris* L.) Production in the States of Aragua and Carabobo, Venezuela

During the last decades, Venezuelan agriculture has not been able to satisfy the country's nutritional requirements. Dry bean is a very important component of the national diet, especially for low-income groups where it represents the main protein supply in food. Bean imports are substantial and variable and have reached the alarming value of 70% of national consumption during certain years. This in itself is a matter of national security. Average bean yields in Venezuela have oscillated for many years around 600 kg $ha^{-1}$. This contrasts sharply with yields in the United States and Chile, for example, which were 1700 and 1300 kg $ha^{-1}$, respectively.

Dry bean is planted nationwide in a great variety of environments, but Aragua and Carabobo States are the two main production regions. About 60% of the national production comes from small production units which have less than 5 ha and grow various associated crops in a system called "conuco." This type of system employs very little technology. The rest (40%) is produced as a sole crop. The sole-crop system uses a certain amount of technology such as certified seeds, fertilizers, irrigation, and mechanization in flatlands and has almost tripled its yield during recent years.

Research will be conducted with the primary aim of improving production in the sole-crop system. Venezuela has developed a certain number of varieties that are planted locally, including two, UCV-Manuare and Montalban (Instituto de Genetica, Facultad de Agronomia, Universidad Central de Venezuela), that have a certain degree of resistance to Southern Bean Mosaic Virus. Many bean farmers plant at the end of the rainy season to avoid viruses and to take advantage of residual soil water during the crop's most critical growth stages. The soil's water retention capacity depends on soil type and its physical characteristics. Also, rain probability may be predicted if sufficient and adequate climatic data are available. Together, these two aspects may help estimate the risk component related to planting dates in a specific region. The achievements obtained by the Genetics Institute of the Facultad de Agronomia regarding improved bean varieties, together with recent developments in the area of climatic and crop simulation models, provide important tools for evaluating alternative technologies and management practices to improve bean production. This research is intended to be applied initially at a regional level.

General objectives are as follows:

* To evaluate the BEANGRO model for its ability to estimate yield of four indeterminate bean varieties, during two contrasting climatic periods and in two experimental areas in the States of Aragua and Carabobo.

* To develop production alternatives for bean in the States of Aragua and Carabobo.

Specific objectives are as follows:

* To collect climatic and soil data in order to establish a representative data set for the States of Aragua and Carabobo.

* To collect detailed experimental data related to biomass and leaf area for four varieties, two experimental areas, and three planting densities during both the "late" planting period (October) and the "early" planting period (January).

* To determine dates of occurrence of phenological stages.

* To calibrate and validate the model.

* To apply BEANGRO to determine and evaluate the risks involved in successive planting date modifications for each of the varieties and edaphic and climatic conditions of the regions studied.

The experimental methods recommended by IBSNAT will be used. Some modifications may be necessary. It is expected that some modifications in the model will be necessary to improve simulation of indeterminate bean varieties. Applications will help quantify differences in yield due to different planting dates and densities.

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# Real-Time Yield Forecasting in Burkina Faso

The development and validation of crop simulation models is a comparatively straightforward process, predicated on the comparison of observed and predicted crop data. Predicting crop yields into the future, however, is a process replete with problems due to inherent spatial and temporal variability. Thus, researchers look not for a given endpoint but rather to a distribution of outcomes. A prototype system linking the CERES-Millet model with a GIS system was developed in conjunction with the USAID Famine Early Warning System project to make real-time projections for millet yield in Burkina Faso.

The goal of this project is the development of a real-time yield forecasting system for Burkina Faso that will project at the earliest possible time during the course of a growing season any significant deviation from long-term mean millet yields so that appropriate action can be taken. In a deficit situation, foodstuffs could be imported to alleviate shortages; with a surplus, plans for export or stockpiling of grains could be initiated.

The prototype Famine Early Warning System for Burkina Faso links the CERES-Millet model with soil and weather databases. Spatial and climatic resources are interfaced through the GIS package IDRISI. Soil resources were determined from the ORSTOM Agricultural Soil Suitability Map of Burkina Faso at a scale of 1:500,000. Historical rainfall data for 231 sites (with a minimum of 14 years data) were available; for daily rainfall, parameters for generating simulated weather were constructed. All coefficients were interpolated on a 0.25° grid. Decadal satellite data images of cold cloud duration are available from the NOAA Climate Analysis Center, which produces decadal estimates using Reading University's interpretation algorithms. Real-time estimated rainfall derived from cold cloud duration is combined with simulated weather to derive a series of outcomes for the millet growing season. Therefore, as more and more real weather, and less probabilistically generated weather is used, we can progressively estimate millet production on a district basis with a corresponding decrease in the deviation of our projected outcomes. The results of the simulations are expressed as a percentage deviation from long-term mean production values.

Because this is a prototype system, the validation of the model has been limited. The two major areas of validation to be addressed include ground truth validation of rainfall estimates from the decadal satellite data and millet model simulation with historical data for yield comparisons with government statistics. In one example, Dori, in northern Burkina Faso (14°2′ N, 0°2′W, average precipitation of 470 mm), the millet model was run for 12 forecast dates in 1986, with 10 replications; historical decadal rainfall totals were split to produce simulated daily data. This was used in lieu of satellite-derived decadal rainfall. Simulations were carried out sequentially, and generated weather was used from the end of each "observed" decadal weather to the end of the growing season. Preliminary data indicated a surprisingly good agreement between observed and predicted yields under

suboptimal conditions in 1986. More importantly, projected yields were near final estimates after only 50 days of simulation.

This system has the potential for producing preliminary yield estimates four to six weeks prior to crop maturity, affording policy makers time to plan for catastrophic crop failure, should this appear possible. The inputs for driving the model are readily available electronically, the system is readily extendable to all at-risk areas, and the cost of the system, which runs on inexpensive personal computers, is minimal. The system would be available in district government offices on an ad hoc basis and to policy analysts with USAID.

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