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IMPROVEMENT CENTER

Directions in Modeling Wheat and Maize for Developing Countries

Proceedings of a Workshop, CIMMYT,
El Batán, Mexico, 4-6 May 1998

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Editors

NRG
Natural Resources Group

Geographic Information Systems
Series 01-02

Correct citation: White, J.W., and P.R. Grace (eds.). 2001. *Directions in Modeling Wheat and Maize for Developing Countries: Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 4-6 May 1998.* NRG-GIS Series 01-02. Mexico, D.F.: CIMMYT.

Abstract: In a workshop sponsored by the Natural Resources Group (NRG) of the International Maize and Wheat Improvement Center (CIMMYT), crop modelers, crop physiologists, and other scientists from around the world met at CIMMYT headquarters in May 1998 to review the relevance of the CERES-Maize and CERES-Wheat models for conditions in developing countries, to define an appropriate role for CIMMYT in promoting the use of crops models, and to consider ways to develop a new generation of wheat and maize models, both for natural resource management research and to link models to genetic research. In addition to invited papers, the publication describes the conclusions of working groups.

ISSN: 1405-7484

ISBN: 970-648-081-1

AGROVOC descriptors: Maize; Wheats; Plant physiology; Food production; Natural resources; Resource conservation; Sustainability; Simulation models; Research projects; Research institutions; Tropical zones; Developing countries

AGRIS category codes: F01 Crop Husbandry

A50 Agricultural Research

Dewey decimal classification: 633.1

Printed in Mexico.

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Preface

Process-based models of crop growth and development are among the most exciting tools for agricultural research and development that are emerging from the on-going information technology revolution. Models can improve our understanding of the complex processes underlying crop production, particularly in water and nutrient management. Their predictive power can help deal with issues that have long proven difficult or intractable, such as system sustainability or the impacts of global change driven by forces such salinization, desertification, and an increased concentration of greenhouse gasses.

Models, however, are only as good as the science and data they are built from. While simulation models have solid foundations in research on temperate environments in developed countries, much less model development and testing has occurred in subtropical and tropical environments and for production systems in developing countries. Furthermore, production practices in developing countries often differ dramatically from the high-input monocultures of the North.

This workshop provides a timely opportunity to examine potential applications of crop models in relation to CIMMYT's mandate of promoting sustainable improvements in the productivity of maize and wheat systems for resource poor farmers. Issues that we might hope to see addressed include:

- How well do available models deal with conditions of low water, nitrogen, and phosphorus availability that are frequent in smallholder systems in developing countries?
- How can CIMMYT best assist in model testing and development?
- What are the most promising or appropriate applications for current models?

To help push model development forward in ways that increase its relevance for research intended to benefit developing countries, CIMMYT is pleased to host its first formal, international workshop on crop modeling.

We thank Jane Reeves and Mike Listman for the style editing of this publication and Wenceslao Almazan for the layout.

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Executive Summary

The CIMMYT Wheat and Maize Modeling Workshop, held from 4 to 6 May, 1998, at CIMMYT's headquarters at El Batan, Mexico, had the broad goal of examining crop modeling needs for research on sustainable maize and wheat systems in developing countries. Specific objectives included:

- Reviewing the current status of the CERES-Maize and CERES-Wheat models, including working on known problems with phenology and growth for conditions prevalent in developing countries.
- Defining an appropriate role for CIMMYT in promoting use of crops models.
- Considering strategies for a new generation of wheat and maize models, both for natural resource management research (e.g., SALUS) and to link models to genetic research (e.g., a gene-based wheat or maize model similar to GENEGRO).

The workshop began with presentations on various aspects of wheat and maize modeling and management of data for crop models. The following two days were dedicated to informal working groups that examined specific topics in detail. In most cases, this involved running test data sets and modifying model codes.

The CIMMYT Wheat and Maize Modeling Workshop, 4 to 6 May, 1998, at CIMMYT headquarters in El Batán, Mexico, examined crop modeling for research on sustainable maize and wheat systems. Specific objectives included reviewing the current status of the CERES-Maize and CERES-Wheat models, examining roles for CIMMYT in promoting use of crops models, and considering strategies for a new generation of wheat and maize models.

Potential applications of crop modeling at CIMMYT include basic agronomy, systems research, and crop improvement (paper by J.W. White and P.R. Grace). Most models now incorporate responses to available soil moisture and nitrogen and can be used for a wide range of research problems relating to these responses. However, there is need to introduce or improve routines for tillage, phosphorus uptake and utilization, pH effects, and soil erosion. CIMMYT can play a valuable role in facilitating access to quality sets of field data in standard formats (e.g., the ICASA standards), promoting more complete documentation of models, and linking modelers with priority research applications.

From a "wish list" for wheat physiologists (M. Reynolds), a key interest is to model canopy temperature differences to help understand observed relations between canopy temperature depression and grain yield under favorable conditions. Other topics include lodging resistance and use of genetic information to improve modeling of vernalization and photoperiod effects on phenology.

In maize (G. Edmeades and J. Bolaños), a major constraint is the failure of existing models to handle stress effects on the anthesis-silking interval and on related processes. CIMMYT's Maize Program has many datasets that could serve for model development and evaluation.

The modular structure of CROPGRO (C.H. Porter, J.W. Jones, and P. Wilkens) was presented as a promising strategy to facilitate integration of information from different disciplines, allow contributions from many authors, provide flexibility in updating, and thus extend the useful life of models. Key features of a modular approach are that the modules should relate to real world components or processes, that inputs and outputs should represent measurable variables, and that communication between modules should occur only through the inputs and outputs.

There is great interest in linking models and GIS to improve regional targeting of new technologies (S.N. Collis and J. Corbett). One approach is to use interpolated climate surfaces as a source of inputs for weather generators. To reduce the potential number of simulations, regional variation can be summarized as "effective environments." These can be overlaid with soil layers and simulations run on unique polygons. As an example, performance of two maize cultivars were compared for rainfed systems of eastern Africa. An ArcView extension is available to automate much of this work.

In the hands-on modeling sessions, widespread concern was noted about problems of version control for models distributed in DSSAT. The next official version of DSSAT was to be Version 3.5, which was released in late 1998. Test versions of models for development should be based on Version 3.5. However, they should be identified as 3.6xx, where "xx" suffix identifies the developer (e.g., "3.6PG" for Peter Grace). A facility is needed in the code to allow for input and display of this suffix.

In CERES-Maize, the number of maize leaves is over-estimated. Although the phyllochron interval (PHINT) appeared in the cultivar file, the value was actually "hard wired" at 75 degree days. In version 3.5, the interval can be varied.

Files of cultivar-specific parameters in CERES (e.g., "MZCER980.CUL") provide no indication of reliability. Ideally, the number of observations, types of data, and method used should all be indicated. Tony Hunt strongly urged that the list of cultivars be shortened to include only the most reliable coefficients. Five generic cultivars should also be provided.

To facilitate modeling of nitrogen mineralization in CERES and CROPGRO, a new soil parameter file was created, SOILN980.PAR, that externalizes many of the coefficients needed for simulating the decomposition of soil organic matter (one pool) and organic matter added as residue or manure (three pools). If the file does not exist in the data directory, it is created using default values upon the first run of the model.

To handle tile drains, Bill Bachelor defined a soil layer 15 cm thick at the approximate depth of the drain. Unfortunately, testing showed that introducing this layer produced unexpected changes in model outputs.

Among changes suggested for subsequent releases of CERES were:

- Improved thermal time calculations.
- Accounting for mass of dead leaves and their subsequent incorporation into soil organic matter.
- Improved modeling of grain number in maize (based on approach of Andre Du Toit).
- For wheat, Zadok stages should be output along with standard phenology stages.
- Routines to simulate:
    - Conservation tillage.
    - Tile drainage.
    - Runoff/erosion.
    - Response to soil phosphorus.
- Generate solar radiation if reliable daily data are or not available.
- Genetic coefficients for winter-kill, vernalization, and prolificacy.
- Improve the water balance routines both for root uptake and estimates of potential evaporation.

Many researchers assume that Jones and Kiniry (1986) is still an accurate description of the CERES models. Much more effort is needed to update documentation. Reports should be sent to the Hawaii for posting on the list server. Links to modeling sites such as Michigan State University, the University of Florida, and elsewhere can easily be included.

The need to assemble quality data sets collected through the IBSNAT project and other sources (e.g., GCTE) arose several times. It is easy to criticize models, but the models are only as good as the data sets they are based upon.

A Crop Modeling Strategy for CIMMYT's Research on Sustainable Wheat and Maize Production Systems

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Abstract

This paper outlines crop improvement, strategic agronomy, and natural resource management research concerns central to CIMMYT's mission and which models can help address. Authors also discuss related issues, including model documentation and data management. Although CIMMYT has little comparative advantage in model development per se, the center has much to contribute to others' development and refinement efforts, to the availability of quality data, and to the promotion of models and training in their use, and active participation in these areas will ultimately result in better models for CIMMYT's own aims.

Introduction

Process-based crop models can increase research effectiveness by allowing researchers to formulate hypotheses in a precise, quantifiable manner and by converting complex hypotheses into quantifiable estimates of crop response to management and environment. These responses may have a temporal scale ranging from a few minutes to multiple decades, the latter scale being of particular relevance where natural resource degradation is a concern.

Researchers at the International Maize and Wheat Improvement Center (CIMMYT) recognize the potential of crop models and have applied them to studies of drought tolerance, yield potential, nitrogen dynamics, farmer risk and impact of climate change, among others. In particular, the Natural Resources Group sees models as key tools for understanding issues related to conserving the resource base of maize- and wheat-based production systems.

Given the diversity of maize and wheat models available and the wide range of potential applications, CIMMYT needs a coherent strategy for developing and applying crop models. This paper outlines the needs for models to satisfy different research objectives and discusses related issues, including model documentation and data management.

Model Needs, as Defined by Research Objectives at CIMMYT

Possible applications of crop models at CIMMYT are conveniently viewed in relation to research objectives (Table 1). These objectives are divided into broad categories of crop improvement, strategic agronomy, and natural resource management, although there is much potential for overlap, especially among the latter two.

Crop improvement

Applications of models to crop improvement efforts include evaluating the impact of specific characteristics on yield or other traits, defining crop ideotypes, and examining genotype x environment interactions.

 Published in White, J.W., and P.R. Grace (eds.). 2001. *Directions in Modeling Wheat and Maize for Developing Countries: Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 4-6 May 1998.* NRG-GIS Series 01-02. Mexico, D.F.: CIMMYT.

The importance of high-yielding wheat regions in several developing countries means that simply characterizing regional variation in yield potential is of fundamental interest. However, in a recent attempt to estimate potential yields in the Yaqui Valley, Sonora, Mexico, the CERES-Wheat model gave maximum yields of 9.5 t/ha, whereas the highest yields reported from large plots in agronomy trials are around 11 t/ha (K. Sayre, personal communication, 1998).

Improved modeling of maize and wheat phenology should assist breeders in understanding how to match phenology to different environments and lead to identification of improved selection criteria, both for high yield and stress conditions. Rapid progress in molecular marker techniques for characterizing the genetic makeup of cultivars suggests the possibility of developing gene-based phenology models.

Research conducted at CIMMYT on the physiology of maize has identified the control of grain set as a key issue, both for yield potential and tolerance to water and nitrogen deficits. The anthesis-silking interval provides a useful field indicator of stress tolerance (Edmeades et al. 1993; Bolaños and Edmeades 1996). Pollination is not limiting. Partitioning to grain is reduced under stress, causing grain abortion. Related to partitioning to grain are prolificacy (formation of multiple ears) and barrenness (where no ear is formed). Accurately describing these responses may be essential for realistic predictions of maize yields under the low yield conditions typical of many smallholder systems in Africa and Latin America.

CIMMYT has identified increasing nitrogen use efficiency (NUE) as a breeding priority for maize. Evidence to date suggests that variation in NUE is related to efficiency of N mobilization from stems and leaves to grains and not to variation in uptake (Bellows 1997; van Beem and Smith 1997). A detailed model of interactions of N uptake and mobilization with growth would allow researchers to examine possible tradeoffs in selecting for high NUE.

Table 1. Needs for different crop models at CIMMYT, as related to research objectives.

Research objective	Crop	Type of model needed
Crop improvement		
Define crop ideotypes.	Maize	Advanced process-based with improved handling of ear and grain set (maize) and canopy temperature (wheat).
Understand cultivar differences in canopy temperature.	Wheat	Advanced process-based with improved handling of canopy temperature (wheat).
Test hypotheses related to cultivar differences specified at the gene level.	Maize, wheat	Gene-based model with detailed treatment of processes.
Agronomy		
Characterize climatic risk in rainfed systems.	Maize, wheat	Robust basic model with cultivar differences in phenology.
Estimate potential yield loss due to growing wheat on beds.	Wheat	Robust basic model that simulates canopy geometry.
Natural resource management		
Estimate long term impact of zero tillage with different levels of residue retention.	Maize, wheat	
Estimate potential impact of green manures relay-cropped with maize.	Maize	Model of legume species, preferably with ability to simulate interspecific competition.

Breeding for increased yield potential is a priority of the CIMMYT Wheat Program. Selection of erect semidwarf cultivars gave a large initial yield increase when combined with increased inputs. Recent efforts focus on selecting for increased yield within semidwarf wheats. Greater canopy temperature depression is associated with increased grain yield (Amani et al. 1996), and there is interest in using models to examine underlying mechanisms and to assess whether the effectiveness of this trait will vary with humidity in the different production regions.

Lodging is also a major concern in high yield wheats. Static models of the mechanics of lodging suggest ways to increase lodging tolerance. These might be profitably linked to process-based models to examine how decreasing the plant's center of gravity and modifying the mechanical properties of stems might affect overall growth and partitioning to grain.

Natural resource management and strategic agronomy

The Natural Resources Group (NRG) at CIMMYT was established in 1996 to work on long-term issues of maize and wheat crop production. Its activities complement those of the maize and wheat agronomists in CIMMYT's two commodity focused programs. The NRG's primary focus is on issues related to conservation tillage and residue management. To structure its activities, the NRG follows a research framework developed from the Center's previous experiences in farming systems research (Table 2). Most steps of the framework involve research where models can increase research efficiency. The steps focusing on initial characterization and final assessment of impact may involve many situations where use of modeling is the only practical alternative.

For rainfed maize and wheat, a central issue is how to improve or, better still, synchronize N availability, particularly in soils with low N status and in systems where external N inputs are low. Low inputs of organic

Table 2. Framework for research activities of the Natural Resources Group, CIMMYT, with suggestions of relevance of crop modeling.

Research step	Examples of possible applications of models
Characterize incidence and pace of resource degradation.	Estimate nutrient dynamics and implications of soil loss in maize-ground nut systems of Malawi and Zimbabwe under current practices.
Understand processes underlying degradation.	Characterize the dynamics of nitrogen and soil organic matter in rainfed maize systems of Zimbabwe.
Develop prototype solutions.	Evaluate potential impact of zero tillage with partial residue removal in Jalisco, Mexico.
	Identify regions in India where wheat production on raised beds is feasible based on soil types.
Conduct adaptive research with farmer participation.	Examine how suggested farmer modifications to soil fertility management strategies respond to climatic risk in Malawi and Zimbabwe.
Assess adoption process.	Provide feedback on how adoption of green manures in Central America compares to expectations from research.
Synthesize and extrapolate to other regions.	Estimate the potential impact of conservation tillage in regions of Mexico that differ in rainfall and soil type.
	Estimate the potential of different green manures to improve productivity of maize systems in Malawi and Zimbabwe.
Assess impact, including consideration of the possible consequences of inaction.	Simulate long term consequences of specific solutions vs. those of present practice.

and inorganic fertilizers, combined with the use of grain legumes or green manures, appear to be among the few options for maintaining or improving system productivity in many low-income, dryland environments. If we can improve our ability to predict changes in soil water storage and N availability in response to various forms of tillage and residue management (particularly surface application of residues), we have the ideal tool for achieving this source-sink synchronization. Unreleased modifications to the surface residue management routines in CERES have made significant improvements in this area. Also available are a great deal of quality data that allow us to include measurable entities such as microbial biomass in our algorithms (Grace et al. 1994). The use of biologically significant soil pools that are actually measurable is becoming more prevalent in modeling circles today and avoids the problem of model re-calibration for each particular soil environment.

Models will be essential for examining the relative benefits of different technologies, including accounting for climatic risk and variation in soil types. While single-season or even single-rainfall event simulations may be of use in research on degradation processes, the ability to simulate multiple years is a must, particularly for investigating changes in soil physical properties. For example, changing from conventional tillage to zero tillage can have a significant impact on soil water and nutrient cycling; a feature that many models fail to capture at present.

In irrigated or high rainfall systems, loss of mineral N from the soil system is a major problem. With respect to gaseous losses, denitrification routines in current models have been shown to be either too data intensive or severely lacking in accuracy. With funding opportunities increasingly available for predicting greenhouse gas emissions, a significant overhaul of these routines in CERES is being done at UC-Berkeley (Riley, unpublished), incorporating water-filled pore space routines using isotope data collected at CIMMYT-Obregon. Ammonia volatilization is not dealt with at all in nutrient cycling models but is a significant loss mechanism, particularly where anhydrous ammonia is applied to irrigation water. A significant amount of data (and interest) on this mechanism are held at Lowry Harper, USDA, for inclusion in the CERES models.

Management of phosphorus and soil pH are also concerns, particularly for maize systems in Africa. Whilst a P module is available in CERES and is currently being modified (Gerakis et al. 1998; Daroub et al. 1999), a critical issue is how to relate soil measurements of available P to pool sizes in a process-based model. More challenging still is how to quantify effects of root architecture and mycorrhizal associations. While the latter is perhaps beyond the scope of CERES/CROPGRO models, the implications of pH on soil processes are readily known and could be incorporated with little problem.

Growing wheat on raised beds offers important advantages in terms of fertilizer, irrigation, and weed management. Effective modeling of this system would require routines for canopy architecture and two-dimensional movement of moisture and nutrients. Relevant data are being collected at CIMMYT in collaboration with Michigan State University, but algorithms need to constructed and tested. The erosion-runoff routines in CERES also appear weak, and improvements are needed.

A systems perspective also requires the ability to model other crops and weeds that may occur within maize or wheat systems, whether in rotation or intercropping situations. As mentioned above, legumes represent the most important set of alternate crops and include sources of grain, feed, and green manure. The CROPGRO model simulates growth of the relevant grain legumes, and intercropping algorithms have been developed. Modeling of forage and green manure species is largely constrained by a lack of growth data from tropical environments. In Asia, rice-wheat systems present a special challenge due to the unusual soil conditions of paddy systems. Other species that may be rotated with maize or wheat include sugar cane, sunflower, cotton, jute, cassava, potatoes, and tomatoes. Like most modeling efforts where funds are at a premium, many of the improvements listed above are not adequately implemented for general use and are inevitably forgotten or lost. This is a major area of concern if the Decision Support System for Agrotechnology Transfer (DSSAT) is going to continue to be a product with credible outputs in agronomically diverse agricultural systems. Other modeling efforts will pass DSSAT by, as will funding agencies, unless a coordinated approach to modification, testing, and, in particular, a release strategy, perhaps Web-based, is developed.

Prioritizing Model Development

The preceding review illustrates many potential applications of models to issues relevant to CIMMYT and its research partners. However, the review is inadequate for priority setting because of overlap in how model improvements benefit different research activities.

Table 3 suggests priority areas for model development. Criteria considered include importance, technical feasibility, and availability of quality data. Highest priority is given to improving the modeling of phenology and basic soil processes, particularly residue handling

Other Modeling Issues

Effective use of models does not depend solely on the availability of suitable models. Factors contributing greatly to the success of the IBSNAT project were that it provided users with a software shell for managing field data and simulation results, and that it established standard data formats that could be used on a range of crop models. Thus, CIMMYT should reflect on what its role is and who its collaborators should be in developing modeling tools and managing data for modeling applications.

Complex versus simple models

Over the past decade, there has been an increase in interest in simple models based on radiation use efficiency (RUE) and harvest index conversions (e.g., Sinclair and Horie 1989). While we endorse the use of simple approaches where feasible, our concern is that apparent functionality can be an artifact of calibrating a given model to a narrow range of conditions or germplasm. For an institute with global research concerns, preference should be given to models that offer a framework for providing varying levels of process detail.

Table 3. Priority areas for model development.

Type of model/subroutine needed	Crop	Possible sources	Priority
Canopy			
Growth response to temperature	Wheat	CERES	***
Canopy temperature	Wheat	CROPGRO	**
Canopy structure (bed system)	Wheat	CROPGRO	*
Basic phenology and leaf development	Maize	CERES	**
Gene-based treatment of phenology	Maize, wheat	CROPGRO, GENEGRO	*
Contribution of senesced material to residue	Maize, wheat	CERES, APSIM	*
Stress effects on grain set	Maize		**
Soil			
Surface residue decomposition	Maize, wheat	SOCRATES, CENTURY	***
Improved runoff	Maize, wheat	APSIM	**
Soil erosion	Maize, wheat		**
Phosphorus	Maize	EPIC, CENTURY	*
pH, including response to liming	Maize		*
Tillage effects	Maize, wheat		**
Systems			
Intercropping	Maize	APSIM	**
Weed competition	Maize	APSIM	*
Model of green manure legume species	Mucuna, Canavalia, etc.	CROPGRO, APSIM	**

User interfaces

Although some modeling activities may primarily be of use to CIMMYT scientists per se, most potential applications need to be readily transferable to national agricultural research systems (NARS) or non-governmental organizations (NGOs). Indeed, our partners will often be co-participants in model development, evaluation, and application. Thus CIMMYT should seek generic tools, which would logically include a standardized model user interface. DSSAT3 (Thornton et al. 1996) provides a well known interface that many CIMMYT and NARS staff have been exposed to. However, it is clear that in the near future most users will expect a Windows-based, graphical user interface. Several options for such interfaces exist or are under development, including APSFRONT (Veraart 1998) and GUICS (Acock et al. 1999). CIMMYT, as a potentially major user, should try to participate in the development of improved user interfaces.

A specialized group of user interfaces worthy of separate consideration is that which allows models to be combined with geographic information systems (GIS).

Documentation of models

Proper documentation of models is perhaps a higher priority for CIMMYT than for model developers. The Center must be prepared to transfer modeling approaches to its own staff, NARS, and NGOs, all of whom may insist upon explanations of the underlying assumptions of a given model. Unfortunately, crop models are notorious for poor documentation. We attribute this to several factors:

- Model developers are pressured to publish research outputs, whereas model descriptions are mistakenly seen as minor, “gray literature” publications.
- Models are continually undergoing revision, rendering documentation obsolete.
- Current models typically have multiple authors, which can make the coordination of publication difficult.

As a partial solution to the difficulties of model documentation, we propose that a dynamic description of models be maintained on a web site and that any CIMMYT participation in model development include requirements for contribution to this documentation.

Data management

CIMMYT is a logical source of crop data to develop and evaluate maize and wheat models. The Center’s research data are dispersed over a wide range of groups, and, in some cases, valuable data are only available in summarized forms in research papers. Initiatives are underway to assemble research data into easily accessible databases. Like most institutions, though, funding constraints limit the speed of development.

The International Wheat Information System (IWIS) provides ready access to results of CIMMYT international wheat trials on CD-ROM (Fox et al. 1997). Besides grain yield, the data reported can include days to heading and maturity, 1000-grain weight, and basic summaries of management. Unfortunately, no weather or soil profile descriptions are given. A further limitation is that results of many CIMMYT wheat experiments are not included because they do not form part of the international trial system.

Recognizing the deficiencies of IWIS, the CIMMYT Wheat Program participates in the development of the International Crop Information System (ICIS). This system is still incomplete, but design specifications include the ability to store a much wider range of data and experimental designs than is possible with the original IWIS design and to output data in model-ready formats such the ICASA standards (Hunt et al. 2000). Another important innovation of ICIS is to allow users to maintain local versions of the database that can be uploaded to the central version at the users discretion.

Data from CIMMYT’s Maize International Testing Unit are also stored in electronic format; currently, access is only possible through specific requests to the Unit. The CIMMYT Maize Program is evaluating options for developing a more flexible information system, and it is likely that they will either join ICIS or create a parallel system with similar functionality. The Maize Physiology group is committed to maintaining a set of quality data for model development and evaluation.

The Natural Resource Group is developing the Sustainable Farming Systems Database (SFSD) as a specialized implementation of ICIS that can manage long term and multiple-species trials. The SFSD should eventually become a major repository of data for long term trials and cropping systems research. ICIS thus holds the promise of making a large amount of data available in model-ready formats. However, parallel to this effort, there is still need for CIMMYT researchers to make more data available for modeling efforts.

Furthermore, although CIMMYT does not seem to have a comparative advantage in maintaining soil and meteorological data, the lack of ready sources of data is a major impediment to model use. A dual strategy seems appropriate here. One component is to collect quality sets of soil and weather data. The other is to develop interpolated surfaces of soil and climatic data that can be used with crop models. CIMMYT has assisted in the development of the Spatial Characterization Tool (SCT; Corbett and O'Brien 1997). The SCT currently includes surfaces of monthly precipitation and temperature from Africa and Latin America, and surfaces for Asia are under development (J. Corbett, personal communication, 2000).

Transfer of modeling skills to national agricultural research systems

Nothwithstanding major projects such as IBSNAT (Harrison et al. 1990) and SARP (Penning de Vries et al. 1991) and continued training efforts, models have seen limited use by NARS except in small workshops, which are usually organized by local agencies with international trainers. Limited access to adequate hardware and software and the turnover of NARS staff trained in modeling are obvious constraints. Ready access to adequate weather and soil data is also a concern.

Perhaps the greatest obstacle, however, is the lack of understanding of the potential applications of models to research concerns in developing countries. Underlying this is an absence of well-documented case studies where modeling has brought major benefits to NARS research concerns. An appropriate strategy for CIMMYT may be to promote workshops that focus on raising awareness of the potential use of models, as opposed to transferring modeling skills to a large number of researchers.

Recommendations

Reviewing the points above, we suggest that CIMMYT should:

1. Participate in the continued development of CERES-Maize, CERES-Wheat, and models such as CROPGRO, which form part of our systems research initiative as robust models for a diverse set of research applications. Priority areas for development include:
    - Externalization of model parameters.
    - Improved handling of phenology, leaf number, and yield components under tropical conditions.
    - Development of more realistic handling of crop residues and runoff.
    - Improved documentation of both models.
2. Support the development of models that provide more detailed representations of processes related to tillage and residue management.
3. Participate in the development of a more mechanistic crop model, possibly based on CROPGRO, that would include effects of canopy architecture and would simulate cultivar differences in canopy surface temperatures.
4. Participate in the development and implementation of intercropping routines in ICASA-compatible models.
5. Promote adherence to ICASA standards for model inputs.
6. Maintain quality maize and wheat datasets for model development and model evaluation.
7. Participate in efforts to make soil and meteorological data widely available.
8. Promote proper documentation of crop models, possibly managing a web site for documentation of models used at CIMMYT.

Given current levels of resourcing, the actual writing of model code at CIMMYT should focus only on key problems where CIMMYT scientists have a clear advantage. However, in most cases, a more appropriate strategy is for CIMMYT to collaborate in model development at other institutions.

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A Physiologist's Wish List for a Robust Wheat Model

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Abstract

The major objective of crop modeling is to explain yield variation by combining physiological processes with environmental data in a quantifiable framework; however, models frequently fall short of this objective. It is suggested that modeling specific physiological processes might be a more achievable goal, in addition to providing building blocks for more comprehensive models. Some reasonably well studied processes that could be modeled include the relationship between stomatal aperture and yield, or the evaluation of alternative grain filling strategies such as stay-green versus remobilization of stem reserves. Lodging, which can have a major impact on wheat yield, would lend itself quite readily to being modeled, since it is a largely mechanical process. Where genetic bases of physiological responses are partially understood, as in the case of Ppd and Vrn on phenological development, a gene-based modeling approach might permit extrapolation whereby phenological patterns that optimize source-sink balance could be determined.

Introduction

The ideal crop breeding model would identify specific trait or gene combinations that optimize yield in a given environment. In reality, our understanding of the interaction between genotype and environment is incomplete at all levels of integration, whether we are talking agronomic traits, physiological process, or genes. Nonetheless, traditional plant breeding has very successfully exploited yield testing to improve adaptation of wheat to most environments. Some geneticists suggest that, in a short time, using new techniques such as functional genomics, a sufficiently comprehensive understanding of the genetic basis of yield will enable cultivars to be designed at the allelic level. Somewhere between the two extremes, physiologists attempt to identify traits (usually representing more than one gene) that, in the right genetic background, will enhance yield. The basic principal of crop modeling is to put these traits into a quantifiable framework. While existing models are not sophisticated enough to accurately simulate differences in genetic yield potential, a step in this direction would be to improve our understanding of genetic differences in the components of crop growth. Working models of specific crop functions that relate to yield could be used as the building blocks for a robust wheat model for crop performance.

Modeling Stomatal Aperture Related Traits

A number of stomatal aperture related traits (SATs), such as stomatal conductance (COND), canopy temperature depression (CTD), and carbon-isotope discrimination, have been shown to be strongly associated with performance in wheat (Fischer et al. 1998; Reynolds et al. 1994). There is considerable interest in the possibility of using SATs as indirect selection criteria in conventional breeding to identify physiologically superior lines in early generations. A modeling procedure may have application in: 1) quantifying potential improvement in breeding efficiency associated with applying selection pressure for SATs in different environments, and 2) predicting the physiological mechanisms that underlie the association of yield potential with expression of SATs.

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In the first case, important factors that would influence the impact of selection for SATs on breeding efficiency include: the typical range of SATs values associated with genetic variability in a given environment, accuracy of instrumentation, measurement errors due to environment (e.g., wind, soil heterogeneity), heritability of SAT, genetic correlation of SAT with yield, and genetic gains associated with visual selection (Table 1). All of these factors can be estimated empirically in different environments. The model could be used, for example, to compare the relative efficiency of selection for different SATs, or to estimate the intensity of SATs measurements required to maximize genetic gains in a given environment (Table 1).

The second example - predicting the physiological mechanisms that underlie the association of yield with SATs - is more challenging, since SATs tend to be complex traits affected by many plant characteristics (Table 2). Capacity for vascular transport may influence evapotranspiration rate and stomatal aperture, and metabolic capacity (e.g., rate of C fixation) has a feedback effect on stomatal conductance. Partitioning to yield (i.e., harvest index) may also influence stomatal conductance during grainfilling, since grain number and filling rate influence the demand for photo-assimilates. Environment can also influence SATs, for example, via the effect of temperature on metabolism (Keeling et al. 1994). Another example would be low soil water potential, which can reduce stomatal conductance via root signals even before water stress is detectable in the leaf (Davies and Zhang 1991). If these processes and their interactions could be accurately simulated and extrapolated, the results might provide a basis for evaluating the extent to which SATs can be used to select for increased yield potential in different environments.

Modeling Alternative Grain Filling Strategies: Stay-Green versus Remobilizing Stem Reserves

If you ask a breeder whether it is more desirable to select for the stay-green trait or remobilization of soluble stem carbohydrates to the grain, the answer is likely to be yes to both. However, Blum (1998) argues that the two traits may be mutually exclusive. Since it is difficult to experimentally quantify the relative effect of these traits, simulation modeling might be a useful approach to establish, in theory, the relative trade-off between the two strategies. The model could be built using empirical observations of assimilation rate during terminal grain filling, calculations of potential photosynthesis based on the range of chlorophyll content observed, and estimates of soluble stem carbohydrates available for translocation taking into consideration respiratory costs (Table 3).

Table 1. Examples of inputs and outputs for a model simulating the association of stomatal aperture related traits (SATs) with yield.

Inputs

Range of SATs associated with genetic variability in a given environment.
Accuracy of measuring instrument.
Measurement errors due to environmental variation.
Heritability of SAT.
Genetic correlation of SAT with yield.
Genetic gains associated with visual selection.

Outputs

Compare the relative efficiency of different SATs.
Estimate how many measurements of SATs are required to maximize genetic gains.

Table 2. Inputs and outputs for a model predicting physiological mechanisms contributing to expression of SATs.

Inputs

Vascular capacity: may not always be sufficient to meet evaporative demand or sink demand.
Partitioning: sink demand effects regulation of photosynthesis and stomatal conductance.
Metabolic processes: e.g., soluble starch synthase is inhibited by heat.
Soil water potential: may reduce stomatal conductance via root signals.
Environmental parameters: temperature, radiation, relative humidity.

Outputs

Optimal stomatal conductance to maximize assimilation rate.
Indication of the physiological mechanisms limiting assimilation rate.

Traits Determining Lodging Tendency in Wheat

Recent research has suggested that lodging is a function of the dissipation of kinetic energy by stems (Farquhar et al. 1997). Observations of the oscillatory motion of wheat stems in response to artificial wind gusts suggest that some wheat lines dissipate kinetic energy through vibration, while others transmit the moment to the base of the plant, inducing root lodging. Traits involved in this process include the center of gravity of the plant, the elasticity of the stem that is modified by its anatomical structure, as well as its biochemical composition (e.g., cellulose and silica contents). If a simulation model was designed that used the measurable physical and anatomical information, and accurately predicted transmission of force to the base of the plant over a range of variables (including wind intensity as well as plant traits), it may be extrapolated to provide information on plant traits that might reduce lodging tendency at current yield levels as well as for the higher-yielding wheat lines (Table 4).

Modeling Phenology to Optimize Source-Sink Balance

The phenological development of a crop plays an important role in determining fertility and grain number. In theory, it should be possible to manipulate the relative duration of phenological stages, such that yield is optimized in a given environment. For example, in high yielding environments, it has been suggested that an increased duration of the rapid spike-growth phase may increase partitioning of assimilates to the spike, improving fertility and optimizing source-sink balance (Slafer et al. 1996).

The genes involved in determining response to photoperiod (*Ppd*) and vernalization (*Vrn*) have a major effect on determining phenological response to the environment, and hence a gene-based modeling approach may be feasible as our knowledge of gene action increases. In addition, since developmental rate is strongly affected by temperature, phenological models can be further improved by using actual plant temperatures. Assuming that temperature is sensed by leaves, it is possible to estimate leaf temperature from air temperature if vapor pressure deficit and water availability are known (Table 5).

Table 3. Inputs and outputs for a model simulating stay-green vs. stem reserve mobilization.

Inputs
Net assimilation rate during terminal grain filling.
Leaf chlorophyll content in late grain filling.
Soluble stem carbohydrates available.
Translocation efficiency.
Sucrose to starch conversion efficiency.

Output
Best strategy genetically for maximizing grain filling.

Table 4. Possible inputs and outputs for a model simulating lodging tendency.

Inputs
Center of gravity of wheat stem.
Stem elasticity.
Anatomical structures of the wheat canopy: spikes, awns, stems, leaves, roots.
Biochemical composition of stem, e.g., cellulose and silica contents.

Outputs
Predict transmission of force to the base of plant over a range of plant traits.
Evaluate plant traits to reduce lodging tendency at current yield levels.
Extrapolate for the higher yielding wheat lines, new plant types.

Table 5. Modeling the impact of phenological patterns on source-sink balance.

Inputs
Environmental: photoperiod, radiation, temperature, soil water, RH, calculated plant temperatures.
Specific genes and alleles: *Ppd*, *Vrn*, *Eps*.
Physiological: cardinal phenological stages, potential number of grains, grain weight potential.

Outputs
Information on how genes and environment interact to determine duration of phenological stages.
Information on strategic deployment of genes to optimize source-sink balance.

Integrating Small Models

The examples given above represent reasonably well studied areas of physiology. By definition we can only model processes which we at least partially understand. Nonetheless, connections between these areas become apparent. One of the outputs for the stomatal aperture model is leaf temperature, which is an input for the model on phenological development. The output for the model on alternative grain filling strategies could be used as input for the model on stomatal aperture, etc. Eventually, models of discrete physiological processes may be integrated to build a more robust model for yield.

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Issues Arising from the Use of CERES for Tropical Maize

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Abstract

The authors describe drawbacks of the CERES model that limit its usefulness in representing the performance of tropical maize. These include the difficulty of measuring thermal time from emergence to the end of the juvenile phase in the field and the model's inability to predict the performance of tropical highland maize or to accurately account for the effects of different seeding densities, key stresses, or variations in daylength. They mention information collected by CIMMYT scientists that bears on the model's genetic coefficients for maize, and list potentially useful datasets available from the CIMMYT Maize Program. Finally, they caution potential users about taking model outputs (sophisticated graphs, extremely precise figures) too seriously or considering numerical outputs as actual "data."

Our Interest in the CERES-Maize Model

The CERES-Maize model can be a valuable tool for examining potential yields and the probability and extent of yield loss due to drought, low soil fertility, and high temperatures in given environments. The International Maize and Wheat Improvement Center (CIMMYT) can assist in the development of a version of CERES-Maize for tropical environments characterized by genotypes and production systems that range in elevation from sea level to over 3,000 masl and from latitudes of 0 to 30º N or S. Such a model would allow us to examine an array of management options that aim to increase productivity while preserving the natural resource base of soil and water in complex maize-based cropping systems. In tropical regions, open pollinated varieties (OPVs) are still used extensively, but are gradually being replaced by hybrids that exhibit higher yield potentials under most conditions. Both types of germplasm carry specific resistances to tropical diseases and are generally highly photoperiod sensitive. To further these goals, the modeling efforts of CIMMYT's Maize Program have focussed on:

1. Quantifying genetic coefficients for tropical cultivars (OPVs and hybrids).
2. Developing and publishing data sets of representative tropical cultivars.
3. Determining whether the model satisfactorily explains genetic differences in stress tolerance (in particular, drought, low nitrogen, plant density, and acid soil tolerance), especially during flowering, when barrenness occurs and ears per plant fall below a value of 1 (i.e., when a significant proportion of plants within the crop have no ears at all).
4. Determining how well the nitrogen submodels predict N uptake, distribution and redistribution among plant parts under N and water stress.
5. Developing a more effective selection strategy in breeding for environments where abiotic stresses are common, using data from 3) and 4).
6. Improving the definition of major production environments (mega-environments) for maize in the tropics through the development of better tropical maize models. Such a definition is needed to prioritize research in CIMMYT's Maize Program.

 Published in White, J.W., and P.R. Grace (eds.). 2001. *Directions in Modeling Wheat and Maize for Developing Countries: Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 4-6 May 1998.* NRG-GIS Series 01-02. Mexico, D.F.: CIMMYT.

Problems with CERES-Maize version 3.1

In using CERES-Maize v3.1, we encountered various areas where the performance of the model was unrealistic. Examples include:

- Leaf number predictions were often around 28-35 on late maturing cultivars and 20-25 on early maturing cultivars, rather than the observed values of 22-25 and 15-19, respectively. The use of a phyllochron value (PHINT) of around 45-50°Cd places a cap on leaf number in the planned release of CERES-Maize v3.5, which will enable us to more realistically predict flowering dates. We see some genetic variation in PHINT in the field, but it is usually not larger than 10-15% of the mean.

- Genetic coefficient P1 (thermal time from emergence to the end of the juvenile phase, i.e., the start of the photoperiod sensitive phase) has a strong effect on final leaf numbers but is very difficult to measure in the field. We have measured P1 experimentally using plants grown under artificially lengthened days. Our measured values must be corrected for thermal time to germination (around 110°Cd) and for time from the end of the juvenile phase to TI (TI taken to be the point when the tassel reaches 0.5 mm in length; about 5 days or 85°Cd). This suggests that our observed values should be reduced by around 195°Cd. Similarly, photoperiod sensitivity measured in the field averages around 2.7 d/h from sowing to TI in lowland tropical genotypes but can vary up to 6 to 7 d/h in highly sensitive varieties. Note that our values are computed by regressing changes in time to TI on photoperiod between the daylengths of 13 to 15 h, rather than from 12.5 h, as assumed in CERES-Maize. If the critical photoperiod was indeed 13 h, and we wish to predict the effects of photoperiod in a site like Tlaltizapan under 13.3 h summer photoperiods, our values have to be reduced by multiplying them by a factor of 0.3/0.8 or 0.38. Furthermore the determination of P1 is difficult. In environments where photoperiod does not vary greatly, an alternative would be to use final leaf number and/or days to anthesis, which are more easily determined.

- Indications from growth chamber data on photoperiod sensitive genotypes are that P_c (the critical photoperiod above which flowering is delayed by lengthening days) is a function of temperature such that P_c is greater in cool conditions than in warm conditions. This helps to explain the apparent reduction of about 35% in photoperiod sensitivity in sensitive germplasm in winter when nights are cooler, as observed in the field in Tlaltizapan, Mexico (Table 1). Note, however, that a similar growth-chamber-based analysis confirmed that the value of P_c for a Corn Belt hybrid B73 x Mo 17 was virtually unaffected by temperature and remained around 12.5 h, as assumed by CERES-Maize.

Table 1. Comparison of sensitivity to daylengths >13 h, as measured for 40 diverse maize cultivars over summer and winter at Tlaltizapan, Mexico. Data are thermal times from time of sowing to tassel initiation (TI), anthesis (AD), and final leaf number (FLN). T_{max} in summer and winter are 31° and 30°C, respectively; corresponding figures for T_{min} are 19° and 12°C, respectively.

	TT to TI (°Cd)	d(TT to TI) (°Cd/h)	TT to AD (°Cd)	d(TT to AD) (°Cd/h)	FLN (lf)	d(FLN) (lf/h)
All genotypes (N=40)						
Summer	360	57	993	103	18.7	1.82
Winter	430	40	1,049	70	20.1	1.05
Lowland tropical (N=15)						
Summer	359	72	978	133	19.2	2.37
Winter	452	55	1,072	83	20.9	1.41
Temperate (N=7)						
Summer	365	16	1,000	36	18.0	0.69
Winter	434	18	1,054	37	19.8	0.33

Source: Edmeades et al. (1994).

- There may be problems with how heat units are calculated for highland-derived genotypes. Growth room comparisons suggest that the T_{opt} for development rate from sowing to tassel initiation is around 20 to 21°C for true highland genotypes, compared to around 30°C for lowland tropical, temperate, and subtropical genotypes (Ellis et al. 1992). During flowering, T_{opt} of highland genotypes seems to be around 26°C. Therefore, classical systems of thermal time calculation, assuming a T_{opt} of 30°C, will not work well for highland-adapted germplasm, nor will predictions of phenology in diverse environments.

- Stress at the time of flowering extends the anthesis-silking interval (ASI), and a close relationship (r=-0.60) is observed between ASI and grain yield (Bolaños and Edmeades 1993, 1996). This response is caused by delayed silk emergence under drought, high plant density, and low soil fertility (Lafitte and Edmeades 1995), and thus is a widespread problem where phenology and production of maize are being predicted for environments where stress at flowering is common (as in many tropical environments). We believe that variation in ASI reflects the rate of growth of the ear (Edmeades et al. 1993). When we select for reduced ASI under stress, plants with more rapid ear growth rates and fewer spikelets are obtained; therefore, ASI reflects partitioning to the ear. If relationships can be determined between kernels per plant (or per m^2) and an integral of crop growth rate during the flowering period (estimated as 120°Cd before anthesis to 250°Cd after anthesis), the slope of the regression of kernel number on crop growth during that period may indicate differences in tolerance to stress during flowering.

- At low plant densities, parameters for kernel number may also be used to describe a genetic tendency to prolificacy (more than one fertile ear per main stem). At present, CERES-Maize does not accurately predict barrenness, nor does it then grow out barren plants as a separate population to the fertile plants within the crop community. As a consequence, the number of ears per plant is poorly predicted, and density experiments conducted using the model provide unrealistic results. Furthermore, plant population is one of the most important factors in yield determination in maize (Bolaños 1992; Duvick 1997). For the CERES model to have applicability in maize cropping system research, it has to offer improved simulation of maize response to both high and low populations.

- If CERES is used to reproduce Denmead and Shaw's (1962) classic experiments on the sensitivity of maize to water stress at different development stages, grain yield only begins to decline 8 to 9 days after pollination, affecting grain size but not grain number. CERES-Maize currently shows no effect of water stress on tassel or ear/ovule development (which control ASI, barrenness, etc.). Ear development, which sets the number of ovules to be pollinated, should be sensitive to water stress from around a third to halfway through development; i.e., from initiation to silking. Grain number should decrease in response to water stress.

- Since the model was developed using silking date rather than anthesis date as a key stage in phenology, anything that increases ASI will result in an error in predicting physiological maturity of the crop. It is important that anthesis date be used as the definitive milestone of development for these sorts of environments.

- The RUE value of 4.5 (or 5) used by CERES-Maize appears to be too high for tropical maize. Respiration is high, and peak intense radiation is conducive to photo-oxidation.

Information That We Have Collected: Genotype Coefficients

- Information on P1 and P2 has been collected from experiments comprising approximately 100 common tropical lowland, subtropical, and highland varieties, with some common Corn Belt checks, under 4 daylengths that varied in 1.5-h steps from the ambient (11.5-13.3 h) to 17.5 h. Unfortunately, we could not estimate thermal time from silking to physiological maturity in these same genotypes, since long days greatly disturb kernel set. Thus, much less data are available on estimates of P5. From the breeder's viewpoint, collecting data on time from sowing to 50% anthesis or silking, final leaf number, and time to brown husk or 50% leaf senescence would be a lot easier than obtaining P1, P2, and P5. So why not express sensitivity in terms of rate of change in time to anthesis or in final leaf number, per hour increase in photoperiod?

- A small amount of data on G2 (maximum kernel number per ear) is available, although kernel number per ear under normal competitive conditions is often measured in many of our trials and typically is around 400 kernels under densities of 5 plants/m^2. G3 has been measured, but we usually cannot assume that it is a maximum rate. Typically it averages around 8 mg kernel/d at 5 plants/m^2 for many of our cultivars and seems little affected by artificially reducing kernels per plant. While G2 and G3 are treated as maximum values, our incentive to measure them or even attempt to estimate them accurately remains small.

- Experimental data on PHINT (rate of appearance of visible leaves versus thermal time) has been reported in a large number of trials (see above).

Datasets Available from the CIMMYT Maize Program

Various datasets suitable for evaluating maize models have been produced at CIMMYT and eventually should be available in DSSAT format. Grouped by the scientist who conducted the trials, they are as follows:

A. Scott Chapman

- Twelve genotypes (four lowland tropical, three subtropical, two temperate, and three highland), representing several maturities and including eight OPVs and four hybrids, were evaluated in four environments. Biomass and leaf area were measured sequentially, together with hourly readings of temperature and daily totals of total radiation, but no soil parameters were recorded. Photoperiod responses were measured under four daylengths, but data from this trial were not processed.
- A subset of four genotypes was measured for growth and green leaf area under drought, high plant density, and low N. Water extraction under drought was also measured.
- Data was almost completely processed from raw form in Excel spreadsheet format rather than DSSAT files.

B. Anne Elings

- Five genotypes (all lowland tropical genotypes varying in maturity, two common to the Chapman set) were evaluated specifically under stress (three drought levels and three N levels) in highland, subtropical, and lowland environments. Measures similar to the Chapman set were taken, with full phenology, limited soil data (0-30 cm, 30-60 cm, 60-90 cm), and extensive data on N content of plant parts available at most sites.
- Maximum kernel growth rate experiments were conducted on two entries, one OPV and one hybrid.
- Data on the five genotypes under three N levels, and from an unstressed site at another location, was in DSSAT format, although the model will not run properly with the files as they are at present.

C. Greg Edmeades: Photoperiod responses

- Approximately 100 genotypic responses (time, thermal time to TI, AD, and delta leaf number) were cataloged using lights at ambient, ambient + 1.5 h, ambient + 3 h, and ambient + 4.5 h as the four photoperiods, and using soil temperature (5 cm) from sowing to TI, and air temperature measured in plot for the rest (Tbase 7 °C, Tmax 30 °C, broken stick response for thermal time, computed hourly).
- Two hundred inbred lines were measured under two photoperiods (ambient and 17.5 h) for a crude assessment of responsiveness.
- Recombinant inbred lines of a cross CML9 (sensitive) x A632 Ht (almost insensitive) were used to map photoperiod sensitivity with molecular markers. Data are currently being analyzed by a PhD student (Ms. Rkia Moutiq) at Iowa State University, USA.

D. Jorge Bolaños: Genetic parameters for a set of lowland and highland cultivars

- A set of 16 lowland and 14 highland maize cultivars (including OPVs and hybrids) was evaluated in at least 6 environments, each ranging in altitude and average temperature (lowland locations from 60 to 1,000 masl; highland locations from 1,000 to 2,300 masl) to determine phenological genetic parameters. Both datasets include: weekly determination (4 to 5 times) of the number of initiated leaves; final number of leaves; days to 50% anthesis, 50% silking, and 50% physiological maturity; rate of kernel growth; development of kernel milk line; final yield and components; senescence patterns with leaf chlorophyll meter; and daily recordings of maximum and minimum temperatures. Datasets are being analyzed and will be available in 2001.

Possible Problems with the Datasets

- Regarding the meteorological data, there is some indication that radiation sensors have drifted with time and are giving questionable values. This should be discussed before CIMMYT data are altered, given the unusually hazy conditions that prevail in winter at Tlaltizapan.
- Soil profile data are usually lacking from our studies, with the exception of Anne Elings' data and a subset of Scott Chapman's data.
- Systematic errors in the way photoperiod responses were measured may have slightly increased estimates of sensitivity.
- Most of our data relate to OPVs, but increasingly these data are being used to predict hybrid responses. Hybrids will generally out-yield OPVs by 15-25%, and show increased kernel numbers, longer filling periods, and delayed leaf senescence.
- An unspecified amount of irrigation water has been applied to most of our trials by furrow irrigation, usually to maintain the trials in a nonstressed state. In most cases, it is better to assume full irrigation, unless otherwise specified.

General Questions Regarding Models

A model is a conceptual representation that can be precisely formulated for a given event or series of related events. The law of gravity, for example, is a simple model: objects are attracted to Earth at 9 m/s^2. Every model is as good as the formulations it contains. Over the last decade, there has been an explosion of crop simulation models in terms of scope and sophistication. There is a danger in that many users do not have the required systems perspective and take the numerology and graphicology generated by the models at face value. This creates a large potential for misuse of crop simulation models. As a result, there is a need to reflect on how models can best serve potential end users, in this case, maize agronomists, since many question the utility of modeling.

Using data from more than 2,700 experiments from CIMMYT's international trials (breeding nurseries and agronomic plots) where maize yield was measured, Crossa et al. (1993) determined an average standard error of the difference (s_d) of 500 kg/m^2. This implies that for a given treatment A to be statistically different to a given treatment B, the two mean yields must differ by at least 1 t/ha (LSD = t s_d). The value 500 kg/m^2 is the best objective measure of the hidden uncertainty in the field determination of maize yield. If this is the best we can measure in reality (using our best instruments of detection), should we be concerned about the extreme detail that is presented in computer outputs? Is the apparent precision of model output misleading?

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Canopy Development, Radiation Interception, and a Simple Model of Maize Productivity

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Abstract

A conceptual model for maize crop productivity that uses canopy radiation interception and its conversion to biomass is described. Crop duration, seasonal radiation, the fraction of radiation intercepted by foliage, the efficiency of conversion into biomass, and the portion partitioned to the harvestable part of the crop are all needed for estimating maize grain yield. Model assumptions are illustrated using schematic examples derived from tropical maize (Zea mays L.) under varying environmental conditions. The model also provides an adequate and easy conceptual framework for ex-ante examination of agronomic and breeding strategies for increasing crop productivity.

Introduction

This paper presents a simple model of the productivity of annual crops, where crop yield is the result of net carbon dioxide assimilation and the partitioning of assimilates to the harvestable part of the crop, integrated over the duration (emergence to harvest) of the crop cycle. Stated mathematically:

$$Y = HI \int A \, dt$$

where Y is harvestable yield, HI is the harvest index or the proportion of Y in the total biomass, A is the net assimilation rate per unit land area, and t is time (Monteith 1990; Loomis and Connor 1992).

Overall assimilation is the product of source size integrated over the time span in question, multiplied by source intensity. In unstressed crops, the major determinant of biomass production is the amount of radiation intercepted over the crop cycle (Loomis and Connor 1992). Biomass accumulation is the product of incident solar radiation, the fraction intercepted by green leaf area, the efficiency with which the radiation is used, and partitioning to the harvestable part of the crop. Therefore, grain yield (Y) can be expressed as:

$$Y = t \times Rs \times \%RI \times E \times HI$$

where t is crop duration in days, Rs is average daily solar radiation ($MJ/m^2/d$), %RI is the percentage of the total seasonal radiation intercepted by the canopy, E is the average radiation use efficiency (g/MJ), and HI is harvest index.

Given no change in crop duration, there are two options to increase biomass: 1) increase radiation interception through faster early-leaf-area development and/or slower senescence, or 2) increase average radiation use efficiency for all or part of the season.

This simple model can predict grain yield with relative accuracy (± 1-2 t/ha) if provided with sound estimates of %RI, E, and HI, taking into account the underlying assumptions of model parameters. It also provides an adequate conceptual framework for the *ex-ante* examination of the potential impact of different breeding or agronomic strategies on crop productivity.

The Radiation Environment

In the tropics (0 to 30° latitude), incident daily solar radiation (R_s) can vary from about 10 to 25 $MJ/m^2/d$, due mostly to changes in latitude, day of year, and degree of cloudiness (Gates 1980). Photosynthetically active radiation (PAR) is normally around 400 to 700 nm or 48 to 52% of total R_s (Loomis and Connor 1992).

 Published in White, J.W., and P.R. Grace (eds.). 2001. *Directions in Modeling Wheat and Maize for Developing Countries: Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 4-6 May 1998.* NRG-GIS Series 01-02. Mexico, D.F.: CIMMYT.

The solar constant (incident radiation just outside the earth's atmosphere) is around 30 MJ/m²/d, but atmospheric attenuation typically decreases R_s to around 20 to 25 MJ/m²/d on clear, sunny days and to around 5 to10 MJ/m²/d on cloudy, rainy days, under typical tropical conditions. Solar radiation is normally measured with pyranometers, although it can be predicted from latitude, day of year, and ratio of bright to cloudy hours (Gates 1980). For example, using a daily average of 20 MJ/m²/d and a total crop duration of 120 d, total available radiation would be 2,400 MJ/m² for the season.

Canopy Development and Radiation Interception

For a given crop, the pattern of canopy development depends on planting density; spatial arrangement; leaf architecture; rate of leaf initiation, expansion, and senescence; and many other genetic and environmental factors. Maize is normally planted at densities ranging from 4 to 7 plants/m² (Fischer and Palmer 1984). In annual crops, canopy radiation interception starts at the time of emergence and increases as foliage expands. During the early stages of crop growth, much of the incident radiation is not intercepted by the canopy, thus biomass production is limited by source size (Hsiao 1982). Given the architecture of most maize cultivars, complete radiation interception occurs with leaf area indices (LAI; m² of foliage per m² of land area) ranging from 3 to 4 for cultivars with large, lax leaves to 5 to 6 for cultivars with small, narrow, erect leaves (Fischer and Palmer 1984; Loomis and Connor 1992). Percent radiation interception decreases during crop maturation and grain filling due to leaf senescence and loss of green leaf area.

Along with crop water use, the cumulative amount of radiation intercepted throughout the season is the most important factor determining total biomass and grain production, more than the intensity at any given moment (Monteith 1990; Loomis and Connor 1992). Total crop duration also helps govern the seasonal amount of radiation intercepted by most crops. If even mild levels of stress occur early in the season, the effects normally compound over time and drastically reduce the seasonal amount of intercepted radiation (Hsiao 1982).

These principles are illustrated using three schematic cases (A, B, C) of maize canopy development, reflecting different management and/or environmental conditions (Fig. 1). Percentages shown refer to the proportion of total incident radiation intercepted by each canopy from emergence to harvest; i.e., the area under each curve (%RI).

Maize crop A exemplifies a crop that received very good agronomic management (high fertility, weed control, etc.), so the canopy rapidly covers the ground, reaching almost full (>95%) cover around flowering. Even under such ideal environmental conditions, the canopy intercepts only 54% of all available radiation (Fig. 1). The dotted line in the figure represents a cultivar with stay-green, which captures only a further 4% radiation (58% of the total).

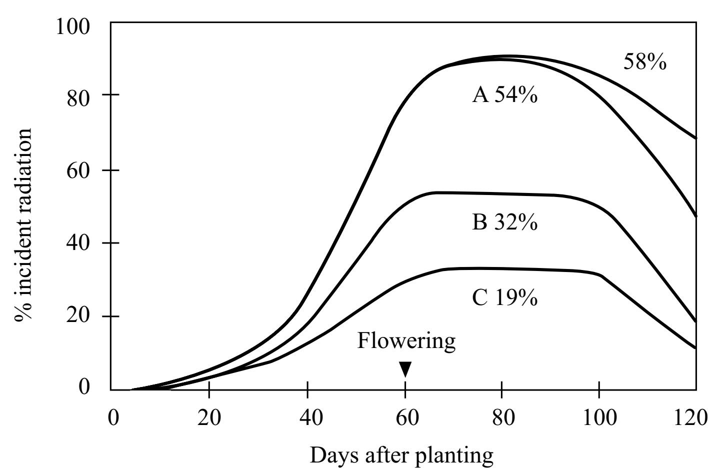

Figure 1. Canopy interception (%) of incident radiation as a function of days for three schematic cases (A, B, C) of maize canopy development reflecting different management and/or environmental conditions. (Refer to text for explanation of each case.) Numbers shown refer to the proportion of total radiation intercepted by each curve (i.e., the area under each curve).

Maize crop B is typical of bad agronomic management and/or environmental stresses occurring during crop establishment (e.g., poor weed control, low fertility, pests), so the canopy never fully covers the ground. Crop B intercepts only 32% of the total radiation available; 22% less than crop A (Fig. 1). In addition, incident radiation intercepted by weeds (rather than the maize canopy) results in an equivalent usage of soil water and nitrogen by the weeds, meaning less are available to the maize. If intercepted by dry bare soil, incident radiation will increase crop evapotranspiration (ET) by inter-row advection.

Maize crop C exemplifies a severely stunted canopy due to bad agronomic management and/or environmental stresses (drought, low fertility, weed competition, etc.) beginning during early crop establishment. The negative effects accumulate over time, so crop C intercepts only 19% of the radiation available; 35% less than crop A.

The three cases show that, even with good agronomic management and no environmental stresses, monocropped maize canopies will intercept a maximum of only 55-60% of seasonally available radiation. This is because canopy cover early in the season is incomplete and canopies senesce during grain filling and crop maturation. In addition, only relatively small changes (5-10%) can be achieved with improved agronomy and/or breeding. Environmental stresses and/or bad agronomic management can reduce cumulative %RI significantly (crop B intercepted only 32% of all available radiation and crop C a mere 19%). Due to the exponential nature of canopy growth during early development, the effects of even very mild stresses early in the season can accumulate over time, leading to substantial reductions in total %RI (Hsiao 1982).

Estimates of %RI for curves A, B, and C (Fig. 1) agree reasonably well with reports: 55-60% under well-watered and fertilized conditions, and 30-40% under drought or low N conditions (Muchow and Davis 1988; Muchow 1989a,b). In a study of 100 tropical and temperate S_1 maize lines, the average RI% was 39% and varied between 30% and 46% among entries (Chapman and Edmeades 1996).

Radiation Use Efficiency and Productivity

By intercepting radiation, canopies produce biomass and use water through photosynthesis, hence the close relationship between radiation interception, biomass production, and water use found in many crops under many different environmental and management conditions (Monteith 1990). Theoretically, the potential productivity of a crop surface is 1.7 g/MJ (3.4 g/MJ PAR), though the highest reported rates are only 50-60% of this potential (Loomis and Connor 1992). In general, radiation use efficiency ("E", or g biomass produced per MJ intercepted) averages 0.5-1.0 g/MJ for C_3 crop species and 1.0-1.5 g/MJ for C_4 species, depending on the photosynthetic capacity of the canopy and the biochemical composition of the biomass produced (Loomis and Connor 1992). In general, E will decrease with reductions in leaf N and will normally be higher during the vegetative phase than during grain filling. Therefore, E for well managed, high-N maize will be around 1.2 g/MJ, but for stressed, N-deficient maize (typical of low input, marginal agriculture), this value can fall below 0.5 g/MJ.

For temperate maize, E values of 1.2-1.5 g/MJ are common for well-managed crops with high N levels (Muchow et al. 1990; Loomis and Connor 1992). However, temperate environments are characterized by more radiation per unit thermal time than tropical environments, which are typified by warm temperatures, rapid phenological development, short crop duration, and higher respiration rates (Fischer and Palmer 1984).

Tropical maize hybrids have E values of around 1.0-1.2 g/MJ under well-watered and well-fertilized conditions and about 0.4-0.6 g/MJ under drought or low N conditions (Muchow and Davis 1988; Muchow 1989a,b). The same authors reported a common linear relationship between E and specific leaf N for maize and sorghum under varying levels of N, after correcting for differences in specific leaf area between the crops (Muchow and Davis 1988).

Bolaños and Edmeades (1993) reported E values of 0.8 and 0.4 g/MJ for the tropical maize population Tuxpeño Sequía under well-watered and droughted conditions, respectively. However, trials were conducted on a site with known iron deficiencies and during the off, winter season. In an unpublished study comprising 10 CIMMYT tropical maize populations, synthetics, and varieties under well-managed conditions, E averaged 1.0 g/MJ with low variability among entries (H.R. Lafitte, personal communication, 1995). In another study with 100 tropical and temperate S_1 lines, E averaged 1.1 g/MJ and ranged from 0.8 to 1.5 g/MJ (Chapman and Edmeades 1996).

Grain Production and Harvest Index

Grain production depends on the partitioning of assimilates to the harvestable portion. Under unstressed conditions, HI values from 50 to 55%, 40 to 45%, and 30 to 35% are reasonable for temperate hybrids, improved tropical, and unimproved maize cultivars, respectively (Fischer and Palmer 1984). Stresses during flowering and/or grain-filling can reduce HI.

Maize is unique among cereals in that male and female inflorescences are on separate parts of the plant and begin and end development at different times, with a relatively limited overlap. Consequently, in the two-week period either side of flowering, maize is especially sensitive to stresses such as drought, increased plant density, reduced leaf area caused by N stress, and long periods of shady weather. Under such conditions, HI can fall below 10% (Fischer and Palmer 1984). During grain filling, yield reductions and reduced grain weight occur largely because of reduced photosynthetic rates and accelerated foliar senescence caused by drought or low N.

Simple model of maize productivity

In summary, grain yield (Y) can be estimated as:

$Y = t \times Rs \times \%RI \times E \times HI$

where:

- t = crop duration in days, which varies with genotype, photoperiod, and temperature. Typical values are 80 d for extra-early, 100 d for intermediate, and 120 d for late-maturing tropical germplasm under lowland conditions.
- Rs = average daily solar radiation ($MJ/m^2/d$), which can vary from 10 to 20 $MJ/m^2/d$ due mainly to changes in cloudiness and day of year for any given latitude.
- %RI = the percentage of seasonal radiation intercepted by the canopy (area under the curve of percent radiation interception from emergence to harvest), ranging from 60% (upper limit, no stress) to 20% (lower limit, stress).
- E = the average seasonal radiation use efficiency (g/MJ), which can range from 1.2 g/MJ (high N status, healthy foliage) to 0.5 g/MJ (low N, stressed).
- HI = Harvest index, ranging from 50-55% for temperate hybrids, 40-45% for improved tropical cultivars, 30-35% for unimproved landraces, to 0-5% due to stress and barrenness.

Using moderate values for these parameters based on the information above, grain yield can be estimated for cases A, B, and C (Fig. 1). Crop A intercepted 54% of available radiation (120 d x 20 $MJ/m^2/d$ x 0.54 = 1,296 MJ/m^2). With an E value of 1.0 g/MJ (high N), the model predicts a total biomass of approximately 13.0 t/ha or a grain yield of 5.8 t/ha, assuming an HI of 0.45. This agrees with the yield potential of many tropical cultivars achieved under good agronomic management. For a cultivar with improved stay-green (i.e., 4% more interception), an extra 1.0 t/ha of biomass or 0.4 t/ha of grain would be produced.

Crop B intercepted 32% of all incoming radiation (2,400 x 0.32 = 768 MJ/m^2). With an E value of 0.8 g/MJ (slightly lower than crop A because of some stress), the model predicts 6.1 t/ha of biomass and 2.5 t/ha of grain, assuming an HI of 0.40 (slightly lower than crop A due to stress).

Crop C intercepted only 19% of total radiation (2,400 x 0.19 = 456 MJ/m^2). With an E value of 0.6 g/MJ (even lower than crop B), the model predicts a total biomass of 2.7 t/ha and grain yield of 1.0 t/ha, assuming an HI of 0.35 (slightly lower than crop B).

A crop surface with 100% radiation interception, an Rs of 20 $MJ/m^2/d$, and an E of 1.0 g/MJ would produce 200 kg biomass/ha/d. Simple estimates such as those above are surprisingly effective in predicting actual grain yield for many maize production systems.

Evapotranspiration: The Water Cost of Productivity

Canopies use water when they intercept radiation. It takes the equivalent energy of 2.4 MJ/m^2 of radiation to evaporate 1 mm of water from the surface (heat of vaporization of 1 g of water at 20°C is 683 calories) (Gates 1980). As long as the surface is wet or acts as a wet surface (e.g., green foliage, vegetation, grasslands), over 90% of incident Rs will be dissipated as evapotranspiration (ET) and very little through sensible heat. The opposite occurs if the surface is dry, whereby incident radiation will dissipate as sensible heat through increases in temperature (e.g., compare the temperature of dry and wet beach sand at midday).

Therefore, the proportion of the surface acting as a wet surface can be used to estimate the fraction of incoming Rs that will be dissipated as ET. This is the underlying basis for crop coefficients (Kc) used to calculate crop ET from potential ET (Dorenboos and Pruitt 1984). The proportion of the surface not acting as a wet surface will not dissipate radiation as ET but as sensible heat. In the cases of advection, when the evapotranspiring surface is surrounded by extensive dry areas, ET can exceed Rs by 20-40% (Gates 1980).

Using these guidelines, together with reasonable assumptions, one can quite easily estimate crop water requirements for different environments. In the tropics, potential ET normally ranges from 3-4 mm/d under cloudy conditions and 5-6 mm/d under summer, tropical conditions, to 7-8 mm/d under hot, arid conditions (Gates 1980). Average ET ranges from 100 to 160 mm per month, in most tropical environments.

The Nutrient Cost of Productivity

Maize needs to absorb nutrients from the soil to support productivity, as described above. Typically, N is the most limiting element in agroecosystems (Loomis and Connor 1992). Young, recently-expanded maize foliage has around 3% N concentration on a dry matter basis. With a specific leaf weight of 6 mg/cm, each m^2 of foliage requires 18 g of N. Therefore, the foliage needed for complete radiation interception (LAIs of 4-5) per hectare has a cost of 70-90 kg N/ha.

Nitrogen concentration decreases with crop age. Maize seedlings can have 5% N, whereas at around flowering, a healthy, well-fertilized maize canopy can have approximately 2.0-2.5% N (Loomis and Connor 1992). Maize grain has around 1.5% N (10-11% protein). Faced with N limitations, the maize plant responds by making less total grain, rather than by varying the N concentration (Lemcoff and Loomis 1986). In other words, N content in maize grain has only a small range of variation, roughly from 1.2 to 1.6 % N (protein = N x 6.25).

Maize stover can have around 0.8-1.2% N, depending on crop history and conditions. Therefore, a grain yield of 6.0 t/ha (1.5% N for 90 kg N/ha) and 7.0 t/ha of stover (HI=46%; 1.0% N for 70 kg N/ha) requires 160 kg N/ha. If this amount of N is not available, then the productivity mentioned above will not be sustained.

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Module Structure in CROPGRO v4.0

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Abstract

As crop simulation models become more complex, a modular modeling approach facilitates collaboration among researchers and improves capability of models. A modular approach has been adopted for the CROPGRO v4.0 model. Modules, which are separated along disciplinary lines, can be independently developed, tested, and "plugged into" the model with minimal or no modification of other modules.

Introduction

As new components are added to crop growth models to expand their capabilities, the models become increasingly complex. This generates the need for a modular structure for the crop models so that new components can be added, modified, and maintained with minimal effort. A modular approach facilitates the ability to integrate knowledge from different disciplines, thereby improving the prediction capability of the models.

A modular approach, based on methods used in the Fortran Simulation Environment (FSE) software, has been implemented for the CROPGRO model (Kraalingen 1995). The model structure includes modules or groups of linked subroutines that represent separate disciplinary functions within the model. This modularization allows greater flexibility in future updates to the model; modules can be added, modified, or replaced with little impact to the main program or other modules.

The CROPGRO model has recently undergone restructuring to the modular format described herein. Modules have been developed for phenology, soil water balance, pest damage, plant growth and partitioning, photosynthesis, and soil nitrogen functions. A general description of this modular approach is available at the website for the International Consortium for Agricultural Systems Applications (ICASA; http://www.icasanet.org/modular).

Module Definition and Structure

Acock and Reynolds (1989) proposed criteria for a generic modular structure for crop models. Three of their criteria are:

1. Modules should separate easily along disciplinary lines.
2. Modules should have a minimum number of input and output variables.
3. Modifying one module should not necessitate changing another.

The following guidelines, based on the approach of Kraalingen (1995) and adapted by Kenig and Jones (1997), are proposed for the construction of modules. Each module should:

1. Read its own parameters
2. Initialize its own variables
3. Accept variables passed to it from other modules and the environment
4. Pass variables that are computed within the module
5. Own its set of state variables
6. Compute rates of change for its state variables
7. Integrate its state variables
8. Write its own variables as output
9. Operate when linked to a dummy test program

Thus, all data input, initialization of variables, rate calculations, integration calculations, and output of data related to a specific function are handled within a single module. Modules should run as stand-alone models when linked to an appropriate driver program.

 Published in White, J.W., and P.R. Grace (eds.). 2001. *Directions in Modeling Wheat and Maize for Developing Countries: Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 4-6 May 1998.* NRG-GIS Series 01-02. Mexico, D.F.: CIMMYT.

Figure 1 illustrates the modular format used in the CROPGRO model, in which each module has the following six components:

1. Run initialization
2. Seasonal initialization
3. Rate calculations
4. Integration
5. Output
6. Final

The main program (CROPGRO.FOR) contains six calls to each module to accomplish each component of processing. Control of processing within the program is regulated with the DYNAMIC variable. Each module is called once at the beginning of simulation with DYNAMIC set equal to RUNINIT, resulting in execution of the run initialization portion of the module. The seasonal initialization (DYNAMIC=SEASINIT) is used for initialization of variables at the beginning of each season of a multi-season simulation. During the daily time loop, each module is called three times: once each for rate calculation (DYNAMIC=RATE), integration calculations (DYNAMIC=INTEGR), and daily output (DYNAMIC=OUTPUT). A final call to each module is made to close input and output files (DYNAMIC=FINAL) after all seasonal simulations are complete. Submodules may be called, as needed, from modules to perform similar processing components.

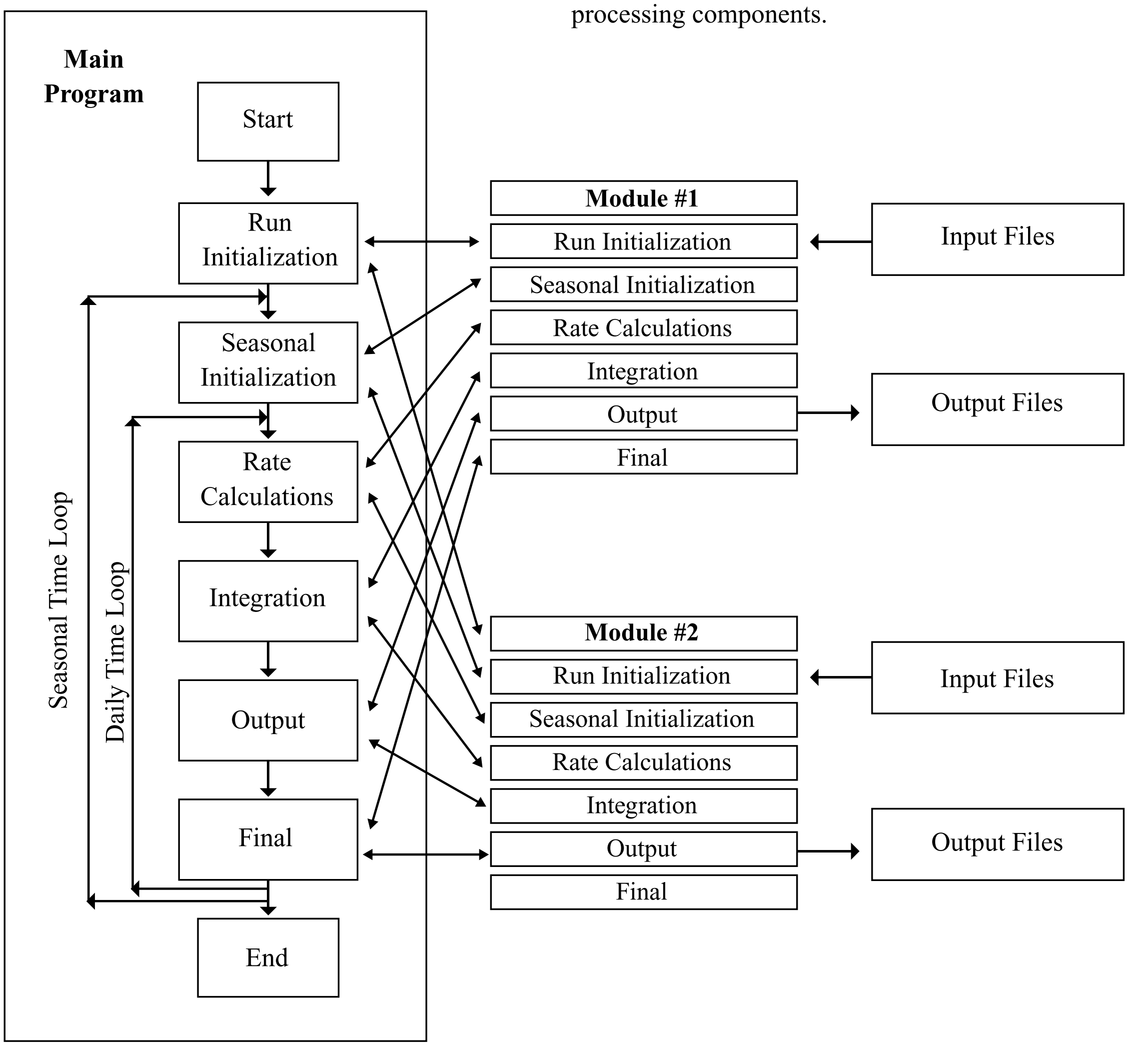

Figure 1. Structure of main program and modules.

The FORTRAN code used for directing calls to a module from the main program is presented in Figure 2. Figure 3 lists typical codes used to control processing within a module.

Run initialization (RUNINIT)

At the beginning of each simulation, modules are called to input data from files and to initialize variables prior to daily simulation. During this phase of processing, each module reads input data from the CROPGRO input data files (e.g., IBSNAT35.INP, SBGRO980.SPE, SBGRO980.ECO, SBGRO980.SBT, etc.). Some of the variables that are read as input from the modules (such as simulation switches and soil characteristics) could have been passed to the module from the main program as arguments but, instead, are read directly from the input files and treated as local variables. This eliminates the need for COMMON blocks, while reducing the number of arguments passed from the calling routine. This section also performs initialization or computation of variables that need to be set only once per simulation. Submodules are called to perform initialization and input calculations as required.

```
!=======================================================================
            PROGRAM DRIVER
!=======================================================================
            INTEGER, PARAMETER :: RUNINIT = 1, SEASINIT = 2, RATE = 3,
   &                                  INTEGR = 4, OUTPUT =5, FINAL = 6
!=======================================================================
            CALL MODULE1(arg1, arg2, . . . . , RUNINIT)
            CALL MODULE2(arg1, arg2, . . . . , RUNINIT)
            .
            .
!=======================================================================
!           Begin Seasonal Loop
!=======================================================================
            CALL MODULE1(arg1, arg2, . . . . , SEASINIT)
            CALL MODULE2(arg1, arg2, . . . . , SEASINIT)
            .
            .
!=======================================================================
!           Begin Daily Loop
!=======================================================================
!           Rate Calculation Section
!=======================================================================
            CALL MODULE1(arg1, arg2, . . . . , RATE)
            CALL MODULE2(arg1, arg2, . . . . , RATE)
            .
            .
!=======================================================================
!           Integration Section
!=======================================================================
            CALL MODULE1(arg1, arg2, . . . . , INTEGR)
            CALL MODULE2(arg1, arg2, . . . . , INTEGR)
            .
            .
!=======================================================================
!           Output Section
!=======================================================================
            CALL MODULE1(arg1, arg2, . . . . , OUTPUT)
            CALL MODULE2(arg1, arg2, . . . . , OUTPUT)
            .
            .
!=======================================================================
!           End Daily Loop
!=======================================================================
!           End Seasonal Simulation Loop
!=======================================================================
            CALL MODULE1(arg1, arg2, . . . . , FINAL)
            CALL MODULE2(arg1, arg2, . . . . , FINAL)
            .
            .
!=======================================================================
!           End of Program
!=======================================================================
            END DRIVER
```

Figure 2. Fortran code showing module processing within main program.

Seasonal initialization (SEASINIT)
When multi-seasonal simulations are performed, each season of simulation must be initialized independently. This is done in the seasonal simulation section.

Rate calculations (RATE)
Rate calculations are updated at the beginning of the daily time loop. This ensures that rates of change of state variables for a given day of simulation are all based on values of these state variables for a common point in time (e.g., the end of the previous day). Submodules are called to compute rate calculations as needed.

Integration calculations (INTEGR)
The integration portion of the model updates state variables throughout the model for each day of simulation using the rates calculated previously.

Daily output (OUTPUT)
Daily output data are written to files in this section.

Final section (FINAL)
The FINAL section of processing is used to close all input and output files and to write simulation summaries.

```
!=====================================================================
        SUBROUTINE MODULE1(arg1, arg2, arg3, . . ., DYNAMIC)
!=====================================================================
        INTEGER, PARAMETER :: RUNINIT = 1, SEASINIT = 2, RATE = 3,
  &                             INTEGR = 4, OUTPUT =5, FINAL = 6
        INTEGER DYNAMIC

!=====================================================================
!       Run Initialization Section
!=====================================================================
        IF (DYNAMIC .EQ. 'RUNINIT') THEN
                <Read input data>
                <Once-only initialization of variables>
                .
!=====================================================================
!       Seasonal Initialization Section
!=====================================================================
        IF (DYNAMIC .EQ. 'SEASINIT') THEN
                <Read initialization data>
                <Date adjustments for management time series>
                .
!=====================================================================
!       Rate Calculation Section
!=====================================================================
        ELSEIF (DYNAMIC .EQ. 'RATE') THEN
                <Calculate rates>
                .
!=====================================================================
!       Integration Section
!=====================================================================
        ELSEIF (DYNAMIC .EQ. 'INTEGR') THEN
                <Update state variables>
                .
!=====================================================================
!       Output Section
!=====================================================================
        ELSEIF (DYNAMIC .EQ. 'OUTPUT') THEN
                <Write daily output>
                .
!=====================================================================
!       Final Section
!=====================================================================
        ELSEIF (DYNAMIC .EQ. 'FINAL') THEN
                <Close files>
                .
                .
!=====================================================================
!       End of Module
!=====================================================================
        ENDIF
!=====================================================================
        END SUBROUTINE MODULE1
!=====================================================================
```

Figure 3. Fortran code showing module structure.

Programming Guidelines for Modules

A general list of guidelines used in programming the modules was developed for the creation of modules for the CROPGRO model:

- Eliminate GO TO statements, which make it difficult to follow code sequence. GO TO statements can usually be replaced with IF-THEN-ELSE or DO-loop constructs.
- Eliminate COMMON blocks. These can be replaced with argument lists, which explicitly call out the flow of data to and from modules and subroutines. In future versions of FORTRAN, the COMMON blocks will be eliminated and are considered to be an obsolescent feature of the language.
- Label input and output lists for each module and subroutine. This labeling has been done in the CROPGRO modules by grouping variables in the argument lists by input, input/output, or output function for the module or subroutine.
- Describe each module or subroutine as it is called.
- Include a list of variable definitions in each module or subroutine.
- Read input variables from files rather than pass to modules in the argument list. This reduces the number of arguments passed to and from modules.

Modifications to Main Program

As modules are added to the CROPGRO model, the main program is modified, as necessary, to perform the appropriate calls to each module. With the addition of modules, the main program is used less for reading input data and initializing variables, thus many of the subroutines that were previously called from the main program are eliminated. For example, rather than initializing and reading phenology variables with calls to subroutines such as IPECO, INPHEN, IPIBS, and IPCROP, the main program calls the PLANT subroutine, with variable DYNAMIC=RUNINIT. In turn, the PLANT subroutine calls subroutine PHENOL, which performs the initialization and data input functions for the phenology module. The PLANT subroutine is called from the main program for each of the six phases of processing corresponding to the values of the DYNAMIC variable.

Simulation Run Times

Preliminary bench tests comparing CROPGRO v4.0, with three modules, to the previous CROPGRO v3.5 indicate that run times are not increased and may actually be slightly decreased by the use of the modular format. Kenig (1998, unpublished) reports that simulation run-times using the modular TOMGRO v3.0 model are significantly reduced when compared with run times produced by the nonmodular format code.

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A Methodology for Linking Spatially Interpolated Climate Surfaces with Crop Growth Simulation Models

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Abstract

When linked to spatial data, a crop simulation model can characterize the adaptation of germplasm or management practices, providing detailed information unavailable except through expensive field trials. We used the Decision Support System for Agrotechnology Transfer (DSSAT) CERES-Maize crop simulation model to synthesize the available geo-referenced soil and climate databases. Spatially interpolated climate surfaces, a growing season model generated from those surfaces, and spatial soils layers were used as inputs into the CERES-Maize sequence simulation model to simulate 30 years of yield for two maize cultivars in East Africa. We were unable to acquire robust genetic coefficients for all tropical maize adaptation zones nor reliable soil profiles appropriate, but our limited results suggest this approach will serve to delineate adaptation zones.

Introduction

Accurate identification and characterization of production zones and potential production zones are vital to agricultural research. Historically, environmental characterization of agricultural areas has been the subject of many research efforts (Koppen and Geiger 1936; Thornthwaite 1948; FAO 1981) that integrated available data and expert opinion to provide powerful interpretations of the resource base for agricultural development. One goal of these typically continental efforts was to map and delineate zones of relative biophysical homogeneity designed to communicate information useful for planning agricultural and other human activities. These methods, however, remain locked into their historical roots since they provided static zones of adaptation that end users could not modify to meet specific needs.

New opportunities exist to greatly improve the characterization mechanisms. Geographic information systems (GIS) and interpolated climate surfaces expand the scope of information readily available to agriculturists (Corbett 1996). GIS and climate surfaces linked with crop simulation models can provide detailed spatial information on many aspects of germplasm and crop management, particularly in relation to natural resource concerns. GIS has provided researchers with powerful tools for overcoming the limitations of traditional agroecological models, which relied on static zones, analog reproduction technology, and fixed crop-environment relationships (Jones and Thornton 1996; Corbett and O'Brien 1997; Corbett et al. 1998). The new generation of more dynamic tools sought mechanisms to use GIS technology and interpolated spatial data to allow users to select boundary or 'discriminating' criteria, with the output uniquely reflecting users' interests, and enabled the characterization of agricultural areas to be enhanced significantly and quickly.

© CIMMYT. Published in White, J.W., and P.R. Grace (eds.). 2001. *Directions in Modeling Wheat and Maize for Developing Countries: Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 4-6 May 1998.* NRG-GIS Series 01-02. Mexico, D.F.: CIMMYT.

Crop simulation models represent a relatively untapped source of analytic power for studying the interactions of germplasm and management practices with the environment. These tools enable analysis that has previously not been possible, even using the more dynamic approaches of classical GIS. When linked to spatial data, however, a crop simulation model can characterize the spatial extent of the adaptation zone for a specific germplasm or management practice, while providing detailed information unavailable through any other mechanism except a massive (and prohibitively expensive) field experiment.

For disaster mitigation, the creation of germplasm specific zones with accompanying risk assessment and scenario information is vital. For planning future agricultural investments, such information is essential to successful mitigation in light of factors such as climate change and population increases. An enormous investment has gone into the development of crop simulation models because field trials are expensive and time consuming. Crop simulation models can reduce the number of field trials required for a particular spatial location or site by narrowing down potential scenarios. Application of crop simulation models across spatially continuous surfaces (by simplifying inputs) to narrow down the potential spatial domain of crop varieties is equally valid as a more efficient means to determine target environments.

We demonstrate the use of crop simulation models for regional analysis in areas where data is scarce. Data availability in the appropriate format can be one of the greatest constraints in applied research activities (Jones and Thornton 1996). To use existing data and technologies, the premise is made that by simplifying the inputs into crop simulation models, thus allowing the application of these models spatially over large geographic areas, we can generate spatially explicit information of sufficient accuracy for indicative analysis at the regional scale.

We used the Decision Support System for Agrotechnology Transfer (DSSAT) CERES-Maize crop simulation model to synthesize the available geo-referenced soil and climate databases. Spatially interpolated climate surfaces, a growing season model generated from those surfaces, and spatial soils layers were used as inputs into the CERES-Maize sequence simulation model to assess the relative performance of two maize cultivars in East Africa (Eritrea, Ethiopia, Somalia, Kenya, Tanzania, Uganda, Rwanda, and Burundi). Yields were simulated for both cultivars for a single repetition over a 30-year sequence.

DSSAT Data Requirements

Due to detailed representation of processes in DSSAT-compatible models such as CERES-Maize, detailed inputs are required to achieve meaningful results. For the DSSAT suite of models, the minimum data sets required for model validation are: 1) daily weather data for the duration of the experiment, 2) soil profile descriptions, 3) management options used, 4) experimental data, and 5) coefficients to characterize cultivars. Running the models over large regions, however, requires judicious simplification of the input data to reduce the number of simulation runs.

Spatially continuous geo-referenced weather and soil data at the level of detail required by the DSSAT models are not commonly available at the regional scale. Lack of historical weather data is also a problem for single field simulations, which has resulted in the development of weather generators to fill gaps in data records. These statistical models use stochastic techniques to generate daily weather data from historical weather data and long term monthly means. The DSSAT simulation models use variations of the SIMMETEO (Geng et al. 1986) and WGEN weather generators, which require a minimum data set of monthly means for solar radiation, minimum air temperature, maximum air temperature, precipitation, and number of wet days (Hansen et al. 1994; Pickering et al. 1994). [1]

[1] Jones and Thornton (1996) describe a proposal to develop DSSAT climate files and third-order Markov chain model parameters for South America and Africa. The rainfall generator based on third-order Markov chain has been shown to better simulate year-to-year rainfall variation in the tropics and requires 36 parameters calculated from historical records (Jones and Thornton 1993). The data is planned to be released on CD-ROM and, once available, could be used relatively easily to replace current weather-generating techniques in the application framework developed here.

Climate Surface Interpolation

Decades of effort to collect and collate historical weather data from stations around the world have culminated in the ability to generate continental spatial climate surfaces (Jones and Thornton 1996). Hutchinson (1991, 1995) developed a "Laplacian" or thin-plate spline technique to interpolate climate variable surfaces from long-term weather station records. Using coefficients generated by Hutchinson (Corbett 1996; Hutchinson and Corbett 1996), Corbett and Kruska (1994) generated long-term monthly mean minimum and maximum temperature, total precipitation, and potential evapotranspiration grids at a resolution of 3 arc minutes for the African continent.

Monthly climate surfaces for global radiation and number of wet days, which are required for weather generation, were interpolated for the East African study area using ANUSPLIN and station data supplied by the Food and Agricultural Organization of the United Nations (FAO) database (FAO 1994).

Soils

In DSSAT, the soils file defines the soil profile properties that are used in the soil water, nitrogen, and root growth sections of the crop models (Jones et al. 1994). Generally the information is collated from a combination of measurements in the field and from soils databases. For spatial simulations at the regional scale, digitized soil map classifications can be associated with soil profile information, based on available pedon data to provide the soil file data (Thornton et al. 1996; Hoogenboom et al. 1993).

For the East African study area, spatial soils data were provided by the World Soils Resources (WSR) group of USDA. WSR used the 1:5,000,000 Soil Map of the World in combination with interpolated climate variables to convert the FAO classification system into a USDA Taxonomy at the Great Group level of classification. We used this classification and the soil pedon database that accompanies DSSAT to select a representative pedon for each soil classification. We sought "typic" soil pedons and then selected the representative pedon, based on completeness of the soil pedon data within the DSSAT databases. Profiles were generated using the DSSAT soil profile programs.

Methodology

Our methodology for linking the spatial data and simulation models first involved reducing the gridded climate surfaces to a more manageable number of climatic environments. This was achieved by performing a cluster analysis on the five climatic variable surfaces required for weather generation plus evapotranspiration over a five-month season defined by maximum precipitation to potential evapotranspiration (P/PE) ratio (see the section "Growing Season Model"). This resulted in what we call an "effective environments" layer (Fig. 1). The number of climate "scenarios" are thus reduced significantly whilst maintaining the majority of the spatial variance. Means were calculated for the five variables required for the weather generator over each clustered region and were output to DSSAT format climate files. The effective environments layer was overlaid with the spatial soils layer and the first month of the optimum season layer resulting in a simulation layer (Fig. 1). An experiment file was generated for each simulation zone from a template, simulations run, and the simulated output variables mapped back to the original zones.

Growing Season Model

To determine planting dates over the region, we used a five-month growing season model to indicate the start month of the planting window. This model avoids premature automatic planting by the simulation model in bimodal season regions.

The five-month optimum growing season was defined by identifying the five consecutive months in which the mean P/PE ratio is maximized. Water is a first-order limiting factor for most of East Africa, and this simple model has been found to be a reasonable identifier for the growing season (Corbett et al. 1995). There are exceptions, particularly in the Lake Region where the long rainy period permits more flexibility in planting, but, even in those locations, our model accurately identifies the principle first month of the main maize planting season. This model did not consider temperature information, although we inspected climate graphs from a sample of sites to ensure that our criteria selected the proper season for crop production.

The five-month optimum growing season was also used as the temporal delimiter for the spatial cluster analysis variables input for the effective environments definition.

Effective Environments

Ward's minimum variance algorithm was used to cluster the climate data (SAS 1990), thus reducing the number of climate scenarios. This was done since climate does not necessarily vary significantly between the interpolated cells, and our objective of discriminating maize environments did not require such high resolution (approximately 29 km^2 cells). A second motive was computational efficiency, with 76,000 cells and 30 years of sequential maize growth simulation effectively exceeding our computation capacity.

Five grids representing the five month sequence of the optimum season for each of the long-term monthly mean variables were generated for precipitation, potential evapotranspiration, solar radiation, number of rainy days, maximum temperature, and minimum temperature. These grids reflect not the calendar month (e.g., January, February, etc) but rather the "biological" sequence of the growing season (e.g., month 1 precipitation, month 2 precipitation, etc.) for the five months. The 30 grids were then ported to statistical analysis software (SAS) for cluster analysis. Plots of R^2 against the number of clusters indicated that approximately 200 clusters would be sufficient to represent the majority of the variance of the East African data set.

Simulation Layer

The simulation layer was generated by simply overlaying the effective environments, first month of optimum season, and soil great groups layers. This layer represents the zones of unique growing season, climate, and soil characteristics, and can be used as the basis for any subsequent simulation scenario or experiment file configuration. For the East African region there were 1,212 unique combinations.

Genetic Coefficients

Two calibrated (but not verified) genetic coefficients, MH-16 and Katumani, were available for maize in the East African region at the time of this study. MH-16 is a hybrid from Malawi and is bred from SR-52 which, despite dating to the 1950s, is still one of the better regional cultivars. This is a fairly long-season variety, with shorter stature, and is capable of good yields. Katumani is a composite that has not performed as well as MH-16 in trials. The genetic coefficients for these cultivars are preliminary but were considered the best option for testing our methodology. These two cultivars and others are currently being calibrated for East Africa. The coefficients assumed for MH-16 and Katumani are given in Table 1.

Simulation Runs

A simple maize-fallow crop rotation with the following planting details, which are considered to be standard for East Africa, were used (P. Thornton, personal communication, 1997):

Plant population (PPOD + PPOE):	**3.9 plants/m^2**
Row spacing (PLRS):	**75 cm**
Planting depth (PLDP):	**5 cm**

Default initial conditions with default amounts of nitrate in the soil profile were used. No residues, fertilizers, chemicals, or tillage were included in the model runs (Phil Thornton, personal communication, 1997). The planting window is set individually for each run using simulation controls and is determined by the first month of the optimum season surface. The window is then "open" for three months in which the crop will be planted if planting conditions are met. The default planting condition requirements were used.

Table 1. Genetic coefficients assumed for two leading cultivars from eastern and southern Africa, for use in a simulation using the CERES-Maize model.

Variety #	Cultivar	Ecotype	P1	P2	P5	G2	G3	Phint
CM0001	KATUMANI	SA0001	172.0	0.50	999.0	398.0	6.27	75.00
CM0005	MH-16	SA0001	245.3	0.28	843.0	417.3	7.87	75.00

Harvest date for the maize crop was set to occur automatically at maturity. Harvest for the fallow period was set to occur one day prior to the maize planting date. To limit the number of unnecessary simulation runs, we excluded zones where the five-month optimum season rainfall was less than 300 mm. Some simulation zones were also excluded due to lack of soil profile data.

An ArcView application interface was developed to integrate the various data sets, run the crop simulations, and map output. Much of our initial efforts to integrate DSSAT and ArcView were based on the AEGIS/WIN application developed by Engel et al. (1995) and adapted for gridded surfaces.

When using sequence simulation, it is highly recommended to carry out at least 10 replicates of each sequence to obtain relatively stable estimates of means and variances. A replicate is the repetition of the same experiment run with a different sequence of weather conditions (Thornton et al. 1994). Due to the preliminary nature of the genetic coefficients, however, initial runs were carried out for 30 years and 1 replicate. As such, the output results for each year were not analyzed individually, as would be possible with 10 repetitions, but were meaned over the 30-year period. The total means were then mapped to the original simulation zones.

Discussion

The simplest comparison between the two maize cultivars was to overlay the 30-year mean yield at harvest maps to indicate where each variety performs best (Fig. 2). Overall, the results suggest higher mean yields from cv. Katumani (dark gray regions). The results correctly identify Katumani as the preferred variety for both the Machakos and Kitui districts of eastern Kenya. Katumani was specifically developed for this area, and its center of origin is the Katumani research station, just south of Machakos town.

Beyond the literal translation of the simulated yields, our method allows the systematic description of an area for its potential yield with respect to specific cultivars. For this study, we were unable to acquire robust genetic coefficients that would represent the spectrum of broad tropical maize adaptation zones, as described by CIMMYT mega-environments (highland, transitional, midaltitude, dryland, and coastal or lowland). Nor were we able to obtain reliable soil profiles appropriate for the CERES-Maize model. However, with more reliable data, simulation of a representative variety of each of the aforementioned mega-environments could be carried out. A map could then be created that outlines the mega-environment or adaptation zone by virtue of initially the highest simulated mean yield. Our more limited results are encouraging: this approach, given a representative set of genetic coefficients, will work to create a map which will delineate adaptation zones.

Highest mean yield is not the only criterion that can be used to delineate zones. Given the power of a simulation environment, it will be possible to build a database of simulation results so that the highest mean yield can be identified, as well as the variability in mean yield. Nitrogen uptake maps could also be used as N application indicators. Adaptation zone delineation would just begin with highest mean yield. Beyond that, zones focused on risk assessment could be created. For example, we could further evaluate the midaltitude adaptation zone as follows: calculate the mean yield during the driest 25% of years and compare that yield to the mean yield of a dryland variety. Those areas of the midaltitude zone in which a dryland variety attained a higher yield than the “correct” variety might be targeted for further socioeconomic analysis. Farmers with little cash or the most risk averse might elect to grow the variety that yields more in the driest of years, rather than attempt to attain a higher mean over the long run. This kind of analysis helps to target research on a different aspects of the issues surrounding germplasm adoption: risk and resource access.

Conclusion

Actual meteorological data exists in sufficient detail for some locations that a risk assessment analysis could use either simulated or actual weather data. Risk assessment offers a valuable addition to the characteristics of any germplasm adaptation zone. Whether simulated or based on actual meteorological records, the ability to estimate variability over space and in time of the yield of a crop variety is a potentially powerful decision-making asset to both agricultural research and agricultural and economic development efforts. At a minimum, this methodology describes an opportunity to improve our characterization and assessment capabilities using spatial data and crop simulation models.

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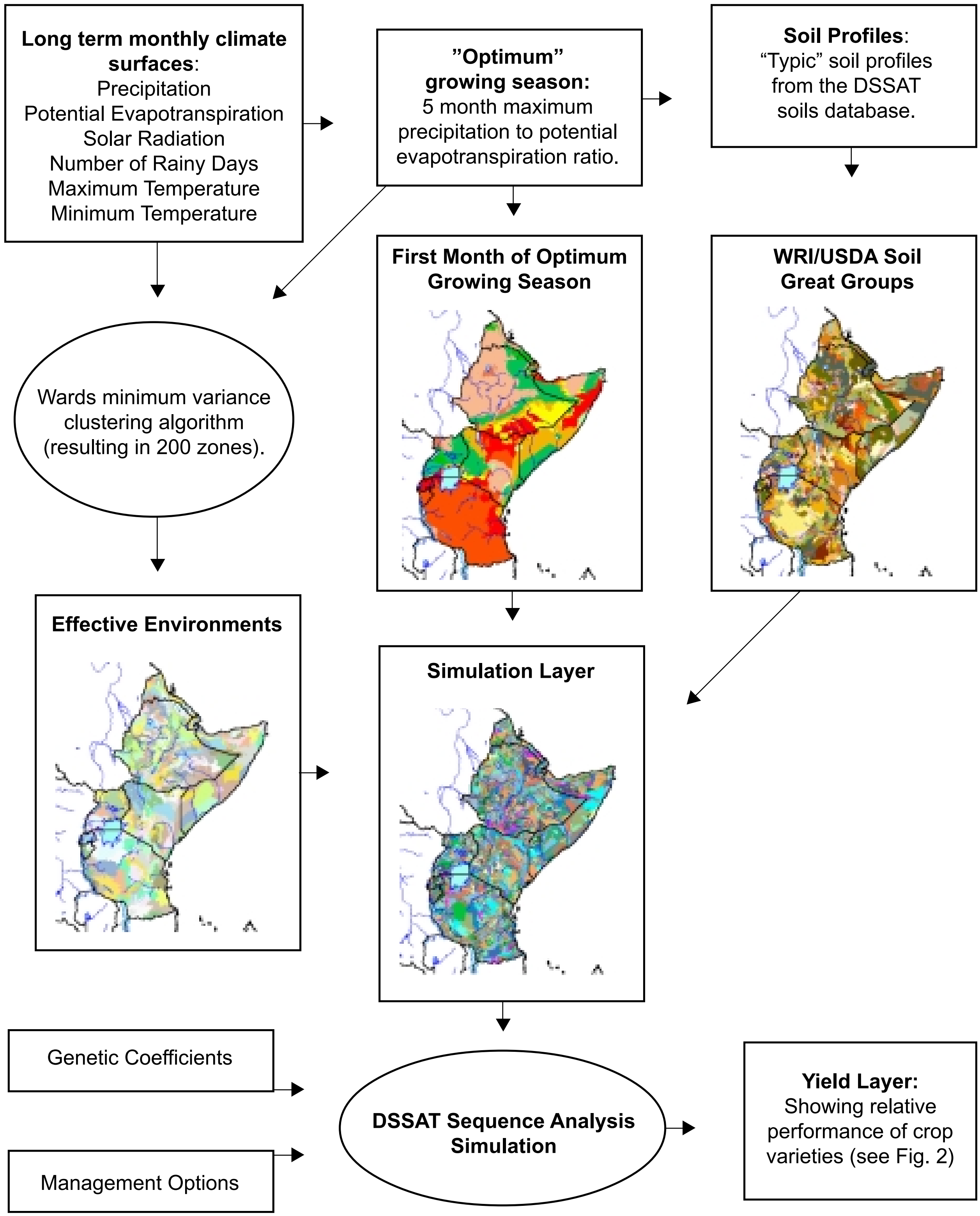

Figure 1: Methodology for linking spatially interpolated climate surfaces with crop growth simulation models in East Africa.

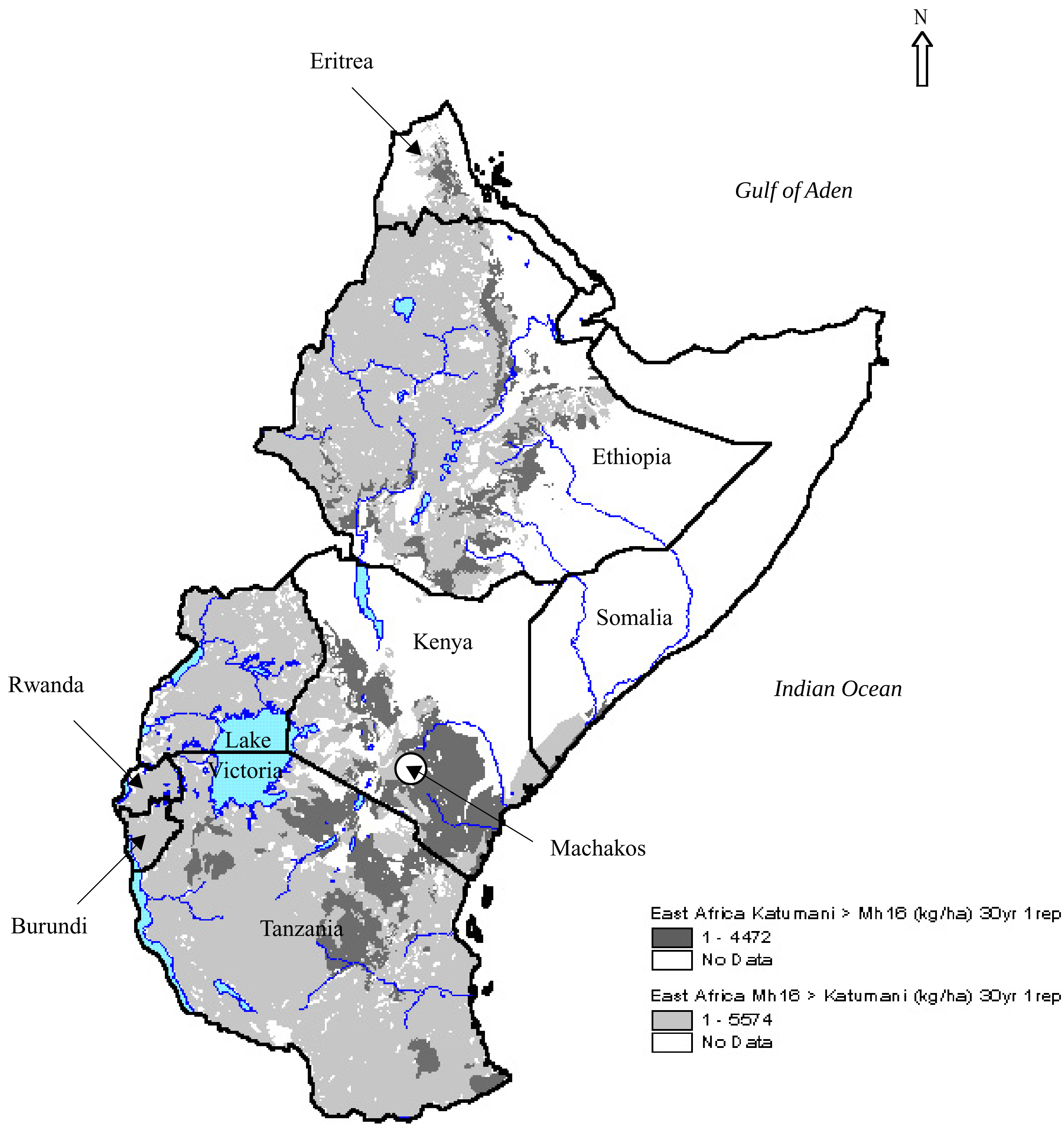

Figure 2. Highest 30 year mean yield at harvest of two maize varieties in East Africa, 1) Katumani (dark gray), a dryland cultivar MH16 (light gray), a midaltitude cultivar.

Work Group Outputs

Compiled by J.W. White
Natural Resources Group, CIMMYT, Mexico

Introduction

Following the formal presentations, possible modifications to models and other modeling-related issues were reviewed to set priorities and resolve a few issues relating to software management (Tables 1 and 2). The discussions were reopened for brief periods throughout the rest of the workshop.

DSSAT Version Control

The multiple pre-releases of DSSAT version 3.1 created confusion over versions that different researchers were using. Naming conventions were proposed to allow upgrading of software on a consistent basis. The next official version of DSSAT was to be version 3.5, which was released in late 1998.

Test versions of models for development should be based on version 3.5. However, they should be identified as 3.6xx, where "xx" suffix identifies the developer (e.g., "3.6PG" for Peter Grace). A facility needs to be included in the code to allow input of this suffix.

Specific Modifications for CERES Version 3.5

Variable phyllochron interval in CERES-Maize
In many situations, the number of maize leaves is overestimated. Although the phyllochron interval (PHINT) appeared in the cultivar file, the value was actually "hard wired" at 75 degree-days. This has subsequently been corrected.

Cultivar-specific parameters
The lists of cultivar-specific parameters in CERES (e.g., MZCER980.CUL) provide no indication of how reliable the values are. Ideally, the number of observations, types of data, and method used should all be indicated. Tony Hunt strongly urged that the list of cultivars be shortened to include only the most reliable coefficients. Five generic cultivars should also be provided.

Externalization of nitrogen mineralization parameters in to a SOIL.PAR file
To facilitate modeling of nitrogen mineralization in CERES and CROPGRO, a new soil parameter file, SOILN980.PAR, was created (Table 3). This file externalizes many of the coefficients needed for simulating the decomposition of soil organic matter (one pool) and organic matter added as residue or manure (three pools). If the file does not exist in the data directory, it is created using default values upon the first run of the model.

Definitions of the parameters are:

DMINR: Potential decomposition rate of SOM pool. Default value is 0.8300E-04 per day
RTCNR: C/N ratio of initial root residue. Default = 40.0.
DSNCV: Depth to which soil C (SCDD) and total N (SNDD) values are integrated for output to CARBON.OUT. Default value is 20.0 cm.
RE001: First three values are the potential decomposition of the carbohydrate, cellulose, and lignin pools; the next three values are the relative of carbohydrate, cellulose, and in the residue or manure dry matter. Default = 0.2000, 0.0500, 0.0095, 0.2000, 0.7000, 0.1000. Up to nine different residue or manure types can be defined.

Reducing the thickness of deeper soil layers
To handle tile drains, Bill Bachelor defined a soil layer 15cm-thick at the approximate depth of the drain.

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Unfortunately, testing showed that introducing this layer produced unexpected changes in model outputs.

Proposed changes for CERES v3.6x

A series of changes were suggested for subsequent releases. These included:

- Improve thermal time calculations.
- Account for mass of dead leaves and their subsequent incorporation into soil organic matter.
- Improve modeling of grain number in maize (based on approach of Andre Du Toit).
- For wheat, Zadok stages should be output along with standard phenology stages.
- Model effects of conservation tillage, tile drainage, and runoff/erosion.
- Model response to soil phosphorus.
- Generate solar radiation if actual data is erroneous or not available.
- Include new genetic coefficients for winterkill, vernalization, and prolificacy.
- Improve the water balance routines both for root uptake and estimates of potential evaporation.

Various software problems that should be rectified were also noted in the version 3.5 or 3.6 releases:

- WINGRAF - default scaling for water content and harvest index.
- WINGRAF - loss of plotted lines on large monitors.
- Sequencing memory problems; need to increase the number of individual phases.
- A and T files to handle replications.
- Data conflicts in A and T files.

Documentation and Modularization of Codes

It was recognized that documentation of models is still very problematic. Many researchers assume that Jones and Kiniry (1986) is still an accurate description of the CERES models. Much more effort is needed on the updating of documentation. Reports should be sent to the Hawaii for posting on the list server. Links to modeling sites such as Michigan State University and University of Florida can also be included.

People identified to provide leadership and quality checking of documentation were:

- CERES-Maize: Joe Ritchie
- CERES-Wheat: Tony Hunt
- CROPGRO: Gerrit Hoogenboom

It was noted that modular programming would facilitate publication of algorithms. A draft Spanish version of DSSAT 3 documentation is available through CIP (Walter Bowen).

Further Discussion

Several additional topics were touched upon. The need to assemble quality data sets collected through the IBSNAT project and other sources, e.g., GCTE, arose several times. It is easy to criticize models, but the models are only as good as the data sets used to develop routines and test model performance.

No progress is being made on incorporating intercropping. Modularization might make it easier to handle more than one crop in a single model, but an approach similar to that used by APSIM, where the soil is the central resource, would still seem necessary.

The ICASA file standards should be modified to handle a wider range of treatments. One set of data includes 25 treatments including GA_3, boric aid, and urea solutions.

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Table 1. Summary of activities during the model development and testing phase of the workshop.

Acti vity	Responsible [1]	Date completed/comments
DSSA T v3.5		
Agreed that the next release of DSSAT and all components should be version 3.5 to remove confusion	All	During the workshop, GH coordinated naming
over intermediate r eleases of v ersion 3.1. applications.		**revisions f or all**
Calculation of degree-days is now calculated on T_{base} and T_{opt} defined in the species file. This allowed simplifying code among species.	JR, GH, BB, PW	7 May 1998. Requires recalibration of cultivars.
CERES v3.5		
Make PHINT (phyllochron interval) a variable input for all crops. This fixed the over-prediction of leaf number for CERES-Maize.	GH, PW	7 May 1998. Requires recalibration of cultivars.
Determine whether soil, air, or crown temperature is used to control phenology in early stages of development using a switch based on leaf number. For maize, sorghum, and millet, the switch is leaf number. For wheat and barley, I-stage 1 is used.	BB, JR, PW	7 May 1998. Requires recalibration of cultivars.
Calculation of degree-days is now calculated on T_{base} and T_{opt} defined in the species file. This allowed simplifying code among species.	JR, GH, BB, PW	7 May 1998. Requires recalibration of cultivars.
Modify and test algorithms for winterkill.	PW, TH	7 May 1998. Is killing off plants, but yield effect is less than expected.
For lower soil layers, automatically divide the profile into 15-cm layers rather than 30-cm layers.	BB	Not implemented. Found to affect yields as much as 500 kg/ha.
Externalization of N mineralization parameters in to a SOLN980.PAR file.	WB, PW, PG	6 May 1998.
Recalibrate cultivars based on the above changes.	TH, JR, PW, GH	8 May 1998.
Shorten the list of cultivars to include reliable coefficients only. Include five generic cultivars in list.		
Maize list	JR, BB	
Wheat list	TH, JW	
Assemble final code and data sets.	PW, GH	6 May 1998.
CERES v3.6xx		
Add genetic coefficient for winter kill (independent of vernalization) in wheat.	JR	
Add genetic coefficient for tolerance to high densities (prolificacy) in maize.	JR	
Zadoks stages output along with standard phenology stages.	TH	
Solar radiation to be calculated if actual data is erroneous or not available.	JR	

Improved thermal time calculations.	JR	
Water balance modifications: root uptake and potential evaporation.		
Conservation tillage.	PG, PW, …	
Output and transfer of dead leaves.	GH, DH	
Improve handling of grain number based on linear relation between crop growth in critical pre-grain set phase and grains/m^2.	JR, GE	
Tile drainage.	BB	
Software and data management		
Endorsed the idea of repeating these meetings on an annual basis, with possible briefer, intermediate meetings (e.g., in conjunction with the ASA meetings).		
Version control and naming conventions		
Agreed that the next DSSAT release should be version 3.5.	All	5 May 1998.
Agreed that modifications based on v3.5 models should be identified as 3.6xx, where the "xx" suffix is a two-letter code to identify the investigator or project.	All	5 May 1998.
Programming issues		
Agreed to evaluate the modular approach. It has clear advantages for model maintenance, revision and improvement, and for documentation. However, implications for run time need to be evaluated.	All	
Agreed that models should move to a 32-bit operating system but try to maintain 16-bit functionality for the next two to three years. Digital Fortran is the preferred compiler.	All	
Endorsed the Michigan meeting's recommendation of a Windows-based user interface for model applications, but more specifics are needed for standards on icons, menu bars, screen layouts, etc.	All	
Documentation		
The need for better model documentation was again cited. The ICASA www site offers one possible access point.		

[1] BB = Bill Batchelor; DH = Dewi Hartkamp; GE = Greg Edmeades; GH = Gerrit Hoogenboom; JR = Joe Ritchie; JW = Jeff White; PG = Peter Grace; TH = Tony Hunt; PW = Paul Wilkens.

Table 2. Summary of data sets prepared or partially prepared during the workshop.

Data set	Responsible
Maize	
CIMMYT trials at Tlaltizapan and Poza Rica, Mexico	G. Edmeades, W. Bowen
Wheat	
CIMMYT historic wheat cultivar series	T. Hunt
Punjab Agricultural University planting dates x cultivars x years	J. White
Velvet bean (*Mucuna*)	D. Hartkamp, G. Hoogenboom

Table 3. Example of the file SOILN980.PAR.

```
*SOIL NITROGEN PARAMETER FILE

!  Model parameter file which externalizes many of the coefficients needed for simulating the decomposition of
!  soil organic matter (one pool) and organic matter added as residue or manure (three pools). If SOILN980.PAR
!  does not exist in the data directory, it is created upon the first run of the model. Definitions follow:
!
! DMINR:   Potential decomposition rate of SOM pool.
!          Default value is .8300E-04 per day.
! RTCNR:   C/N ratio of initial root residue.
!          Default = 40.0.
! DSNCV:   Depth to which soil C (SCDD) and total N (SNDD)
!          values are integrated for output to CARBON.OUT.
!          Default value is 20.0 cm.
! RE001:   First three values are the potential decomposition
!          rates of the carbohydrate, cellulose, and
!          lignin pools; next three values are the relative
!          proportions of carbohydrate, cellulose, and
!          lignin in the residue or manure dry matter.
!          Defaults = 0.2000, 0.0500, 0.0095, 0.2000, 0.7000, 0.1000.
!          Up to nine different residue or manure types can be defined

*CHARACTERISTICS

@C    VARIABLE   VALUES
DS    DMINR       0.8300E-04
DS    RTCNR      40.0
DS    DSNCV      20.0
DS    RE001       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
DS    RE002       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
DS    RE003       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
DS    RE004       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
DS    RE005       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
DS    RE006       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
DS    RE007       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
DS    RE008       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
DS    RE009       0.2000    0.0500    0.0095    0.2000    0.7000    0.1000
```

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