Modeling Extremes of Wheat and Maize Crop Performance in the Tropics

Proceedings of a Workshop, CIMMYT

El Batán, Mexico, 19-22 April 1999

Jeffrey W. White and Peter R. Grace

Editors

Natural Resources Group
Geographic Information Systems
Series 00-01

CIMMYT (www.cimmyt.mx or www.cimmyt.cgiar.org) is an internationally funded, nonprofit scientific research and training organization. Headquartered in Mexico, the Center works with agricultural research institutions worldwide to improve the productivity, profitability, and sustainability of maize and wheat systems for poor farmers in developing countries. It is one of 16 similar centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR comprises over 55 partner countries, international and regional organizations, and private foundations. It is co-sponsored by the Food and Agriculture Organization (FAO) of the United Nations, the International Bank for Reconstruction and Development (World Bank), the United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP). Financial support for CIMMYT's research agenda also comes from many other sources, including foundations, development banks, and public and private agencies.

CIMMYT supports Future Harvest, a public awareness campaign that builds understanding about the importance of agricultural issues and international agricultural research. Future Harvest links respected research institutions, influential public figures, and leading agricultural scientists to underscore the wider social benefits of improved agriculture: peace, prosperity, environmental renewal, health, and the alleviation of human suffering (www.futureharvest.org).

Printed in Mexico.

Correct citation: White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

Abstract: In a workshop sponsored by the Natural Resources Group (NRG) of the International Maize and Wheat Improvement Center (CIMMYT), scientists from the USA, Canada, South Africa and CIMMYT gathered at CIMMYT headquarters during 19-22 April, 1999, to examine the performance of leading maize and wheat simulation models, particularly CERES, for tropical environments of high and low yield potentials. Major outcomes are reported in this publication and include: * revision of temperature effects on development in CERES Wheat 3.5; * examination of strategies for modeling barrenness and prolificacy in maize; * identification of the temperature effect on radiation use efficiency as a priority for subsequent revision; * heightened recognition of the need to compile quality data sets for maize and wheat growth from diverse environments.

ISSN: 1405-7484

AGROVOC descriptors: Cereals; Maíz; Zea mays; Wheats; Triticum; Crop performance; Yield factors; Environmental factors; Drought stress; Rain; Temperature resistance; Heat; Nutrient deficiencies; Crop yield; Yield increases; Models; Simulation models; Tropical zones; Mexico; Research projects

Additional Keywords: CIMMYT; CERES

AGRIS category codes: F01 Crop Husbandry; H50 Miscellaneous Plant Disorders

Dewey decimal classification: 633.1

Contents

Preface

For the past several years, CIMMYT has worked hard at shaping its research endeavors and collaborative activities around a new paradigm, known as G x E x M x P (germplasm x environment x management x people). CIMMYT aims to help develop sustainable maize and wheat systems for the poor by combining the right germplasm for the right environment, using suitable crop and system management practices, in ways that are consistent with people's needs. This new paradigm requires the use of a systems perspective, in which biophysical factors and policy and institutional factors guide technical change, in turn consisting of interacting crop and system management practices and new varieties.

Understandably, then, CIMMYT is increasing its reliance on systems tools. This embraces "soft" systems tools (e.g., farmer participatory research and farmer experimentation), as well as "hard" systems tools (e.g., simulation models and geographic information systems, or GIS). Much of CIMMYT's capacity to engage in systems research is housed in a new Program: the Natural Resources Group, or NRG. The NRG is keenly interested in the use of simulation models for a variety of purposes:

- To understand the biophysical processes underpinning resource degradation.
- To understand the processes whereby new sustainable technologies make their favorable effects felt.
- To anticipate longer-term consequences of technical change for system productivity and resource quality.
- To understand (and thereby help manage) the variability of performance in new technologies across production environments (including weather conditions and soil types).
- To assist with extrapolating and scaling up research results.

The NRG is committed to improving the capacity of simulation models to address these kinds of questions. This is why the NRG was delighted to host this workshop. It is the second modeling workshop in as many years, and we anticipate making these workshops an annual event to promote continued development of simulation models for maize and wheat systems in developing countries.

We would like to thank CIMMYT science writer, Mike Listman, for the style editing and layout of this publication.

Larry Harrington
Director
Natural Resources Group (NRG)
CIMMYT

Workshop Summary

Maize and wheat simulation models have been developed largely for favorable production environments in temperate regions. They function well for the yield ranges representative of these regions (e.g., 4 to 10 t/ha), but simulations for conditions in developing countries are often less satisfactory, both for high and low yield potential environments. This four-day workshop looked at opportunities for improving model responses for both types of condition. In brief oral presentations, speakers examined various features of maize and wheat modeling related to the workshop theme:

- Upendra Singh (IFDC) presented data showing increases in the anthesis-silking interval (ASI) of up to 20 days for severe nitrogen stress in West Africa. His initial impression is that the phenology effect alone is enough to explain most of the yield decline, and he will incorporate this effect.
- Andre du Toit (ARC-Grain Crops Institute, South Africa) reviewed statistical approaches for identifying algorithms that need improvement in models. For CERES Maize, the number of ears per plant and water stress before and during silking were identified as priorities for further improvements.
- Dewi Hartkamp (CIMMYT NRG) explained how she simulates spatial variation in rainfed maize yield in Jalisco state, Mexico, and in Honduras. Handling variation in soil parameters is still a major challenge.
- Jeff White (CIMMYT NRG) examined the temperature response of CERES Wheat using data extracted from the International Wheat Information System (IWIS). CERES predicts that the highest yields occur at very low temperatures, while IWIS data shows a plateau of yields of 10 to 12 t/ha from 10° to 22°C.
- Garry O'Leary (South African Sugar Association Experiment Station, Mount Edgecombe, South Africa) compared published reports on wheat model errors over various yield levels. For stress conditions, models will need to include improved translocation of stem reserves and responses to low populations.
- Tony Hunt (University of Guelph, Canada) reviewed the new ICASA file standards. These are an evolutionary step beyond the widely used DSSAT formats. Software using the new formats will be available by the end of the year to ensure Y2K compatibility.

On the second day, Joost Lieshout demonstrated a prototype shell for decision support tools that might be used to launch databases and crop models. The "TACO Shell" (Texas and CIMMYT Object Shell) will be used in the International Crop Information System (ICIS). He and Marvin Stapper subsequently demonstrated how ICIS could be used to store and export files in the ICASA formats.

The following three days focused on "hands-on" model testing and code modification. For CERES Wheat and Maize, a critical distinction was made between changes that are appropriate for a service release of CERES V3.5 and modifications that should considered in beta testing.

 Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

For wheat, considerable effort was devoted to modeling temperature response for flower and grain development. CERES Wheat 3.5 assumed an optimal temperature of 26°C throughout development. An optimum of 15° appears to be more realistic for pre-anthesis development and will be used in Service Release 1.

Discussions on maize focused largely on handling of grain number both at very high yield conditions and under stress. A strategy is needed for modeling differences by cultivar in the tendency to form barren plants at high populations and to set multiple ears under low populations.

For both maize and wheat, the temperature effect on radiation use efficiency (RUE) has too high and narrow an optimum. This has major effects on the yield to temperature; identifying a more appropriate response should be a research priority in coming months.

Various “bug fixes” will be incorporated in the Service Release 1 of CERES. The upcoming modeling workshop at IFDC will be used for final testing of SR1. Various beta versions will be created in 1999 and reviewed at the next CIMMYT NRG modeling workshop. Key to this work is developing a set of quality model validation datasets for maize and wheat.

Challenges in Modeling Extremes of Wheat and Maize Yields in the Tropics

J.W. White and P.R. Grace
Natural Resources Group, CIMMYT

Abstract

Simulating maize or wheat crop performance in extreme environments presents special challenges for crop modelers. However, such conditions are of relevance for a range of problems facing researchers both in developed and developing countries. This paper provides background on why modelers should consider high and low yield cropping circumstances and identifies challenges in work targeted to such environments.

Introduction

Maize and wheat simulation models have been developed largely for favorable production environments of temperate regions. While they function well for the yield ranges representative of these regions (e.g., 4 to 8 t/ha), simulations under conditions found in developing countries are often less satisfactory, both for high and low yield potential environments. This workshop was proposed as a means to examine the performance of maize and wheat models under extremes of environmental conditions and to suggest priorities for further model improvement. Since it may not be clear why high and low yield situations should be addressed in a single workshop, we provide further background for this workshop, including offering specific challenges to crop modelers.

Why Consider High and Low Yield Situations?

The foremost reason for examining the extremes represented by high and low yield environments was circumstantial evidence that maize and wheat models perform poorly for such conditions. At the high yield extreme, one of the authors (J. White) was unable to simulate wheat yields as high as reported in credible agronomic trials for CIMMYT's station at Cd. Obregon. At the low end, water and nitrogen deficits both can delay silking in maize crops. Underlying this effect is a shift in partitioning that results in a disproportionate reduction in grain yield as compared to overall growth. However, these stress responses are not incorporated in current maize models and, not surprisingly, current maize models have problems simulating grain yield under extreme nitrogen and water deficits.

There is also wide discussion on the relative environmental and social impact of seeking production increases in favorable, high-yield environments vs. in marginal production areas (Heisey and Edmeades 1999). Systems offering high yield potential are perhaps easier to improve both in terms of biological "leverage points" and of the ability of farmers to adopt promising technologies. Particularly, the economic risks of adoption are buffered in these systems. Improving production in high-yield areas can also relieve pressure on marginal lands. This is easily noted in developed countries. Near-subsistence farming in

 Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

marginal areas was often associated with severe environmental degradation, including soil erosion, deforestation, and nutrient depletion. However, modern agricultural, coupled with industrial development, has not resulted in adoption of improved production practices for marginal areas. Rather, crop production has simply disappeared in many such areas.

Counter arguments that favor research for low-yielding environments correctly note that crop yields of most developing countries are far below yields in other regions (Fig. 1). Furthermore, since low yields influence rates of resource degradation, particularly through soil erosion, improving these systems may reduce degradation. It is worth noting that modeling has a special role to play in addressing climatic risk in low-yielding environments, because it offers one of the few approaches for assessing the risk and long-term consequences of new technologies.

A further justification for examining model performance under high yield conditions is that if model performance is suspect in the absence of stress, results under stress conditions will usually be worse. A model has to have the basics of growth and development right. And from a more political view, we note increasing interest in robust estimates of yield potential as a tool for policy making (Hobbs et al. 1998). Such interest is usually linked to “yield gap analyses,” where the analytic powers of models can help in prioritizing subsequent research activities.

Challenges

In a four-day workshop, we do not expect to revolutionize modeling of maize and wheat systems. However, we hope the workshop will challenge our views on how to model such systems and lead to insights on how to improve models. Below are five questions that suggest possible directions our discussions and modeling efforts might pursue.

Can RUE-based Models Provide Meaningful Estimates of Yield Potential?

Recent years have seen a rise in interest in models that use radiation use efficiency (RUE) as a key determinant of growth and grain production (Muchow et al. 1990). While simplicity is usually a commendable research criterion, one can question whether simplified models of complex systems can predict critical aspects of system behavior.

Consider a very simple RUE-based crop model:

$$\text{CWAM} = \text{RUE} \times \Sigma\text{SRAD},$$

where CWAM is crop dry weight at maturity and ΣSRAD is the sum (integral) of intercepted solar radiation from crop emergence to maturity. Assuming a constant harvest index (HI), then

$$\text{Y} = \text{CWAM} \times \text{HI},$$

where Y is grain yield. Thus,

$$\text{RUE} = \text{Y}/(\text{HI} \times \Sigma\text{SRAD}).$$

Given the direct relation between RUE and grain yield, it is difficult to see how a simple RUE-based model will provide more insights into variation in yield potential than direct measurement of grain yield. While we would not argue that the more mechanistic the model, the better the estimate of yield potential, oversimplification carries significant risks.

What about Hybrid Maize and Wheat?

Whereas heterosis is recognized as a source of high yields in hybrid maize, wheat crosses can also show significant heterosis (Cukadar et al. 1997). To our knowledge, no crop models explicitly deal with heterosis—probably reflecting our poor understanding of the underlying physiological mechanisms. Stuber (1997) commented that "the causal factors for heterosis at the physiological, biochemical, and molecular levels are today almost as obscure as they were at the time of the conference on heterosis held in 1950."

Interestingly, data both for wheat and maize (Cukadar et al. 1997; Gaytan-Bautista and Padilla-Ramirez 1997) suggest that heterosis results in greater overall growth in a shorter time span. This implies that the efficiency of growth is even greater than is suggested by heterosis for yield *per se*, and this presents an even greater challenge for models that assume that potential growth and yield are assimilate limited.

Is There a Unified, Underlying Stress Response?

In modeling crop adaptations and responses to stress, it is reasonable to consider whether crop species share basic mechanisms of stress tolerance. Common mechanisms should lead to simplifications in model development and testing, and many lines of evidence certainly support such commonality.

Cereal genomes are highly similar (Paterson et al. 1995), suggesting that biochemical pathways for basic stress response processes must also be similar. Free proline accumulates in water-stressed leaves of crops, including wheat, barley, rice, sorghum, and cotton (Stewart and Hanson 1980) and is presumed to play a critical role in osmotic adjustment. Various stresses induce synthesis of groups of proteins, such as those produced by plants under heat shock, which share characteristics across species (Ho and Sachs 1989). And at a level nearer the process complexity managed by most crop models, abscisic acid (ABA) plays a key role in root-to-shoot signaling of water deficits, soil compaction, and other soil-based stresses (Sharp and Davies 1989; Davies and Zhang 1991), causing a rapid reduction of leaf and shoot expansion.

By the same token, we must not undervalue the differences between crops such as maize and wheat. Maize has a short day response to photoperiod and requires no vernalization. Its C_4 photosynthetic pathway is usually argued as conferring greater tolerance to water deficits, high temperatures, and nitrogen deficiencies (Loomis and Connor 1992). Conversely, maize's monoecious reproductive system and extreme determinant growth reduce the ability of the crop to compensate for stresses during flowering and grain filling (Denmead and Shaw 1960; Edmeades et al. 1997).

The long day photoperiod response and vernalization requirement of wheat may suggest totally different physiological mechanisms but, in practice, very similar modeling approaches can represent temperature and photoperiod effects on development for the two crops, as well as many other cereals. The C_3 photosynthetic pathway of wheat, however, may require substantial differences in modeling responses to temperature and to water and nitrogen deficits. Furthermore, although wheat tillers are morphologically determinate, wheat plants show a much greater ability to compensate for stresses during grain filling than is found in maize.

How Can We Measure the Impact of Weeds, Insects, and Diseases?

Various approaches have been used for modeling the impact of weeds, insects, and diseases on maize and wheat production. In many cases, the underlying processes are well understood, and the main constraint is the availability of field data.

We would cite soil-borne diseases, however, as a specific challenge. Plant responses are less well understood and potentially involve changes in root growth and metabolism that are notoriously poorly represented in simulation models. Furthermore, soil borne diseases often have complex interactions among themselves, with water and nutrient deficits, and with soil organic matter. Relationships with soil organic matter link these diseases to conservation tillage and residue management, which most agronomists would agree are key to obtaining sustainable increases in tropical wheat and maize production.

How Can We Get Better Field Data?

Most workshops emphasizing systems approaches note the need for measuring relevant parameters correctly and exchanging data with colleagues. This workshop provides an opportunity to query whether data are still a major constraint. One might ask whether we measure the wrong things the wrong way and at the wrong locations. A glance at smallholders' fields in developing countries often reveals sparse and very irregular plant stands. Perhaps models should move away from the concept of an “average plant” and consider plant populations.

Incorrect measurement procedures include too small and improperly bordered plots, lack of clarity on whether grain weights are dry weights or at commercial grain moisture contents, and incorrectly calibrated instruments. The proposed file format standards being developed by ICASA (Hunt et al., these proceedings) offer one obvious vehicle for improving data exchange. However, the flexibility of these standards precludes requiring users to report details of methods and instruments used to obtain data. The International Crop Information System (ICIS) offers the promise of providing much more extensive documentation of research procedures, while still allowing modelers to use the ICASA standards (Lieshout et al., these proceedings).

We can also question whether research is conducted under relevant field conditions. The problems of experiment station biases are well known. Research sites are often selected for reasons related to suitability for plantation crops or ease of access and may lack soil or climatic regimes representative of smallholder, low-yield conditions. Another dimension for crop modeling, however, is whether enough extreme environments are incorporated. Crop research seldom includes environments that are hot or cold enough to shed light on the transition between crop failure and commercial viability. The large systems of international trials conducted by centers of the Consultative Group for International Agricultural Research (CGIAR) offer one under-exploited resource for such work, but access to “model ready” data is lacking.

Conclusion

Simulating performance of maize or wheat crops in environments offering extremes of high or low yield potential presents special challenges for crop modelers. However, such conditions are of relevance for a range of problems facing researchers both in developed and developing countries.

References

CIMMYT 1999. *CIMMYT 1997/98 World Maize Facts and Trends: Maize Production in Drought-Stressed Environments: Technical Options and Research Resource Allocation.* Mexico D.F.: CIMMYT.

Cukadar, B., R.J. Peña, D. Dunphy, and M. van Ginkel. 1997. The potential of hybrid wheat under irrigated conditions in Mexico. In *A Book of Abstracts. The Genetics and Exploitation of Heterosis in Crops: An International Symposium*, 190-191. Mexico, D.F.: CIMMYT.

Davies, W.J., and J. Zhang. 1991. Root signals and the regulation of growth and development of plants in drying soils. *Annual Review of Plant Physiology and Molecular Biology* 42:55-76.

Denmead, O.T., and R.H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. *Agronomy Journal* 52:272-274.

Edmeades, G.O., J. Bolaños, and S.C. Chapman. 1997. Value of secondary traits in selecting for drought tolerance in tropical maize. In G.O. Edmeades, M. Bänziger, H.R. Mickelson, and C.B. Peña-Valdivia (eds.), *Developing Drought and Low N-Tolerant Maize. Proceedings of a Symposium, March 25-29, 1996, CIMMYT, El Batán, Mexico*, 222-234. Mexico, D.F.: CIMMYT.

Gaytan-Bautista, R., and J.S. Padilla-Ramirez. 1997. Heterosis estimation for different quantitative maize characteristics using highland and subtropical progenitors. In *A Book of Abstracts. The Genetics and Exploitation of Heterosis in Crops: An International Symposium*, 36-37. Mexico, D.F.: CIMMYT.

Heisey, P.W., and G.O. Edmeades. 1999. Maize Production in Drought-Stressed Environments: Technical Options and Research Resource Allocation. Part 1 of *CIMMYT 1997/98 World Maize Facts and Trends; Maize Production in Drought-Stressed Environments: Technical Options and Research Resource Allocation*. Mexico, D.F.: CIMMYT.

Ho, T.-H. D., and M.M. Sachs. 1989. Environmental control of gene expression and stress proteins in plants. In H.G. Jones, T.J. Flowers, and M.B. Jones (eds.), *Plants Under Stress. Society for Experimental Biology Seminar Series 39,* 157-180. Cambridge: Cambridge University Press.

Hobbs, P.R., K.D. Sayre, and I. Ortiz-Monasterio. 1998. *Increasing Wheat Yields Sustainably Through Agronomic Means. NRG Paper 98-01.* Mexico, D.F.: CIMMYT.

Loomis, R.S. and D.J. Connor. 1992. *Crop Ecology: Productivity and Management in Agricultural Systems.* Cambridge: Cambridge University Press.

Muchow, R.C., T.R. Sinclair, and J.M. Bennett. 1990. Temperature and solar radiation effects on potential maize yield across locations. *Agronomy Journal* 82:338-343.

Paterson, A.H., Y.-R. Lin, Z. Li, K. Schertz, J.F. Doebley, S.R.M. Pinson, S.-C. Liu, J.W. Stansel, and J.E. Irvine. 1995. Convergent domestication of cereal crops by independent mutations at corresponding genetic loci. *Science* 269:1714-1718.

Sharp, R.E., and W.J. Davies. 1989. Regulation of growth and development of plants growing with a restricted supply of water. In H.G. Jones, T.J. Flowers and M.B. Jones (eds.), *Plants Under Stress. Society for Experimental Biology Seminar Series 39,* 71-93. Cambridge: Cambridge University Press.

Stewart, C.R., and A.D. Hanson. Proline accumulation as a metabolic response to water stress. In N.J. Turner and P.J. Kramer (eds.), *Adaptation of Plants to Water and High Temperature Stress*, 173-189. New York: John Wiley & Sons.

Stuber, C. 1997. The biology and physiology of heterosis. In *A Book of Abstracts. The Genetics and Exploitation of Heterosis in Crops: An International Symposium*, 108-109. Mexico, D.F.: CIMMYT.

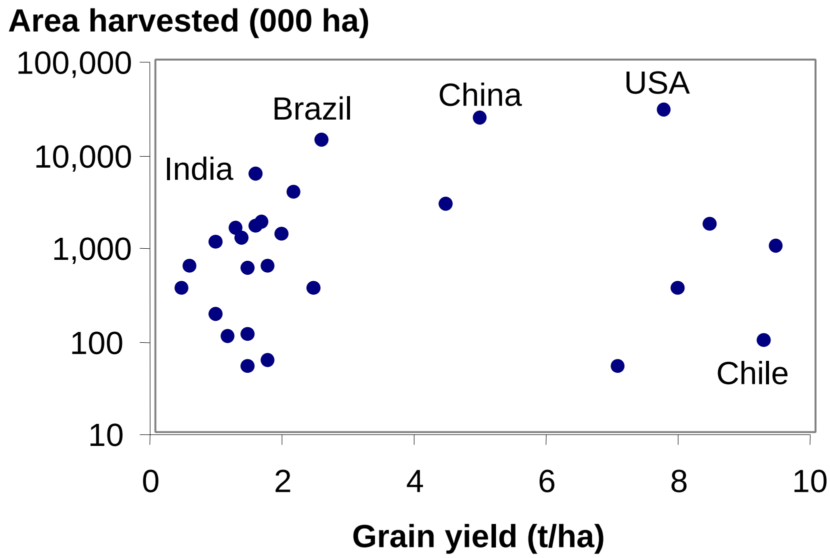


Figure 1. Comparison of maize production and area harvested (annual mean for 1995-97) for selected countries.
Sources: Aquino et al. 1999; CIMMYT 1999.

Simulating Nutrient Stress Effects on Phenological Development in Maize

Upendra Singh and Paul W. Wilkens
Research and Development Division, International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama

Abstract

Crop growth simulation models for maize reliably predict effects of temperature and photoperiod on crop duration, a major determinant of yield. But they usually ignore possible effects of extreme high/low temperatures, drought stress, or nutrient deficiencies on duration. Drought stress and nitrogen and phosphorus deficiencies during the vegetative phase can delay tassel initiation and silking. Similarly, stresses during ripening can cause early senescence and maturity. Thus, harvest management, yield forecasting, and planting of the subsequent crop can be affected. The performance of a modified maize model that simulates the effect of N deficiency on phyllochron and phenological stages is described and compared with actual data from maize trials in Nigeria, Hawaii, and Florida.

Introduction

The duration of growth for a particular cultivar is highly dependent on its thermal environment and photoperiod. Hence, the phenology of a crop is one of the major determinants of yield (Rabbinge et al. 1993). Accurate modeling of crop duration and growth is necessary for reasonable yield prediction. The essence of genotype x environment interaction is primarily associated with the timing of phenological events and environmental conditions (rainfall, temperature, radiation and photoperiod). Optimum timing of irrigation, fertilizer, and pesticides is also dictated by a crop's phenology, and any delay or acceleration of phenology affects the above management inputs and harvest operation. This paper summarizes the effect of temperature, photoperiod, and nitrogen deficiency on crop development in maize as reported by Singh et al. (1999).

Effect of Environment on Crop Development

As an approximation, one can consider crop development to be independent of growth. The phasic development or phenology is an ordered sequence of processes punctuated by discrete events, such as sowing, emergence, floral initiation, anthesis, and maturity. It is implicitly assumed that the plant, or part of the plant, possesses a development clock that proceeds at given rate (day^{-1}) for each of the above phases (Thornley and Johnson 1990). Variation between modern annual cultivars within a species is usually most evident in the duration of growth, duration of the vegetative and reproductive phases, and the least in the rate of growth. Growth and development processes have different degrees of variation and sensitivity to environmental and management factors (Table 1). Crop development has two distinctly unique features: phasic and morphological development. There is greater genotypic diversity for phasic development than for morphological development (Table 1).

 Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

Effect of Nitrogen Stress on Phenology

The current version of the CERES-Maize model, which is distributed in the DSSAT package (Tsuji et al. 1994) simulates nitrogen (N) response for growth, leaf area, leaf weight, stem weight, grain yield, and yield components (grain weight and grains per ear). The model uses two sets of N stress indices as a function of the N deficiency factor (NFAC) to simulate the effect of N stress on leaf expansion and photosynthesis. The NFAC is estimated as the ratio of N supply (from soil and fertilizers) to plant N demand. Godwin and Singh (1998) have presented a complete description of the N model. The model, however, does not simulate the effect of N stress on phenology.

N stress was shown to delay slightly the appearance of leaves. However, due to delayed silking, the final number of leaves was quite similar at low and high N rates (Bennett et al. 1989). Associated with the delayed silking, anthesis-silking interval (ASI) increased with N stress. A drastic reduction in grains per ear occurs as ASI goes beyond five days (Elings et al. 1996). The modifications to the CERES-Maize model to simulate the effect of N stress on crop development have been fully discussed by Singh et al. (1999).

The delay in phasic development prior to silking was modeled with severe N stress, resulting in a decreased rate of thermal time accumulation. For the same degree of N stress, the delay was more pronounced during the reproductive phase (tassel initiation to silking) than during the vegetative phase (emergence to tassel initiation). The relationship was based on results from field trials and greenhouse studies (Singh et al. 1999).

The average N stress effect over the reproductive period (tassel initiation to silking) was used by the model to modify ASI, which in turn determines the number of grains per ear. As illustrated by the sensitivity analysis on maize cultivar Pioneer X304C sown during the dry season in Waipio, Hawaii (Singh 1985), the days to silking increased from 78 to 108 as N deficiency in the plant increased (Fig. 1). In association with the delayed silking, ASI also increased.

The phyllochron, or leaf appearance rate, is least affected by N stress; as a result, the final leaf number changes only slightly. In contrast, P deficiency resulted in an up to 32% increase in phyllochron (Rodriguez and Goudriaan 1995). Under increasing P stress conditions, final leaf numbers were reduced.

Nitrogen stress during grain-filling shortens the duration of this phase; the opposite effect of stress during pre-silking (Table 2). However, the combined effect of N stress on the duration of sowing to maturity may be small. Under N limiting conditions, both the effect on growth and the shortened duration of the grain-filling stage contribute to lower grain yield.

Effect of N Stress on Grain Number

Grain number per unit area is usually the most critical determinant of maize grain yield (Ritchie et al. 1998). Since maize cultivars vary in grain numbers, the CERES-Maize model uses a cultivar coefficient for a reference grain number, G2 (Ritchie et al. 1989). The model uses the concept of Edmeades and Daynard (1979) to estimate grain number from the average rate of photosynthesis around silking. The effect of N stress on grain number occurs indirectly through N stress effect on photosynthesis and also via its effect on silking date and ASI.

The sensitivity of grain number and hence grain yield to mean N stress during the reproductive phase is apparent on the maize cultivar Pioneer X304C, grown in Hawaii (Fig. 2). The cultivar coefficient, G2, for X304C is 690 grains per ear. The CERES-Maize model simulated 50-500 grains per ear over the range of N deficiency. Grain yields for these treatments ranged from 555 to 7,180 kg/ha.

Validation of the Phenology Model

The effect of N stress on growth (expansion and mass), phasic development (growth stages), and morphological development (leaf numbers and grain numbers) was simulated by the modified CERES-Maize model. The performance of the model on actual field trials from Zaria, Nigeria (Oikeh et al. 1997), Gainesville, Florida (Bennett et al. 1989), and Waipio, Hawaii (Singh 1985) is presented in Figure 3. The model accurately captured the observed delays of up to 10 days to silking and a reduced grain-filling duration of up to 14 days. Further validation of the model is planned with tropical maize data from IFDC-Africa, CIMMYT, and IITA.

Conclusions

The availability of nutrients and water is a primary constraint to agricultural production in much of sub-Saharan Africa. With increasing population pressure and continued soil nutrient mining, these limitations will become even more pronounced. Implicit with managing cropping systems under nutrient-limited conditions is quantifying the duration and timing of phenological development to utilize limited water and nutrient resources more effectively. The modified CERES-Maize model is sensitive to changes in crop duration based on the effect of environment and nutrient management. The model coupled with real-time weather will facilitate and enhance the ability to forecast yields under limiting conditions, improve resource use efficiency, and minimize deleterious effects of cropping practices on the environment.

Acknowledgments

The Soil, Water, and Nutrient Management Program of the CGIAR supported part of this research.

References

Bennett, J.M., L.S.M. Mutti, P.S.C. Rao, and J.W. Jones. 1989. Interactive effects of nitrogen and water stresses on biomass accumulation, nitrogen uptake, and seed yield of maize. *Field Crops Research* 19:297-311.

Edmeades, G.O., and T.B. Daynard. 1979. The relationship between final yield and photosynthesis at flowering in individual maize plants. *Canadian Journal of Plant Science* 59:585-601.

Elings, A., J. White, and G.O. Edmeades. 1996. Modelling tropical maize under drought and low N. Agronomy Abstracts, 1996 Annual Meeting, Indianapolis, Indiana, November 3-8, 1996, p. 109. Madison, Wisconsin, USA: American Society of Agronomy.

Godwin, D.C., and U. Singh. 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In G.Y. Tsuji et al. (eds.), *Understanding Options for Agricultural Production*, 55-77. Dordrecht: Kluwer Academic Publishers.

Oikeh, S.O., J.K. Kling, W. Horst, and V.O. Chude. 1997. Yield and N-Use efficiency of five tropical maize genotypes under different N levels in the moist savanna of Nigeria. In J.K. Ransom et al. (eds.), *Maize Productivity Gains Through Research and Technology Dissemination; Proceedings of the Fifth Eastern and Southern Africa Regional Maize Conference held in Arusha, Tanzania, 3-7 June 1996*,163-167. Addis Ababa, Ethiopia: CIMMYT.

Rabbinge, R., H.C. van Latesteijn, and J. Goudriaan. 1993. Assessing the greenhouse effect in agriculture. In *Environmental Change and Human Health. Ciba Foundation Symposium 1975*, 62-79. Chichester, UK: John Wiley & Sons.

Ritchie, J.T. 1991. Specification of the ideal model for predicting crop yields. In R.C. Muchow and J.A. Bellamy (eds.), *Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics. Proceedings, International Symposium, St. Lucia, Brisbane, Queensland, Australia,* 97-122. Wallingford, UK: CAB International.

Ritchie, J.T., U. Singh, D.C. Godwin, and W.T. Bowen. 1998. Cereal growth, development, and yield. In G.Y. Tsuji et al. (eds.), *Understanding Options for Agricultural Production*, 79-98. Dordrecht: Kluwer Academic Publishers.

Rodriguez, D., and J. Goudriaan. 1995. Effects of phosphorus and drought stresses on dry matter production and phosphorus allocation in wheat. *Journal of Plant Nutrition* 18:2501-2517.

Singh, U. 1985. A crop growth model for predicting corn (*Zea mays* L.) performance in the tropics. Ph.D. Thesis, University of Hawaii, Honolulu, Hawaii, USA.

Singh, U., P. Wilkens, V. Chude and S. Oikeh. 1999. Predicting the effect of nitrogen deficiency on crop growth duration and yield. In P.C. Robert et al. (eds.), *Proceedings of the Fourth International Conference on Precision Agriculture. 19-22 July 1998, St. Paul, Minnesota, USA*, 1379-1393. Madison, Wisconsin, USA: American Society of Agronomy.

Thornley, J.H.M., and I.R. Johnson. 1990. Plant and Crop Modelling: A Mathematical Approach to Plant and Crop Physiology. Oxford: Oxford Science Publications.

Tsuji, G.Y., G. Uehara, and S. Balas. 1994. DSSAT V.3: A decision support system for agrotechnology transfer. Honolulu: University of Hawaii.

Table 1. Factors influencing plant growth and development processes in CERES models (Adapted from Ritchie, 1991).

	Growth		**Development**	
	Mass	**Expansion**	**Phasic**	**Morphological**
Environmental factor	Solar radiation	Temperature	Temperature, photoperiod	Temperature
Degree of variation among cultivars	Low	Low	High	Low
Sensitivity to plant water deficit	Low – stomata Moderate – leaf rolling and wilting	High – vegetative phase Low – grain filling stage	Low – delay in vegetative stage	Low
Sensitivity to N and P deficiency	Moderate	High	Low	Low – main stem High – tillers and branches

Table 2. Effect of three nitrogen application rates on phenological stages of two maize cultivars grown in Hawaii (Singh, 1985).

Cultivar	**N rate (kg N ha^{-1})**	**Days to silking**	**Grain filling duration (d)**	**Days to maturity**
Pioneer X304C	0	83	53	136
	50	78	59	137
	200	78	59	137
H610 (Hawaii)	0	80	51	131
	50	76	57	133
	200	75	58	133

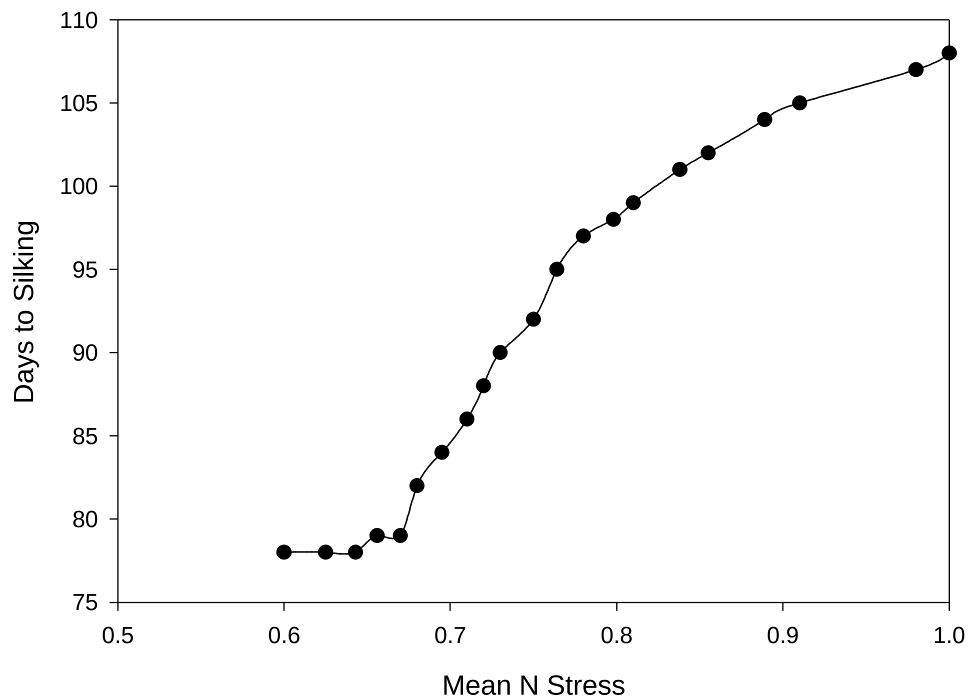


Figure 1. Sensitivity of CERES-Maize to the effect of mean N stress during reproductive phase on silking date (days after sowing). *Source: Singh et al. (1999).*

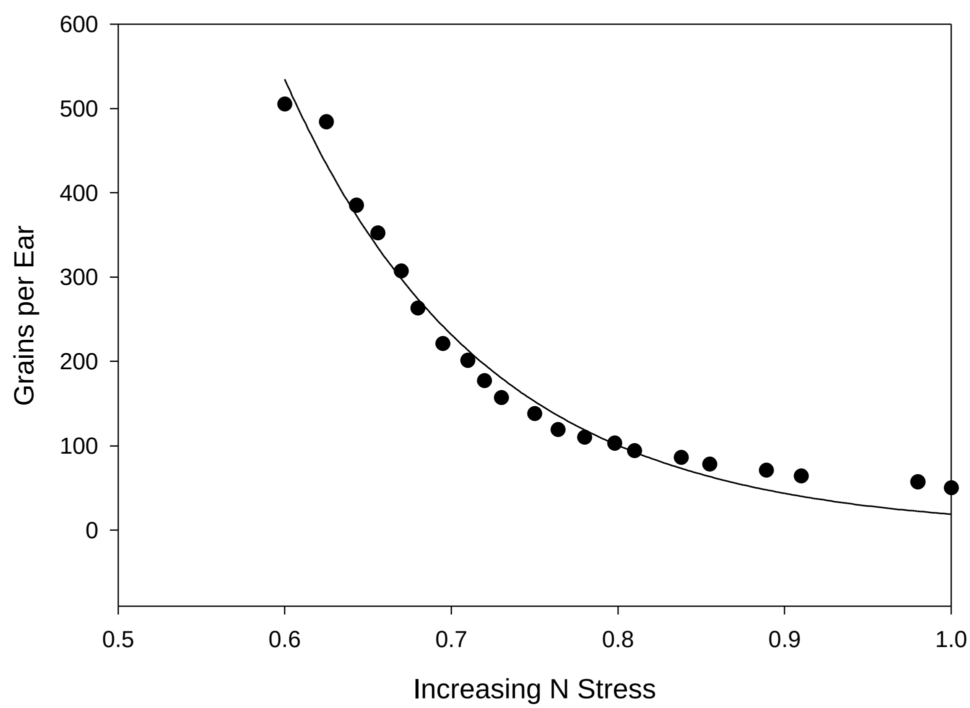


Figure 2. Sensitivity of grain numbers per ear to the mean N stress during the reproductive phase as simulated by CERES-Maize. *Source: Singh et al. (1999).*

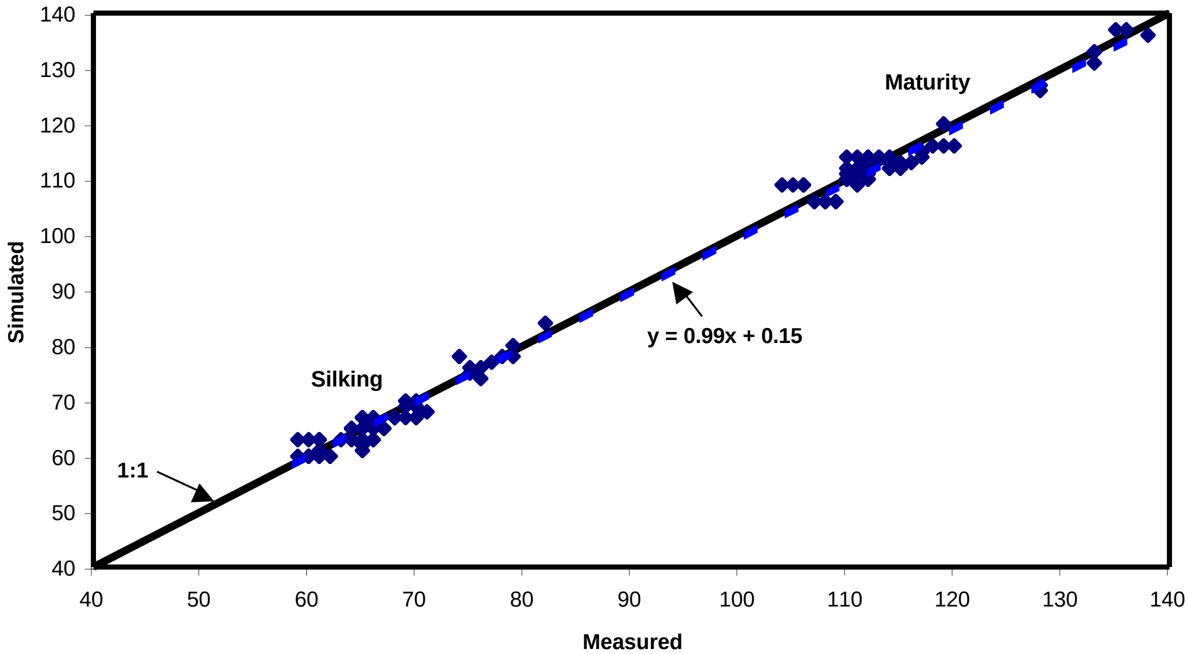


Figure 3. Comparison of observed and simulated days to silking and maturity.
Source: Singh et al. (1999).

Use of Linear Regression and a Correlation Matrix to Evaluate CERES3 (Maize)

A.S. du Toit,[1] J. Booysen,[2] and J.J. Human[3]
[1]Agricultural Research Council, Summer Grain Centre, RSA; [2]PU vir CHO, Navorsingsinstituut vir Hervestigingsekologie, RSA; [3]UOVS, Department of Agronomy, RSA

Abstract

A historical dataset (soil water content, growth, phenology, yield) for six cultivars and three planting dates was used to evaluate the CERES3 crop growth model. Linear regression and a correlation matrix were used to identify model algorithms in need of calibration. Results indicated that the model simulates yield and kernel number with low accuracy under local conditions. Ears per plant and water stress before and during silking were identified as factors that could explain the low accuracy.

'n Historiese datastel (grondwaterinhoud, groei, fenologie en opbrengs) bestaande uit 6 cultivars en 3 plantdatums is gebruik om die CERES3 gewasgroeimodel te evalueer. Met behulp van linêre regressie en korrelasie matriks is algoritmes in die model geidentifiseer wat gekalibreer moet word. Die resultate toon aan dat die model graan opbrengs en pitmassa met lae akkuraatheid simuleer. Aantal koppe per plant en water stremming voor en gedurende blom is as faktore geidentifiseer wat die lae akkuraatheid vir beide pit aantal en opbrengs simulasie verklaar.

Introduction

Water is the most limiting factor in dryland maize production in South Africa. Use of low population densities, in combination with wide rows and prolific cultivars, makes it possible to produce maize under these semiarid conditions.

To verify and calibrate a crop growth model, criteria are needed to evaluate model performance. It is generally accepted that the ultimate test of a simulation model is the accuracy with which it describes the actual system, thus requiring comparison of simulated and observed data (Willmott 1982; Jones and Kiniry 1986; Oreskes et al. 1994) . A number of statistical methods are available to analyse model performance, including linear regression techniques (Jones and Kiniry 1986; Flavella 1992), D-index and systematic and unsystematic mean square errors (Willmott 1982).

Jones and Kiniry (1986) used linear regression techniques of the form $y = a + bx$ with simulated results as the independent variable. Good model performance was obtained when the intercept (a) approached zero and the slope of the regression (b) approached unity, indicating a near perfect relationship between observed and simulated values. Complementary to this regression, the Pearson correlation coefficient (r) can also be calculated, indicating the similarity or inverse similarity of a response in *y* for a response in *x*. The coefficient of determination (r^2) can be obtained from r, signifying the percentage of variance accounted for by the model.

 Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

Deficiencies in the above-mentioned statistical parameters were noted by Willmott (1982) and Harrison (1990). Observed and simulated data may occur in a narrow band, whereas this is usually not the case with the coefficients. Secondly, it is difficult to identify the point at which a model ceases to be valid or invalid. Savage (1993) warned against the use of a correlation coefficient if data are not randomly distributed.

Willmott (1982) recommended use of the D-index (index of agreement), RMSEs (root mean square error systematic), RMSEu (root mean square error unsystematic), and RMSE (root mean square error) for model evaluation. Due to limitations in the use of correlation coefficients as an agreement index, Savage (1993) stated that the statistics defined by Willmott (1982) are preferable. According to Wilmott (1982), a "good" model's D-index should approach unity and the RMSEs zero, whereas RMSEu should approach RMSE.

The Mean Absolute Error (MAE) and RMSE are among the best overall measures of model performance, and are calculated as follows:

$$\text{MAE} = n^{-1}\sum_{i=1}^{n} |Pi - Oi| \qquad (1)$$

$$\text{RMSE} = \left[n^{-1}\sum_{i=1}^{n} (Pi - Oi)^2 \right]^{0.5} \qquad (2)$$

where n is the number of treatments and i the number of a specific treatment. These statistical parameters quantify the mean difference between observed (Oi) and predicted (Pi) values (Willmott 1982).

The advantage of RMSEs is that it indicates the bias (deviation of the actual slope from the 1:1 line) in a particular model, compared with the random variation (RMSEu) that may occur (Savage 1993). The RMSEs and RMSEu are calculated as follows:

$$\text{RMSEs} = \left[n^{-1}\sum_{i=1}^{n} \left(\hat{P}i - Oi \right)^2 \right]^{0.5} \qquad (3)$$

$$\text{RMSEu} = \left[n^{-1}\sum_{i=1}^{n} \left(Pi - \hat{P}i \right)^2 \right]^{0.5} \qquad (4)$$

where $\hat{P}i$ is regarded as the best estimate of the predicted quantity (Savage 1993) calculated with the intercept (a) and slope (b) of the least-squares regression, $\hat{P}i$ = a + b0i (Willmott 1982). Willmott (1982) proposed an "index of agreement" (D) of the form

$$D = 1 - \left[\sum_{i=1}^{n} (Pi - Oi)^2 / \sum_{i=1}^{n} \left(|P'i| + |O'i| \right)^2 \right] \qquad (5)$$

where $P'i = Pi - \bar{O}$ (average of the observed) and $O'i = Oi - \bar{O}$. The index (D) is intended to be a descriptive measure, which is both a relative and bounded measure and can be widely applied to make cross-comparisons between models (Willmott 1982).

Observed vs. simulated graphs, also known as 1:1 graphs, are widely used in simulation evaluations (Willmott 1982; Jones and Kiniry 1986). Harrison (1990) stated that any statistical method can be combined with 1:1 graphs, to help identify the pattern of differences between the predicted and observed values.

The evaluation of CERES3 using different statistical parameters for this particular trial was done for yield, kernel number, and silking date. These where chosen because of the low accuracy experienced in yield simulations under certain climatic conditions and management practices (Carberry et al. 1989; Du Toit et al. 1994), in the simulation of kernel number (Jones and Kiniry 1986; Carberry et al. 1989; Ogoshi 1995), and in the simulation of silking date, which contributes to a low accuracy in yield simulation.

In this study, we evaluated the ability of CERES3 (Hoogenboom et al. 1994) to simulate the compensation potential of the maize plant under local conditions of reduced plant populations, comparing model outputs against field data. The purpose was to identify the most sensitive algorithms in the model and thus improve the accuracy of simulated yield.

Materials and Methods

For the present study, we chose a trial from the so-called "Phoenix project"[1] (De Vos and Mallett 1986) in which data were taken for both low yields (indicating a low or negative level of yield compensation) and above average yields (indicating a high level of yield compensation) for the particular management practices. Data on silking date, grain yield and kernel number were taken from the trial for Potchefstroom, (26 ^{o}44' S, 27 ^{o}06' E, 1,345 masl). The trial included six cultivars—two early maturing, two of intermediate maturity, and two late maturing—sown at 1.8 plants/m^2 in 1.1 m wide rows (Table 1). Yields ranged from 1,214 to 5,323 kg/ha for the three planting dates.

The crop model used was CERES3, in which the CERES models for maize, sorghum, wheat, millet and barley are combined to provide a generic, multicrop model to run with a single set of code, incorporating the development and growth sections for each individual model into a single module with a single soil component (Tsuji et al. 1994). According to Ritchie (1991), generic models should allow users to have more uniform procedures for validating models or to link with components not included in the sole crop model. The generic CERES3 (Hoogenboom et al. 1994) was used for the simulations.

Results and Discussion

Yield Simulation

The simulation accuracy of yield was extremely low (r^2=0.0001; Table 2, Fig. 1). This contrasts with previous results of Thornton et al. (1995), who reported r^2 values of 0.94 (CERES-Maize v2.1) for trials in Malawi, but agrees with the assessment by Mbabaliye and Wojtkowski (1994), who reported an r^2 of 0.10 (CERES-Maize v1.0) in Rwanda.

---

[1] South African field datasets collected since 1982/83 that can be used to evaluate and calibrate maize growth simulation models. The data were taken for proven cultivars grown under variable climatic conditions, soil types, planting dates and plant densities.

Comparing the observed and simulated means in Table 2, CERES3 shows a slight under-prediction. The RMSEs value of 1,001 kg/ha in comparison with the RMSE value of 1,374 kg/ha shows that a high level of bias is associated with the model. Willmott (1982) observed that the differences described by RMSEs are a linear function. This could easily be reduced by new parameterization, such as changing soil parameters or genetic coefficients, or by recalibrating existing functions. Savage (1993) observed that the model might become site specific in such cases. The fact that both systematic and unsystematic errors were relatively close to RMSE indicated the error to be biased and random. The D-index of 0.39 and r^2 of 0.00 suggest that the model does not adequately simulate yield regardless of the statistical measurement used. The slope of the linear regression line of 0.0087 in Figure 1 indicates a tendency to over-predict at low grain yield and under-predict at higher values.

Jones and Kiniry (1986) suggested that input errors are more likely and, in practical terms, a more serious source of poor model predictions than are logic or calibration errors. The following input data were investigated as possible sources of error in the simulation of grain yield.

Genetic coefficients. The genetic coefficients for the Phoenix project were determined in different field trials subjected to minimal water stress as described by Jones and Kiniry (1986). In this study it was assumed that those genetic coefficients were correct and not the factor causing error. Genetic coefficients could be used to decrease the variation between observed and predicted values (the error), but these could possibly be site specific (Ogoshi 1995).

Soil input data. Sensitivity analyses done on CERES-Maize V1.0 (Jones and Kiniry 1986) with regard to soil input data showed that simulated yield was sensitive to factors such as initial soil water content, lower limit of plant extractable water (LL), and drained upper limit (DUL). In the Phoenix project, the initial soil water content was measured (gravimetrically) for each of the planting dates, so this variable is unlikely as a possible input error in the simulation of the trial. Both the visual analysis of Figures 2 to 4 and the quantitative measures in Table 3 indicate that CERES3 gave a reasonably accurate prediction of the change of plant extractable water over the growing season for the three planting dates of the historical data. The error in simulation could not therefore be attributed to errors in LL and DUL.

Plotting the difference between observed and simulated yield (error) in Figure 5 indicated a strong negative correlation between yield and error ($r^2 = 0.52$). Yields below 2,908 kg/ha showed a positive error, whereas yields above this value showed a negative error, implying that it is possible that the positive (underestimation) and negative (overestimation) errors could have been caused by different factors. These factors need to be identified to explain the bias of the model with the observed range of yields.

- *Positive error.* One possible factor was water stress, which Carberry et al. (1989) identified in CERES-Maize v1.0 as the reason for low simulation accuracy at low yields. To identify whether water stress could explain the positive error, the observed yields (Fig. 5) where replaced by the simulated water stress index during different growth stages and incorporated in a linear regression (Table 4). These results indicated that 30% of the error could be explained by water stress before silking and 44% by water stress during silking, both of the correlation coefficients being significant. Inaccurate water stress simulations could therefore explain the positive error in Figure 5.

- *Negative error.* Another possible factor is ear prolificacy, which Du Toit, Booysen, and Human (1994) identified in CERES-Maize v2.1 as one of the main reasons for low simulation accuracy at above average yields. The observed numbers of ears per plant, as an indicator of prolificacy, replaced observed yield (Fig. 5) and were fitted against the error in a yield simulation (Table 4). These results indicated that 42% of the error could be explained by the inability to simulate ear number per plant, as indicated by the significant correlation.

Kernel Number

Grain yield simulation represents the net integration of every operative system in the model. In Table 4 water stress during silking was identified as a reason for low accuracy in yield simulation. The algorithm that is directly influenced by water stress during silking is the simulation of kernel number. If accuracy in the simulation of kernel number is low, accuracy of the simulation of grain yield can be expected to be inadequate (Jones and Kiniry 1986).

The simulation of kernel number per plant was identified as a system of CERES-Maize in need of calibration by both Jones and Kiniry (1986) and Carberry et al. (1989) for version 1.0, and Ogoshi (1995) for version 2.1. This was confirmed in the present study as indicated by the quantitative measures provided in Table 5. Kernel number was simulated with low accuracy, explaining the low accuracy of yield simulation. Comparison of RMSEs with RMSE indicates a high level of bias in the kernel simulation of CERES3, whereas RMSEu compared to RMSE shows a low level of random error. In Figure 6 the slope of the regression (broken line) of -0.005 for the simulation of kernel number per unit area indicates a similar tendency in the regression for yield simulation (Fig. 1). Both the statistics and the 1:1 graph indicate that the low accuracy of kernel number simulation could explain the low accuracy in yield prediction.

The effect of water stress and ear prolificacy on simulation error associated with kernel number were recalculated, using the same procedure described for yield in Table 4. Water stress during silking explained 61% of the error associated with simulation of kernel number, while ear number per plant contributed 52% to the error. Both correlation coefficients were significant at P= 0.001. The sensitivity of kernel number to water stress during silking has been well documented (Herrero and Johnson 1981; Schussler and Westgate 1991; NeSmith and Ritchie 1992; Basseti and Westgate 1993; Otegui et al. 1995). It appears that the simulation error for kernel number should decrease, if the effect of water stress is calibrated and prolificacy is simulated (Table 6).

Silking Date

Errors in the prediction of silking date may have contributed to errors in kernel number simulation and, consequently, in yield simulation. This was indicated by Carberry et al. (1989), who reported improved yield simulation by CERES-Maize v1.0 through improving the simulation of silking date. The four days for which the simulated mean was lower than the observed mean (Table 7) indicate an underestimation by CERES3 as confirmed by a MAE value of 3.94 days. The RMSEs value of 3.98 days against the RMSE value of 4.51 indicates that, by calibrating the functions that simulate silking, error in silking simulation would decrease. The simulation of delayed germination and of leaf number (Carberry et al. 1989; Du Toit et al. 1994) are functions in need of calibration because of their influence on silking date.

Conclusion

A plant population of 1.8 plants/m^2 in combination with row widths of 1.1 m for this trial was beyond the limits for which CERES was originally developed. Prolificacy simulation is not relevant at populations of 6.0 plants/m^2 but is applicable to densities of 1.8 plants/m^2. These factors could have contributed to the low accuracy of the yield simulation of the 1986/87 trial.

Grain yield simulation represents the net integration of every component in the model. The differences between the observed and simulated yields (error) revealed a significant correlation with water stress and ears per plant. Simulation of these two variables was poor and needs to be improved to minimize the error in simulated grain yield.

Kernel number is an important component of grain yield and is sensitive to environmental stresses during silking. The lack of simulation of sensitivity of kernel number to water stress during silking explains the consequent errors in kernel number and yield simulation. The significant correlation between prolificacy and the simulation error in kernel number highlights the need to include simulation of prolificacy in models such as CERES3.

References

Basseti, P., and M.E. Westgate. 1993. Water deficit affects receptivity of maize silks. *Crop Science* 33:79-282.

Carberry, P.S., R.E. Muchow, and R.L. McCown. 1989. Testing the CERES-Maize simulation model in a semiarid tropical environment. *Field Crops Research* 20:297-315.

de Vos, R.N., and J.B. Mallett. 1987. Preliminary evaluation of two maize (*Zea mays* L.) growth-simulation models. *South Africa Journal of Plant and Soil* 4:131-135.

du Toit, A.S., J. Booysen, and J.J. Human. 1994. Evaluation and calibration of CERES-Maize. 3. Row widths for the western Highveld. *South Africa Journal of Plant and Soil* 4:153-158.

Flavella, P. 1992. A quantitative measure of model validation and its potential use for regulatory purposes. *Advances in Water Research* 15:5-13.

Harrison, S.R. 1990. Regression of a model on real-system output: An invalid test of model validity. *Agricultural Systems* 34(3): 183-190.

Herrero, M.R., and R.R. Johnson. 1981. Drought stress and its effects on maize reproductive systems. *Crop Science* 21:105-110

Hoogenboom, G., J.W. Jones, P.W. Wilkens, W.D. Batchelor, W.T. Bowen, L.A. Hunt, N.B. Pickering, U. Singh, D.C. Godwin, B. Baer, K.J. Boote, J.T. Ritchie, and J.W. White. 1994. Crop models. In G.Y. Tsuji, G. Uehara, and S. Balas (eds.). DSSAT3. Vol. 2-2. Honolulu: University of Hawaii.

Jones, C.A ., and J.R. Kiniry. 1986. CERES-Maize: A simulation model for maize growth and development. College Station: Texas A&M University Press.

Mbabaliye, T., and P.A. Wojtkowski. 1994. Problems and perspectives on the use of a crop simulation model in an African research station. *Experimental Agriculture* 30:441-446.

NeSmith, D.S., and J.T. Ritchie. 1992. Effects of soil water deficits during tassel emergence on development and yield components of maize (*Zea mays* L.). *Field Crops Research* 28:251-256.

Otegui, M.E., F.H. Andrade, and E.E. Suero. 1995. Growth water use, kernel abortion of maize subjected to drought at silking. *Field Crops Research* 40:87-94.

Ogoshi, R.M. 1995. Determination of genetic coefficients from yield experiments for CERES-Maize and Soygro crop growth models. PhD dissertation, University of Hawaii, Honolulu, Hawaii.

Oreskes, N., K. Shrader-Frechette, and K. Belitz. 1994. Verification, validation, and confirmation of numerical models in the Earth science. *Science* 263:641-646.
Ritchie, J.T. 1991. Specifications in the ideal model for predicting crop yields. *In*: R.C. Muchow and J.A. Bellamy (eds.), *Climatic Risk in Crop Production: Models and Management for the Semi-arid Tropics and Subtropics. Proc. Int. Symp., St. Lucia, Brisbane, Queesnland, Australia. July 2-6, 1990,* 97-122. Wellingford, U.K.: C.A.B. International.
Savage, M.J. 1993. Statistical aspects of model validation. Presented at a workshop on the field water balance in the modeling of cropping systems, University of Pretoria, South Africa.
Schussler, J.R., and M.E. Westgate. 1991. Maize kernel set at low water potential: I. Sensitivity to reduced assimilates during early kernel growth. *Crop Science* 31:1189-1195.
Thornton, P.K, A.R. Saka, U. Singh, J.D.T. Kumwenda, J.E. Brink, and J.B. Dent. 1995. Application of a crop simulation model in the central region of Malawi. *Experimental Agriculture* 31: 213-226.
Tsuji, G.Y., J.W. Jones, G. Hoogenboom, L.A. Hunt, and P.K. Thornton. 1994. Introduction *In*: Tsuji, G.Y., Uehara, G and Balas, S (eds.) DSSAT3. Vol. 1-1. University of Hawaii, Honolulu, Hawaii.
Willmott, C.J., 1982. Some comments on the evaluation of model performance. *Bulletin of the American Meteorological Society* 63:1309-1313.

Table 1. Grain yield (kg/ha) and planting dates of six cultivars of various maturity classes.

Cultivar	Maturity class	Planting dates 15/10/86	05/11/86	27/11/86
PAN394	Early	4,508	2,598	1,696
PAN6364	Early	3,450	3,088	2,459
SNK2244	Medium	3,429	3,767	2,038
PAN473	Medium	3,401	3,322	1,799
TX24	Late	5,323	3,351	1,214
PAN6528	Late	3,726	2,668	2,063

Table 2. Quantitative measures of CERES3 yield (kg/ha) performance.

	Observed	Simulated
Minimum	1,214	1,362
Maximum	5,323	4,261
Mean	2,994	2,930
Std Dev	1,036	969
Slope		0.01
Intercept		2,968
MAE		1,250
RMSE		1,374
RMSEs		1,001
RMSEu		941
D-Index		0.39
r^2		0.00

Table 3. Quantitative measures of CERES3 plant extractable water (mm) performance.

	Observed	**Simulated**
Minimum	0	0
Maximum	134	125
Mean	38	52
Std Dev	43	37
Slope		1.05
Intercept		-16
MAE		17
RMSE		22
RMSEs		16
RMSEu		15
D-Index		0.92
r^2		0.82

Table 4. Correlation (r) and probability (P) associated with observed, simulated and observed-simulated yield (kg/ha), with possible different error factors.

Possible error factors	**Observed yield**	**Simulated yield**	**Obs-Sim yield (Error)**
Water stress before silking (Simulated)	r = -0.55 P = 0.02 *	r = 0.22 P = 0.38 ns	r = 0.55 (30%) P = 0.02 *
Water stress during silking (Simulated)	r = -0.68 P = 0.00 **	r = 0.22 P = 0.37 ns	r = 0.66 (44%) P = 0.00 **
Water stress after silking (Simulated)	r = -0.57 P = 0.01 *	r = -0.65 P = 0.00 **	r = -0.03 (0%) P = 0.90 ns
Ears per plant (Observed)	r = 0.74 P = 0.00 **	r = -0.15 P = 0.54 ns	r = -0.65 (42%) P = 0.00 **

* P < 0.05 ** P < 0.01

Table 5. Quantitative measures of CERES3 kernel number performance.

	Observed	Simulated
Minimum	419	990
Maximum	1,566	1,105
Mean	1,049	1,050
Std Dev	352	35.37
Slope		-0.01
Intercept		1,053
MAE		299
RMSE		343
RMSEs		341
RMSEu		34
D-Index		0.11
r^2		0.05

Table 6. Correlation (r) and probability (P) associated with the correlation between observed, simulated and observed-simulated kernel number m^{-2} with possible different error factors.

Possible error factors	Observed yield	Simulated yield	Obs-Sim grain number(Error)
Water stress before silking (Simulated)	r = -0.65 P = 0.00 **	r = 0.02 P = 0.94 ns	r = 0.64 (44%) P = 0.00 **
Water stress during silking (Simulated)	r = -0.80 P = 0.00 **	r = -0.13 P = 0.61 ns	r = 0.78 (61%) P = 0.00 **
Water stress after silking (Simulated)	r = -0.26 P = 0.29 ns	r = -0.02 P = 0.92 ns	r = 0.26 (7%) P = 0.29 ns
Ears per plant (Observed)	r = 0.77 P = 0.00 **	r = 0.37 P = 0.13 ns	r = -0.72 (52%) P = 0.00 **

* P < 0.05 ** P < 0.01

Table 7. Quantitative measures of CERES3 silking date performance for the 1986/87 Potchefstroom trial.

	Observed	**Simulated**
Minimum	64	60
Maximum	77	73
Mean	70	66
Std Dev	4.28	3.85
Slope		0.9
Intercept		9.54
MAE		3.94
RMSE		4.51
RMSEs		3.98
RMSEu		2.12
D-Index		0.74
r^2		0.68

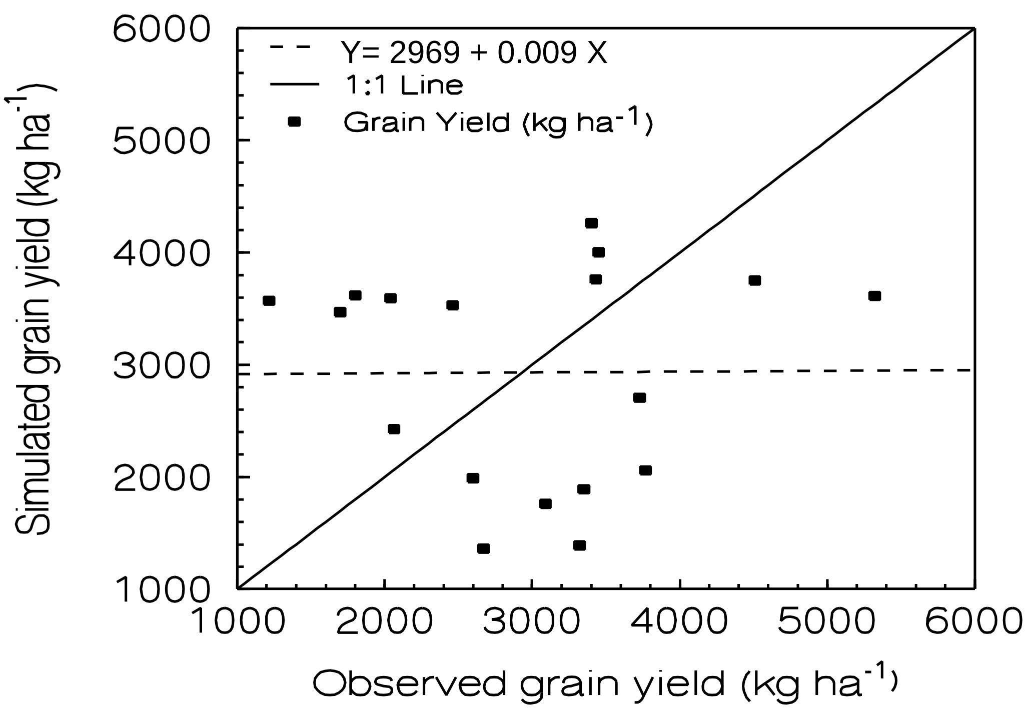


Figure 1. A comparison of observed and simulated maize grain yield at Potchefstroom, Grain Crops Institute, 1986/87 season (r^2 = 0.00).

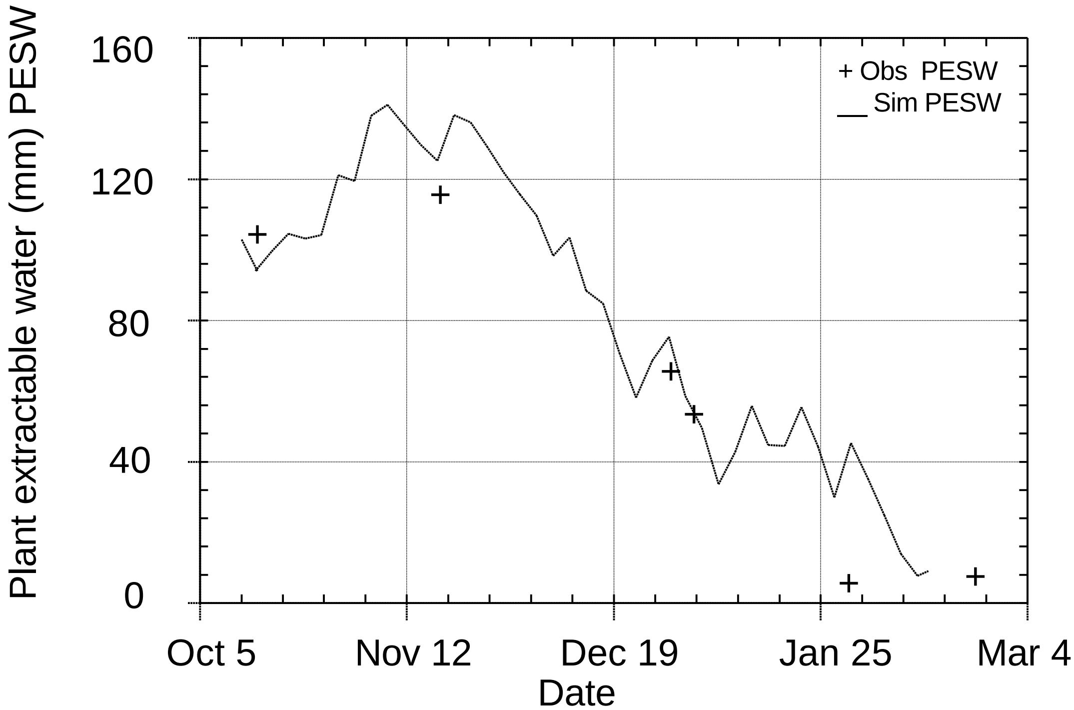


Figure 2. A comparison of observed and simulated plant extractable water over time for the 15 October 1986 planting date for 6 cultivars.

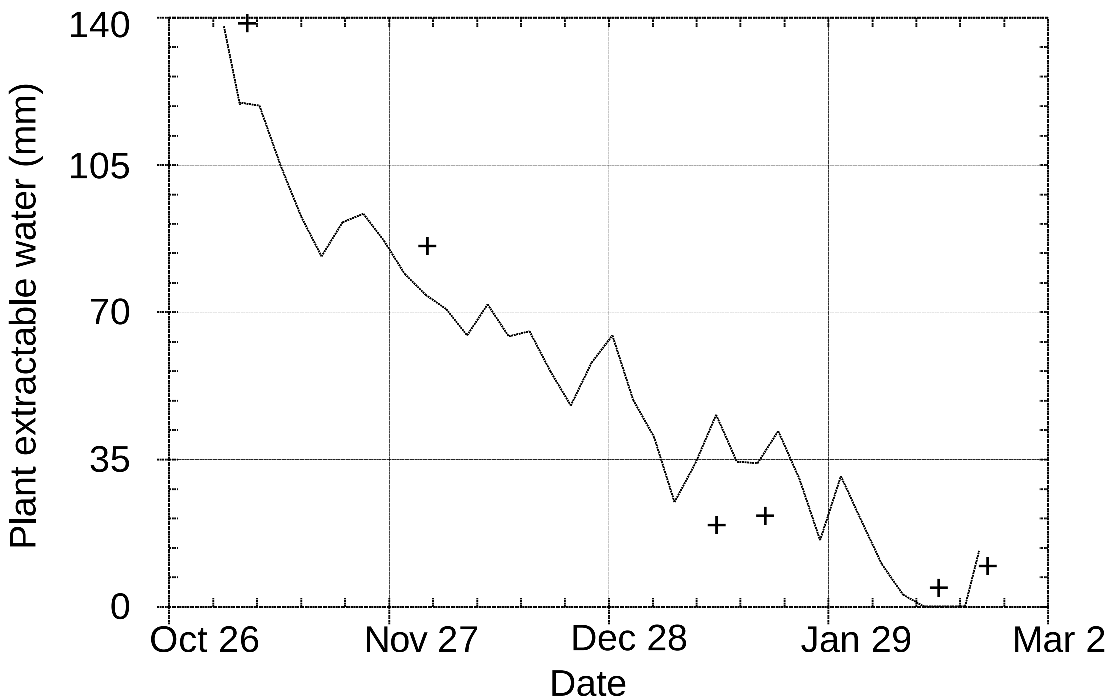


Figure 3. A comparison of observed and simulated plant extractable water over time for the 5 November 1986 planting date for 6 cultivars.

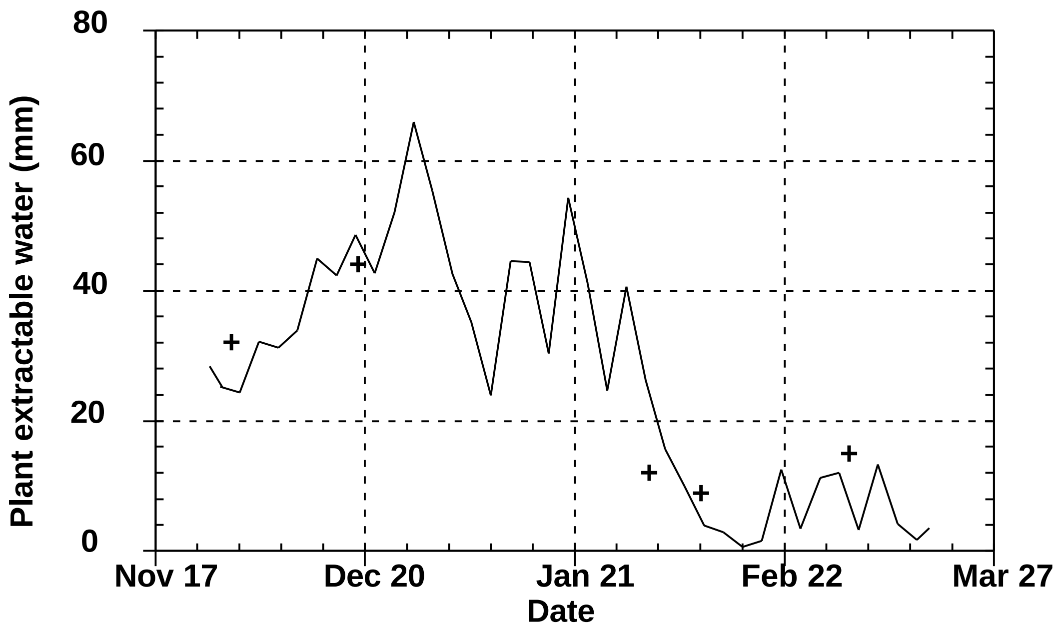


Figure 4. A comparison of observed and simulated plant extractable water over time for the 27 November 1986 planting date for 6 cultivars.

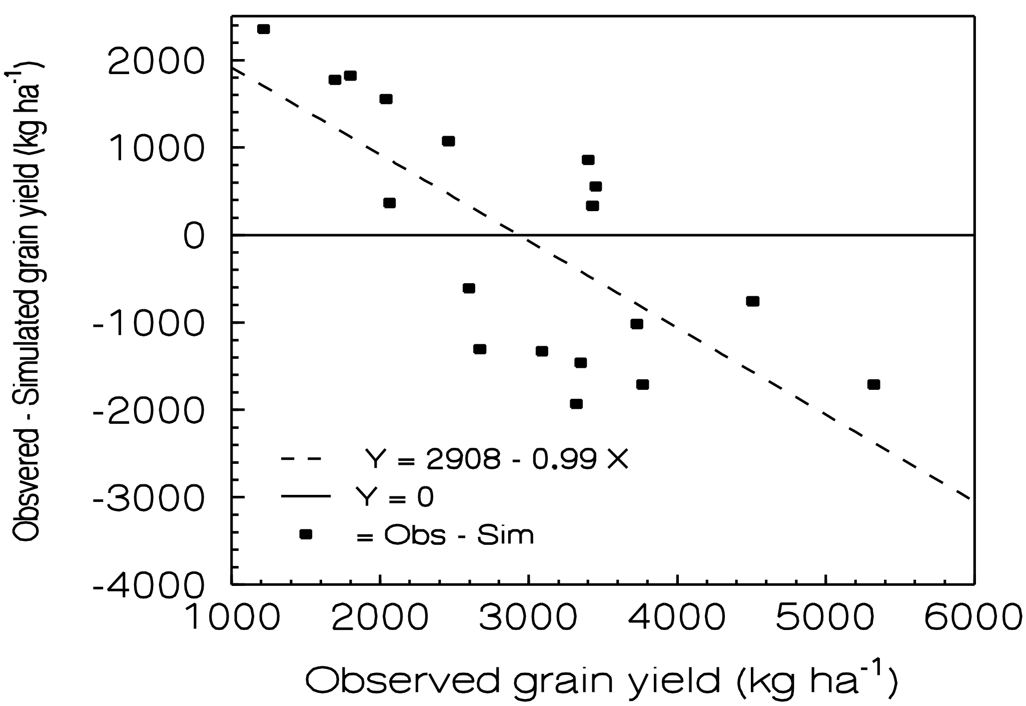


Figure 5. A comparison of observed grain yield and the difference between observed and simulated grain yield (error), (r^2 = 0.52).

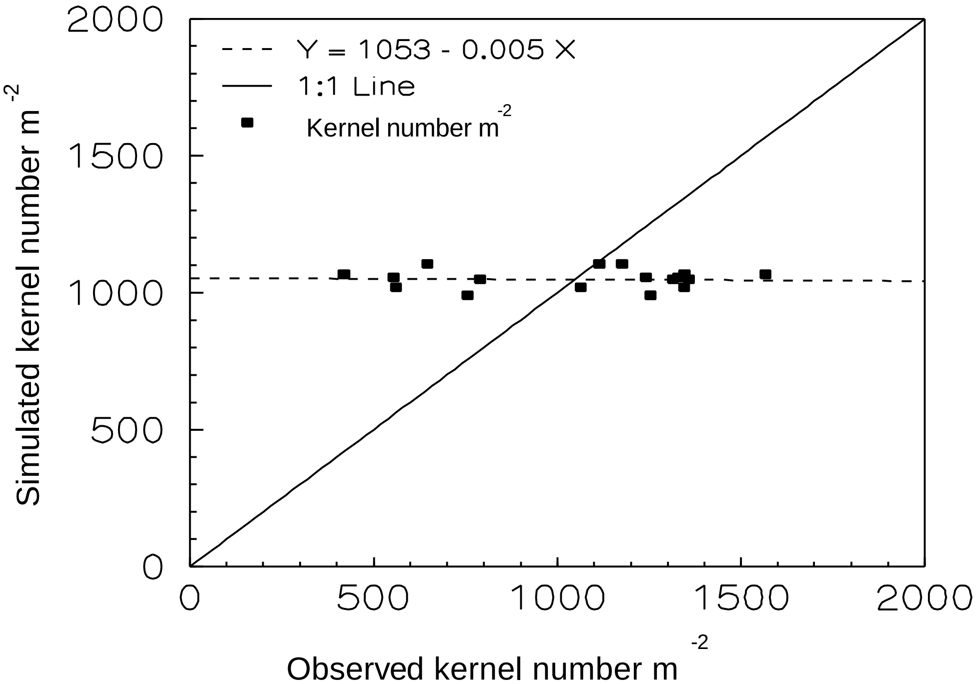


Figure 6. A comparison of observed and simulated kernel number m^{-2}, (r^2 = 0.01).

Simulating Low-input, Rainfed Maize over Regions of Jalisco, Mexico

A.D. Hartkamp

Natural Resources Group, CIMMYT

Abstract

The integration of geographic information systems (GIS) and crop simulation models can allow more effective evaluation of promising technologies over spatial and time scales. The present study involved integrated use of ArcView GIS (gridded surfaces) and DSSAT-compatible crop models (sequence simulations) via software developed at Texas A&M Research Center. Prior to application, interpolation techniques were evaluated for creating spatial input in the form of gridded climate surface.The performance of low-input maize cropping in western Mexico is simulated as a first application of the software. Preliminary results match expectations of Mexican agronomists and point up challenges for future applications of this approach.

Introduction

Geographic information systems (GIS) and crop simulation models can allow researchers to evaluate the performance of technologies in space and over time. Integrating these tools can help significantly in overcoming the site-specific nature of much agronomy and natural resource management research. It can also expand the time horizon of such research far beyond that possible in conventional field trials, providing a truly long-term view. The variable spatial and temporal performance of a given cropping system can be examined to improve targeting based on biophysical suitability. Staff in the geographic information systems/modeling laboratory (GIS/ML) at CIMMYT are studying spatial variation in the performance of conservation tillage in Jalisco, Mexico, as a test case to evaluate approaches for integrating GIS and crop models.

Background

Jalisco State is in western Mexico, on the Pacific coast. Annual precipitation ranges from 400 to 2,000 mm. The main growing season is from May or June to November. Maize area occupies 60% of agricultural land. Jalisco is the largest producer of maize, accounting for 15% of Mexico's maize production (INEGI 1994; SAGAR 1997). Production is in valley bottoms and on hillsides and is primarily rainfed. Average yield is 1.8 t/ha; around half the systems are mechanized. Typical row spacings for maize are 80 cm, with plant densities between 3 to 4 plants/m^2. In general, local varieties are grown on hillsides and hybrids are grown in mechanized systems in valley bottoms. The main alternative crops are sorghum, sugarcane and soybean (INEGI 1994).

 Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

Major natural resource management problems related to agriculture in the region are soil erosion (caused by deforestation, overgrazing, leaving soil bare and natural phenomena such as slope, weather), and contamination of soil, water and aquifers (INIFAP 1996). Furthermore, demand for maize continues to rise in Mexico. In 1998-99, maize imports were at least 5 million tons per year (CEA-SAGAR 2000).

CIMMYT and its partners are evaluating the potential of conservation tillage for the region (Erenstein 1999; Scopel 1997) to increase the productivity of maize systems in an environmentally sustainable manner.

Methodology

Software System

Various strategies exist to integrate crop models and GIS (Hartkamp et al. 1999a). Our approach used an interface between ArcView GIS (gridded surfaces) and DSSAT-compatible crop models (sequence simulations). This software was developed at Texas A&M Research Center (Collis and Corbett 1999) and applies the following procedure:

- Gridded climate surfaces (1 km^2 scale) are created and clustered in SAS to create an 'effective environment' layer, which is then processed to obtain climate profile (*.cli) files. Daily weather files are generated from these climate profiles.
- An optimal season layer—the growing season—is defined from monthly climate surfaces based on the precipitation to potential evaporation ratio (P/PE). This determines the planting date for the simulation model.
- A soil profile layer is created, which can be based on soil taxonomy group.

A simulation layer is generated by overlaying the spatial layers for effective environments, start of the optimum season, and soil profiles. This simulation layer represents grid cell groups with unique combinations of planting date, daily weather data, and soil information, and forms the basis for any subsequent simulation scenario or experimental file configuration. The model is then run for the unique groups of the simulation layer. Model outputs are processed statistically and variables may be mapped and undergo further manipulation or analysis in the GIS.

Methods for Creating Spatial Data

Before integrating GIS and modeling software, spatial interpolation techniques that create spatial climate surfaces from meteorological station data were evaluated. Three techniques were compared: inverse distance average weighting (IDWA), cokriging, and thin plate smoothing splines for climate variables (Hartkamp et al. 1999). Inverse distance showed a better performance for rainfall, while thin plate splines were preferred for temperature variables. The IDWA method gave a smaller rainfall range than thin plate splines.

Simulation Conditions

The simulation conditions as driven by the *.sqx files were a simple five-year maize fallow sequence with ten replicates. A replicate is a repetition of the same experiment run with a different sequence of weather conditions (Thornton et al. 1994). These *.sqx files were run for a deep- and shallow sandy loam profile. A planting window was set (management depth = 30 cm; lower soil water limit = 40%; upper soil water limit = 100%; maximum soil temperature = 40ºC; minimum soil temperature = 10ºC). Simulations were rainfed, and no fertilizer was applied. The Tuxpeño cultivar was used with a density of 3 pl/m^2 and a row spacing of 80 cm.

Results

Preliminary simulations of maize yield match expectations of agronomists from the Mexican National Institute of Forestry, Agriculture, and Livestock Research (INIFAP) and suggest that our overall approach is sound (Fig. 1). Average simulated maize grain yield was 1.78 t/ha for shallow soils and 3.52 t/ha for deep soils. Modeling with thin plate spline surfaces gave a different pattern of yield, but yield predictions were generally similar, averaging 1.79 t/ha for shallow soils and 3.47 t/ha for deep soils.

Challenges

Questions and challenges to this application and the spatial use of the DSSAT-type models relate largely to issues of spatial scale and data quality:

- How can large amounts of point based soil profile information be converted into the soil information file (*.sol). How are these profiles best used to characterize spatial variation? How large an area can be designated to one soil profile? Is it more useful to run a sensitivity analysis on initial soil conditions than to compile the range of soil profiles that are available?
- How many years and repetitions are needed to assess medium-term issues of environmental sustainability?
- How good are weather generators? For example, simulated yield using monthly averages will differ as much as 10-15% from that based on daily weather data (Nonhebel 1994).
- How detailed should genetic information (coefficients) be? Should various agro-ecological zones of germplasm adaptation be identified and implemented in the spatial modeling?
- To target conservation tillage/residue management practices within the region, a residue management module is needed that tracks residue and organic matter on top and in the first soil layers. (The International Fertilizer Development Center and CIMMYT are developing routines to model these practices.)

References

Collis, S.N., and J.D. Corbett. 1999. Linking crop growth simulation models with interpolated climate surfaces: An East African example for CERES Maize. Internet: http://www.brc.tamus.edu/char/cropsimulation.html. As of May, 2000.

Erenstein, O. 1999. *La conservación de residuos en los sistemas de producción de maíz en Ciudad Guzmán y San Gabriel, Jalisco. NRG Paper 99-01 Es.* Mexico, D.F.: CIMMYT.

Hartkamp, A.D., J.W. White, and G. Hoogenboom. 1999a. Interfacing geographic information systems with agronomic modeling: A review. *Agronomy Journal* 91(5): 761-772.

Hartkamp, A.D., K. de Beurs, A. Stein, and J.W. White. 1999b. *Interpolation Techniques for Climate Variables. NRG-GIS Series 99-01*. Mexico, D.F.: CIMMYT.

INEGI. 1994. CIMA, Información estadística y geográfica municipal. Censo Económico, 1989, Censo Agropecuaria 1991, Censo General de Población y Vivienda 1990. Aguascalientes, México: Instituto Nacional de Estadística Geografía e Informática. CD ROM.

INIFAP. 1996. Manejo integral del la cuenca agropecuaria y forestal El Jihuite. Campo Experimental Altos de Jalisco, Tepetitlan, Jalisco. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias.

Nonhebel, S. 1994. The effects of use of average instead of daily weather data in crop growth simulation models. *Agricultural Systems* 4:377-396.

CEA-SAGAR. 2000. Centro de Estadística Agropecuaria de la Secretaria de Agricultura, Ganadería y Desarrollo Rural (CEA-SAGAR), Mexico. Internet: www.sagar.gob.mx/users/cea. As of May.

Scopel E. (ed.). 1997. *Memoria del Taller, Transferencia de labranza de conservación para maíz de temporal en Jalisco.11-13 Marzo 1996.* Mexico, D.F.: CIMMYT/INIFAP/CIRAD/SDR.

Thornton, P.K., P.W. Wilkens, G. Hoogenboom, and J.W. Jones. 1994. Sequence Analysis. Volume 3 DSSAT Version 3 Manual. Tjuji, G.Y., G. Uehara, and S.Balas (ed.) IBSNAT University of Hawaii, Honululu, Hawaii.

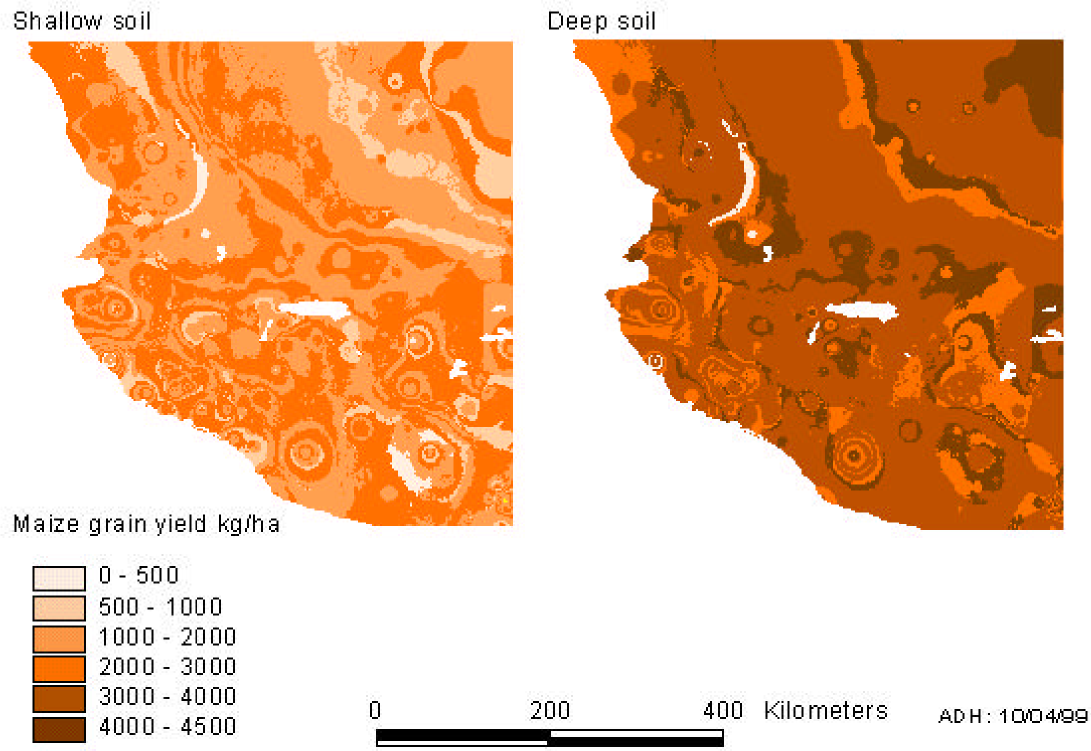


Figure 1. Simulated maize grain yield (kg/ha) for Jalisco, assuming either a shallow sandy loam or a deep sandy loam.

Modeling the Response of Wheat Yield Potential to Temperature -- A Global Perspective

Jeffrey W. White,[1] Peter Grace,[1] Paul N. Fox,[2] Adriana Rodriguez-Aguilar,[1] and John D. Corbett[3]

[1]Natural Resources Group, CIMMYT; [2]Applied Biotechnology and Informatics Center, CIMMYT;[3]Blacklands Research Center, Texas A&M University

Abstract

To evaluate and improve the performance of crop simulation models, in this case CERES, this paper examines variation in yield response of a spring wheat cultivar as affected by temperature, using model simulations and data from international trials of the International Maize and Wheat Improvement Center. Results suggest that efforts to improve the modeled response to temperature should first consider temperature effects on growth and partitioning and that data should be pre-filtered to exclude values where low yields were attributable to disease, pest, or water deficit effects.

Introduction

Crop yield potential varies greatly with environment. In the absence of nutrient or water limitations, yield is still influenced by solar radiation, temperature and day length. Whereas there is extensive research on how wheat yields vary with these factors at specific locations, model-based characterizations over diverse geographic regions appear to be lacking. There is a growing need for such information, given increasing interest in regional analyses of potential productivity, particularly in relation to impacts of global climate change.

One reason for this apparent deficiency is limited access to diverse sets of field data. The International Wheat Information System (IWIS; Fox et al. 1997) provides a readily accessible source of digital data for phenology and grain yield from CIMMYT Wheat Program international trials. This paper examines variation in yield response of spring wheat as affected by temperature, using both simulations and IWIS data.

Materials and Methods

Field data were extracted from IWIS for cv. Seri M 82, one of CIMMYT's highest yielding spring wheat lines. A total of 316 datasets were used, representing four international trials with approximately 160 distinct locations. Because reports from individual locations did not include temperature data, we used interpolated monthly climate surfaces linked to a GIS (Corbett and O’Brien 1997) to estimate climatic conditions for each location and planting date. For each location, we estimated the mean temperature from date of planting through the subsequent four months. Due to incomplete geographic coverage of the surfaces, this resulted in 185 datasets.

 Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

For simulation experiments, CERES Wheat V 3.5 was used (Godwin et al. 1989; Hoogenboom, et al. 1996; P. Wilkens, personal communication, 1999). Due to concerns about temperature effects on phenology being unrealistic, we considered two sets of optimal temperatures. One case posited a lower limit of 15°C for optimal temperature range from emergence to maturity; the other, a lower limit of 26°C during grain filling. Performance of a hypothetical cultivar with no vernalization or photoperiod response was simulated for mean temperatures from 6° to 32°C (constant day/night range of 10°C and 12 h photoperiod) with daily solar radiation of 20 MJ/m^2day. No water or nitrogen stress was allowed; population density was set at 250 $plants/m^2$, row width at 0.2 m.

Results and Discussion

IWIS grain yields show a broad optimum of 10 to 12 t/ha for mean temperatures from perhaps 9° to 22°C (Fig. 1). In contrast, CERES predicted near-linear yield declines from 6° to 32°C. The simulated yield response was driven by a large temperature effect on growth duration. Cooler temperatures delayed time to anthesis and maturity (Fig. 2 A and B), with much less effect on growth or partitioning to grain. Thus, the relationship between yield and days to maturity for CERES implies that yield will increase indefinitely as the growth cycle is extended (Fig. 3).

Since no vernalization or photoperiod effect was assumed for CERES, simulated days to anthesis and maturity should represent estimates at or very near the minimum field values. The simulation values should follow the lower boundary of the data from IWIS. Allowing for possible errors in measuring site mean temperatures, the IWIS data for anthesis and maturity do seem to approximate this lower limit, with the 15°/26°C model providing a slightly better match to the IWIS data. Efforts to improve the modeled response to temperature should first consider temperature effects on growth and partitioning.

Linking international trial data to modeled responses offers considerable promise for more extensive and robust testing of crop simulation models. However, various improvements would enhance data reliability. IWIS data could be filtered further to exclude values where low yields were attributable to disease, pest, or water deficit effects. IWIS allows data providers to report such information, but the querying structure does not allow data to be filtered prior to export. High temperature sites are a particular concern, because extreme disease pressure often limits yields under such conditions.

Because only climate for the first four months from planting was considered, estimates of mean temperatures for some sites were undoubtedly biased. Of particular concern are high latitude sites where wheat was sown in cooler months (e.g., November), survived through a cold winter period, but probably achieved most of its growth in warmer months after the first four months. For sites where time to maturity was provided, this problem could be avoided by matching the number of months used to estimate the mean temperature to crop duration. A further limitation of the climate data is that the location information (e.g., latitude and longitude) contains positional errors and the interpolated surfaces themselves have estimation errors.

IWIS data show enough promise to justify examining additional cultivars. Most modern spring wheats grown in the tropics have low vernalization and photoperiod responses, but CERES calibrations suggest that the variation present can cause differences as large as 20 to 30 days in time to anthesis.

Conclusions

The results suggest that the model over-predicts yields at low and high temperatures. Overall growth and partitioning are much more of a concern than phenology, but the proposed 15°/26°C optimal temperatures for development seem justified.

References

Corbett, J.D., and R.F. O'Brien. 1997. The Spatial Characterization Tool. Texas A&M University System, Blackland Research Center Report N. 97-03, CDROM.

Fox, P.N., R.I. Magaña, C. López, H. Sánchez, R. Herrera, V. Vicarte, J.W. White, B. Skovmand, and M.C. Mackay. 1997. International Wheat Information System (IWIS), Version 2. Mexico, D.F.: CIMMYT. CD-ROM.

Godwin, D.C., J. T. Ritchie, U. Singh, and L. A. Hunt. 1989. *A user's guide to CERES Wheat: V2.10.* Muscle Shoals, Alabama: International Fertilizer Development Center.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, W.D. Batchelor, W.T. Bowen, L.A. Hunt, N.B. Pickering, U. Singh, D.C. Godwin, B. Baer, K.J. Boote, J.T. Ritchie, and J.W. White. 1996. Crop models. p. 95-281. In G.Y. Tsuji, G. Uehara and S. Balas (eds.), *DSSAT version 3.* Volume 2. Honolulu, Hawaii: IBSNAT, University of Hawaii.

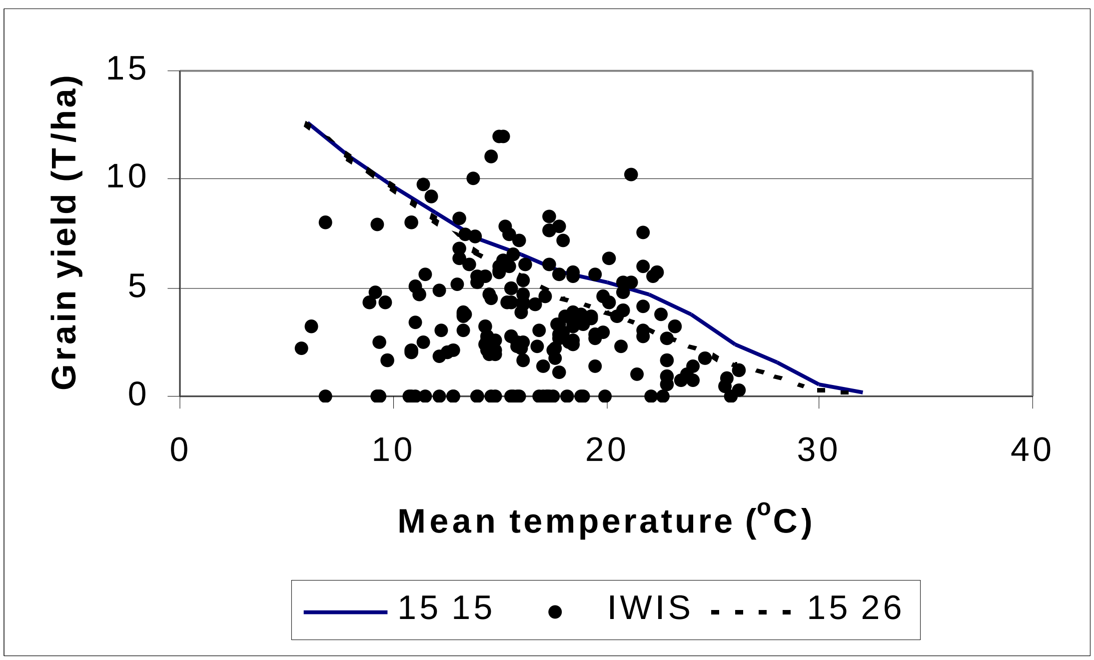
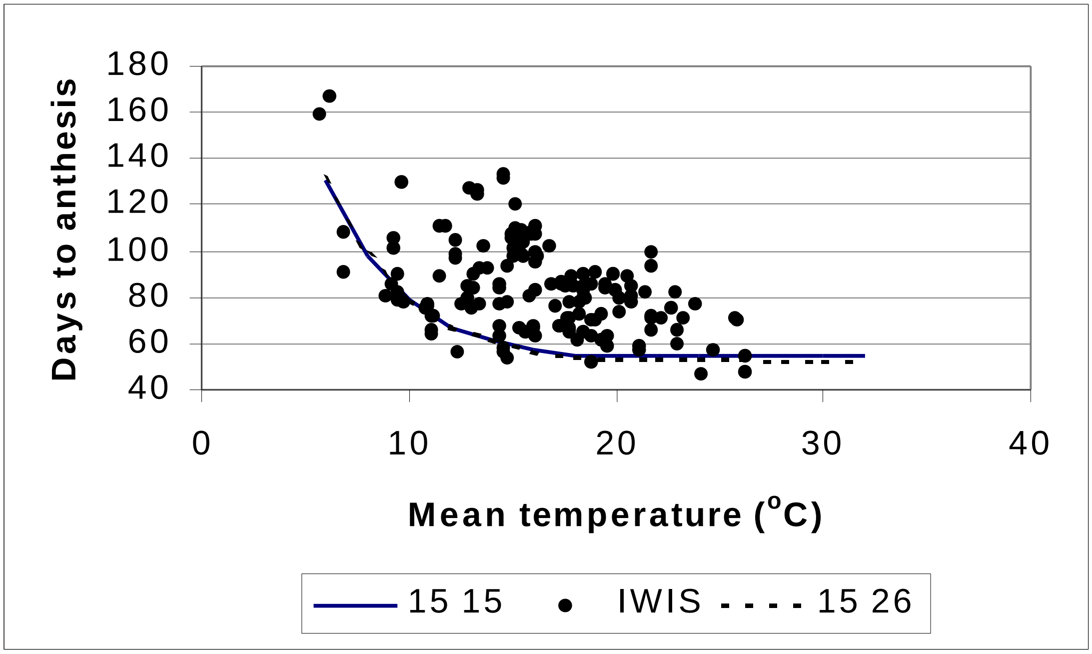


Figure 1. Relation between grain yield and mean temperature. Points are for cv. Seri M 82 from IWIS. The curve is for simulations using CERES Wheat V3.5.

A.



B.

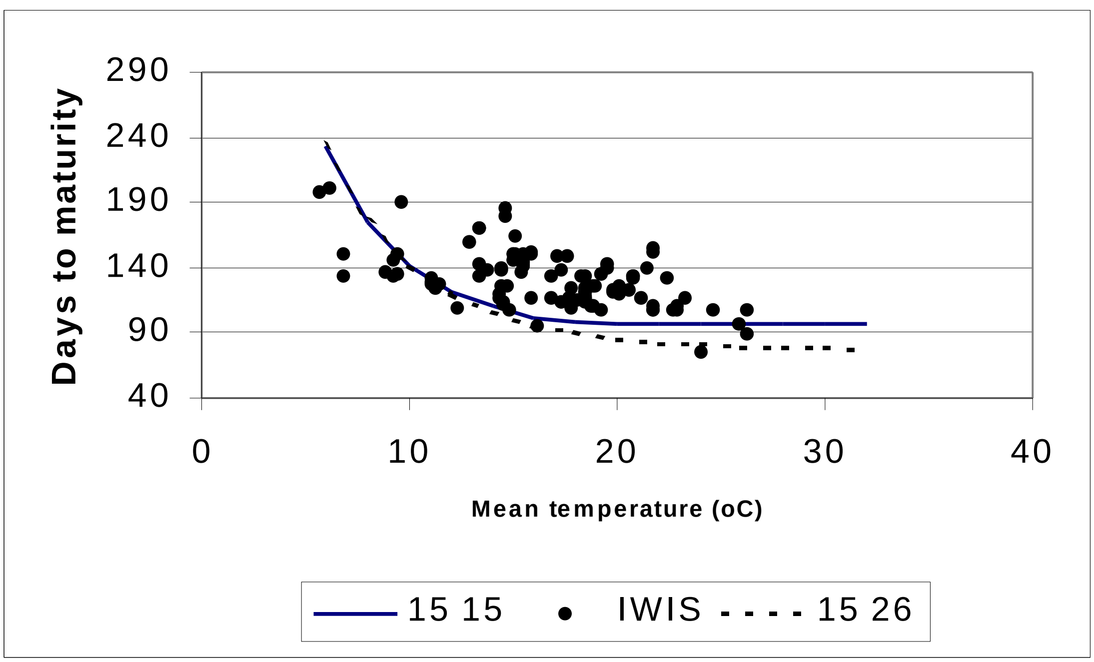


Figure 2. Relations between days to anthesis and mean temperature (A) and days to maturity and mean temperature (B). Points are for cv. Seri M 82 from IWIS. The curve is for simulations using CERES Wheat V3.5.

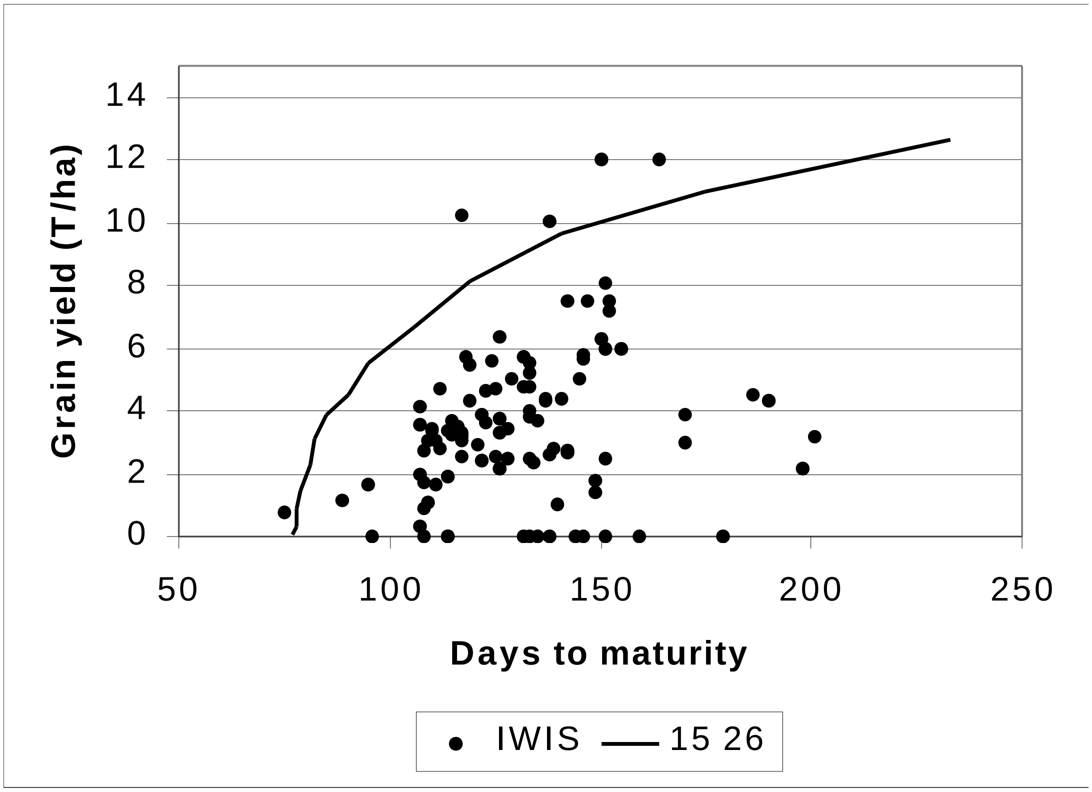


Figure 3. Relation between grain yield and days to maturity. Points are for cv. Seri M 82 from IWIS. The curve is for simulations using CERES Wheat V3.5.

Can Contemporary Wheat Models Simulate Grain Yield Accurately in Low-potential Environments?

Garry J. O'Leary
South African Sugar Association Experiment Station, RSA

Abstract

The accuracy of eight wheat simulation models was compared for mean simulated yield. The error of prediction generally increased with mean yield. This suggests that, for models designed to simulate yield in low-potential environments, the published errors determined in high-potential environments are not directly applicable for lower yielding environments. Underestimation of wheat yield under stressed conditions was a common problem for many models. Such shortcomings need to be addressed before the models can be expected to exhibit low errors that are commensurate with the low yields. Indeed, new models may need to be derived for accurate simulation at very low yields involving isolated plants.

Introduction

Recent tests of wheat simulation models have shown varying levels of accuracy for predicting grain yield over a range of yields. The error of the models measured against observed yields is typically around 0.4 to 0.8 t/ha over the range 1 to 5 t/ha, in stressed environments (Asseng et al. 1998; O'Leary and Connor 1996a and 1996b) and around 0.6 to 1.4 t/ha over 0 to10 t/ha in both stressed and non-stressed environments (Otter-Nacke et al. 1986; Arora and Gajri 1998; Jamieson et al. 1998). Indeed, Angus et al. (1993) showed that model accuracy was very much less than that of classical field experimentation. The question arises whether this level of accuracy justifies model use for low-yield circumstances, particularly environments where yields are less than 1 t/ha. This paper examines the errors of various wheat models, highlighting weaknesses and suggesting ways to improve performance in crop modeling for low-potential environments.

Methods

An analysis was made of reported errors for several models. To compare models that have employed datasets of varying ranges and degrees of freedom, Root Mean Squared Errors (RMSE) or the Root Mean Squared Deviations (RMSD) were plotted against simulated mean yields. For large degrees of freedom, the RMSD approaches the RMSE, reflecting the true population error. However, no distinction was made here for sample size; quoted errors were accepted as the best measure of accuracy.

Where the mean simulated yield was not given, it was estimated as the mean of the range of simulated yield. Although this is not precise, it is a better measure than quoting, for example, the maximum yield, since the error is likely more applicable at the mean than at the extremes.

© CIMMYT. Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

Results and Discussion

Model Errors

Figure 1 shows the published error for eight wheat models in relation to their simulated mean yield. A clear trend of error increasing with mean yield is seen. This indicates that the yield of low-potential yield models could be much lower than those quoted in wide ranging tests that have a high mean simulated yield. What is needed is a performance test over a low yield range, certainly below 1 t/ha.

Pre-anthesis Reserves

An important feature of wheat crops subjected to significant water stress is their ability to re-translocate photosynthate stored in the stems into grain, to meet grain growth demands. The amount that may be transferred varies from 5 to 25% of the total biomass at anthesis and can account for up to 90% of the final grain yield. Grain growth models have been rather conservative and used average values (e.g., 10%), but to capture the response in drought years it was necessary to adjust the transferred amount to around 25% in semiarid environments in southeastern Australia (O'Leary and Connor 1996a).

The model of Arora and Gajri (1998) used 10% of the total reserves that could be transferred to simulate the pre-anthesis contribution to grain. However, this was probably insufficient in the dry years where they underestimated yield, despite their suggestions that non-grain growth contributed to the error. Similarly, the wheat model of Asseng et al. (1998) also underestimated grain yield in drought conditions for the same reasons. What is needed is a better model of crop response under drought conditions.

How Low can Our Models Go?

An obvious conclusion is that a model with a large error — on the order of the low yields that might be sought — is inappropriate for such analyses. This will certainly be the case if the model is biased at low yields, such as those of Arora and Gajri (1998) and Asseng at al. (1998). However, one might expect that a well-constructed model that copes well with drought response should exhibit satisfactory error performance. Of course, the question still remains: how low can our models go? When does the crop cease to be a crop? If a crop is comprised of what are effectively isolated, individual plants, then the assumptions used in models designed for higher yield potential need to be questioned. Under these circumstances the model becomes a spatial-plant model requiring new concepts for light interception, transpiration, growth and partitioning.

Conclusions

Despite a limited examination of the errors of current wheat models, there is evidence that the error in simulating yield below 1 t/ha would be less than those at much higher yield levels. To simulate yields at low extremes, models need to take crop behavior fully into account. This is particularly important for processes such as stem reserve translocation in wheat. As plant populations decrease, attention should also be placed on the three-dimensional nature of response.

References

Angus, J.F., J.W. Bowden, and B.A. Keating. 1993. Modeling nutrient responses in the field. *Plant & Soil* 155/156:57-66.

Arora, V.K., and P.R. Gajri. 1998. Evaluation of a crop growth-water balance model for analysing wheat responses to climate- and water-limited environments. *Field Crops Research* 59:213-224.

Asseng, S., B.A. Keating, I.R.P. Fillery, P.J. Gregory, J.W. Bowden, N.C. Turner, J.A. Palta, and D.G. Abrecht. 1998. Performance of the APSIM-Wheat model in Western Australia. *Field Crops Research* 57:163-179.

Jamieson, P.D., J.R. Porter, J. Goudriaan, J.T. Ritchie, H. van Keulem, and W. Stol. 1998. A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. *Field Crops Research* 55:23-44.

O'Leary, G.J., and D.J. Connor. 1996a. A simulation model of the wheat crop in response to water and nitrogen supply: 1. Model construction. *Agricultural Systems* 52:1-29.

O'Leary, G.J., and D.J. Connor. 1996b. A simulation model of the wheat crop in response to water and nitrogen supply: 2. Model validation. *Agricultural Systems* 52:31-55.

Otter-Nacke, S., D.C. Godwin, and J.T. Ritchie. 1986. Testing and validation of the CERES-Wheat model in diverse environments. AgRISTARS Yield model development. USDA-ARS Grassland, soil and water research laboratory, Temple, Texas. Muscle Shoals, Alabama: International Fertilizer Development Center.

Travasso, M.I., and G.O. Magrin. 1998. Utility of CERES-Barley under Argentine conditions. *Field Crops Research* 57:329-333.

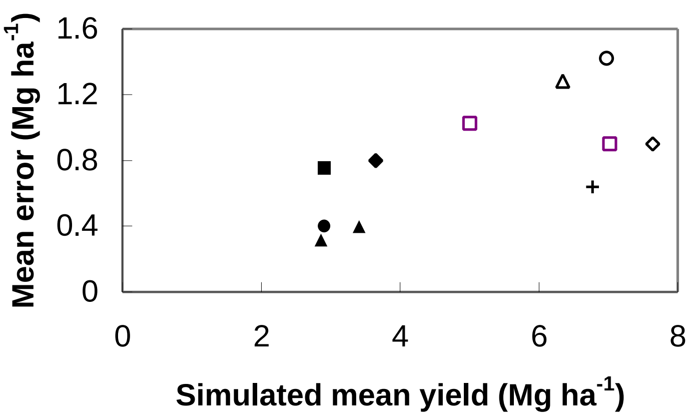


Figure 1. Published Root Mean Square Error (RMSE) or the Root Mean Square Deviation (RMSD) plotted against simulated mean yield. The models are: (◆) Arora and Gajri (1998); (●) Asseng et al. (1998); (■) O'Leary and Connor (1996a); (+) AFRCWHEAT2, (□) CERES-Wheat, (Δ) Sirius, (◆) SUCROS2 and (○) SWHEAT Jamieson et al. (1998). For comparison the performance of the (▲) CERES-Barley model is also included (Travasso and Magrin 1998).

The ICASA File Standards

L.A. Hunt,[1] G. Hoogenboom,[2] J.W. Jones,[3] and J. White[4]

[1]University of Guelph, Guelph, Canada; [2]University of Georgia, Griffin, Georgia, USA; [3]University of Florida, Gainsville, Florida, USA; [4]Natural Resources Group, CIMMYT

Abstract

Standard formats for data files in crop simulation modeling can greatly facilitate data and software exchange, allowing researchers to focus on research rather than data management. Standards from the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project have found varied applications but contain ambiguities. The International Consortium for Agricultural Systems Applications (ICASA) has revised these standards to allow their use in a wider range of decision support tools. Data are aggregated into a three-level hierarchy and make use of character strings to link information both in different parts of a file and in different files. In essence, they constitute a relational database in an easily editable, transferable, and readable ASCII file format. If adopted by experimenters and modelers, these standards could enhance data exchange and crop model and decision support system applications.

Introduction

The IBSNAT project developed data file structures and standards to be used for both experimental documentation and for model input. The files have eased the interactions between some experimenters and modelers (Hunt et al. 1994; Jones et al. 1994), have been used widely by experimenters and modelers using the DSSAT system (Tsuji et al. 1994), and have been adopted by the Global Change and Terrestrial Ecosystem project (GCTE) for use in documenting experiments and regional yield investigations. Within GCTE, the standards have greatly assisted model comparisons (Goudriaan 1996; Jamieson et al. 1998; Hunt 1998; Hunt and Boote 1998) that have led to model improvements. The formats have also been used for direct recording of information from a researcher's diary or field-book (e.g., within the Ontario, Canada, Winter Wheat Co-operative Performance testing system).

Experience with IBSNAT file structures has shown, however, that they contain ambiguities and are not entirely suited for generic use. Members of ICASA and other organizations have thus defined a revised set of standards for file structures that are unambiguous and easily read by a broad range of software tools. This paper provides a brief overview of the new file structures. A full description with additional examples can be found at the ICASA web site (http://icasanet.org).

File Structure

The basic file structure uses ASCII characters with a line length restriction of 254 characters, and with information arranged in columns headed by associated codes. A file may also contain certain special symbols and headings and have data aggregated into sections. The structures make use of 'keys' and character strings to link information in different parts of a file and in different files. In essence, this constitutes a relational database in an easily edited and transferred ASCII file format. Figure 1 presents an example of a file that describes an experiment, including all components that are associated with experimental methods and procedures.

© CIMMYT. Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

Data Items

A file mainly contains data items, each of which has one or more pieces of information and an associated code. The information can be either:

- Variates — Information pertinent to the experiment/situation documented.
- Level indicators — Character strings (maximum length of 31) or numbers that can be used as a link to data reported elsewhere in the file. These indicators are also termed 'keys'.

Codes are character strings (maximum length of 31), with no distinction being made between upper and lower case. They are presented above the variates or level indicators on a line (the 'codes line') that begins with an '@' symbol. Multiple codes can occur on one line.

Variates can be numbers (real or integer), character strings without blanks, or text to a maximum length of 31 characters. Text must be specified by a string of dots after the data code, and the text itself must be presented below the code plus dots. For data items at the end of a row, however, text can be used without the dots that are necessary elsewhere, and the maximum length including blanks can be 80 characters. Variates associated with one data code must be of the same data type.

Hierarchy of Data Items

Data items are organized into a hierarchy with three levels:

- Data clusters
- Data groups
- Data units

The most basic (smallest level) aggregation within the hierarchy is the DATA CLUSTER, which consists of a number of variates and/or level indicators clustered together under one line of codes:

```
@CU  CR   CULCODE    CULTIVAR_NAME    CULTIVAR_NOTES
1    WH   IB0488     Newton           Hard red winter of Central Gt. Plains
2    GW   IB0001     Quackgrass       Central Gt. Plains ecotype
```

The second level of aggregation is the DATA GROUP, which must begin with a group symbol (*) in the first column followed by defining text to a maximum of 31 characters with no blanks:

```
*TREATMENTS
*CULTIVARS
```

Explanatory text can be placed after the defining text (separated by at least one blank):

```
*IRRIGATION AND WATER MANAGEMENT
*FERTILIZERS (INORGANIC)
```

The character strings `IRRIGATION` and `FERTILIZERS` constitute the defining text for the respective groups.

The third and highest level of aggregation is the DATA UNIT. This allows a complete set of related data to be kept together. Examples of data that might be so aggregated are:

- Details of a particular experiment
- Weather information from different sites within a region.
- Collections of soil information from one institute.
- Results of a particular experiment that involve several sites.

Data units begin with an indicator line that has a unit symbol ($) in the first column followed by defining text (maximum of 31 characters with nor blanks). Examples are given below:

```
$EXPERIMENT:UCEA9601SB
$CULTIVAR:SBGRO960
$SOIL:UC
```

As with data groups, explanatory information can be placed after the defining text if it is separated by at least one blank. Figure 1 shows a data unit with a number of embedded data groups.

Other Syntax or Forming Rules

Specific rules for comments, missing data, data flags, including software commands, blank lines and end-of-file markers are summarized in Table 1. For further details, see the full ICASA documentation (http://icasanet.org).

File Standards

Codes

The ICASA standards can be used with codes specified locally for use within one research group. However, to ensure that files can be interchanged among workers or research groups, a number of reserved data and variate codes can be defined for use within specific subject areas. The many codes defined by IBSNAT have been updated by ICASA and are used as an initial standard. Preferred units for numeric variates are largely SI, but “cm” and “ha” (hectare) are sometimes used to conform with dominant practices (e.g., by the American Society of Agronomy).

Dates and Timing of Operations

The dates on which operations such as planting or fertilization are carried out are usually recorded using both a year and a day of year (Gregorian) under individual data codes, as demonstrated below for planting information:

```
@ PL  PLYR  PLDAY
  1   1981  289
```

This convention differs from the previously used, year-within-century-plus-day-of-year approach (e.g., 81289). Dates of operations on established crops can also be recorded in terms of the time elapsed since planting (days after planting) by entering -99 for the year and the appropriate days after planting for the day:

```
@ FE  FEYR  FEDAY
  1   -99   231
```

The same convention can also used for rotational sequences, to specify that the next crop should be planted a certain number of days after harvesting:

```
@ PL    PLYR    PLDAY
   1    -99     05
```

Clusters, Groups, and Units

As with codes, the file structures used with data clusters, groups, and units can be defined locally. However, for exchange among researchers, clusters should be similar and data units and groups identified uniformly. ICASA has reviewed and slightly modified the set of files used by IBSNAT. The clusters and groups in these files provide a set of standard configurations and the files form a set of standard units. The standard file units defined to date are:

- Experimental details
- Plot (experimental) data
- Soils
- Weather

These units can be placed in separate files or be aggregated into one OVERALL file to facilitate data transfer.

File Names

File names follow the IBSNAT convention. It has two components: 1) the file extension, used to specify the type of file, and 2) the prefix, used to identify the data source of data. File extensions are given below:

ccD	Plot data (ie., experimental results).
ccX	Experimental details.
SOL	Soil profile characteristics
WTH	Weather data

where “cc” is a prefix indicating a crop code (e.g., “WH” = wheat and “MZ” = maize).

File prefixes for the experimental data and details files are constructed from an institute code (two characters), a site code (two characters), the year in which the experiment was planted (two characters), and an experiment number (2 characters). For example, the first experiment conducted by the University of Florida (UF) at Gainesville (GA) in 1988 (88) would yield a prefix of UFGA8801. For the weather files, the prefix is constructed from the institute and site codes plus, if needed, the starting year (2 digits) followed by the number of years of data, or a full 4 digit year specification. For soil, the institute code is used as the prefix.

For files that contain experimental details and results, soil characteristics, and possibly weather data, the file name should follow that which would be used for an experimental details file, but with the final 'X' replaced by a '$'. UFGA8801.SBX would thus become UFGA8801.WH$.

Additional Level Indicators

To avoid repeating information in groups that contain more than one cluster of data items (e.g., irrigation in the experimental details unit), secondary level indicators are used. These secondary level indicators complement those already used within a standard file by making it possible to reference specific clusters within a group:

```
*TREATMENTS
@ TRNO       IR      IR2
  1          1       1
  2          2       1
  3          3       1

*IRRIGATION (AND WATER MANAGEMENT)
@ IR  IRYR   IRDAY   IROP     IRVAL
  1   1982   100     IR001    65
  2   1982   100     IR001    75
  3   1982   100     IR001    85
@ IR2 IREFF
  1   0.90
```

IR is the code for the irrigation level indicators and IR2 is the additional code that eliminates the need to have three separate but identical rows of data for IREFF.

File Additions and Modifications

To satisfy specific needs, some researchers will add new variables to the files. This might involve adding additional rows of data items within a data group or adding new data groups. Adding additional data items at the end of existing rows of data items is not recommended. However, this may be necessary when the variate is needed as a link to data elsewhere in the file or file unit (e.g., additional factors in the treatment group), or when adding extra rows of data items would disrupt the overall configuration of the file (e.g., in a weather file). Such additional requirements should be communicated to ICASA, so they can be considered for addition to the ICASA standards.

The same variable may also be measured on several different dates or using different techniques. As long as the data are arranged in vertical columns in date sequence, the defined codes can be used in a straightforward manner to identify variables that have been recorded on several different days. However, they cannot be used as easily for data that have been arranged in separate vertical columns for different days. For such cases, a single digit should be added at the end of the code and a definition should be provided for this enhanced code. This approach is also used when the same variable has been measured using two or more techniques. An example of the usage of this form of code enhancement is shown below:

```
@ TRNO   R#   CWAD1   CWAD2
  1      1    5700    10100
  1      2    5350    9900
```

File Validation and Verification

A valid file has no data item codes repeated within a data group, uses unique data group names within a data unit, and uses unique data unit names within a file. This is distinct from data verification, which involves consideration of consistency between components of data items, ranges of values, etc. Data verification is crucial to data exchange and can be aided by including information on the range of values to be expected, units, and a brief description of data associated with each data code, along with a specification of the missing value identifier. An example of how such information could be conveyed is:

```
@ CODE     MAX   MIN   MISS UNIT   CODE_DESCRIPTION
  TRNO     6     1     -99  #      Treatment number
  HWAM     5000  1000  -99  kg/ha  Total dry wt. of grain at maturity
  HWUM     .020  .040  -99  g      Dry wt. of individual grains at maturity
```

Implementation of the New Standards

The new file structures and standards will be used in the next major release of the DSSAT software. This will overcome problems that would occur if the old file structures and standards were to be used well after the Millennium change. Within the DSSAT system, software will ultimately be able to handle both the old files and the new, so no conversion of old files will be necessary. Dates in the previously used year within century plus day of year approach will be interpreted by assuming that they belong to the 20th century if the year if greater than 09. It is recommended, therefore, that researchers begin using the new structures and standards right away, and that they use the new standards exclusively once the new Millennium is underway.

References

Goudriaan, J. 1996. Predicting crop yields under global change. In B.H. Walker and B.H. Steffen (eds.), *Global Change and Terrestrial Ecosystems,* International Geosphere-Biosphere Programme Book Series #2, 260-274. Cambridge: Cambridge University Press.

Hunt, L.A., J.W. Jones, G. Hoogenboom, D.C. Godwin, U. Singh, N.B. Pickering, P.K. Thornton, K.J. Boote, and J.T. Ritchie. 1994. Input and output file structures for crop simulation models. In P.F. Uhlir and G.C. Carter (eds.), *Crop Modeling and Related Environmental Data*: *A Focus on Applications for Arid and Semiarid Regions in Developing Countries,* 35-72. Paris: CODATA, International Council of Scientific Unions.

Hunt, L.A., and K.J. Boote. 1998. Data for Model Operation, Calibration, and Evaluation. In G.Y. Tsuji, G. Hoogenboom, and P.K.Thornton (eds.), *Understanding Options for Agricultural Production*, 9-39. Dordrecht: Kluwer Academic Publishers.

Hunt, L.A. 1998. Recent attempts to evaluate and apply wheat simulation models, and to simplify the storage and exchange of experimental data. In H.J. Braun, F. Altay, W.E. Kronstad, S.P.S. Beniwal, and A. McNab (eds.), *Wheat: Prospects for Global Improvement, Proceedings of the 5th International Wheat Conference, 10–14 June 1996, Ankara, Turkey,* 445-454. Dordrecht: Kluwer Academic Publishers.

Jamieson, P.D., J.R. Porter, J. Goudriaan, J.T. Ritchie, H. van Keulen, and W. Stol. 1998. A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. *Field Crops Research* 55:23-44.

Jones, J.W., L.A. Hunt, G. Hoogenboom, D.C. Godwin, U. Singh, G.Y. Tsuji, N.B. Pickering, P.K. Thornton, W.T. Bowen, K.J. Boote, and J.T. Ritchie. 1994. Input and output files. In G.Y. Tsuji, G. Uehara, S. Balas (eds.), *DSSAT v3.Vol 2-1*, 1-94. Honolulu: University of Hawaii.

Tsuji, G.Y., G. Uehara, and S. Balas. 1994. DSSAT version 3 Volumes 1, 2, and 3. International Benchmark Sites Network for Agrotechnology Transfer. Honolulu: University of Hawaii.

Table 1. Summary of other syntax and formatting rules for the ICASA file standards.

Item	Rule
Comments	On a separate line with '!' as the first character.
Missing data	Are indicated by one of the following symbols: '-99', '*', '-' and '.' The preferred value is '-99' following the IBSNAT standard.
Non-applicable data	Marker of '-99' also is used where data are not applicable as opposed to missing *per se*. For example, row width and spacing for a crop that is broadcast sown.
Data "flags"	A single letter following a numerical variate can be used to indicate outliers, data filled with an estimate, etc.
Commands	The symbol '#' is used at the beginning of a line to indicate the start of a file statement that can be interpreted as a command by software (e.g., '`#INCLUDE C:\Icasa\Newdata\FileA.dat`').
Blank lines	Blank lines may be placed anywhere in a file.
End-of-file	The symbol '=' as the only character on the last line of a file is used to indicate the end of a file. Its use is optional but recommended for electronic file transfer to indicate whether a file has unintentionally been truncated.

Figure 1. Example of an ICASA standard experimental details file.

```
$EXPERIMENT:KSAS8199WH Fictitious experiment based on KSAS8101

*GENERAL
@ NAME
 Nitrogen response of wheat at 2 irrigation levels
@ MAIN_FACTOR   FACTORS   LOCAL_NAME
  Nitrogen      3N*2I     Godwin
@ PEOPLE
  Wagger,M.G. Agronomy,Kansas State Univ,Manhattan,Kansas
  Kissel,D. Agronomy,Kansas State Univ,Manhattan,Kansas
  Hunt,L.A. Plant Ag.,Univ.Guelph,Guelph,Ontario Thunt@Plant.Uoguelph.Ca
@ VERSION
  31-08-99(LAH,Guelph);26-08-99(LAH,Guelph);15-08-99(LAH,Guelph)

! The above are recommended as a minimum for general information.
Additional
! data, as illustrated below, can be added for a comprehensive
documentation.

@ OBJECTIVES
 To demonstrate the new ICASA data standards
@ ANALOGIES
 Ashland site considered representative of production area of Kansas.
@ MEASUREMENTS
 Canopy biomass,component biomass,and LAI at intervals during growing
season.
@ METHODS
 LAI using air-flow planimiter on subsamples.
@ DESIGN
 Assumed to be a randomized complete block.
@ LAYOUT
 Not known.

@ PLTA PLTR# PLTLN PLTOR PLTOD PLTSP PLTHA PLTH# PLTHL PLTHM
 11.5 16.00 4.000 90.00 90.00 18.00 0.72   4  1.0 Hand
@ SEED
 From University plant breeder. Germination in standard test 97%
@ CONDITIONS
 Soil well prepared for planting
 Weather well within normal range for site.
@ PROBLEMS
 Seed mixed for 2 plots in rep 1.
 (Hypothetical to illustrate problems that could be entered here).
@ NOTES
 File based on KSAS8101.WHX but with many modifications.
 It should only be taken as a 'fictitious' experiment.
@ QUALITY
```

```
 Overall quality assumed to be good although no error terms available.
@ PUBLICATIONS
 Wagger,M.G., 1983 N cycling in the plant-soil system. Ph.D.,Kansas State
@ DISTRIBUTION
 Public


! The following six data groups are necessary in all files. Some of the
! clusters within a group may not be required, however (e.g. the second
! cluster shown in the fields and initial conditions groups, or the third
! cluster in the planting group).

*TREATMENTS                                  -------------FACTOR LEVELS-------------
@TRNO R#  C#  O#  S# TREATMENT_NAME......   CU  FL  SA  IC  PL IR  FE RE  CH TI EM
 HA
 1     1   1   1   1 0N,dryland+weeds Rep1   1   1   1   1   1  0   0  1   1  1  1
 1
 1     2   1   1   1 0N,dryland+weeds Rep2   1   1   1   1   1  0   0  2   1  1  1
 1
 1     0   1   1   2 0N,dryland+weeds        2   1   1   1   2  0   2  1   1  1  1
 1
 2     0   1   1   1 180N,dryland            1   1   1   1   1  0   3  1   1  1  1
 1
 3     0   1   1   1 0N,irrigated            1   1   1   1   1  1   0  1   1  1  1
 1

*CULTIVARS
@ CU    CR CULCODE   CULTIVAR_NAME    CULTIVAR_NOTES
 1      WH IB0488    Newton           Hard red winter,Central Plains
 2      GW IB0001    Garytown         Central Gt.Plains quackgrass

*FIELDS
@FL FL_NAME
 1  Research  park
@FL FIELD_ID  WEATHER_ID  FLSL   FLOB  FLDT   FLDD   FLDS   FLST   FLSTX  SOIL_ID
 1  KSAS0001  KSAS        20     0     FLD00  0      0      0      CSI    KSAS81IF1
@FL FIELDLAT  FIELDLONG   FLELE  FAREA FLSLL  FLLWR  FLSLA
 1  37.11     -90.45      -99    226   200    -99    90

*SOIL_ANALYSES
@SA   SAYR  SADAY SAMHB SAMPX SAMKE
 1    1981  260   -99   -99   -99
@SA   SABL  SABDM SAOC  SANI  SAPHW SAPHB SAPX  SAKE
 1    15    -99   -99   -99   5.85  5.21  -99   -99

*INITIAL_CONDITIONS
@IC   ICYR  ICDAY ICPCR ICRDP ICRIP ICRAM ICRN  ICRP  ICRK  ICRT  ICND  ICWT
 1    1981  270   WH    10    50    2000  1.00  1.00  -99   100   -99   100
@IC   ICSW  ICIN  ICRZ# ICRZE
 1    300   100   -99   -99
@IC   ICBL  ICH2O ICNH4 ICNO3
 1    5     .205  3.4   9.8
 1    15    .205  3.4   9.8
 1    30    .170  3.2   7.3
```

```
  1    60    .092  2.5   5.1
  1    90    .065  2.2   4.7
  1    120   .066  2.7   4.3
  1    150   .066  2.7   4.3
  1    180   .066  2.7   4.3

*PLANTING
@PL   PL_NAME
  1    Early planting
  2    Late  planting
@PL   PLYR  PLDAY PLDOE PLPOP PLPOE PLME  PLDS  PLRS  PLRD  PLDP  PLMWT PLAGE
  1    1981  270   -99   162   162   PLM0S PLD0R 17    90    5.5   120   0
  2    1981  289   -99   40    40    PLM0S PLD0R 17    90    3.5   20    0
@PL   PLENV PLPH  PLSPL
  1    -99   1.0   -99
  2    -99   1.0   -99

! The remaining data groups are necessary if irrigation, fertilization, etc.
! are experimental factors.

*IRRIGATION AND WATER MANAGEMENT
@IR   IR_NAME
  1    Irrigation  on    specified   dates
@IR   IREFF IRDEP IRTHR IREPT IROFF IRAOP IRAMT
  1    1.0   -99   -99   -99   -99   -99   -99
@IR   IRYR  IRDAY IRSTG IROP  IRVAL
  1    1982  96    -99   IR001 65
  1    1982  110   -99   IR001 78
  1    1982  117   -99   IR001 70

*FERTILIZERS (INORGANIC)
@FE   FE_NAME
  2    Single application at planting
  3    Applications at planting and in spring
@FE   FEYR  FEDAY FESTG FECD  FEACD FEDEP FEAMN FEAMP FEAMK FEAMC FEAMO FEOCD
  2    1981  289   -99   FE001 AP001 15    60    -99   -99   -99   -99   -99
  3    1981  289   -99   FE001 AP001 15    90    -99   -99   -99   -99   -99
  3    1982  56    -99   FE001 AP001 1     90    -99   -99   -99   -99   -99

*RESIDUES AND ORGANIC FERTILIZERS
@RE   REYR  REDAY RESTG RECD  REACD REDEP REINP REAMT RESN  RESP  RESK
  1    1981  280   -99   RE000 -99   10    80    1000  0.1   -99   -99
  2    1981  280   -99   RE000 -99   10    80    1500  0.1   -99   -99

*CHEMICALS
@ CH  CHYR CHDAY CHSTG CHCD  CHACD CHDEP CHAMT CHEM_TARGETS.... CHEM_NOTES
  1    1981  300  -99   CH001 AP001  1.3  2.2    NOT RECORDED    NONE

*TILLAGE
@ TI  TIYR TIDAY TISTG TIIMP TIDEP TIMIX TILLAGE_NOTES
  1    1981  250  -99   TI005 15.0  30    Lea type plough with long moldboard

*ENVIRONMENTAL_MODIFICATIONS
@EM   EMYR  EMDAY EMSTG EMDLN EMRAD EMMAX EMMIN ERAIN EMCO2 EMDEW EWIND
```

```
 1    1982  180   -99   0     0     0     0     0     R600  0     0
 1    1982  220   -99   0     0     0     0     0     R360  0     0

*HARVESTS
@ HA  HAYR HADAY HASTG HACOM HASIZ HAPC HABPC
   1  1982  273   90   HAC0P HAS0A  100  50
=
```

Linking ICIS and ICASA

Marvin L.M. Stapper[1] and Joost G.F. Lieshout[2]
[1]Droevendaalsesteeg 41, 6708 PB, Wageningen, the Netherlands; [2]Natural Resources Group, CIMMYT

Abstract

The International Crop Information System (ICIS) and the Sustainable Farming Systems Database (SFSD) developed at CIMMYT provide a searchable repository of quality datasets on crop growth and development. This paper describes progress in work to develop an data interchange tool by which data from the SFSD can be extracted in files compatible with International Consortium for Agricultural Systems Applications (ICASA) formats. The focus is on an interface that provides query capabilities and follows standards of the Texas and CIMMYT Object Shell (TACO), which allows programmers to integrate and share application modules.

The International Crop Information System

Poor integration of data on genetic resources, breeding, characterization, evaluation, is a major constraint in crop research. The International Crop Information System (ICIS) is a management and integration tool for global information on genetic resources, crop improvement, and crop management. (ICIS 1998a). Genetic resource specialists, crop scientists, and information specialists from centers of the Consultative Group for International Agricultural Research (CGIAR), in national agricultural research systems, and elsewhere are collaborating on its development.

ICIS will provide a comprehensive system implemented separately for each crop and based on unique identification of germplasm, management of nomenclature (including homonyms and synonyms), and storage of all pedigree information. The Genealogy Management System is the core database that performs these functions and links data from all disciplines. Distinct but compatible crop databases result in focused data management for each, while allowing collaborative software development among specialists for each crop. For research involving multiple crops, a specialized systems implementation of ICIS is also under development, as described below.

The SFSD

In developing countries crops are frequently grown in association or rotations. To help assess and refine the performance of multi-crop systems, the CIMMYT Natural Resources Group (NRG) has created a modified version of ICIS to manage data on crop performance, farming practices, environmental and other impacts of practices, and agricultural land use. Called the Sustainable Farming Systems Database (SFSD; ICIS 1998b), it is a logical home for data from long-term experiments, on-farm trials, monitoring studies, and surveys. The SFSD can be queried by crop, location (with map display), research theme, or other criteria. Data are currently entered and exported via spreadsheets, but work is in progress to facilitate data exchange between ICIS and crop models. Future plans emphasize equipping the SFSD for day-to-day data management.

 Published in White, J.W., and P.R. Grace, (eds.). 2000. *Modeling Extremes of Wheat and Maize Crop Performance in the Tropics. Proceedings of a Workshop, CIMMYT, El Batán, Mexico, 19-22 April 1999.* NRG-GIS Series 00-01. Mexico, D.F.: CIMMYT.

The ICIS-ICASA Data Interchange Tools

Crop modelers have frequently expressed interest in extracting data from the SFSD and other ICIS implementations. The recently described crop model file formats for the International Consortium for Agricultural Systems Applications (ICASA; Hunt et al., these proceedings) provide a logical framework for such data export. Furthermore, field data used by modelers often provide a ready source of well-tested and documented data that might be included in the SFSD.

The SFSD is a logical test-case for developing tools that allow data exchange between ICIS and ICASA. Begun in April 1999, work has first addressed the convertibility of ICASA data to ICIS formats and vise versa. Two DSSAT files were loaded into the SFSD by hand and several queries were run to extract the data in a form as close to the original ICASA file format as possible. The results showed that data extraction from the SFSD is fairly straightforward. A prototype with this function was developed and is being equipped with diverse querying tools by which users can select subsets of data.

Work continues to focus on extracting data from the SFSD into ICASA formats; specifically, a user interface with query capabilities that match crop modelers' data needs. Important search criteria already identified are study name, country, treatments used, species or cultivars, field locations, planting information, use of irrigation and fertilizers, traits measured and availability of time series data. For each study selected, the software will create a template for any ICASA file, fill it in using available information, and save this “skeleton” file. Since very few datasets are complete enough to be model ready, files will have to be edited for model use. An initial version of the data conversion tool is available on CD (ICIS Project 2000).

Development of the user interface will follow the standards of the Texas and CIMMYT Object Shell (TACO), which allows programmers to integrate and share application modules.

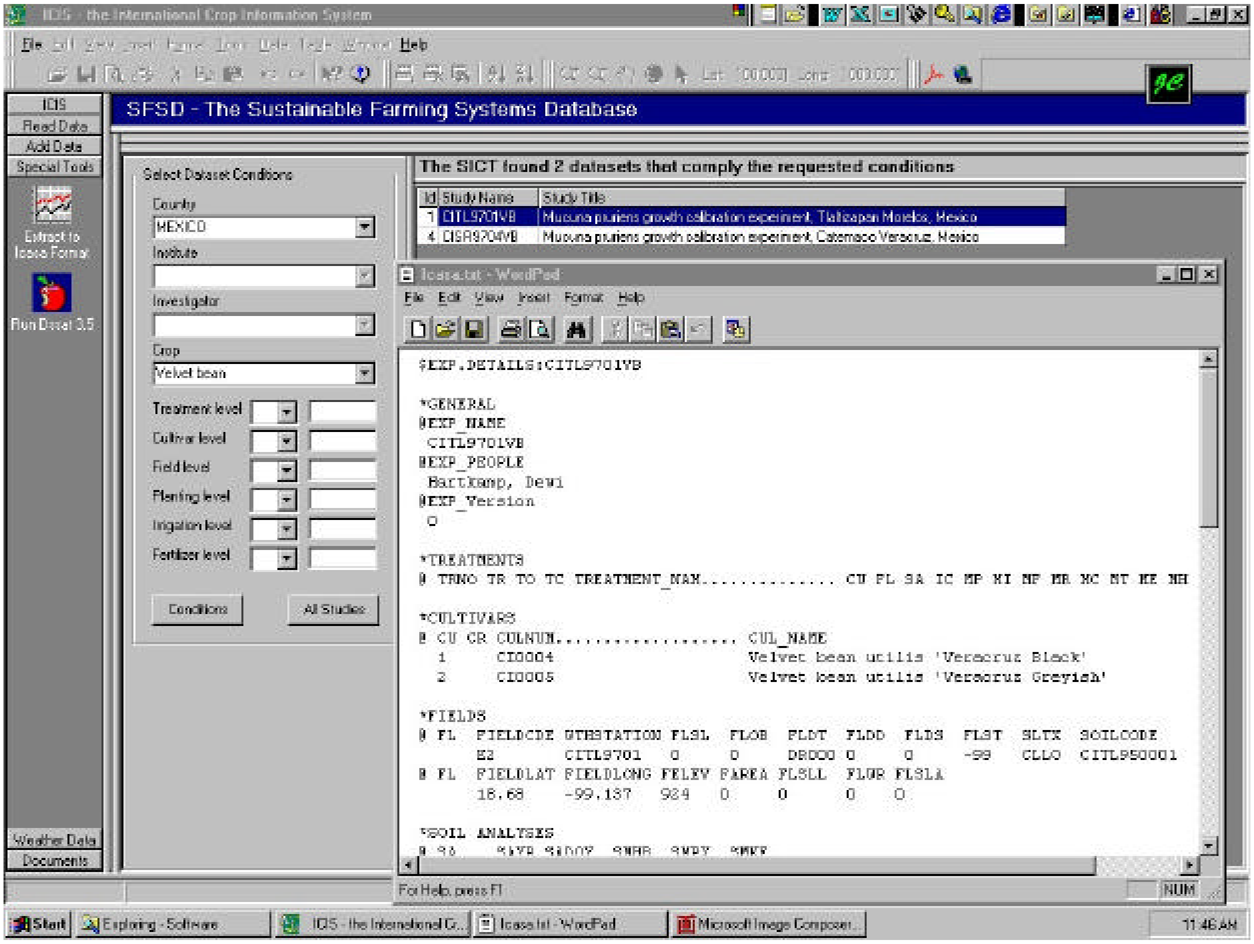
References

ICIS. 1998a. ICIS, the International Crop Information System. Available at www.cgiar.org/icis/ (posted 24 Dec., 1998; verified 16 May, 1999).

ICIS. 1998b. SFSD, the Sustainable Farming Systems Database. Available at www.cgiar.org/icis/SFSD.htm (posted 24 Dec., 1998; verified 16 May, 1999).

ICIS Project. 2000. International Crop Information System CD V1.0. Published by CIMMYT and IRRI.

Figure 1. Draft user interface for the ICIS-ICASA data interchange tool showing sample time series data.



Work Group Outputs

Introduction

Following the oral presentations, participants examined various aspects of model performance relating to high and low yield potential conditions. Outputs of these "hands-on" activities are summarized below.

Wheat

Garry O'Leary and Tony Hunt first checked that CERES 3.5 as released had the intended temperature response. Some unintended discontinuities (bugs) were noted. Paul Wilkens fixed these as part of a proposed Service Release 1.

Several people have reported problems calibrating CERES 3.5, and the suspicion was that the single temperature response (with BASE = 0 and TOPT = 15) is incorrect. Paul Wilkens created a V3.5x that allows the optimum temperature for grain filling response (ROPT) to be set independently, and this version was tested for various datasets.Jeff White compared TOPT = 15° vs. TOPT = 26° (with ROPT = 26° for both), using planting date data from Punjab Agricultural University and cv. PBW 34. TOPT = 15° allowed for slightly better simulation of phenology.

Tony Hunt examined 1993 and 1994 U. Guelph data for planting date effects on leaf appearance:

- For a May planting in 1993, 15°C is under-predicting leaf number, as compared to a 0-22-33°C response.
- 5 July showed a similar effect.
- For 22 September, 15°C resulted in over-prediction.
- For 9 June 1994, 15°C was still under-predicting
- 10 Aug, 1994 gave similar results for all temperature responses.

The conclusion is that 15°C is probably too low but much better than 26°C.

Tony also examined the effect of other temperature regimes for time to anthesis, using cv. PBW 34 and the PAU 1985 dataset. Again, 15, 18 and 22°C can give reasonable fits, and 26°C is too high. He also emphasized that we are still vague on the best approach for temperature effects from anthesis to onset of grain fill. (Most of this work was done with CROPSYS but taking advantage of common DSSAT file formats.)

Joe Ritchie said his experience suggests that phyllochron varies with photoperiod (e.g., Siberia vs. England – and England in fall vs. N. Dakota or Canada). Tony noted that his work with Piara Singh suggested no such effect, and he showed data for leaf appearance of cv. Norseman with natural and artificial photoperiod where no photoperiod effect was found, except for a slight effect once reproductive development started. This issue merits further attention, but we need more data where photoperiod and temperature effects can be separated.

The point was made that we will always need a phyllochron constant that indicates a potential or reference developmental rate.

The consensus of the group was that, for SR-1 of CERES Wheat, we should have TOPT = 15°C up to last leaf, and then use 26°C for grain fill. Over the year, people may want to explore:

- Whether 15°C is too low.
- How we should handle intermediate phase (e.g., use a third, intermediate value of TOPT).
- Whether there is an effect of photoperiod *per se* on phyllochron.

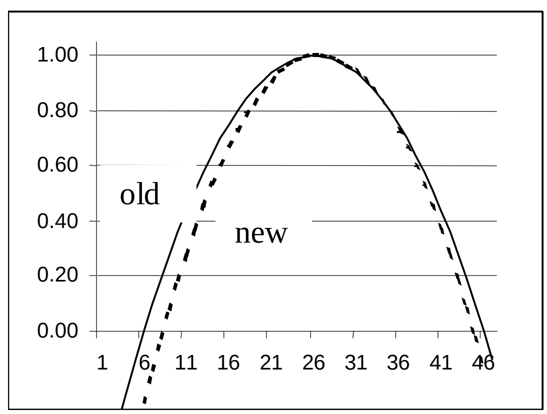
Maize

Paul Wilkens first reported on reported on minor "bug fixes" that will go into Service Release 1:

- Fix irrigation and fertilization errors when dates are given as DAP.
- Changes to TLNO and P3 where PHINT was hard-wired (suggested by Upendra).
- The current nitrification mechanism is too source-driven; so, under some conditions, ammonium gets converted to nitrogen too fast.
- Fixed the minor errors in temperature functions.
- A single day of low temperatures used to be enough to shut down growth. This is now buffered by requiring 5 or 10 days of low temperatures (depending on growth stage).

Proposed future changes covered a wide range of problems. The temperature effect on grain filling probably allows too much filling at low temperatures (Fig. 1). The old equation was:
RGFILL = 1.0 – 0.0025*(TEMPM – 26.0)**2

The proposed new version is:
RGFILL = 1.4 – 0.003*(TEMPM – 27.5)**2



This is supposed to reduce sensitivity of filling rate to high temperatures, but Figure 1 suggests the effect is minor. Wheat has a very complex function, and JR suggested all cereal crops need review.

Many researchers have expressed concern over modeling of grain number in maize (and wheat), especially under stress. In CERES 3.5, grains per plant is determined by a relation between PSKER and GPP, where the cultivar coefficient G2 (maximum kernel number per ear) fixes the maximum kernel number. At low values of PSKER (e.g., 10), GPP is still positive. One consequence is that, at extremely high populations, you still get an increase in yield with population. T. Tollenaar (Guelph) has used a curve that zeros at 10. Adding a second ear is also problematic too, and older varieties have more barren plants, so we also need a barrenness factor for cultivars. JR suggests that GPP should vary with cumulative IPAR instead of biomass production (PSKER). Ease of measurement is an issue. There was a lively exchange on this point:

- IPAR can be calculated easily for high densities but is very difficult to measure at low populations.
- If you use growth, do you use total growth or top growth (easier to measure)? To model, have to get both total growth and partitioning correct, which is often difficult.
- The IPAR approach may break down at low pops, but other problems may dominate under these conditions (e.g., heterogeneity of population).
- How would you handle CO2 effects with the IPAR approach?

Also, what is the correct time interval for modeling grain number? Tolenaar uses 1 week before and three weeks after. CERES 3.5 uses a GDD sum (327) that has to be carried forward. It would seem logical to link GDD to a specific developmental stage. One suggestion is to use date of formation of the next-to-last leaf.

The issue of how to add a second ear, which is needed for prolific varieties, was also discussed. One approach is to place a maximum value using G2 and add new ears if growth is sufficient to exceed this limit. Would need three values:

- G2
- Barrenness function
- Prolificacy switch: Could be add a second ear if IPAR

Note that to calibrate cultivars, data from populations of at least 120,000 plants/ha are required.

Grain number in wheat also requires revisions. Accuracy of wheat depends on how well stem weight is estimated. Both maize and wheat might be handled with a generic approach.

Joe and Upendra showed their strategy for handling barrenness at high populations. The proposed code assumes that if you get low levels of GPP (e.g., 200), then the number of ears is reduced:

```
     EARMIN = 250
     EARINT = 0.15
IF (GPP .LT. EARMIN) THEN
     EARSL = 0.85
     EARS = PLTPOP * (EARINT + EARSL * GPP/EARMIN)
     EARS = AMAX1(EARS, 0.0)
     GPSM = EARMIN * EARS
     GPP = GPSM/PLTPOP
 ELSE
     GPSM = GPP * EARS
 ENDIF
```

Tony asked what the strategy should be for handling growth of barren plants. Do you modify photosynthesis to reflect non-available assimilate? This may be important for late-season stresses. The consensus of the group was that, for SR-1 of CERES Maize, we should accept the various minor fixes. Over the year, people may want to explore:

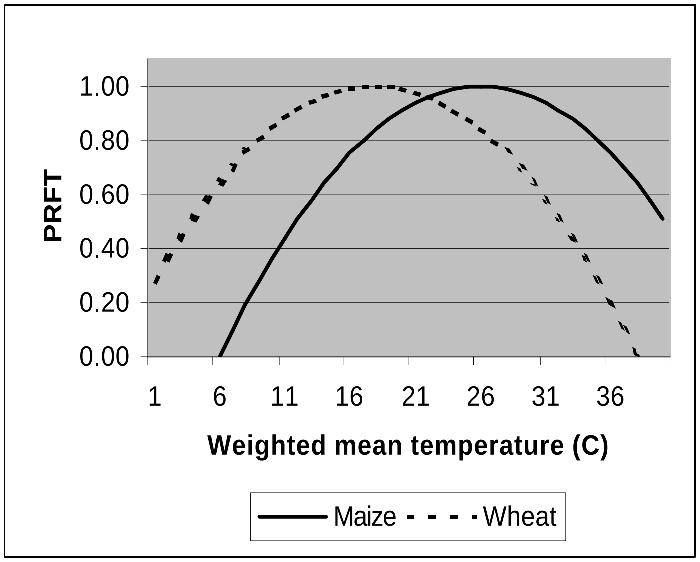
- How to model GPP using either IPARE or growth while allowing for multiple ears.
- How to handle barren plants (U. Singh and J. Ritchie).

General Concerns on RUE

For both CERES Maize and Wheat, radiation use efficiency (RUE) shows a parabolic response to temperature. For maize:

PRFT = 1.0 – 0.0025*((0.25*TMIN+0.75*TMAX) -26.0)**2
And for wheat:
PRFT = 1.0 – 0.0025*((0.25*TMIN+0.75*TMAX) -18.0)**2,

where PRFT is a 0-to-1 scaling modifier for RUE. These give an optimal value of RUE that is too high and a near optimal temperature range that is very narrow.



Joe Ritchie explained that the original idea came from single leaf data with rapid changes in temperature. However, experience has shown that plant adaptation (acclimation) results in a much broader optimum. The consensus was that this needs testing for both crops. To facilitate the work, we should place RUE = f(temperature) in the species' files (*.SPE). For CERES 3.5 SR-1, we should retain a curve identical to that in the model, and people can manipulate this file to suggest a new set of values.

Recommendations

Paul Wilkens and Upendra Singh will use the IFDC crop modeling workshop this May to further test and consolidate the proposed release. For next year, we hope people will have looked much further at:

1. Temperature response and phenology.
2. Temperature effect on RUE.
3. Stress effects on phenology (especially low N and maize).
4. Temperature effect on rate of grain filling.

Various sources for data were suggested, but it is clear that this workshop needs to be supported by a large set of quality datasets that are available at the onset of the workshop. This is clearly a good challenge for the CIMMYT hosts to address.

Joe Ritchie emphasized that the CERES group needs to look harder at test criteria for release of new model versions. In particular, we need to ensure that "fixing" one problem doesn't create other problems. Again, this goes back to the idea of having diverse sets of test data for different aspects of the models.

Participants and Contact Information

Andre Frans du Toit
Agricultural Research Council
Summer Grain Centre
Private Bag X1251
Potchefstroom 2520
South Africa
Phone: +27 (018) 299-6249
Fax: +27 (018) 294 7146
Email: ANDRE@IGG2.AGRIC.ZA

Dewi Hartkamp
Natural Resources Group
International Maize and Wheat
Improvement Center (CIMMYT)
Apartado Postal 6-641
06600 México D.F.
Mexico
Phone: +52 5804 2004
Fax: +52 5804 7558, or 7559
Email: d.hartkamp@cgiar.org

L. Anthony Hunt
Professor
Plant Agriculture, Crop Science
Division
University of Guelph
Guelph ON N1G 2W1
Canada
Phone: 519-824 4120 Ext. 3595/2414
Fax: 519-763 8933
Email: thunt@crop.uoguelph.ca

Garry J. O'Leary
South African Sugar Association Experiment
Station
PB X0
Mount Edgecombe 4300
KZN
South Africa
Email: gjoleary@yahoo.com

Joost Lieshout
Natural Resources Group
International Maize and Wheat
Improvement Center (CIMMYT)
Apdo. Postal 6-641
06600 México D.F.
Mexico
Phone: +52 5804-2004
Fax: +52 5804-7558, or 7559
Email: j.lieshout@cgiar.org

Joe T. Ritchie
Professor
Homer Nowlin Chair
Michigan State University
Crop and Soil Sciences
A570 Plant and Soil Sciences Bldg.
East Lansing, MI 48824-1325
U.S.A.
Phone: +1 (517) 353-4702
Fax: +1 (517) 355-0270
Email: ritchie@pilot.msu.eta

Upendra Singh
International Fertilizer Development
Center
P.O. Box 2040
Muscle Shoals AL 35662
U.S.A.
Phone: +1 (256) 381-6600
Fax: +1 (256) 381-7408
Email: upendras@IFDC.org

Marvin L.M. Stapper
Droevendaalsesteeg 41, 6708 PB,
Wageningen, the Netherlands
Email:
marvin.stapper@94.student.wau.nl

Jeff White
Natural Resources Group
Centro Internacional de Mejoramiento
de Maíz y Trigo, Int.
Lisboa 27, Col. Juárez
Apdo. Postal 6-641
06600 México D.F.
Mexico
Phone: +52 5804-2004
Fax: +52 5804-7558, or 7559
Email: j.white@cgiar.org

Paul W. Wilkens
International Fertilizer Development
Center
P.O. Box 2040
Muscle Shoals AL 35662
U.S.A.
Phone: +1 (256) 381-6600
Fax: +1 (256) 381-7408
Email: pwilkens@IFDC.org

Contact Information, Second Authors

J. Booysen
PU vir CHO, Navorsingsinstituut vir
Hervestigingsekologie, Private bag X
6001, Potchefstroom 2520, R.S.A

J.D. Corbett
Senior Systems Analyst
Texas Agricultural Experiment Station
Blacklands Research Center
Texas A&M University
808 East Blackland Road
Temple , TX 76502 USA
Phone +1(817) 770-6636
Fax +1(817) 770-6561
Email corbett@brc.tamus.edu

J.J. Human
UOVS, Department of Agronomy ,
P.O Box 339, Bloemfontein 9300, RSA

J.W. Jones
P.O. Box 110570
University of Florida, Gainesville
FL 32611-0570 USA

Other numbers in this series:

Hodson, D., J.D. Corbett, P.C. Wall, and J.W. White. 1998. *An Agroclimatological Overview of Wheat Production Regions of Bolivia.* NRG-GIS Paper 98-01. Mexico, D.F.: CIMMYT.

Hartkamp, A.D., K. De Beurs, A. Stein, and J.W. White. 1999. *Interpolation Techniques for Climate Variables.* NRG-GIS Series 99-01. Mexico, D.F.: CIMMYT.

Barreto, H.J., and A.D. Hartkamp. 1999. *Analysis of Maize Production in Honduras: Linking Census Data to Environment Variables through Geographic Information Systems.* NRG-GIS Series 99-02. Mexico, D.F.: CIMMYT.

ISSN: 1405-7484