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Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT)

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Editors
Job Kihara
CIAT – Malawi Office
Tropical Soil Biology and Fertility (TSBF)
Institute of CIAT, c/o ICRAF, Nairobi
Kenya

James W. Jones
Agricultural and Biological Engineering
Department, University of Florida
Gainesville 32611, FL
USA

Ramadjita Tabo
Forum for Agricultural Research
in Africa (FARA), Accra
Ghana

Dougbedji Fatondji
Soil & water management
International Crop Research
Institute for the Semi-Arid Tropic
P.O. Box 12404
Niamey
Niger

Gerrit Hoogenboom
AgWeatherNet, Washington
State University, Prosser, WA 99350
USA

Andre Bationo
Soil Health Program
Alliance for a Green Revolution
in Africa (AGRA)
Agostino Neto Road, Airport Res. Area 6
Accra, PMB KIA 114, Airport-Accra
Ghana

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Preface

In sub-Saharan Africa (SSA), increasing agricultural productivity is critical to meeting the food security and economic development objectives in the face of rapid population growth. Presently, the agricultural sector supports over 80% of the people in SSA, which is also the major contributor of GDP. A key challenge for scientists, governments and other stakeholders in the region is that food production should increase by 70% by the year 2050 to meet the caloric nutritional requirements of the growing population. Agricultural intensification is expected to be the main avenue for achieving these food increases. Crop models offer the benefit of increasing our understanding of crop responses to management in different soil and climatic conditions. Such responses are often of a complex and non-linear nature given the innumerable interactions among weather, soil, crop, and management factors throughout the growing season. Crop models can also provide insights in what might happen to productivity under various climate change scenarios, a domain beyond the reach of field experimentation. The outputs can inform key decision-makers at local, national, and regional levels in order to put the appropriate measures in place. Although major advances in modelling have been made in the USA, Europe and Asia, sub-Sahara Africa (SSA) lags behind due to the limited number of soil scientists and agronomists with the skills to set-up and run crop model simulations. Having a well-trained cadre of African modellers would greatly facilitate the design of best crop management and adaptation measures in the varied environments and to boost agricultural productivity in the region.

Over the past 20 years, efforts have been put in place to train scientists in the use of crop models, but the human resource base remains meagre. Most of the training was in the form of workshops and due to post-workshop financial constraints, limited or no follow-up efforts were made. Moreover, the disciplinary nature of university training in the region is not conducive to integrated, interdisciplinary, systems approaches. It is against this backdrop that the African Network for Soil Biology and Fertility (AfNet) and their collaborators, realizing that sustained follow-up was the key roadblock, organized a training programme which culminated in this publication. Many more such programmes are needed in order to strengthen the African modelling community in communicating effectively with decision makers as well as global community of modellers.

The chapters in this book present the context, key experiences and the results on the use of DSSAT in crop simulation. Chapter 1 presents the key steps and provides insights into building capacity for modeling in SSA. The experiences should inform capacity building efforts in order to choose carefully the training pathway. Chapter 2 summarizes the minimum data set required to set up and run crop models for (a) model applications, (b) general model evaluation and (c) detailed model calibration and evaluation. The chapter shows that little additional data could be all that one needs to have experimental data useful for modeling purposes. Chapter 3 discusses African soils and the key limitations to productivity. Chapter 4 focuses on sensitivities of DSSAT to uncertainties in input parameters while Chaps. 5–10 present key results of modelling from specific programs conducted in Ghana, Niger, Senegal and Kenya. The chapters present the key steps followed in the model calibrations and simulations for different themes including responses to fertilizer, organic resources and water management. Although the use of crop models is important in understanding African agriculture, there are key market and policy issues that must be addressed if agriculture is to be really improved. Thus Chap. 11 focuses on these issues and presents an integrated soil fertility management-innovative financing concept.

It is my hope that the approach to training, the model calibration and assessment procedures, the knowledge and wealth of experiences presented in this book will enhance the understanding and catalyse the use of crop growth models among the scientific community in Africa.

Prof. Dr. Paul L.G. Vlek
Executive director, WASCAL

Contents

Chapter 1
Building Capacity for Modeling in Africa

Andre Bationo, Ramadjita Tabo, Job Kihara, Gerrit Hoogenboom, Pierre C.S. Traore, Kenneth J. Boote, and James W. Jones

Abstract The use of models in decision support is important as field experiments provide empirical data on responses to only a small number of possible combinations of climate, soil, and management situations. Yet, crop modeling by African scientists so far has been limited. Therefore, to build the capacity of African scientists in the use of decision support systems, a provision was made for training within two main projects: Water Challenge Project (WCP) and Desert Margins Programme (DMP), jointly led by TSBF-CIAT (Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture) and International Centre for Research in the Semiarid Tropics (ICRISAT). A unique approach to training on modeling was developed and was based on four main pillars: (a) learning by doing, (b) integrated follow-up, (c) continuous backstopping support and (d) multi-level training embedded in a series of three training workshops. Although crop models are useful they have limitations. For instance, they do not account for all of the factors in the field that may influence crop

A. Bationo (✉)
Soil Health Program, Alliance for a Green Revolution in Africa (AGRA) Agostino Neto Road, Airport Res. Area 6 Accra, PMB KIA 114, Airport-Accra, Ghana
e-mail: abationo@agra-alliance.org

R. Tabo
Forum for Agricultural Research in Africa (FARA), Accra, Ghana

J. Kihara
CIAT – Malawi Office, Tropical Soil Biology and Fertility (TSBF) Institute of CIAT, c/o ICRAF, Nairobi, Kenya

G. Hoogenboom
AgWeatherNet, Washington State University, Prosser, WA 99350, USA

P.C.S. Traore
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Bamako, Mali

K.J. Boote • J.W. Jones
Agricultural and Biological Engineering Department, University of Florida, Gainesville 32611, FL, USA

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yield and inputs must be accurate for simulated outputs to match observations from the field. Thus it is imperative that these issues are carefully considered and weighted before attempting to evaluate the predictability of a crop model. However, the use of crop models and decision support systems in concert with experiments can provide very useful alternative management options for resource-poor farmers in Africa and other regions across the globe.

Keywords Crop models • Decision Support Systems • Africa • Farmers • African scientists

Introduction

Farmers adapt their management systems to prevailing climate, soils, pests, and socio-economic conditions by selecting suitable crops, varieties, and management practices. Seasonal climate variability often results in highly variable yields that may cause economic losses, food shortages, inefficient resource use, and environmental degradation. Market and policy changes occur at the same time, thereby creating highly complex combinations of factors that farmers must consider when making decisions related to agricultural production. Information is needed to help farmers and policy makers to evaluate all these factors in order to anticipate changes and make decisions and policies that promote long-term sustainable management practices.

A major role of agricultural science is to develop methods for analyzing and selecting production options that are well adapted to the range of weather and climate conditions that may occur, taking into account the needs and capabilities of farmers in a given region. Crop responses to weather are highly complex and non-linear; they are determined by many interactions among weather, soil, crop, and management factors throughout the growing season. Field experiments provide empirical data on responses to only a small number of possible combinations of climate, soil, and management situations. Also, existing management systems from other regions, new crops and varieties and other technologies being developed by scientists may provide useful adaptation options. However, it is impossible to conduct experiments that cover the full range of possible management options and climate conditions to determine production systems that are more resilient to climate variability, potential changes in climate, and farmers' goals (Nix 1984; Uehara and Tsuji 1991; Jones 1993). Instead of prescriptions, farmers need information on options that can increase their resilience and capacity to adapt to current climate risk and likely future climate conditions (Tsuji et al. 1998).

Nix (1984) criticized the predominance of a "trial and error" approach in agricultural research for evaluating management practices. He emphasized the need for a systems approach in which: (1) experiments are conducted over a range of environments; (2) a minimum set of data is collected in each experiment; (3) cropping system models are developed and evaluated; and (4) models are used to simulate production technologies under different weather and soil conditions so as to provide a broad range of potential solutions for farmers. Nix (1984) referred to the high cost of field experiments in addition to their limited extrapolation domain because results are site-specific. These concepts led to the development of the DSSAT (Decision Support System for Agrotechnology Transfer) under the auspices of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project suite of crop models that was designed to help researchers use this systems approach (e.g., IBSNAT 1989; Uehara and Tsuji 1991; Jones 1993; Jones 2003 Hoogenboom et al. 1994, 2004). Some crop simulation models and soil water models were already available (e.g., Ritchie 1972; de Wit and Goudriaan 1978; de Wit and Penning de Vries 1985; Jones et al. 1974; Williams et al. 1983; Arkin et al. 1976; Wilkerson et al. 1983), but prior to the IBSNAT initiative, there had not been a broad international effort focusing on the application of crop models to practical production situations. Although crop models were not originally developed for use in climate change research, they have been widely used for this purpose (e.g., Rosenzweig et al. 1995). They are well suited for these studies because they incorporate the effects of daily weather conditions on crop growth processes, predicting daily growth and development and ultimately crop yield. By simulating a crop grown in a particular soil, under specified management practices, and using a number of years of daily historical weather data at a site, one obtains an estimate of how a particular management system would perform under current and changed climate conditions.

The basic concept of crop modeling is that simulating crop growth and yield using dynamic crop models will produce results that represent how a real crop growing under specific environment and management conditions would perform. However, there are practical limitations that must be considered before making use of this approach in any study. One main limitation is that crop models do not account for all of the factors in the field that may influence crop yield. For example, crop diseases, weeds, and spatial variability of soils and management implementation can cause large differences in yield, and these factors are seldom included in crop simulation analyses. Another limitation is that inputs must be accurate or else simulated outputs are unlikely to match observations from the field. Attempts to evaluate the predictability of a crop model thus require that weather, management and soil inputs are measured in the field where the evaluation experiments are conducted. Furthermore, model evaluation experiments would ideally be designed to eliminate yield-reducing factors that are not included in the model. And finally, parameters that are used to model the dynamics of soil and crop processes need to be accurate for comparison with observed field data. For example, if one uses a crop model to simulate crop yield responses to water or N management using incorrect soil water parameters, results will show that the model fails to mimic results from field experiments or, more problematically, provide results that may mislead researchers or other model users.

Capacity Building

The use of models in decision support by African scientists is limited. Although most research on land productivity has traditionally focused on plot level approach, there has been low extrapolation of the findings to wider scales. The main problem is the limited availability of agricultural scientists (both soil scientists and agronomists) due to low resource allocation to training and capacity building in

African countries (Bationo et al. 2004). Secondly, the training approach employed in most training institutions especially those of higher learning in Africa is disciplinary. Modeling for extrapolation requires integration of various disciplines in what is now called systems approach and is based on the practical impossibility to do research everywhere.

In order to build capacity of African scientists in use of decision support systems, a provision was made for training within two main projects, Water Challenge Project (WCP) and Desert Margins Programme (DMP), undertaken jointly by TSBF-CIAT and ICRISAT among other partners. WCP aimed to enhance water productivity through the integration of water efficient and high yielding germplasm, water and soil conservation options, and nutrient management technologies coupled with strategies for empowering farmers to identify market opportunities, and scaling up appropriate technologies, methodologies and approaches. The project was implemented in Burkina Faso, Niger and Ghana. The specific objectives were to:

1. Develop, evaluate and adapt, in partnership with farmers, integrated technology options that improve water and nutrient use efficiency and increase crop yields in the Volta Basin.
2. Develop and evaluate methodologies, approaches and modern tools (GIS, models, farmer participatory approaches) for evaluating and promoting promising water, nutrient and crop management technology options.
3. Improve market opportunities for small holder farmers and pastoralists, identify and assess market institutional innovations that provide incentives for the adoption of improved water, nutrient and crop management technologies that benefit different categories of farmers, especially women and other marginalized groups of farmers.
4. Build the capacities of farmers and rural communities to make effective demands to research and development organizations, and influence policies that promote the adoption of sustainable water and nutrient use technologies.
5. Promote and scale up and out 'best bet' crop, water, and nutrient management strategies in the Volta Basin through more efficient information and methodology dissemination mechanisms.

Desert Margins Program (DMP) initiated in 2003 under the funding of UNEP-GEF operated in nine African countries namely: Burkina Faso, Botswana, Mali, Namibia, Niger, Senegal, Kenya, South Africa, and Zimbabwe. The overall objective of the DMP was to arrest land degradation in Africa's desert margins through demonstration and capacity building activities developed through unravelling the complex causative factors of desertification, both climatic (internal) and human-induced (external), and the formulation and piloting of appropriate holistic solutions. The project addressed issues of global environmental importance, in addition to the issues of national economic and environmental importance, and in particular the loss of biological diversity, reduced sequestration of carbon, and increased soil erosion and sedimentation. Key sites harbouring globally significant ecosystems and threatened biodiversity serve as field laboratories for demonstration activities related to monitoring and evaluation of biodiversity status, testing of most promising natural resources options, developing sustainable alternative livelihoods and policy guidelines and replicating successful models. In this project, models serve as decision guides for extrapolation of field results to wider recommendation domains. The broader objectives of the overall DMP were to:

1. Develop a better understanding of the causes, extent, severity and physical processes of land degradation in traditional crop, tree, and livestock production systems in the desert margins, and the impact, relative importance, and relationship between natural and human factors.
2. Document and evaluate, with the participation of farmers, NGO's, and NARS, current indigenous soil, water, nutrient, vegetation, and livestock management practices for arresting land degradation and to identify socio-economic constraints to the adoption of improved management practices.
3. Develop and foster improved and integrated soil, water, nutrient, vegetation, and livestock management technologies and policies to achieve greater productivity of crops, trees, and animals to enhance food security, income generation, and ecosystem resilience in the desert margins.
4. Evaluate the impact and assist in designing policies, programs, and institutional options that influence the incentives for farmers and communities to adopt improved resource management practices.
5. Promote more efficient drought-management policies and strategies.
6. Enhance the institutional capacity of countries participating in the DMP to undertake land degradation research and the extension of improved technologies, with particular regard to multidisciplinary and participative socio-economic research.
7. Facilitate the exchange of technologies and information among farmers, communities, scientists, development practitioners, and policymakers.
8. Use climate change scenarios to predict shifts in resource base and incorporate these into land use planning strategies.

Within the framework of these two main projects, we identified the need for new scientific and technical training on the use of DSSAT models in order to hasten implementation and fulfillment of all the proposed outputs.

A New Approach

We developed a unique approach to modeling training based on four main pillars: (1) learning by doing, (2) integrated follow-up, (3) continuous backstopping support and (4) multi-level training. Our learning by doing strategy required that scientists being trained not only work on individual computers for hands-on-experience but also collect their own data that was used to run the models. Data collection by the scientists was done within the framework of the two main projects (WCP and DMP) as well as in the African Network for soil biology and fertility (AfNet of TSBF-CIAT) supported sites. The arrangement attracted self-sponsored scientists working in Africa in addition to those financed through the two projects. Follow-up was achieved through continuous communication of the organizers who were also the lead investigators within WCP and DMP and the scientists using data from these projects. A minimum dataset for DSSAT was developed for use by scientists as a checklist during field data collection. A concise summary of data requirements for modelling is presented in Hoogenboom et al. (2012, this volume). Professional and technical backstopping support was given by scientists associated with the International Consortium for Agricultural Systems Applications (ICASA) and progressive DSSAT modelers working in Africa mainly ICRISAT and IFDC. Scientists and organizers were continuously in contact with the trainers during and after a training workshop. Modeling is quite complex and one training session often does not lead to sufficient understanding and know-how for use of models. TSBF-CIAT and ICRISAT-Niamey in conjunction with ICASA therefore organized a series of three workshops. The training workshops focused on both biophysical and socio-economic issues to allow the screening and identification of scenarios that will lead to best bet management practices and policies for rebuilding biodiversity and restoring degraded and collapsed ecosystems.

The first workshop, held in Arusha Tanzania in 2004, was to expose people to the theory and familiarize with DSSAT software and its operations as well as on general modeling concepts. The second workshop, held in Accra Ghana in 2005, aimed at enabling trainees to input and use their own datasets in DSSAT as well as familiarize them with the minimum dataset concept for modeling. The scientists then used the period 2005–2007 to collect the required minimum dataset and or fill in gaps in the data they already held. Thus, the third training and last in the series was held in Mombasa Kenya in 2007 to have the trainees model different scenarios using their own datasets and write a scientific manuscript for publication. The training workshops provided participants, mainly young scientists with an opportunity to learn from model developers, to peer review and positive criticism and information sharing between sub-regions and countries.

The themes addressed by scientists include: tillage and nitrogen applications, soil and water conservation practices including effects of zai technology, phosphorus and maize productivity, generation of genetic coefficients, long-term soil fertility management technologies in the drylands, microdosing, manure and nitrogen interactions in drylands, optimization of nitrogen x germplasms x water, spatial analysis of water and nutrient use efficiencies, and tradeoff analysis.

Conclusions

Crop models are useful for simulating crop and soil processes in response to variations in climate and management. Building a critical mass of African modelers requires an integrated approach to learning at the start of a scientific career. Training of scientists in crop modeling should be step-wise and systematic to ensure the scientists gain the minimum ability to start using models. A minimum dataset of good quality is required to ensure accurate comparison with observed field data. Attempts to evaluate the predictability of a crop model require that whenever possible, weather, management and soil inputs are measured in the field where the evaluation experiments are conducted. Crop models should be evaluated with caution as they seldomly contain all of the factors in the field that may influence crop yield, e.g., crop diseases, weeds, and spatial variability of soils and management implementation that can cause large differences in yield.

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Chapter 2
Experiments and Data for Model Evaluation and Application

Gerrit Hoogenboom, James W. Jones, Pierre C.S. Traore, and Kenneth J. Boote

Abstract Crop models and decision support systems can be very useful tools for scientists, extension educators, teachers, planners and policy makers to help with the evaluation of alternative management practices. Many of the current crop models respond to differences in local weather conditions, soil characteristics, crop management practices and genetics. However, computer-based tools require inputs in order to provide reliable results. Especially for those new to crop modeling, the data requirements are sometimes somewhat overwhelming. In this chapter we provide a clear and concise summary of the input data requirements for crop modeling. We differentiate between requirements for model evaluation, model application and model development and improvement. For model inputs we define daily weather data, soil surface and profile characteristics, and crop management. For model evaluation and improvement we define crop performance data as it relates to growth, development, yield and yield components, as well as additional observations. We expect that this chapter will make the use and application of crop models and decision support systems easier for beginning modelers as well as for the more advanced users.

Keywords Crop modeling • Simulation • Decision support systems • Minimum data set • DSSAT • Cropping System Model (DSSAT) • CROPGRO• CERES

G. Hoogenboom (✉)
AgWeatherNet, Washington State University, Prosser, Washington 99350, USA
e-mail: gerrit.hoogenboom@wsu.edu

J.W. Jones
Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida 32611, USA

P.C.S. Traore
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Bamako, Mali

K.J. Boote
Department of Agronomy, University of Florida, Gainesville, Florida 32611, USA

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Introduction

With the increasing interest in the applications of crop modeling and decision support systems, there is a need to clearly define the type of experiments that are required for both crop model evaluation and application. Especially for those new to crop modeling it is unclear what types of experiments should be conducted and what information should be collected in these experiments. Over the years several publications have been written to document these requirements (IBSNAT 1988; Hunt and Boote 1998; Hunt et al. 2001). The most extensive ones can be found in the documentation that was developed for the Decision Support System for Agrotechnology Transfer (DSSAT) Version 3.5, especially Volume 4 (Hoogenboom et al. 1999). This information is still relevant and has been included as electronic documents in the documentation section of DSSAT Version 4.0 (Hoogenboom et al. 2004) and DSSAT v4.5 (Hoogenboom et al. 2010).

Volume 4.8 entitled "Field and Laboratory Methods for the Collection of the Minimum Data Set" by Ogoshi et al. (1999) is based on Technical Report 1 that was published by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project (IBSNAT 1988). It includes extensive documentation on data collection procedures for modeling. In volume 4.7 entitled "Data Requirements for Model Evaluation and Techniques for Sampling Crop Growth and Development" Boote (1999) provides detailed procedures on the actual sampling techniques for growth analysis and crop development. However, an easy to use summary is currently not available. The goal of this chapter is, therefore to provide a clear and concise summary for experimental data collection for model evaluation and application.

Overview

In order to run a crop model and to conduct a simulation, a set of data are required. Sometimes this is referred to as a "Minimum Data Set." The terminology Minimum Data Set was first introduced by the IBSNAT Project. Although the type and details required for model inputs might vary somewhat depending on the crop or agricultural model, in general we can differentiate between three broad levels or groups. Level 1 defines the data required for model applications, Level 2 defines the data required for general model evaluation, and Level 3 defines the data required for detailed model calibration and evaluation. Potentially this type of data can also be used for the development of a model for a crop for which currently no dynamic crop simulation model exists.

Level 1 includes daily weather data, soil surface characteristics and soil profile information, and crop management. Level 2 includes the environmental and management data from Level 1 and some type of observational data that are collected during the course of an experiment. At a minimum the two key phenological phases, i.e., flowering or anthesis and physiological or harvest maturity, and yield and yield components are needed for observational data. Level 3 would include the environmental, management and observational data described under Level 2 and additional observations related to growth and development, such as growth analysis, soil moisture content, and soil and plant nitrogen, phosphorus, potassium, and others, depending on the overall intended model application or evaluation.

Experiments and Modeling

It is important to understand that one rarely develops an experiment for modeling only, but that experiments should be conducted in such a manner that they also have a modeling component that can be used for either model evaluation or application or both. It is also important to keep in mind that some of the basic data that are required for any model application, especially those described under Level 1, should be a basic set of data that are collected for documentation of any experiment. For instance, for many experiments local weather and soil conditions have a major impact on the outcomes of an experiment and should be included as part of the overall analysis.

Location of Experiments

Normally data for model evaluation are obtained from experiments, although in some cases one might only have access to statistical yield and production data. Although this information can be used, one should understand the level of detail and the quality of this type of data and expected outcomes with respect to the accuracy of the evaluation of a model. In general experiments can be conducted under controlled management conditions, referred to as "on-station" and in farmers' fields, referred to as "on-farm." For Level 3 one normally would not use data from on-farm experiments, but the data can be useful for Level 2 model evaluation if one understands the limitations of the data, such as the lack of replications in most cases, variability of environmental conditions and uncertainty of the inputs. In some cases experiments can be conducted in growth chambers or in Soil-Plant-Atmosphere Research (SPAR) chambers where most environmental conditions can be controlled. However, for accurate model evaluation, on-station experiments with at least three or four replications are preferred.

General Purposes of Experiments

It is always important to keep the overall goal of the research in mind and design appropriate experiments accordingly, rather than concentrating on the model only. There is a wide range of applications with some of the key ones listed below.

– Technology evaluation, such as evaluation of new cultivars, inputs, including irrigation and fertilizers, and soil preparation, such as tillage and conservation agriculture.

- Characterization of yield limiting factors in order to focus on new technology development and evaluation.
- Understanding the interactions among management factors, such as water, nutrients, etc., and aiming at refining agricultural management technologies.
- Understanding the interactions of the environment, such as increases in temperature and CO_2.
- Understanding the interactions between genotype and environment (G x E).
- Long-term soil sustainability and soil health, including improvement of soil organic matter.
- Understanding environmental impact, such as nitrogen pollution due to different management practices.
- Potential application of agricultural crops for food, feed, fiber and fuel production.

General Purposes of Model Use

It is important to determine the overall purpose of the use of modeling and how it contributes to the overall research goal. In many cases adding a systems analysis and modeling component can strengthen the overall research approach. A partial list of model applications is listed below.

- Understand and interpret experimental results.
- Enhance quality of field research and the results that are derived from it.
- Diagnose yield gaps by looking at the differences between potential, attainable and actual yield from on-station and on-farm research, and to help develop technologies to test these under field conditions.
- Help publish results of field trials via systems and modeling analysis.
- Estimate impacts on production, water use, nitrogen use, and other inputs and determine various resource use efficiencies at scales from field to farm to watershed to region and higher.
- Estimate economic implications of different technologies.
- Estimate the impact of climate change and climate variability on crop production and develop adaptation scenarios.
- Plant breeding, Genotype * Environment interaction and the development of ideotypes.
- Enhance interdisciplinary research through interaction of soil scientists, agronomists, economists, engineers, GIS/remote sensing scientists, and others.

Level 1 Data

Level 1 data for model applications include daily weather data, soil characteristics and crop management. These data are an absolute requirement for any successful model evaluation and application. Well-documented experiments