TESTING AND CALIBRATION OF THE CERES-WHEAT MODEL IN OKLAHOMA

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Chapter 1

INTRODUCTION

More wheat is grown than any other cereal grain in the world. In the United States, food products from wheat contribute about one fourth of the total food energy requirement of man (Geddes and Shellenberger, 1998). The state of Oklahoma ranks second or third nationally in the amount of winter wheat produced in each of the last 25 years. Wheat is the third most valuable agricultural product in Oklahoma trailing only cattle and hay (Bloyd and Cole, 1996). The total value of Oklahoma wheat in 1996 was over $460 million (Bloyd and Cole, 1996).

It has been estimated that by the year 2025, the demand for food will double (Nichols, 1996). With most of the arable land in the world currently being used for agricultural production, increasing the area of farmed land is not likely to appreciably increase the amount of food produced. In order to meet the nutritional needs of the world population, yields per unit area must increase. One way to increase production is to improve management of current resources. Many different tools are available as aids in crop management. Crop growth models have been used to evaluate production alternatives over a range of soil and climate settings.

Engineers and scientists have been working on crop growth simulation models for many years. A model that accurately predicts growth and yield is a valuable tool for many reasons. One application of such a model would be to study the economic benefits of applying different rates of fertilizer. Applying excessive fertilizers to crops can lead to environmental problems. A model can be used to determine the amount of nitrogen that the plant needs. This allows for cost effective and environmentally friendly applications of fertilizer. The effects of different varieties, planting and harvesting dates, and irrigation management can be studied and optimized for maximum yield potential. Many governmental agencies use crop models to forecast yields for different regions of the world. The output of these models are often used to set policy and prices in world trade markets. Mearns et al. (1992) used the CERES-Wheat crop model to study the effects of climatic variability on wheat yields. Most importantly, farmers may be able to use crop models directly as a management tool.

The main objective of this study is to test and calibrate a model to simulate wheat growth in Oklahoma. We will select a process-based model that has been tested and validated. All necessary input parameters needed to simulate wheat growth will be obtained. The model will need to accurately predict yields in all geographic regions of the state where wheat is grown. To test the mobility of the model, it will be tested at three sites where the soil type and climate are different. An accurate response in yield to applied nitrogen is essential. Another important consideration is the type of input parameters needed to use the model and the amount of effort needed to acquire them. An accurate model may be of limited use if the input parameters are difficult and costly to obtain.

Chapter 2

LITERATURE REVIEW

Crop Models

Ritchie (1991) defined a model as a small imitation of the real thing or as a system of postulates, data and inferences presented as a mathematical description of an entity or state of affairs. This definition indicates that there are many different factors that must be taken into consideration when modeling the plant and soil system. Another important consideration is the inherent random variability in nature that is impossible to account for when modeling. Peart and Curry (1998) described the model of a system as the set of equations and rules that quantitatively describe the operation of the system through time. They defined simulation as the process of solving these equations through changing time by calculating variables in a series of steps.

The acceptance and use of crop models has greatly increased during the last decade. The main reasons for this increase are the development of the personal computer and the acceptance by potential users (Hoogenboom et al., 1992). Engineers and scientists have attempted to predict the growth and yield of agricultural crops since the early 1970s (Stapleton, 1970; Bowen et al., 1973). The early models developed were not widely used for several reasons. These include the amount of computing time needed to execute the models on mainframe computers and the time and effort required to make these models easy for others to use (Hoogenboom et al., 1992).

Most crop models can be described as either a mechanistic/process-based model, an empirical model based on regression techniques, or a combination of these two approaches. The main objective of earlier models was to accurately predict crop yields based on a set of inputs. The emphasis of current models has expanded to include a variety of outputs such as yield, leaf area index (LAI), biomass, nitrogen fixation and other growth related parameters.

Empirical models are typically the simpler of the two. Many are based on regression equations developed at a single site or a specific region (Touré et al., 1994). Often these models provide good results, but they may not be responsive to the specific cause and effect relationships that influence crop growth.

Mechanistic or process based models use complex equations to describe the physical and physiological factors that influence growth of a crop based on many input parameters. Some of these relationships are empirical or semi-empirical, but they attempt to reflect the processes involved in crop growth and development.

Modeling Wheat Growth and Yield

Both empirical and mechanistic models exist for modeling the growth of wheat. To perform this study, we reviewed several different models. Since our data are based on well-documented soil fertility experiments, we have most of the inputs needed by a complex mechanistic model. This type of model is also more sensitive to changes that occur from year to year. For these reasons, we decided that a mechanistic model would best suit our needs.

CERES (**C**rop **E**stimation through **R**esources and **E**nvironment **S**ynthesis)-Wheat is a computer model that simulates growth, development and yield of both spring and winter wheat (Otter-Nacke et al., 1986). The model operates on a daily time step and is designed to work in any location where wheat can be grown. The model is written in

FORTRAN77 and uses many subroutines for weather information, soil water balance, growth and development, cold hardening and winterkill, and soil.

The EPIC (Erosion Productivity Impact Calculator) model is another mechanistic model that is used to estimate yields for a wide variety of crops including wheat. The model was originally developed to study the relationship between crop growth, erosion, and soil productivity (Williams et al., 1989). The model has several different components including soil erosion (water and wind), economics, hydrology, weather, nutrients, plant growth and crop management. The inputs for weather and soil can be in GIS format using GRASS. The output from the model allows for analysis of yield and fertilizer economics.

There are several other mechanistic models for wheat. Many of these model spring wheat, e.g. SWHEAT (Porter et al., 1993), or winter wheat, e.g. Stewart (Touré et al., 1994), but not both. Other models, e.g. Sinclair and Century, use a simplistic approach to modeling plant growth and yield and have detailed routines for modeling nutrients and water (Touré et al., 1994). AFRCWHEAT2 is a mechanistic model that details the movement of water and nitrogen in the soil profile (Porter et al., 1993). The ARFRCWHEAT2 model has been combined with a stochastic weather generator to provide the ability to evaluate the impact of climatic variability on crop yields in weather generation (Semenov and Porter, 1995). Some models are used and tested only in specific environments. The model WTGROWS (Aggarwal et al., 1994) was written specifically for tropical and sub-tropical regions of India.

Several validation studies exist for these models. The most widely tested model, CERES-Wheat, was evaluated using almost 300 different plot years of independent data from around the world (Otter-Nacke et al., 1986).

Landau et al. (1998) tested the ability of CERES-Wheat, AFRCWHEAT2 and SIRIUS to predict yield in the United Kingdom. Wheat yields were measured at many different locations from 1975 to 1993. The models were run with nitrogen not limiting, and the same soil characteristics were used at all sites. Weather variables were interpolated from the nearest measured location. They concluded that none of the models accurately predicted yield.

Porter et al. (1993) compared CERES-Wheat, AFRCWHEAT2 and SWHEAT for non-limiting growth conditions. Testing indicated that both CERES-Wheat and AFRCWHEAT2 performed well in certain areas while SWHEAT did not. They concluded that the models needed to be validated independent of their original calibration and validation. This allows the genetic parameters to be better estimated which results in better yield estimates.

Five different wheat models were tested in southern Alberta, Canada (Toure et al., 1994). The test included CERES-Wheat, EPIC, Century, Stewart and Sinclair. The Century model was not designed to predict yields. The emphasis of the Century model was the modeling of the soil nitrogen, phosphorus, carbon and sulphur cycles. The Sinclair model used a simplistic approach with only a few relationships to define wheat growth. The Stewart model was written to predict hard red spring wheat yields and was also a simplistic model using few relationships. The Stewart model included routines for soil and weather conditions that were unique to Western Canada built into the model.

CERES-Wheat and EPIC were the only models based on complex physical relationships within the plant and soil system. The authors concluded that the CERES-Wheat and EPIC models tended to underestimate yield in years where yield is high and overestimate when yield is low. None of the models accounted for the full range of variability in yields.

Both CERES-Wheat and EPIC models were tested in Saskatchewan for their ability to predict spring wheat yield over long periods of time (Moulin and Beckie, 1993). They used observed data from 1960-1989 to compare with model results. Even though the models performed poorly on an annual basis, they predicted long term yields accurately. The authors concluded that both models could be used as valuable decision making tools.

CERES-Wheat

Based on the literature, we decided that CERES-Wheat would be the best model to test and calibrate using our existing data. CERES-Wheat is a comprehensive model with nitrogen routines that allowed comparison of different nitrogen application rates. Some of the routines in the CERES-Wheat model are used in other CERES models, namely CERES-Maize. In addition to the research testing the ability of CERES-Wheat to predict yield and growth, several studies have been performed on specific routines within the model.

With proper calibration, the CERES-Wheat model has demonstrated the ability to predict yields and important phenological dates. Chipanshi et al. (1996) used historical data to examine the model's ability to predict the occurrence of important phenological and growth stages. These values are used in the model as genetic inputs. With the model calibrated, historical data was used to test the ability of the model to predict yield. Using a ratio of predicted to observed yield, the model had an average of 1.08 which meant that the model slightly over predicted yield for long term averages. They also analyzed the ability of the model to predict five different growth stages. Using historical weather, a potential yield was determined at each of the growing stages. The model demonstrated an ability to predict yield potential and this information proved useful for those making agronomic decisions.

The CERES-Wheat model was tested for the ability to predict yield in the irrigated plains of the Indian Punjab from 1985-1993 (Hundal and Prabhjyot-Kaur, 1997). They used the 1990-1991 year to calibrate the genetic coefficients used in the model. The results of the study indicated that the model accurately predicted the important physiological dates. Predicted yield ranged from 80-115% of the observed yield with an average of 97.5%. They concluded that the model can be used to predict yield of wheat in this location. The authors suggest that an improved understanding of the genetic growth coefficients would improve the accuracy of the model.

In Argentina, CERES-Wheat has been used to predict regional yields of wheat (Travasso and Delécolle, 1995). Genetic coefficients and measured input parameters were calibrated. The model estimated yields well but did not predict dates of maturity or properly simulate canopy development under stress.

The CERES-Wheat model was applied in the Mediterranean region to simulate growth and yield of wheat (Pecetti and Hollington, 1997). Genetic coefficients were calibrated so that reasonable dates for physiological events were predicted. While the model provided reasonable results for yield, it was suggested that the model needs adjustment to work well in a Mediterranean environment.

CERES-Wheat has been used in studies on the effects of climate change (Rosenzweig and Tubiello, 1996; Mearns et al., 1992). These studies compared the predicted and observed yields, but focused on the projected effects of climate changes. . Examples would be increasing CO_2 levels and increasing temperatures as suggested by most global warming theories.

CERES-Wheat is being used with **G**eographic **I**nformation **S**ystems (GIS) and **R**emotely **S**ensed (RS) data. RS can be a valuable tool when applying GIS to crop simulation models (Barnes et al., 1997a). RS can assist in addressing variability issues in soil, evapotranspiration (ET) and LAI. Many government agencies have an interest in large area yield estimation. The use of RS and GIS has been used in the past and the integration of a crop model has improved this process. The BEANGRO model was used in conjunction with the DSSAT data management software (Lal et al., 1992). This software can also be used with the CERES-Wheat model for the same purposes.

Chapter 3

DESCRIPTION OF DSSAT AND CERES-WHEAT

DSSAT v3.0 Structure

Currently, the CERES models, CERES-Barley, CERES-Maize, CERES-Millet, CERES-Rice, CERES-Sorghum and CERES-Wheat, are distributed as part of the Decision Support System for Agrotechnology Transfer (DSSAT). This software is a product of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). The DSSAT software includes a database management system to assist in organization of the information that is required of the models. Important components of the software are the utility programs used for the creation of input files. Several different validated models are also included as well as several analysis programs. This decision support system can assist the user in making future management decisions.

The data requirements are defined as are their formats. This allows all programs in DSSAT to access this information as needed. All programs run under a shell so that it is easy for the user to work in many different programs efficiently (Tsuji et al., 1994). DSSAT also contains menus for executing the crop models and some analysis, spreadsheet and graphing programs. The DSSAT version 3.0 software is distributed on nine 3.5 inch floppy diskettes and three volumes of manuals. The installation program allows the user to select specific portions of the DSSAT software and individual crop models. Many of the models are written in FORTRAN while some of the analysis and interface portions of the utility programs are written in Borland C++ and TurboVision.

Once the software has been installed, it is ready to use. The compiling of programs is not required. The system requirements for using DSSAT are a minimum of an IBM 286 or compatible microcomputer with a math co-processor. The system requires 640K of RAM with a minimum of 590K free DOS RAM and approximately 12 MB of disk storage space for a full installation. The software runs in a DOS environment and works with most operating systems.

WeatherMan

The DSSAT software includes a weather utility program to assist in the creation of weather data files that conform to the DSSAT v3.0 format. WeatherMan allows the user to import data files in almost any format. The user must create a weather station for a given location and input latitude, longitude, elevation, reference height of temperature sensors, wind reference height, mean annual temperature, temperature amplitude, start of growing season and length of growing season. Limits can be set on the variables that are imported and the program will flag missing data and data that are not within the limits. The program contains two weather models to fill in missing data, WGEN (Richardson and Wright, 1984) and SIMMETEO (Geng et al., 1988). The data can then be exported to yearly weather files that conform to the DSSAT v3.0 format. The databases within DSSAT must be updated to include exported weather files before the models can access them. Any of the crop models can access weather data from the database.

Experiment Files

The models in DSSAT execute in experiment, seasonal and sequence modes. Experiment mode will independently model one growing season. The seasonal mode is applied in situations involving large experiments or several treatments. Sequence mode allows for up to nine rotations of different crops and fallow periods. The files created for experiments are referred to as FILEX's. There is a program to assist with the creation of the files so that they are in the DSSAT v3.0 file format. All of the details of an experiment are defined in this file. Important information includes the crop variety or cultivar, soils information, initial conditions, planting method, irrigation schedules, fertilizer applications, tillage operations and harvest options. Simulation settings are also defined in this file. One of the more important options is the ability to use the nitrogen and water options with input data, or to assume that they are non-limiting. The settings for using historical or generated weather and the use of pest and disease routines can also be selected. There are also selections for different output files. Experiment files used in this study for the year 1992 can be found in Appendix A.

Soil Information

There are several soil parameters that are needed to perform an accurate model analysis. DSSAT has a program to assist in the estimation of these variables if they are not available. Variables include the depth of rooting, drained upper limit, lower limit, saturation, soil nitrogen, soil organic carbon, soil texture and bulk density. Since water stress is a critical factor that affects yield, it is important to have accurate soil descriptions with as many layers as possible.

Genetic Parameter Calibration

When using the CERES-Wheat model, it is important to have measured data for the occurrence of several physiological events. The growth stages of wheat are defined as shown in Table 1. The model uses coefficients for six of the nine growth stages. They can also be found in Table 1.

Table 1. Growth Stages Used in CERES-Wheat (Larrabee and Hodges, 1985)

Stage	Coefficient	Description
7		Pre-sowing
8		Sowing to Germination
9		Germination to Emergence
1	P1V	Emergence to Terminal Spikelet
2	P1D	Terminal Spikelet to End of Vegetative Growth
3	P5	End of Vegetative Growth to End of Pre-Anthesis Ear Growth
4	G1	End of Pre-Anthesis Ear Growth to Beginning of Linear Grain Fill
5	G2	Linear Grain Filling
6	G3	End of Grain Filling to Harvest

The genetic coefficients P1V and P1D define the sensitivity to vernalization and photoperiod for a specific variety. P5 is the relative grain filling duration based on thermal time. The growth coefficients G1, G2 and G3 are the kernel number per unit weight of stem, kernel filling rate under optimum conditions, and dry weight of a single stem and spike when elongation ceases (Tsuji et al., 1994).

The GENCALC utility program included with DSSAT is used to estimate genetic coefficients. This program did not converge to a set of genetic parameters so it was not used. A common calibration technique (Porter et al., 1993; Travasso and Delécolle, 1995; Barnes et al., 1997b) is to use years of data when the above parameters were measured and adjust the values of the coefficients until the model provides accurate results. These new genetic coefficients are then used in other years when the same variety has been planted.

Executing the CERES-Wheat Model

The CERES-Wheat model is executed from the DSSAT shell. The model will run provided that at least one experiment file exists without any errors. The weather and soils information contained in the experiment file must also be correct. An overview of the model structure can be found in Figure 1 in flowchart form.

Upon execution of the model, the user is prompted to select an experiment. The database management portion of DSSAT allows the user to specify which experiment files appear in the list. The model first reads the number of treatments used in the experiment and it will run each treatment independently. Then the specific variables defining the soil, genetic variety, fertilizer type and amounts, and the weather location are initialized. The model then verifies that weather files exist for the start and end date of the experiment. If the user specified model inputs for soil water or soil nutrients, they are read at this time. The management options of the experiment file allow the user to turn the routines for water and nitrogen on or off. When the routines are on, calculations are made for needed parameters. If the routines are off, the model assumes that water and nitrogen are not limiting to the plant.

Soil Water Balance Model

Water stress is often the most critical factor in production of dryland wheat. For this reason, the soil water balance is an important routine in the model. This routine is the same for both the CERES-Wheat and the CERES-Maize models.

Along with the rest of the model, the soil water balance operates on a daily time step. Infiltration, runoff, evapotranspiration and upward fluxes are calculated on this daily time step. The soil profile can be divided into a maximum of ten layers with each layer having defined values for all variables. Some critical variables are often the field capacity (drained upper limit, DUL), the permanent wilting point (lower limit, LL),

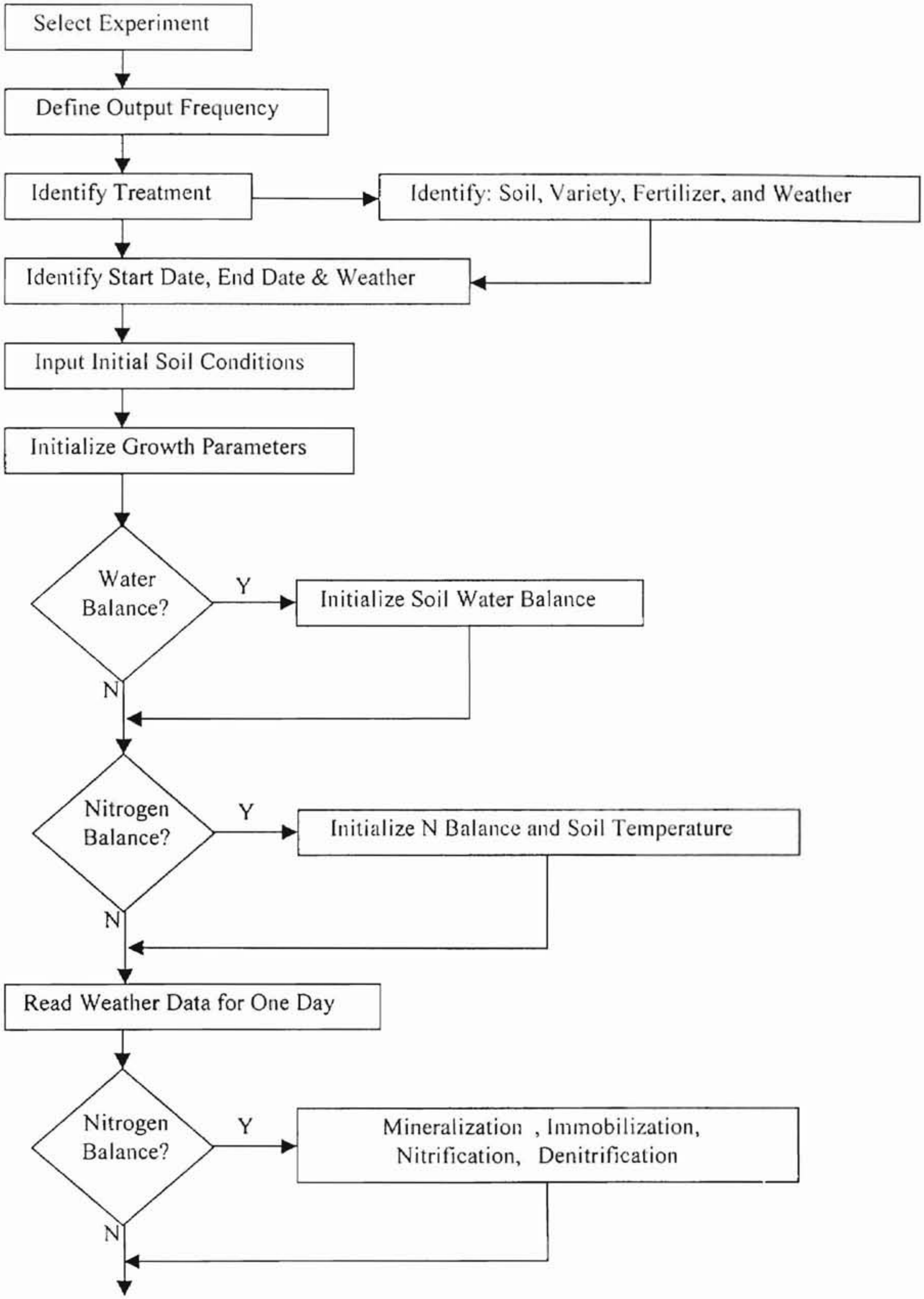
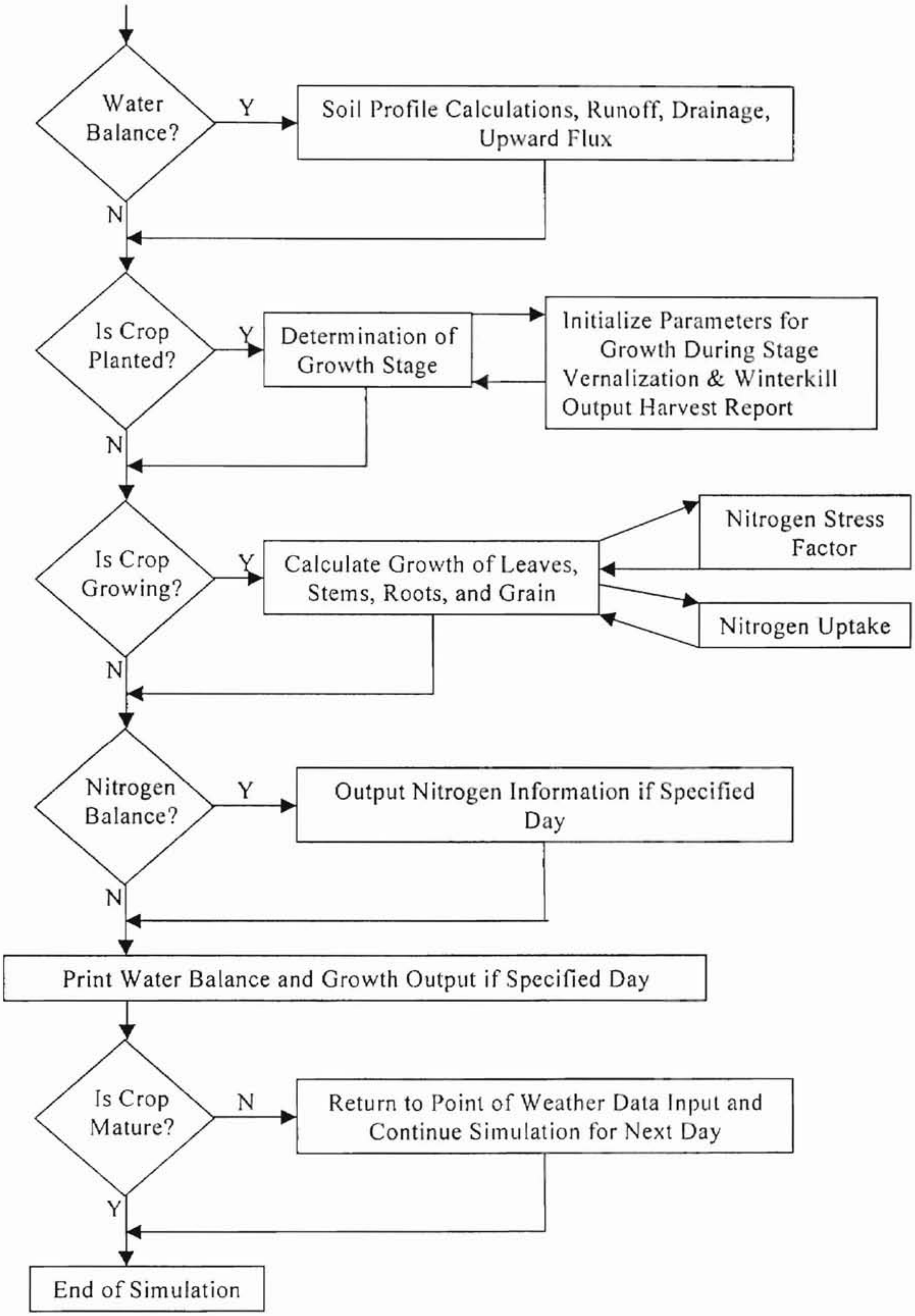


Figure 1. Flowchart for CERES-Wheat, after Ritchie and Godwin (1998)



(Figure 1. Continued)

and the saturation (SAT). Runoff is calculated using the USDA-NRCS curve number method. Infiltration at the surface is then calculated as the sum of rainfall and irrigation minus the runoff. If water content is above field capacity, water will drain into the layer below it. This continues for each subsequent layer until the end of the profile is reached. Evapotranspiration is calculated using a procedure that is similar to a model presented by Ritchie (1985). The Priestly-Taylor equation is used for potential ET and an empirical equation is used to evaluate the effects of temperature and net radiation on the equilibrium evaporation (Ritchie and Otter, 1985). A more complete description as well as a field analysis of the performance of the soil water balance used in CERES-Wheat is provided by Gabrielle et al. (1995).

Nitrogen Sub-Model

The nitrogen sub-model (CERES-N) is used in both CERES-Maize and CERES-Wheat. Nitrogen is an important factor in the growth and development of wheat. This model is not the most comprehensive nitrogen model and is designed to work within the CERES models. It is not a stand-alone model. The simplicity of the model is a result of the desire for a minimum set of inputs. The model accounts for application of fertilizer, mineralization and immobilization, nitrification, denitrification, plant uptake, nitrogen concentration in the plant, and nitrate leaching. An evaluation and detailed explanation of the CERES-N model has been performed (Godwin and Jones, 1991). Another evaluation of the nitrogen transfer and transformations can be found in Gabrielle and Kengni (1996).

Modeling Plant Growth

The growth stages and the corresponding model parameters are listed in Table 1. The use of these coefficients was discussed in the same section. However, a brief description of the methods that the model uses to simulate plant growth needs to be presented.

The primary experimental variable influencing the growth and development of wheat, providing there is adequate water, is temperature. The model assumes that growth in most stages of development is linearly related to temperature between 0 C and 26 C (Ritchie, 1991). The thermal time for each of the growth stages is not fixed. Sowing to germination is assumed to take one day provided that temperature and water are adequate. Wheat requires relatively low temperatures for vernalization to occur. Vernalization occurs between 0 C and 18 C with 7 C an optimum and 7 to 18 C a detrimental effect on the process (Ritchie, 1991). Even though 50 vernalization days are considered sufficient for all varieties to complete the process, the coefficient P1V is used to calibrate the length of vernalization for specific varieties. A short photoperiod can delay the stage 1 development. The coefficient P1D is used to account for the genetic sensitivity of a specific variety to photoperiod.

Another important characteristic affecting the growth and development of wheat is the length of time between leaf appearance, or phyllochron. There are several equations that have been developed to estimate the phyllochron but observed local estimates are often used. In CERES-Wheat, the parameter PHINT is used to define this length in degree-days. The calculations in the model consider vernalization, photoperiod and phyllochron together when simulating growth during stage 1 of development.

Stage 2 is considered to be completely temperature dependent. The model assumes three phyllochrons from terminal spikelet to the final leaf appearance. The third stage is important when determining the final number of grains per plant. The length of this period is considered two phyllochrons even though there is not further leaf development. The fourth stage requires 200 degree days. This stage also has a significant impact on the final grain numbers since the overall biomass production depends on the length of the period. The final stage is used only if the user would like a decrease in yield when the crop is not harvested.

Temperatures below 0 C can cause damage to the wheat plant. The CERES-Wheat model has routines that calculate damage due to both hardening due to cold temperatures and winterkill. Since the depth of snow can have an impact on plant survival when the temperatures are between –10 and –30 C, a depth of snow model has been incorporated. The model also assumes that all reported rainfall when the maximum air temperature is less than or equal to 1 C is snow. Using 113 different independent data sets from around the world, Otter-Nacke et al. (1986) tested this portion of the model and concluded that the agreement between estimated and measured yields was acceptable.

Chapter 4

DEVELOPMENT OF MODEL INPUT PARAMETERS

Introduction

In order to test and calibrate the model, several input parameters were needed. Weather parameters needed include maximum and minimum temperature, solar radiation, and rainfall. Soil parameters are needed for the water balance portion of the model to perform well. Other parameters include date of planting, fertilizer application date, amount of fertilizer application, and harvest date. Complete and accurate sets of input parameters are essential to the testing and calibration of the model.

The Plant and Soil Sciences Department at Oklahoma State University performs several experiments at research locations throughout the state. One experiment is the response of wheat yield to long-term fertilizer applications. Locations for this experiment are Stillwater, Altus, and Lahoma and relatively complete data sets exist from 1971. The Plant and Soil Sciences Department has maintained records for many of the needed input parameters required for testing and calibrating the CERES-Wheat model.

Oklahoma Agricultural Experiment Station

The Oklahoma Agricultural Experiment Station (OAES) is the agricultural research arm of the Division of Agricultural Sciences and Natural Resources at Oklahoma State University. The OAES was created in 1890 by the Oklahoma Territorial Legislature. Defined by Congress, the OAES is also part of the federal-state partnership in agricultural research.

The OAES system includes 18 research stations throughout the state. One of the research stations is located near the main campus of Oklahoma State University in Stillwater. The research stations are distributed throughout the state in an attempt to represent the variety of agricultural conditions present in Oklahoma.

Stillwater Site

The experiment station in Stillwater, OK is on the west edge of town, approximately 97 km (60 miles) north-northwest of Oklahoma City. The site is located at in Payne County at 36.1211 N latitude, 97.0950 W longitude, with an elevation of 272 m (893 ft) above sea level.

Mean annual climatic data were obtained from the Oklahoma Climatological Survey (OCS) (Bloyd and Cole, 1996). The average annual temperature is 15 C (59 F) and the mean annual precipitation is 89 cm (35 in). The monthly average temperature and precipitation can be found in Table 2. The climate in Payne County is described as hot in the summer and mild in the winter with occasional surges of cold air causing sharp drops in temperature (Henley et al., 1987).

The Natural Resources Conservation Service (NRCS) classifies the soil at the Stillwater Experiment Station as a Kirkland silt loam with 0 to 2 percent slopes. The soil is deep and well drained and slopes are nearly level to gently sloping. Livestock production is the major land use in Payne county with approximately 70% of the county in pasture and rangeland (Henley, 1987). About 20% of the 181,300 hectares (448,000 acres) in the county are cropland with wheat being the major crop.

Table 2. Payne County Mean Annual Temperature and Precipitation (OCS, 1998)

	Temp (C)	Precip (cm)
Jan	1.1	2.9
Feb	3.8	4.2
Mar	9.2	7.4
Apr	15.4	7.8
May	19.9	13.6
Jun	24.6	10.7
Jul	27.7	7.3
Aug	26.9	6.8
Sep	22.4	10.9
Oct	16.2	7.4
Nov	9.4	6.2
Dec	3.2	3.7

Experiment #222 was established at the Agronomy Research Station in Stillwater, OK in 1969. This trial was established to evaluate the long-term responses of yield to the application of nitrogen (N), phosphorus (P), and potassium (K). Three different varieties, TAM W 101, Karl, and then Tonkawa, have been planted since 1969 with 13 combinations of N-P-K fertilizer treatments. The design of the experiment utilized four replications in a randomized complete block design. Four of the 13 different treatments of N-P-K were examined in this study, 0-68-45, 45-68-45, 90-68-45, and 135-68-45 kg ha^{-1} (Sembiring et al., 1997). Differing phosphorus and potassium treatments were not used since CERES-Wheat will only model nitrogen.

Historical data for variety, planting, harvesting and fertilizer application for this experiment can be found in Table 3. The year of the experiment listed is the harvest year of the data. Some field operation dates were assumed due to missing data and are noted as such.

Table 3. Stillwater Experiment #222 Historical Data (Sembiring et al., 1997)

Year	Variety	Fertilizer Application Date	Planting Date	Harvest Date
1981	TAM W-101	9-18-80*	9-22-80*	6-31-81
1982	TAM W-101	9-18-81	9-22-81	6-14-82
1983	TAM W-101	9-29-82	10-4-82	6-21-83
1984	TAM W-101	8-31-83	10-5-83	6-25-84
1985	TAM W-101	8-23-84	10-2-84	6-12-85
1986	TAM W-101	10-1-85	10-7-85	6-12-86
1987	TAM W-101	8-20-86	10-17-86	6-15-87
1988	TAM W-101	8-20-87*	9-17-87	6-14-88
1989	TAM W-101	8-18-88	10-01-88*	6-20-89
1990	TAM W-101	8-29-89	10-11-89	6-13-90
1991	TAM W-101	9-1-90*	10-01-90*	6-17-91*
1992	TAM W-101	9-10-91	9-30-91	6-17-92
1993	Karl	9-16-92	10-12-92	6-17-93
1994	Karl	9-22-93	9-27-93	6-8-94
1995	Tonkawa	8-30-94	9-29-94	6-20-95
1996	Tonkawa	10-9-95	10-10-95	6-11-96
1997	Tonkawa	9-5-96	10-3-96	6-19-97

* - Assumed Values

The soil at the Stillwater Experiment Station has been extensively sampled. One study examining the effects of long term nitrogen application on organic carbon and total nitrogen for the Stillwater site was done by Raun et al. (1998). The data in Table 4 were taken from the 1995 sampling data. These numbers were used for all years since research by the Plant and Soil Sciences Department indicates that they have not changed significantly during the length of the experiment.

The Stillwater Experiment Station operates the official weather station for the City of Stillwater. Historical weather data from 1980 through 1993 were obtained from the Department of Plant and Soil Sciences, Oklahoma State University and converted to digital format. The recorded data consisted of daily maximum and minimum temperature and rainfall. For the period of January 1994 to December 1997, weather data were obtained from the Oklahoma Mesonet station located at the Stillwater Experiment

Station. The weather monitoring station is located less than 400 meters west of the field plots. The maximum temperature recorded during the period of 1993 to 1997 was 44 C (111 F) and the minimum was –28 C (–19 F). In addition to maximum and minimum temperature and rainfall, solar radiation was also recorded at the Mesonet station. A complete set of weather data described above was imported into the utility program WeatherMan.

Table 4. Stillwater Experiment Station Soil Data

Layer	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g/cm^3)	Organic Carbon (%)	Soil N (%)
1	0-5	33.3	43.2	23.5	1.53	0.81	0.07
2	5-28	20.4	43.5	36.1	1.51	0.35	0.07
3	28-53	25.9	37.3	36.8	1.66	0.47	0.05
4	53-73	27.8	36.2	36.0	1.66	0.34	0.04
5	73-96	32.6	32.0	35.4	1.65	0.20	0.04
6	96-124	27.0	32.0	41.0	1.64	0.16	0.04
7	124-152	34.0	30.5	35.5	1.70	0.13	0.02
8	152-175	26.4	37.8	35.8	1.71	0.11	0.02
9	175-198	29.1	41.2	29.7	1.77	0.07	0.01
10	198-218	17.3	47.2	35.5	1.70	0.04	0.01

Using years 1994 to 1997, monthly summaries were calculated. These monthly summaries were used along with the WGEN weather generator to estimate the solar radiation for the years 1981 to 1993 based on minimum and maximum temperature and rainfall. The weather data were then exported in the IBSNAT 3.0 format and the DSSAT database was updated. Tables of monthly rainfall with totals for each growing season are listed in Appendix B for each site.

Altus Site

The research station in Jackson County is near Altus, OK. The town of Altus is located in Jackson County approximately 193 km (120 miles) southwest of Oklahoma

City, at 34.5872 N latitude, 99.3378 W longitude and 417 m above sea level. Approximately 91,000 hectares (225,000 acres) in Jackson County are planted in wheat with about 400 of these irrigated (Bloyd and Cole, 1996). These numbers indicate 45% of the 202,300 hectares (500,000 acres) in the county are planted in wheat.

According to the Oklahoma Climatological Survey, Jackson County has a mean annual temperature of 17 C (62.8 F) and the mean annual precipitation is 64.5 cm (25.4 in). The monthly averages for temperature and precipitation are presented in Table 5.

Table 5. Jackson County Mean Annual Temperature and Precipitation (OCS, 1998)

	Temp (C)	Precip (cm)
Jan	4.2	2.1
Feb	6.8	2.8
Mar	11.9	4.0
Apr	17.4	4.9
May	22.0	10.7
Jun	26.6	8.9
Jul	29.2	4.5
Aug	28.2	6.2
Sep	23.9	8.7
Oct	18.1	6.0
Nov	11.2	3.3
Dec	5.4	2.3

The Tillman-Hollister clay loam soil is the most extensive in Jackson County according to the NRCS soil survey. These soils usually have zero to one percent slopes and are considered excellent for growing wheat and fairly good for cotton, sorghum and alfalfa (Bailey and Graft, 1958). Erosion is not usually a problem, but lack of water available to the plant can limit production.

In 1965, experiment #406 was established at the Irrigation Research Station near Altus, OK to examine long-term responses of yield to fertilizer application. The site uses conventional tillage with dryland winter wheat planted in 25.4 cm (10 in) rows and a seeding rate of 100 kg ha^{-1}(90 lb acre^{-1}). The experiment was designed using six replications and a randomized complete block (Sembiring et al., 1997). Planting, harvest, and fertilizer application dates can be found in Table 6. In this study, five different N application rates were examined, 0, 45, 90, 120 and 180 kg ha^{-1}. There was no phosphorus or potassium applied to these treatments during the experiment. The model assumes that both P and K are not limiting.

Table 6. Altus Experiment #406 Historical Data (Sembiring et al., 1997)

Year	Variety	Fertilizer Application Date	Planting Date	Harvest Date
1981	TAM W-101	8-22-80	11-7-80	6-10-81
1982	TAM W-101	9-9-81	10-27-81	6-30-82
1983	TAM W-101	8-16-82	8-16-82	6-15-83
1984	TAM W-101	8-25-83	11-3-83	6-13-84
1985	TAM W-101	8-29-84	10-10-84	6-20-85
1986	TAM W-101	8-23-85	11-4-85	6-10-86
1987	TAM W-101	9-18-86	11-15-86	6-8-87
1988	TAM W-101	9-1-87	10-6-87	6-9-88
1989	TAM W-101	10-24-88	11-17-88	6-22-89
1990	TAM W-101	88-10-89	9-22-89	6-9-90
1991	TAM W-101	8-30-90	10-10-90	6-18-91
1992	TAM W-101	9-22-91	9-27-91	6-15-92
1993	Karl	10-15-92*	10-20-92	6-15-93
1994	Karl	8-17-93	9-28-93	6-3-94
1995	Tonkawa	8-19-94	10-27-94	6-17-95
1996	Tonkawa	8-17-95	10-12-95	6-5-96
1997	Tonkawa	8-15-96	10-1-96	6-14-97

* - Assumed Values

Sampling for soil characteristics throughout the profile similar to the Stillwater site does not exist. The soil at the site was described using four layers as shown in Table 7 with data taken from the Jackson County soil survey and the Oklahoma Mesonet.

The maximum and minimum temperatures as well as rainfall were recorded on a daily basis for the site. These data were converted to electronic format for the years 1980-1993. The Oklahoma Mesonet provided these parameters and solar radiation from

1994 to 1997. The weather station is located less than 300 meters from the field plots. The data were converted to IBSNAT form using the WeatherMan utility program and the same method as the Stillwater site. The maximum daily temperature recorded by the Mesonet weather station from 1994 to 1997 was 48 C (119 F) and the minimum was –17 C (1 F). Tables of monthly rainfall with totals for each growing season are listed in Appendix B.

Table 7. Altus Experiment Station Soil Data

Layer	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g/cm^3)	Organic Carbon (%)	Soil N (%)
1	0-15	22.7	40.2	37.1	1.45	0.82	.06
2	15-30	21.8	42.0	36.2	1.50	0.57	.04
3	30-65	20.3	38.6	39.3	1.50	0.35	.03
4	65-80	14.0	36.0	50.0	1.55	0.27	.02

Lahoma Site

The Lahoma site is in northwest Oklahoma about 129 km (80 miles) from Oklahoma City in Major County, at 36.3844 N latitude and 98.1114 W longitude. The elevation is 395 meters above sea level. Approximately 35% of the more than 250,000 hectares (616,000 acres) in Major county is cropland with wheat the dominant crop (Bloyd and Cole, 1996).

The climate for Major County is similar to that of Payne County according to the Oklahoma Climatological Survey. It is hot in the summer and relatively mild in the winter with occasional surges of much colder air. The monthly averages for temperature and precipitation can be found in Table 8.

Table 8. Major County Mean Annual Temperature and Precipitation (OCS, 1998)

	Temp (C)	Precip (cm)
Jan	1.2	1.8
Feb	4.0	2.6
Mar	9.5	5.3
Apr	15.4	6.6
May	20.4	9.6
Jun	25.8	9.4
Jul	28.6	6.6
Aug	27.6	7.0
Sep	22.9	7.8
Oct	16.7	4.8
Nov	8.9	4.4
Dec	2.8	2.1

In the fall of 1970, experiment #502 was established in Lahoma, OK, to examine the effects of annual application of nitrogen (N), phosphorus (P), and potassium (K) on wheat yields. Winter wheat has been planted since then on 25.4 cm (10 in) rows with seeding rates of 67 kg ha^{-1} (60 lb $acre^{-1}$) (Sembiring, 1997). Fourteen different treatments were applied, including a check of 0-0-0. Nitrogen application rates of 0, 22, 45, 67, 90, and 112 kg ha^{-1} were examined using CERES-Wheat in this study. Each of these treatments had phosphorus applied at a rate of 45 kg ha-^{1} and potassium at 60 kg ha^{-1}. The planting, harvesting, and fertilizer dates along with the variety are detailed in Table 9 for the years 1981-1997.

The soil survey describes the soil at the Lahoma Experiment Station as a Grant Silt Loam. Major County consists mostly of loamy soils with some small locations of sand and clay soils. The data in Table 10 were created by using sampling data from the Oklahoma Mesonet and the Soil Survey for Major County (Algood, 1965). The organic carbon and total nitrogen values were sampled in 1995. These numbers were used for all years since research by the Plant and Soil Sciences Department indicates that they have not changed significantly during the length of the experiment.

Table 9. Lahoma Experiment #502 Historical Data (Sembiring et al., 1997)

Year	Variety	Fertilizer Application Date	Planting Date	Harvest Date
1981	TAM W-101	10-20-80*	10-31-80	6-18-81
1982	TAM W-101	10-15-81*	10-25-81*	6-28-82
1983	TAM W-101	10-10-82*	10-18-82	7-1-83
1984	TAM W-101	10-10-83*	10-20-83*	6-21-84
1985	TAM W-101	10-25-84*	10-30-84	6-13-85
1986	TAM W-101	10-15-85*	10-21-85	6-11-86
1987	TAM W-101	10-20-86*	10-28-86	6-18-87
1988	TAM W-101	8-31-87	10-2-87	6-20-88
1989	TAM W-101	10-10-88	10-14-88	6-19-89
1990	TAM W-101	10-10-89*	10-13-89	6-20-90
1991	TAM W-101	8-2-90	10-15-90	6-6-91
1992	TAM W-101	9-9-91	9-26-91	6-20-92*
1993	Karl	8-24-92	10-1-92	6-20-93*
1994	Karl	9-14-93	9-28-93	6-20-94
1995	Tonkawa	8-5-94	10-28-94	6-19-95
1996	Tonkawa	8-31-95	10-10-95	6-21-96
1997	Tonkawa	9-4-96	10-3-96	6-13-97

* - Assumed Values

The maximum and minimum temperatures as well as rainfall at the Lahoma site were recorded on a daily basis from 1980-1993. Solar radiation data were measured by the Oklahoma Mesonet from 1994 to 1997 and were estimated for the other years using the WeatherMan utility program. The weather station is located less than 100 meters from the field plots. Tables of monthly rainfall with totals for each growing season are listed in Appendix B.

Table 10. Lahoma Experiment Station Soil Data

Layer	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g/cm^3)	Organic Carbon (%)	Soil N (%)
1	0-15	26.7	55.3	18.0	1.45	0.59	0.07
2	15-30	20.9	50.1	29.0	1.50	0.50	0.06
3	30-65	15.5	49.3	31.2	1.53	0.31	0.03
4	65-80	13.4	55.5	31.1	1.55	0.19	0.02

Chapter 5

RESULTS AND DISCUSSION

Initial Model Testing

An important consideration when testing any model is the accuracy of the input parameters. Inaccurate input parameters often result in a "garbage in equals garbage out" response to computer simulation. The CERES-Wheat model requires weather, soil and experiment inputs. These parameters are described in Chapter 4 for all three sites.

Our first task was to examine the feasibility of using the model with the required inputs and supplied genetic parameters and no other calibration used. The model included genetic parameters for the variety TAM W 101, but no parameters existed for the varieties Karl and Tonkawa. As listed in Table 3, Table 6, and Table 9, the variety TAM W 101 was grown from 1981 to 1992 at all three sites. Karl was grown in 1993 and 1994 and Tonkawa was grown from 1995 to 1997.

All of the sites have similar input data. The only exception is the soil data at the Stillwater site where the profile information is more detailed than at Altus and Lahoma. For this reason, the first site tested was Stillwater. Due to the long duration of the TAM W 101 variety experiment, we decided to study the results of the model prediction for the years 1981 to 1992. The varieties Karl and Tonkawa were grown for two and three years, respectively, and the short duration of these experiments would not allow a comprehensive test of the model. A time series plot of predicted and observed yield for the Stillwater site is shown in Figure 2. Two important determinations can be made using the time series plot. These are the ability to accurately predict yield and the ability to predict the response of yield to increased rates of N application. In years 1983, 1985, and

1990, the model accurately predicted yields. In other years, the predicted yield ranged from –95% to 178% of the observed yield. Overall the model did not accurately predict yields for Stillwater from 1981 to 1992. Also, the model did not accurately predict the observed response to N application. The model predicted as little as 0.2 times the observed response in 1981 and over predicted the response by as much as 8.4 times in 1986.

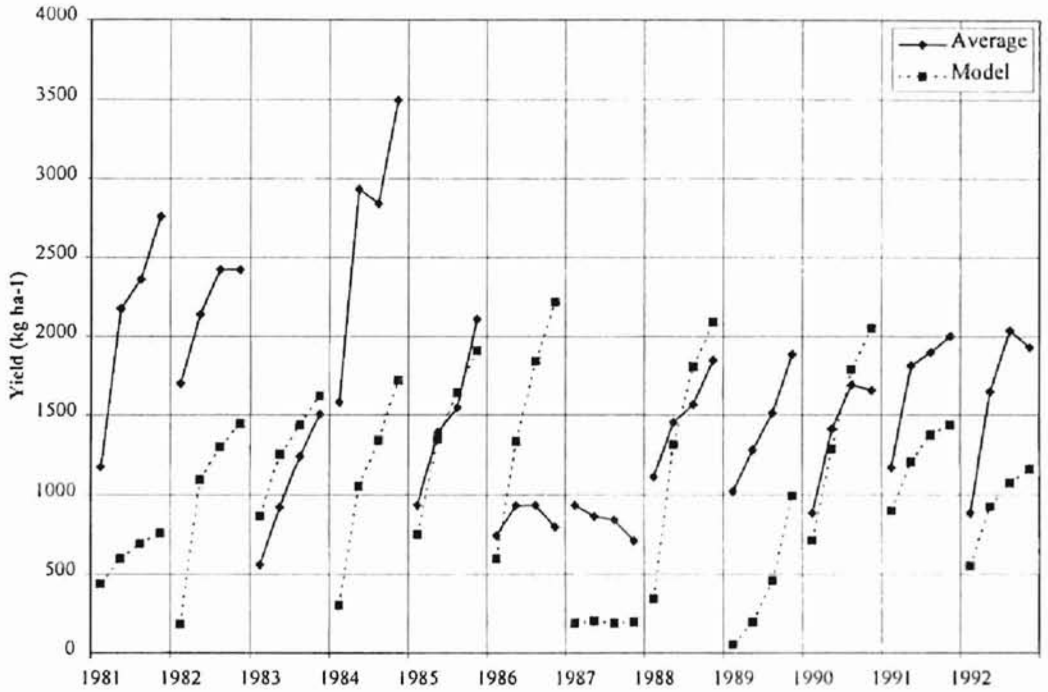


Figure 2. Time series plot of observed and model yields for Stillwater without calibration for four N application rates per year, 1981-1992.

Another indication of the poor model performance is a plot of the predicted versus observed yields (Figure 3). A linear regression was performed on the data and the results for the equation of the line that best fits the data and the r^2 value are shown on the graph. With no calibration, the regression line for the Stillwater site had a slope of 0.28 and an intercept of 610 kg ha^{-1}. The r^2 value for this regression equation was 0.097, which indicates that there was considerable scatter even about a best-fit line which was itself vastly different than the 1:1 line.

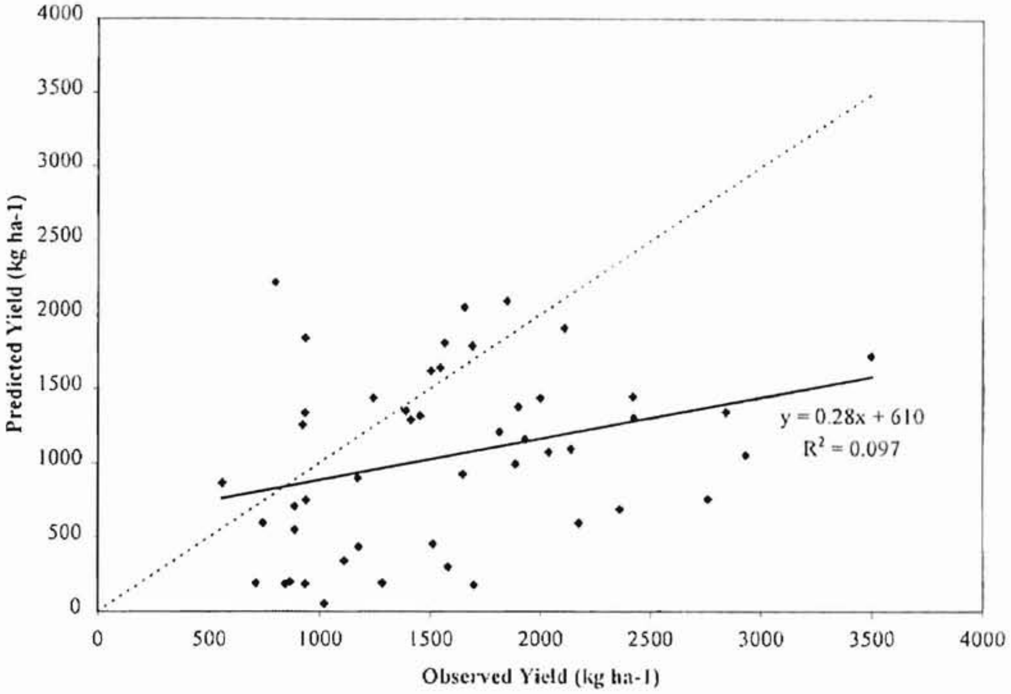


Figure 3. Predicted versus observed yield for Stillwater without calibration, 1981-1992.

Due to the poor performance of the model at the Stillwater site, we decided to test it at the other sites before attempting any calibration techniques. We tested the model for the Lahoma site from 1981 to 1992 for the same reasons as the Stillwater site. The time series plot of this data is shown in Figure 4. In 1990 and 1986, the model performed reasonably well in predicting N response. In all years the model under predicted yield and in 1982 the model over predicted the response to N considerably. Overall, the model substantially under predicted yield for the entire length of the test. This is best shown by the plot of predicted versus observed yields shown in Figure 5.

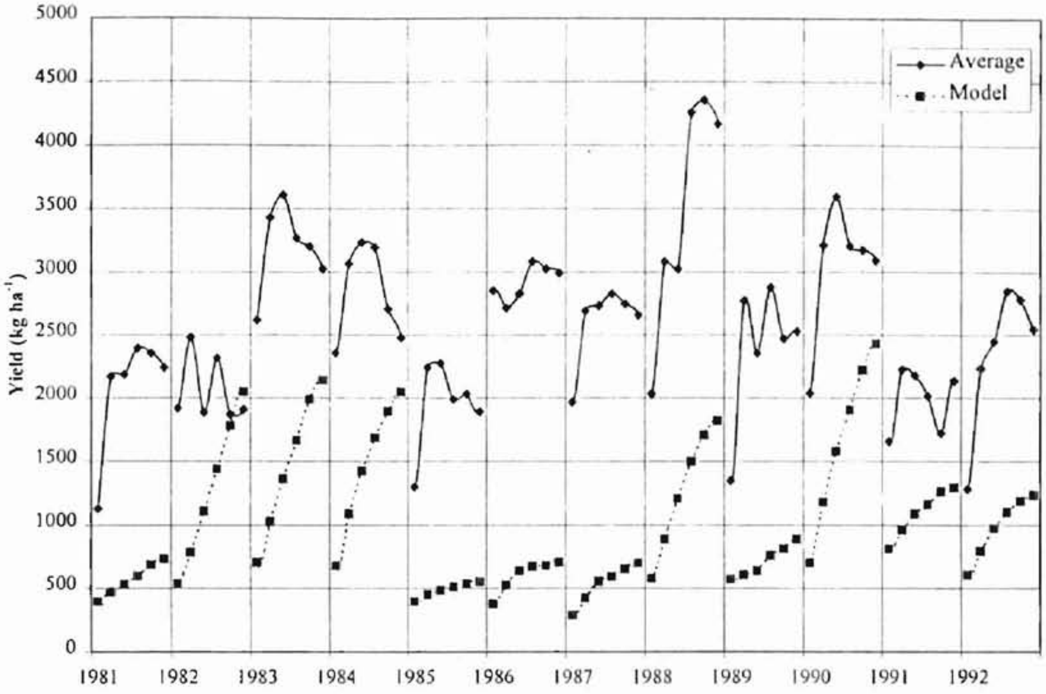


Figure 4. Time series plot of observed and model yields for Lahoma without calibration for six N application rates per year, 1981-1992.

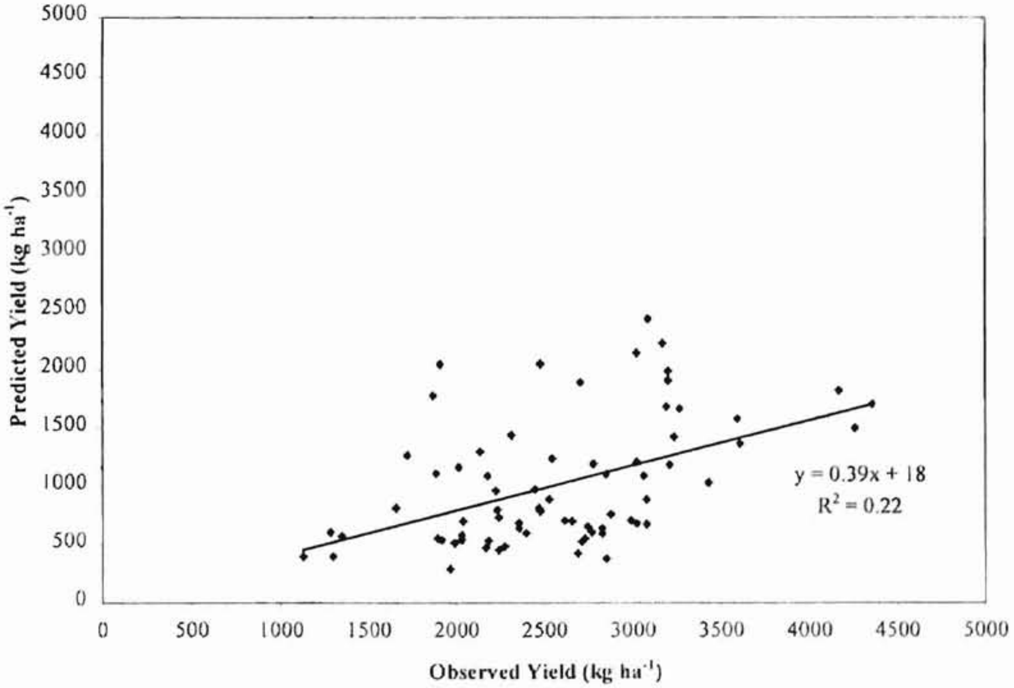


Figure 5. Predicted versus observed yield for Lahoma without calibration, 1981-1992.

Although the data are less scattered for Lahoma (r^2 value of 0.22) the poor performance of the model is evident. The value of 0.39 for the slope of the regression line indicates the model consistently under predicted yield.

The model was also tested for the ability to accurately predict yields at the Altus site using the genetic coefficients supplied with the model. The soil input data was not as detailed as the Stillwater site and the other inputs were created using the same methods as at the other two sites. As shown by the time series plot, Figure 6, the model, in general, did not accurately predict the observed yields and usually under predicted yield.

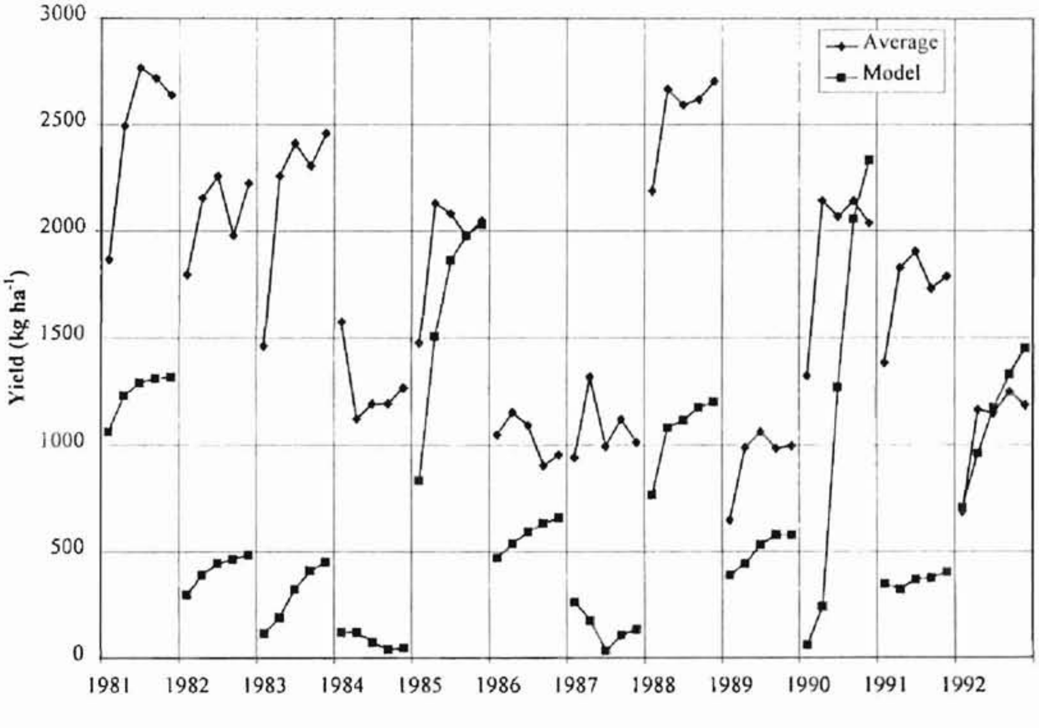


Figure 6. Time series plot of observed and model yields for Altus without calibration for five N application rates per year, 1981-1992.

A linear regression of the predicted and observed yields is shown in Figure 7. The slope of 0.40 indicates that the model under predicted yield. The r^2 value of 0.18 illustrates the inability of the model to account for the variability in the observed yields.

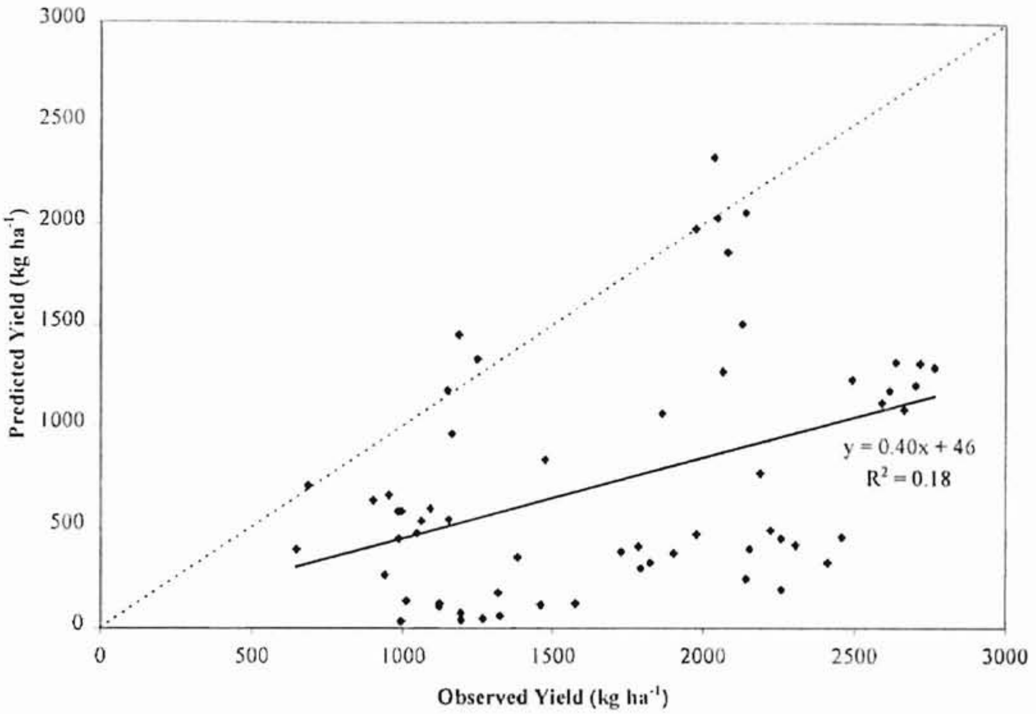


Figure 7. Predicted versus observed yield for Altus without calibration, 1981-1992.

Calibration

A thorough review of the literature and personal communication with Dr. G. Hoogenboom, University of Georgia, indicated model performance could be improved with calibrated parameters for the TAM W 101 variety of wheat. In order to calibrate the model, the dates of several physiological events were needed. The genetic parameters representing these dates are described in Chapter 3 and defined in Table 1. Personal communication with Dr. E. G. Krenzer, Plant and Soil Sciences Department, Oklahoma State University, provided estimates of the dates for the physiological events corresponding to the genetic parameters for the year 1992 at the Stillwater site. The growth stages and their corresponding dates used to calibrate the model can be found in Table 11.

Table 11. Calibration Data

Growth Stage	Date
Terminal Spikelet	March 6
End of Vegetative Growth	April 15-21
End of Ear Growth	4 to 8 days from previous stage
Beginning of Grain Fill	Data Not Available
Maturity	June 10
Harvest	June 17

Trial and error was used to modify the genetic coefficients P1V and P1D until the predicted terminal spikelet date was within a few days of the observed date. Another parameter that was calibrated was the PHINT parameter, which represents the number of heating degree-days required for one phyllochron. Personal communication with Dr. E. G. Krenzer suggested a value of 100 for PHINT. The other genetic variables changed were G1 and G2. The parameters G1 and G2 correspond to the kernel number per unit stem weight and the kernel filling rate, respectively. Table 12 details the values of the original and the calibrated coefficients (coefficients for Lahoma will be discussed in a later section titled "Additional Calibration").

Table 12. Genetic Coefficient Values for CERES-Wheat

Site(s)	Condition	Variety	P1V	P1D	P5	G1	G2	G3	PHINT
All	Original	TAM W 101	3.0	4.0	2.0	2.5	1.0	1.8	95
Stillwater	Calibrated	TAM W 101	2.6	3.5	2.0	3.0	1.5	1.9	100
Lahoma	Calibrated	TAM W 101	2.6	3.5	2.0	3.2	2.5	1.9	100

Calibrated Model Testing

The calibrated coefficients listed for Stillwater in Table 12 were used to obtain model predictions for the years 1981 to 1992. A time series plot of the data is shown in Figure 8.

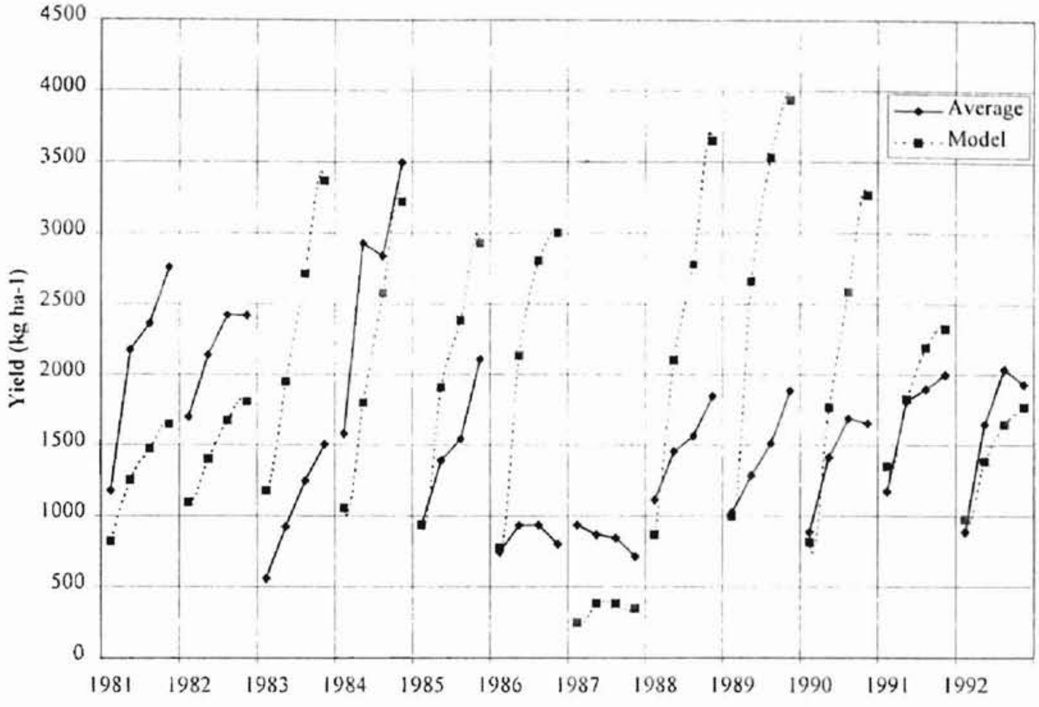


Figure 8. Calibrated time series plot of observed and model yields for Stillwater for four N application rates per year, 1981-1992.

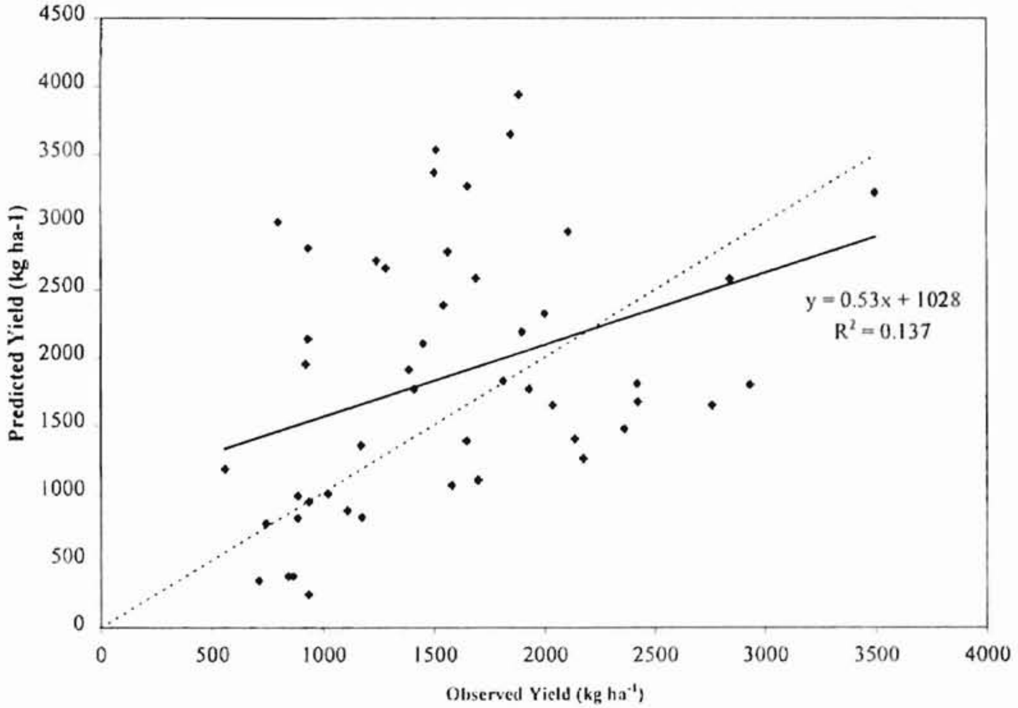


Figure 9. Calibrated predicted versus observed yield for Stillwater, 1981-1992.

Even though the model was calibrated for Stillwater, it did not precisely predict the observed yields. For the years 1991 and 1992, the model predicted yield within ±19% of observed yield. The model over estimated yields considerably in 5 of the 12 years. The N response ranged from half of the observed response in 1981 to as much as 11 times the observed response in 1986. The unusually high difference in yield response in 1988 is mainly due to a small response for the observed yields. As expected, the overall the performance of the model has improved. The slope of a regression of the predicted versus observed yields in Figure 9 is 0.53. However, the intercept of the regression line only increased slightly from 907 to 1029 kg ha^{-1}, and the r^2 value is still only about 0.14.

Using the coefficients for TAM W 101 calibrated at the Stillwater site at the Lahoma and Altus sites allowed us to test the model in different geographic locations in Oklahoma. The results of this test are shown graphically in Figure 10 and Figure 11 for Lahoma. The performance of the model at Lahoma improved with the use of the genetic coefficients calibrated at Stillwater. The new coefficients increased the slope of the regression line from 0.39 to 0.67. The r^2 value increased from 0.22 to 0.27. Even though the accuracy of the model increased, 90% of the predicted yields were less than the observed yields. The time series plot of Figure 10 illustrates the improved prediction of N response in most of the 12 years, especially the years where the observed N response was high. Even though the model performs well in some years, overall it does not satisfactorily predict the observed yields.

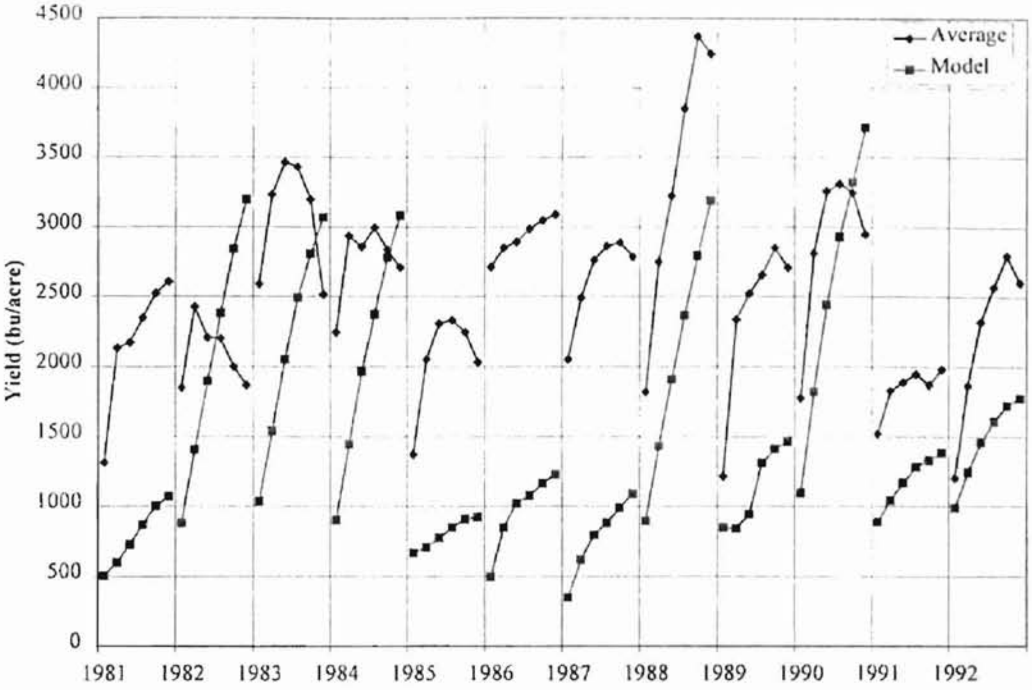


Figure 10. Time series plot of observed and model yields for Lahoma using genetic coefficients calibrated at Stillwater for six N application rates per year, 1981-1992.

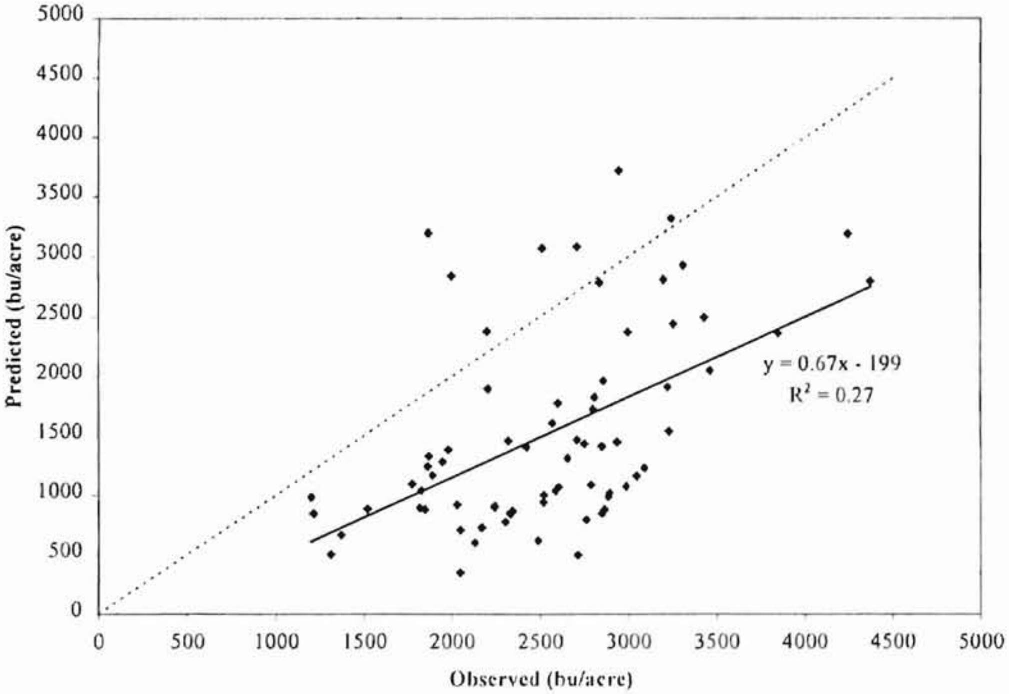


Figure 11. Predicted versus observed yield for Lahoma using genetic coefficients calibrated at Stillwater, 1981-1992.

At Altus, the genetic coefficients were changed to those values calibrated at Stillwater (Table 12). The results of the test are shown in two plots. Figure 12 is a time series plot of the predicted and observed yields and Figure 13 is a plot of the predicted yield versus the observed yield.

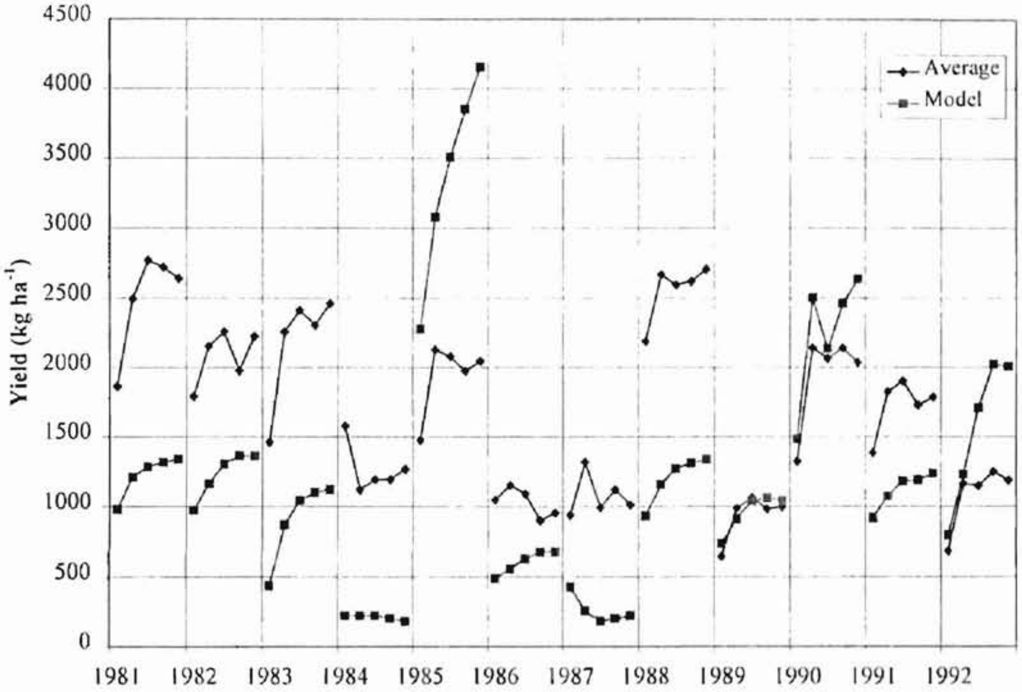


Figure 12. Time series plot of observed and model yields for Altus using genetic coefficients calibrated at Stillwater for five N application rates per year, 1981-1992.

Use of the coefficients calibrated at Stillwater only marginally improved the overall performance at Altus. Even though the slope of the regression line was closer to one, the intercept increased dramatically. The r^2 value of 0.16 indicates the inability of the model to predict yields and did not improve from the r^2 of 0.18 with no calibration.

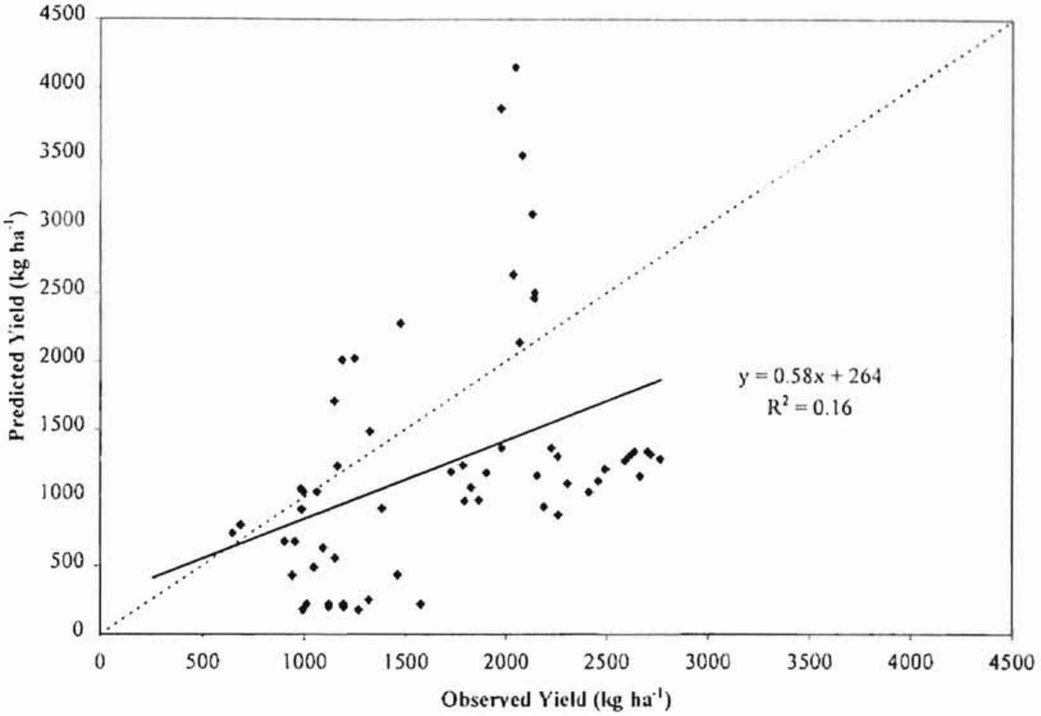


Figure 13. Predicted versus observed yield for Altus using genetic coefficients calibrated at Stillwater, 1981-1992.

Although the calibration of the model at the Stillwater site somewhat increased the accuracy of yield prediction at all these sites, model performance was still not acceptable. The greatest improvement in performance seemed to occur at Lahoma.

Additional Calibration

The improvement in the ability to predict yields for the Lahoma site indicated that further calibration could improve the results. Using the coefficients calibrated at Stillwater, the model under predicted yield but was less variable than for the other sites. Table 12 illustrates the changes made to the genetic coefficients for the calibration at Lahoma. The coefficients for P1V and P1D were not changed. The climate and day length at Lahoma are similar to those in Stillwater and the dates for reaching terminal spikelet and the end of vegetative growth were assumed to be similar based on personal communication with Dr. E. G. Krenzer. The values for the coefficients G1 and G2 were increased. This increased the overall yields at Lahoma by increasing the number of kernels per unit stem and increasing the rate of kernel filling. The new coefficients improved the ability of the model to predict the observed yields as shown by Figure 14 and Figure 15.

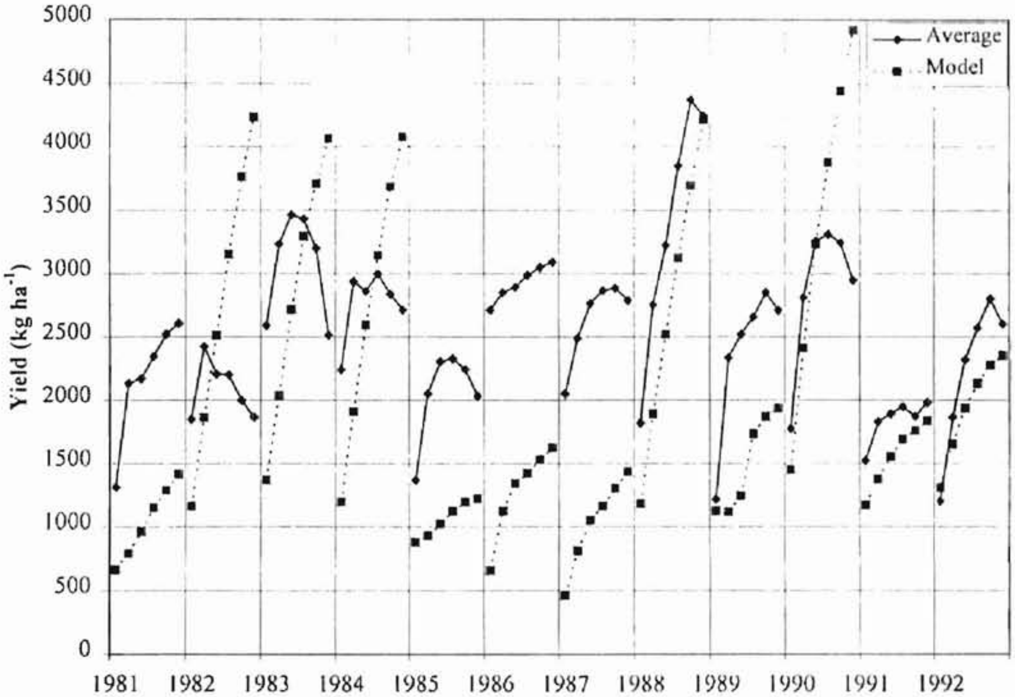


Figure 14. Calibrated time series plot of observed and model yields for Lahoma for six N application rates per year, 1981-1992.

The time series plot of Figure 14 indicates the improved ability of the model to predict yield and response to N application. The slope of the regression of the predicted versus observed yield in Figure 15 dramatically improved to 0.89. However, a relatively low r^2 value of 0.27 indicates that the model does not account for much of the variability in the observed yields.

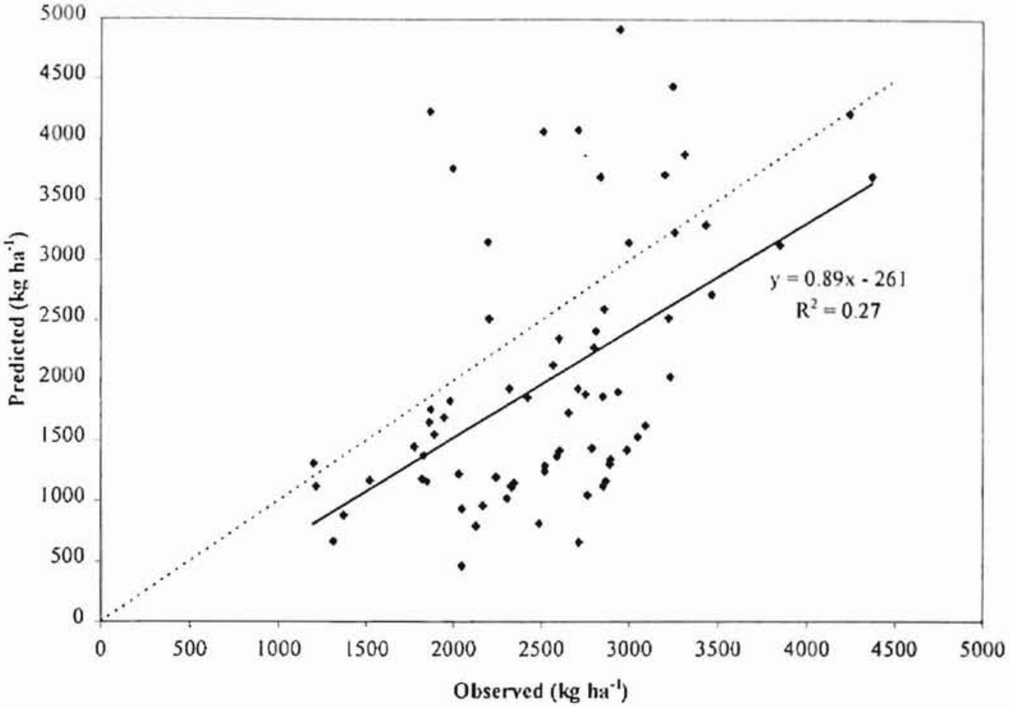


Figure 15. Calibrated predicted versus observed yield for Lahoma, 1981-1992.

The data used to generate all of the plots for testing and calibration can be found in Appendix C. This includes all of the predicted and observed yields.

Water Stress Analysis

Water availability for the plant is one of the most important factors affecting the growth of dryland wheat. The output of the model includes a parameter that indicates the amount of water stress on the plant during each physiological stage. Water stress is reported as a value between zero and one, with zero being no water stress and one being severe water stress.

In an attempt to explain some of the variability in the prediction of yields, we noted the modeled water stress during each growth stage for the Stillwater and Lahoma sites (with calibrated genetic coefficients). The water stress values for all growth stages were added to obtain an overall measurement of water stress to compare with the percent difference between predicted and observed yields. The cumulative water stress and percent difference from observed yield for Stillwater were plotted from 1981 to 1992 in Figure 16. Percent difference from observed yield is defined as (predicted yield – observed yield)/(observed yield) times 100 for percent.

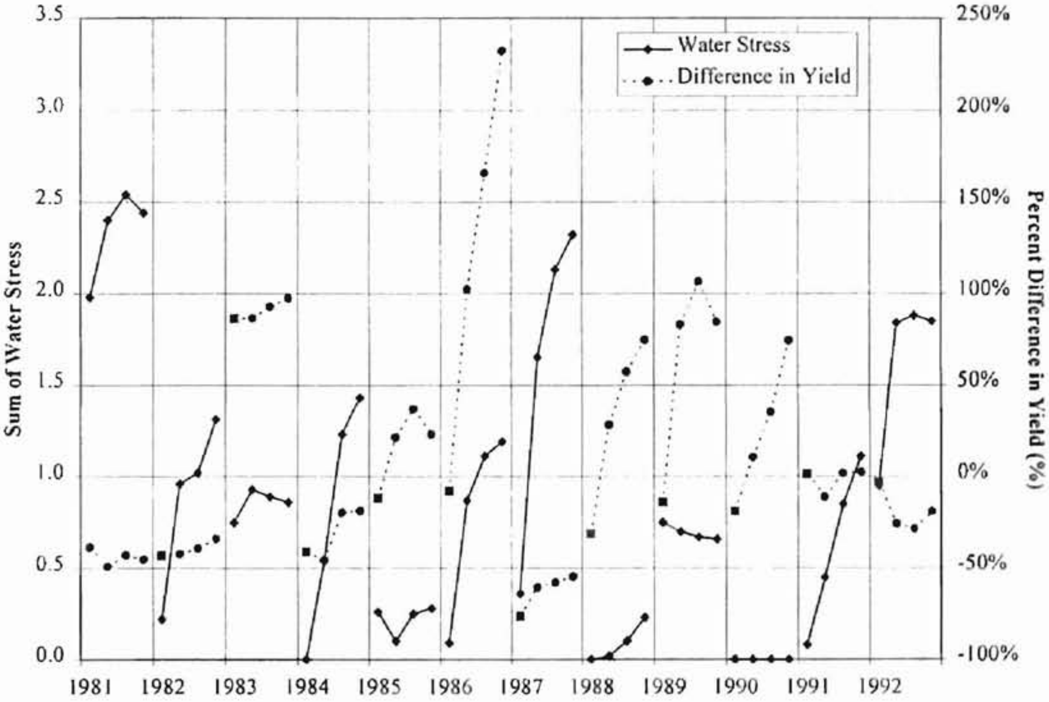


Figure 16. Sum of water stress for all growth stages and percent difference from observed yield for Stillwater using calibrated genetic coefficients for 1981-1992.

In most years, high water stress resulted in an underestimation of yields. This is especially true of 1987, 1982, and 1981. There are also years where the water stress was moderate and yields were over predicted. This would include the years 1989, 1983, and 1986. Further study was done to examine the effects of water stress in the individual growth stages. The plots of water stress and percent difference in yield at the Stillwater site for each growth stage can be found in Appendix D.

The influence of water stress on yield prediction was also examined for the Lahoma site. A plot of the sum of water stress and percent difference in yield versus time is illustrated in Figure 17. In years of high water stress, the model under predicts yields considerably. Over prediction was more common in years of low water stress. No correlation was found between water stress and yield predictions for each of the individual growth stages. The plots of water stress and percent difference in yield for each growth stage for Lahoma can be found in Appendix D.

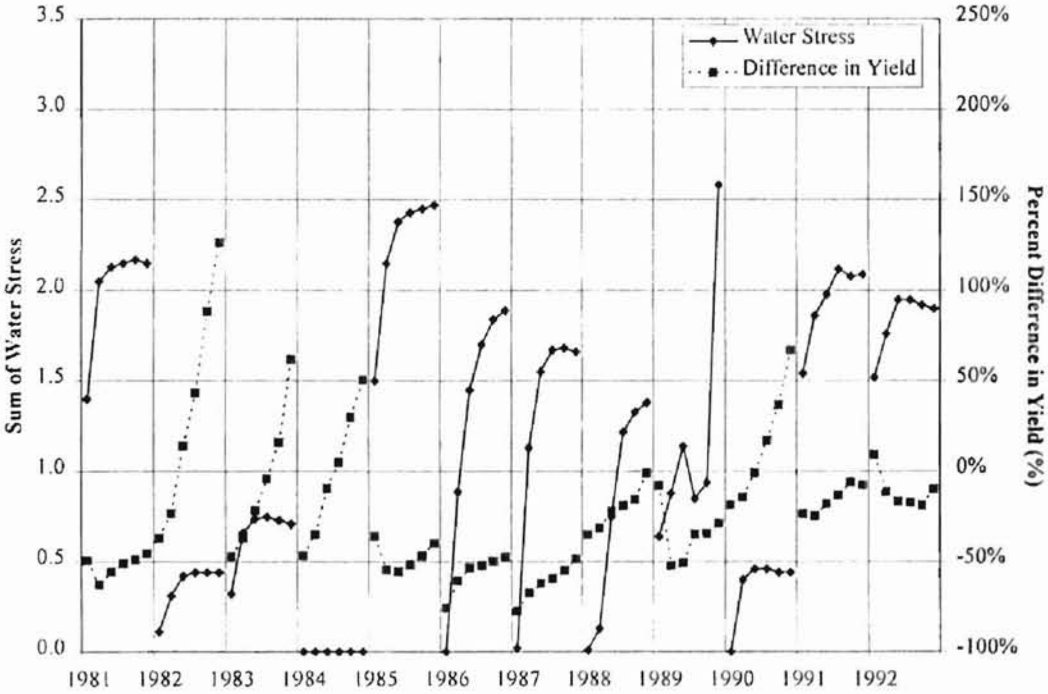


Figure 17. Sum of water stress for all growth stages and percent difference from observed yield for Lahoma using calibrated genetic coefficients for 1981-1992.

Water stress often has the most critical effect on yields of dryland wheat grown in Oklahoma. It is not surprising to see the model identify some water stress in many years of this experiment. We had hoped that an analysis of water stress would account for some of the variability between observed and predicted yields. This was not the case as no consistent relationship was identified for either the seasonal summation (Figure 16 andFigure 17) or the individual growth stages (Appendix D).

Other Observations

During our attempts to test and calibrate the CERES-Wheat model, we gained some experience that may be useful for others using the model. Applying the CERES-Wheat model is a complex process and defining the necessary input parameters accurately can be a challenge. Also, learning the DSSAT support programs requires considerable time commitment and effort.

Our first attempts to model wheat growth and yield in Oklahoma often resulted in yields in excess of 6720 kg ha^{-1} (100 bu acre^{-1}). At that time, we were using default soil inputs supplied with the model. This resulted in the overestimation of available water and increased organic matter in the soil. The importance of a well-defined soil is not fully addressed in the model documentation but must be considered before using the model as a management or research tool.

In our attempts to explain the high original yield predictions, we executed the model with the water and nitrogen routines turned off. With these routines off, the model assumed they are not limiting to plant growth. Our estimates of yield were only 5 to 10% higher than before. We then tested the model with the water routines turned on and the nitrogen routines turned off. In one treatment, the model predicted higher yields with the water routines on than it did with the water routines off. Since the model assumes that water is not limiting with the routines off, we can not explain how yields increased using the same historical weather data.

Personal communication with the model developers stressed the importance of calibrating the genetic parameters used in the model. This should only be done after all other inputs are defined as precisely and accurately as possible. The need for historical data including the dates of many physiological events is not indicated in the literature supplied with the model. This data can be difficult to obtain, yet it is imperative to the application of the model.

Residual nitrogen often affects wheat yield response according to personal communication with Dr. Bill Raun, Department of Plant and Soil Sciences at Oklahoma State University. If the amount of nitrogen available to the plant before nitrogen application is adequate, the increase in yields due to high rates of nitrogen application is small. In the experiment mode, CERES-Wheat models each growing season independently. It is difficult to account for residual nitrogen without sampling prior to each growing season and this is one possible source of error in the predicted yields. The model does have the ability to operate on a continual basis where residual effects are considered, but it is limited to nine rotations that would convert to four and a half years of wheat growth. In this mode of operation, the fertilizer application, planting and harvest dates must be the same for all years. This makes it difficult to compare model predictions to historical data.

In summary, the CERES-Wheat model is used throughout the world and is cited in many journals as an effective management tool. Using this model appropriately requires a significant amount of accurate input data, as is the case with many other simulation models. Based on our experiences, the CERES-Wheat model can not be used with confidence at the regional level without rigorous testing and calibration. Currently we are not satisfied with the calibration results for hard red winter wheat in Oklahoma.

Chapter 6

SUMMARY AND CONCLUSIONS

Summary

The state of Oklahoma ranks second or third nationally in the amount of winter wheat produced in each of the last 25 years. Wheat production is an important part of the Oklahoma and U.S. economies. This study attempted to determine if a process-based wheat growth simulation model could be used in Oklahoma to assist in management decisions related to producing wheat. The model would have to be tested and validated for various regions of the state where wheat is produced.

A review of literature indicated that there are several process-based wheat models used throughout the world. The most documented of these, the CERES-Wheat model, was a well-tested model with reasonable input requirements. Uses of the model include predicting yields, assisting in irrigation management, large area yield forecasting using remote sensing, and studying the effects of climate variability on yields. The CERES-Wheat model was purchased, the structure of the model was reviewed, and attempts to obtain the necessary input parameters began.

The CERES family of models includes CERES-Barley, CERES-Maize, CERES-Millet, CERES-Sorghum, CERES-Rice, and CERES-Wheat. The models work within the DSSAT database management system. The input parameters for weather and soil are stored in independent databases. This allows any of the models to have access to this information. The experiment files describing the methods of management are similar in structure, but unique to each individual model. Most of the models are written in FORTRAN while some of the interface applications and utility programs are written in

Borland C++ and TurboVision. A full installation of the DSSAT system and the crop models requires approximately 12 MB of hard disk space.

The CERES-Wheat model was to be tested under Oklahoma conditions. The field data were obtained from continuous wheat research plots managed by the Oklahoma Agricultural Experiment Station and the Department of Plant and Soil Sciences at Oklahoma State University. Three different Experiment Station sites were studied (Stillwater, Lahoma, and Altus). The available data included fertilizer application, planting, and harvest dates. Also, rates of nitrogen application for the different treatments and the observed yields for four to six replications were included. Genetic parameters needed to execute the model were included with the software for the variety TAM W 101. The weather input parameters needed are maximum temperature, minimum temperature, rainfall, and solar radiation. These values were obtained from data archives for on-site weather stations. The solar radiation values for 1981 to 1993 were estimated using 1994-1997 Mesonet data and monthly averages as input parameters for the WGEN weather simulation program. These data were converted to IBSNAT 3.0 format using the DSSAT utility program WeatherMan. The input parameters needed for the soil database are percent sand, silt, and clay for each layer defined. Additionally, bulk density, organic carbon, total nitrogen, and water retention characteristics are required. Initial modeling attempts required additional research and input parameters. Eventually, all needed inputs were well defined and model testing was conducted.

The Stillwater site was selected as the first test site due to a more detailed soil profile description than Altus or Lahoma. The genetic coefficients supplied with the model were used as inputs and the model was tested over 13 years. The model was also tested at the Altus and Lahoma sites with the same genetic coefficients but with their respective weather, experiment, and soil inputs. Poor performance of the model suggested that calibration of the genetic coefficients for the TAM W 101 variety was necessary. Calibration efforts at Stillwater improved the performance of the model but yields were still not accurately predicted. The genetic coefficients calibrated for Stillwater were then tested at the Altus and Lahoma sites. A test to calibrate the model at the Lahoma site resulted in somewhat better agreement between predicted and observed yields. In an attempt to explain some of the variability in the prediction of observed yields, water stress during each model growth stage was noted for the Stillwater and Lahoma sites with calibration. No consistent relationship between yield and water stress was identified.

Conclusions

When tested "off the shelf" using the genetic coefficients supplied with the model, CERES-Wheat was unable to accurately predict the observed yields at the Stillwater Site. Also, the model considerably overestimated the response to N in some years and underestimated it in others. Using these same genetic coefficients, the model substantially under predicted the observed yields at Lahoma and Altus.

After the genetic coefficients for the TAM W 101 variety were calibrated for the Stillwater site based on phenological development, yield predictions improved but were still not satisfactory. When the model was tested for the Lahoma and Altus sites using the calibrated genetic coefficients from the Stillwater site, the ability to accurately predict yields increased but not significantly. For all sites, the model did not accurately predict the observed response to applied nitrogen. An independent calibration of the genetic coefficients was performed at the Lahoma site. This calibration produced the most accurate yield predictions but there was still a tendency to under predict yields.

Water stress in the model could not be successfully correlated with differences in the observed and predicted yields. There was no consistent relationship between water stress or lack of water stress and the under or over prediction of observed yields.

One limitation of the model is the difficulty of accounting for residual N. The modeling done in this study examined each growing season individually. The model does have the ability to operate on a continual basis where residual effects are considered, but it is limited to nine rotations that would convert to four and a half years of wheat growth. In this mode of operation, the fertilizer application, planting and harvest dates must be the same for all years. This makes it difficult to compare model predictions to historical data.

The soil inputs for the model are substantial. It can be difficult to obtain values for total N and organic carbon throughout the soil profile. Testing of the model shows that it is sensitive to these parameters. Additionally, the model requires percent sand, silt and clay and the water retention characteristics of each layer. The lab work needed to obtain these values is costly and time consuming and estimating these parameters accurately is difficult.

Recommendations

The CERES-Wheat model and other process-based crop models have the potential to be valuable research and management tools. Model calibration and validation are extremely important, and should preferable be done at regional or local level scales.

Through this study, a significant data set of input parameters has been compiled. Testing other models using this input data may be worthwhile. Perhaps another process-based model may be more suitable for use in the Southern Great Plains. Also, a thorough sensitivity analysis may help to identify those CERES-Wheat input parameters which have the greatest influence on yield.

One potential explanation of the years in which the model significantly over predicted nitrogen response is the effect of residual nitrogen. Response to applied nitrogen can be minimal if the residual nitrogen in the soil is adequate for plant growth and production. In this case, observed yields are similar for each of the nitrogen treatments even though there are dramatic differences in rates of nitrogen applied. Total nitrogen, one of the model's input parameters, is not a good indicator of the amount of nitrogen available to the plant. Also, this experiment was done using a different simulation for each growing season. The CERES-Wheat model has an option for continuous simulation where residual effects are taken into consideration, but planting, fertilizer application, and harvest dates can not be changed from year to year. Also, the model only allows for nine rotations. Growing wheat with a fallow period would only allow the user to examine 4.5 years for each model test. Modification of the model to include variable planting, fertilizer application, and harvest dates while performing long term simulations should improve the performance of the model.

There is a considerable amount of documentation provided with the model. Three volumes of material and on-line help within the programs are provided. Most of the information in these manuals is directed at the DSSAT structure, file formats, and utility programs. DSSAT version 3.0 contains 15 different crop models. The documentation provided does not adequately discuss each of the individual models.

Additionally, personal communication was required to learn that genetic coefficients must be developed for each variety and each region in which the variety is grown. For example, the model contained genetic parameters for the TAM W 101 variety of wheat. Since they were not developed in Oklahoma, they should not be applied when testing the model in that season. A complete manual describing the importance of all inputs and methods of calibration would certainly be helpful.

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APPENDICES

APPENDIX A

CERES-Wheat Input Files

Stillwater Experiment Input File, 1992

```
*EXP.DETAILS: OKST9201WH STILLWATER, TEST NITROGEN RESPONSE 1992

*GENERAL
@ PAREA  PRNO  PLEN  PLDR  PLSP  PLAY HAREA  HRNO  HLEN HARM.........
   89.2    19  18.3   -99   -99        55.8    18 -99.0

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 0 0 0 N=1                        1  1  0  0  1  0  1  0  0  0  0  1  1
 2 0 0 0 N=40                       1  1  0  0  1  0  2  0  0  0  0  1  1
 3 0 0 0 N=80                       1  1  0  0  1  0  3  0  0  0  0  1  1
 4 0 0 0 N=120                      1  1  0  0  1  0  4  0  0  0  0  1  1


*CULTIVARS
@C CR INGENO CNAME
 1 WH IB0541 TAM W 101

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX   SLDP ID_SOIL
 1 -99      OKST     -99       0 DR000     0     0 00000  SILO   241 OK00970001

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH
 1 91273   -99 200.0 162.0 S     R        25     0   2.5   -99   -99 -99.0 -99.0

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 1 91253 FE001 AP002    15     1     0     0     0     0
 2 91253 FE001 AP002    15    45     0     0     0     0
 3 91253 FE001 AP002    15    90     0     0     0     0
 4 91253 FE001 AP002    15   135     0     0     0     0

*HARVEST DETAILS
@H HDATE  HSTG  HCOM HSIZE   HPC
 1 92168 GS000 H     A       -99

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 1 GE              1     1     S 91105  2150 TEST RUN FOR 87-88
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES
 1 OP              Y     Y     Y     Y     Y     N
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO
 1 ME              M     M     E     R     S     C
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     N     R     N     R
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG
 1 OU              Y     Y     Y     5     Y     N     Y     Y     N     Y     N

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL            155   200    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR             30    50   100 GS000 IR001    10  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI             30    50    25 FE001 GS000
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0   365   100     0
```

Lahoma Experiment Input File, 1992

```
*EXP.DETAILS: OKLH9201WH LAHOMA, Test for Nitrogen Response 1992
*GENERAL
@ PAREA  PRNO  PLEN  PLDR  PLSP  PLAY HAREA  HRNO  HLEN HARM..........
   89.2    19  18.3   -99   -99        55.8    18 -99.0

*TREATMENTS                        ------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 0 0 0 N=1                        1  1  0  0  1  0  1  0  0  0  0  1  1
 2 0 0 0 N=20                       1  1  0  0  1  0  2  0  0  0  0  1  1
 3 0 0 0 N=40                       1  1  0  0  1  0  3  0  0  0  0  1  1
 4 0 0 0 N=60                       1  1  0  0  1  0  4  0  0  0  0  1  1
 5 0 0 0 N=80                       1  1  0  0  1  0  5  0  0  0  0  1  1
 6 0 0 0 N=100                      1  1  0  0  1  0  6  0  0  0  0  1  1

*CULTIVARS
@C CR INGENO CNAME
 1 WH IB0541 TAM W 101

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX   SLDP ID_SOIL
 1 -99        OKLH       -99     0 DR000     0     0 00000  SILO    80 OK00950001

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH
 1 91269   -99 200.0 178.0 S     R        25     0   2.5   -99   -99 -99.0 -99.0

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 1 91221 FE001 AP002    15     1     0     0     0     0
 2 91221 FE001 AP002    15    22     0     0     0     0
 3 91221 FE001 AP002    15    45     0     0     0     0
 4 91221 FE001 AP002    15    67     0     0     0     0
 5 91221 FE001 AP002    15    90     0     0     0     0
 6 91221 FE001 AP002    15   112     0     0     0     0

*HARVEST DETAILS
@H HDATE  HSTG  HCOM HSIZE   HPC
 1 92171 GS000 H     A       -99

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 1 GE              1     1     S 91182  2150 TEST RUN FOR 87-88
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES
 1 OP              Y     Y     N     N     N     N
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO
 1 ME              M     M     E     R     S     C
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     N     R     N     R
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG
 1 OU              Y     Y     Y     5     Y     N     Y     Y     N     Y     N

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL            155   200    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR             30    50   100 GS000 IR001    10  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI             30    50    25 FE001 GS000
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0   365   100     0
```

Altus Experiment Input File, 1992

```
*EXP.DETAILS: OKAL9201WH ALTUS, Test for Nitrogen Response 1992

*GENERAL
@ PAREA  PRNO  PLEN  PLDR  PLSP  PLAY HAREA  HRNO  HLEN HARM..........
   89.2    19  18.3   -99   -99         55.8    18 -99.0

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 0 0 0 N=1                        1  1  0  0  1  0  1  0  0  0  0  1  1
 2 0 0 0 N=40                       1  1  0  0  1  0  2  0  0  0  0  1  1
 3 0 0 0 N=80                       1  1  0  0  1  0  3  0  0  0  0  1  1
 4 0 0 0 N=120                      1  1  0  0  1  0  4  0  0  0  0  1  1
 5 0 0 0 N=160                      1  1  0  0  1  0  5  0  0  0  0  1  1

*CULTIVARS
@C CR INGENO CNAME
 1 WH IB0541 TAM W 101

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX   SLDP ID_SOIL
 1 -99        OKAL     -99       0 DR000     0     0 00000  SILO    85 OK00810001

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH
 1 91270   -99 200.0 178.0 S     R        25     0   2.5   -99   -99 -99.0 -99.0

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 1 91265 FE001 AP002    15     1     0     0     0     0
 2 91265 FE001 AP002    15    22     0     0     0     0
 3 91265 FE001 AP002    15    45     0     0     0     0
 4 91265 FE001 AP002    15    67     0     0     0     0
 5 91265 FE001 AP002    15    90     0     0     0     0
 1 92040 FE001 AP002    15     1     0     0     0     0
 2 92040 FE001 AP002    15    22     0     0     0     0
 3 92040 FE001 AP002    15    45     0     0     0     0
 4 92040 FE001 AP002    15    67     0     0     0     0
 5 92040 FE001 AP002    15    90     0     0     0     0

*HARVEST DETAILS
@H HDATE  HSTG  HCOM HSIZE   HPC
 1 92166 GS000 H     A       -99

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 1 GE              1     1     S 91120  2150 TEST RUN FOR 87-88
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES
 1 OP              Y     Y     y     y     y     N
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO
 1 ME              M     M     E     R     S     C
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     N     R     N     R
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG
 1 OU              y     Y     Y     5     Y     N     Y     Y     N     Y     N

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL            155   200    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR             30    50   100 GS000 IR001    10  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI             30    50    25 FE001 GS000
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0   365   100     0
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APPENDIX B

Rainfall Data for Altus, Lahoma, and Stillwater

Monthly rainfall for all three sites with totals for the growing season of July to June.

	Altus (mm)	Lahoma (mm)	Stillwater (mm)
Jul-80	5.3	1.3	1.5
Aug-80	18.0	88.4	110.0
Sep-80	27.1	35.6	59.7
Oct-80	6.3	42.7	79.3
Nov-80	10.7	9.9	9.1
Dec-80	44.4	40.7	35.8
Jan-81	3.3	1.8	5.1
Feb-81	7.9	27.5	11.0
Mar-81	49.5	56.6	58.6
Apr-81	128.7	22.7	31.7
May-81	132.1	162.4	122.0
Jun-81	125.5	121.9	172.6
Total	**558.8**	**611.5**	**696.4**
Jul-81	36.5	140.9	87.2
Aug-81	41.9	82.8	35.9
Sep-81	3.4	65.6	100.3
Oct-81	80.1	104.4	106.8
Nov-81	27.6	88.6	65.8
Dec-81	7.1	5.3	5.1
Jan-82	35.1	8.9	18.3
Feb-82	7.9	60.9	0.0
Mar-82	56.7	30.5	50.3
Apr-82	20.3	62.7	66.0
May-82	223.1	371.0	235.4
Jun-82	131.6	111.1	80.3
Total	**671.3**	**1132.7**	**851.4**
Jul-82	50.2	50.4	82.6
Aug-82	6.4	35.0	1.5
Sep-82	37.2	58.5	17.5
Oct-82	5.0	24.6	44.7
Nov-82	50.1	70.2	38.7
Dec-82	35.1	59.1	37.6
Jan-83	18.2	8.4	21.3
Feb-83	40.8	76.5	41.7
Mar-83	53.1	77.6	86.9
Apr-83	29.6	41.4	85.1
May-83	99.8	188.9	109.4
Jun-83	84.9	92.7	145.2
Total	**510.4**	**783.3**	**712.2**

Jul-83	0.0	0.0	0.0
Aug-83	21.8	22.4	35.8
Sep-83	80.5	52.0	95.0
Oct-83	298.7	193.3	120.5
Nov-83	50.5	54.8	42.0
Dec-83	8.4	10.1	5.3
Jan-84	0.0	5.1	32.3
Feb-84	18.3	17.8	18.5
Mar-84	35.5	130.8	56.1
Apr-84	24.1	73.0	124.0
May-84	7.9	68.3	170.5
Jun-84	63.9	151.8	100.8
Total	**609.6**	**779.4**	**800.8**
Jul-84	23.6	16.0	1.5
Aug-84	16.5	25.9	110.0
Sep-84	8.6	30.2	59.7
Oct-84	21.8	126.0	79.3
Nov-84	46.7	56.2	9.1
Dec-84	119.3	100.9	35.8
Jan-85	25.9	77.3	20.3
Feb-85	47.0	116.6	63.8
Mar-85	97.5	126.8	59.7
Apr-85	78.7	136.2	131.6
May-85	48.7	43.3	36.1
Jun-85	210.9	161.8	114.3
Total	**745.2**	**1017.2**	**721.1**
Jul-85	29.2	61.9	102.4
Aug-85	38.3	57.8	116.8
Sep-85	119.6	152.3	93.5
Oct-85	127.3	117.0	71.1
Nov-85	27.0	71.6	69.6
Dec-85	17.8	45.0	0.0
Jan-86	0.0	0.0	0.0
Feb-86	28.0	19.9	0.0
Mar-86	13.5	26.6	41.9
Apr-86	54.6	140.9	51.2
May-86	135.8	127.5	97.7
Jun-86	95.6	87.7	174.8
Total	**686.7**	**908.2**	**819.0**

Jul-86	41.6	49.3	85.4
Aug-86	149.0	178.6	146.8
Sep-86	151.4	213.3	186.0
Oct-86	170.6	168.9	296.5
Nov-86	67.7	106.9	63.1
Dec-86	14.0	36.7	28.8
Jan-87	38.8	63.9	16.2
Feb-87	66.0	165.2	61.4
Mar-87	41.7	57.2	68.3
Apr-87	1.8	15.7	18.5
May-87	254.0	172.5	238.9
Jun-87	139.4	175.3	77.3
Total	**1136.0**	**1403.5**	**1287.2**
Jul-87	32.5	74.2	102.2
Aug-87	75.5	53.5	79.3
Sep-87	87.0	112.1	102.1
Oct-87	58.4	31.5	0.0
Nov-87	5.5	66.7	24.4
Dec-87	83.1	96.9	75.9
Jan-88	12.0	35.6	22.9
Feb-88	2.5	8.9	1.5
Mar-88	52.9	139.0	62.1
Apr-88	55.6	106.5	140.8
May-88	43.9	79.9	54.1
Jun-88	89.8	33.0	86.8
Total	**598.7**	**837.8**	**752.1**
Jul-88	53.2	67.5	89.6
Aug-88	15.2	24.6	10.2
Sep-88	151.3	197.6	107.3
Oct-88	22.9	39.7	65.1
Nov-88	0.8	87.6	38.1
Dec-88	19.5	24.4	7.4
Jan-89	37.8	42.2	31.5
Feb-89	31.7	43.4	18.4
Mar-89	53.3	95.0	54.6
Apr-89	8.7	4.3	4.1
May-89	89.2	171.7	97.0
Jun-89	194.7	138.8	184.2
Total	**678.3**	**936.8**	**707.5**

Jul-89	50.0	112.3	62.2
Aug-89	51.1	127.8	204.1
Sep-89	133.6	123.4	80.9
Oct-89	20.3	71.6	59.6
Nov-89	0.0	0.0	0.3
Dec-89	0.8	12.8	1.6
Jan-90	39.4	47.0	41.2
Feb-90	72.6	111.5	69.6
Mar-90	103.0	167.7	83.0
Apr-90	86.4	149.2	89.2
May-90	79.3	121.9	61.9
Jun-90	66.4	25.6	22.9
Total	**702.9**	**1070.8**	**776.5**
Jul-90	100.1	36.8	62.5
Aug-90	131.1	91.4	47.5
Sep-90	37.4	97.1	58.7
Oct-90	22.1	31.5	25.6
Nov-90	76.2	44.5	51.7
Dec-90	19.8	25.1	7.8
Jan-91	35.3	24.5	2.8
Feb-91	1.8	1.5	0.0
Mar-91	38.8	24.8	45.3
Apr-91	84.1	79.5	41.2
May-91	223.7	179.0	101.4
Jun-91	280.5	101.6	110.0
Total	**1050.9**	**737.3**	**554.5**
Jul-91	44.2	11.5	69.1
Aug-91	50.4	36.0	62.5
Sep-91	116.7	144.8	58.2
Oct-91	69.4	108.2	38.6
Nov-91	29.9	69.1	70.2
Dec-91	102.9	129.6	79.7
Jan-92	36.8	19.7	22.2
Feb-92	40.9	37.8	7.0
Mar-92	23.5	24.0	47.9
Apr-92	60.1	89.6	56.6
May-92	142.7	69.0	91.1
Jun-92	154.0	203.5	179.7
Total	**871.5**	**942.8**	**782.8**

APPENDIX C

Predicted and Observed Yield Data

Stillwater observed and predicted yields with no calibration for each treatment.

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg	Model
1992	0	954	764	901	929	887	551
1992	45	2023	1645	1466	1459	1648	927
1992	90	1867	2223	2081	1979	2037	1075
1992	134	1790	1838	2357	1734	1930	1163
1991	0	1374	935	1252	1130	1173	900
1991	45	1878	1757	1675	1943	1813	1210
1991	90	1862	1919	2073	1740	1899	1378
1991	134	1667	2065	2179	2090	2000	1438
1990	0	878	853	943	870	886	712
1990	45	1650	1179	1260	1561	1413	1290
1990	90	1545	1667	1789	1765	1691	1788
1990	134	1041	2309	1521	1748	1655	2050
1989	0	1025	813	1097	1154	1022	54
1989	45	1521	1439	935	1244	1285	195
1989	90	1472	1610	1415	1553	1512	457
1989	134	1943	1910	2090	1602	1886	995
1988	0	837	1106	1122	1382	1112	343
1988	45	1382	1431	1415	1585	1453	1317
1988	90	1309	1634	1618	1699	1565	1808
1988	134	1838	1699	2326	1529	1848	2090
1987	0	992	1057	894	797	935	188
1987	45	724	1057	894	789	866	202
1987	90	1106	894	585	789	844	188
1987	134	984	642	732	488	711	195
1986	0	894	642	756	683	744	598
1986	45	1097	919	894	821	933	1337
1986	90	960	1057	829	894	935	1841
1986	134	537	1073	561	1025	799	2218
1985	0	528	1049	1130	1041	937	753
1985	45	1748	1285	1146	1382	1390	1351
1985	90	1585	1464	1496	1634	1545	1640
1985	134	1691	2781	1910	2049	2108	1908
1984	0	1626	1537	1585	1577	1581	302
1984	45	3326	2724	3074	2602	2931	1055
1984	90	3618	2765	2773	2212	2842	1344
1984	134	3293	3659	3586	3447	3496	1720
1983	0	293	667	667	610	559	867
1983	45	1073	650	1293	675	923	1257
1983	90	1553	1016	1187	1220	1244	1438
1983	134	1456	1585	1675	1301	1504	1620

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg	Model
1982	0	1577	1781	1691	1748	1699	181
1982	45	2846	2203	1529	1976	2138	1095
1982	90	2431	2212	2431	2618	2423	1304
1982	134	2675	2382	2171	2455	2421	1445
1981	0	1220	1025	1293	1171	1177	437
1981	45	2334	2154	2065	2146	2175	598
1981	90	2309	2464	2545	2130	2362	692
1981	134	2838	2854	2707	2642	2760	759

Lahoma observed and predicted yields with no calibration for each treatment.

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Model
1992	0	1538	1538	1001	986	1285	605
1992	22	1560	1560	1631	2027	2236	793
1992	45	1921	1921	2378	2534	2449	974
1992	67	2576	2576	2267	2584	2852	1102
1992	90	2569	2569	2896	2957	2781	1189
1992	112	2782	2782	2321	2765	2547	1236
1991	0	1220	1220	1545	1667	1658	813
1991	22	1513	1513	1480	2090	2228	961
1991	45	1439	1439	1821	2122	2179	1089
1991	67	1626	1626	2130	2017	2017	1163
1991	90	1464	1464	2098	2195	1724	1263
1991	112	1585	1585	2220	1984	2138	1297
1990	0	1553	1553	1740	1773	2041	699
1990	22	2439	2439	2382	3211	3211	1183
1990	45	2618	2618	3187	3627	3594	1579
1990	67	3033	3033	3455	3554	3203	1908
1990	90	3147	3147	3358	3302	3171	2224
1990	112	2618	2618	2911	3171	3090	2433
1989	0	1366	1366	1065	1081	1350	571
1989	22	1943	1943	2082	2537	2773	605
1989	45	2342	2342	2553	2830	2358	638
1989	67	2642	2642	2602	2505	2878	759
1989	90	2797	2797	3195	2943	2472	813
1989	112	2691	2691	3066	2553	2529	887
1988	0	1675	1675	1748	1821	2033	578
1988	22	2610	2610	2269	3049	3082	887
1988	45	2480	2480	2976	4415	3025	1210
1988	67	3838	3838	3187	4115	4260	1499
1988	90	3862	3862	4716	4553	4359	1707
1988	112	4651	4651	4098	4058	4171	1821
1987	0	1927	1927	2220	2082	1968	289
1987	22	2220	2220	2195	2854	2691	423
1987	45	2415	2415	2757	3147	2732	551
1987	67	2951	2951	2854	2830	2830	591
1987	90	2886	2886	2959	2959	2748	652
1987	112	2789	2789	2781	2927	2659	699

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Model
1986	0	2594	2594	2789	2618	2854	376
1986	22	2984	2984	2724	2984	2716	524
1986	45	2675	2675	2976	3098	2830	638
1986	67	3163	3163	2878	2830	3082	672
1986	90	2943	2943	3074	3155	3025	679
1986	112	3236	3236	3090	3049	2992	706
1985	0	1333	1333	1398	1456	1301	396
1985	22	1919	1919	1894	2138	2244	450
1985	45	2187	2187	2496	2261	2277	484
1985	67	2521	2521	2269	2537	1992	511
1985	90	2464	2464	2073	2407	2033	538
1985	112	2187	2187	1927	2114	1894	551
1984	0	2090	2090	2480	2041	2358	679
1984	22	3033	3033	2732	2919	3066	1089
1984	45	2455	2455	2870	2878	3236	1425
1984	67	3058	3058	3211	2529	3195	1687
1984	90	2846	2846	2683	3114	2707	1895
1984	112	2838	2838	2886	2642	2480	2050
1983	0	2390	2390	2846	2505	2618	706
1983	22	3082	3082	3025	3391	3431	1028
1983	45	2699	2699	3504	4041	3610	1364
1983	67	3342	3342	3635	3480	3269	1667
1983	90	3513	3513	3033	3049	3203	1989
1983	112	2464	2464	2309	2261	3025	2144
1982	0	1561	1561	1968	1943	1919	538
1982	22	2529	2529	2350	2334	2480	786
1982	45	2472	2472	2187	2277	1886	1109
1982	67	2106	2106	2618	1757	2317	1438
1982	90	2001	2001	1789	2334	1870	1781
1982	112	1927	1927	1862	1773	1910	2050
1981	0	1317	1317	1366	1439	1130	396
1981	22	2171	2171	1927	2253	2171	470
1981	45	1220	1220	2683	2586	2187	531
1981	67	2854	2854	1325	2805	2398	598
1981	90	2578	2578	2797	2358	2358	685
1981	112	2773	2773	2838	2570	2244	732

Altus observed and predicted yields with no calibration for each treatment.

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Avg.	Model
1992	0	648	660	649	703	793	668	687	706
1992	45	1064	1015	1345	1121	1120	1320	1164	961
1992	90	861	1009	1107	1478	1205	1241	1150	1176
1992	145	899	1253	1517	1400	1242	1183	1249	1331
1992	180	1163	1105	946	1375	1425	1114	1188	1452
1991	0	1308	1503	1495	1276	1324	1398	1384	349
1991	45	2113	2275	1414	2088	1487	1576	1825	323
1991	90	2316	1893	2413	1463	1528	1804	1903	370
1991	145	2096	1828	1609	1568	1609	1658	1728	376
1991	180	1552	2389	1788	1763	1584	1641	1786	403
1990	0	1422	1259	1471	1235	1300	1259	1324	60
1990	45	1869	2088	2178	2316	2096	2308	2142	242
1990	90	2064	2048	1983	2324	1974	2007	2066	1270
1990	145	1918	2356	1999	1901	2275	2397	2141	2056
1990	180	1828	2072	2259	2121	2072	1869	2037	2332
1989	0	609	618	723	512	788	634	647	390
1989	45	910	1186	967	1081	861	926	989	444
1989	90	1178	1024	1300	1016	943	918	1063	531
1989	145	1008	959	967	1008	1024	943	984	578
1989	180	926	1105	1016	837	934	1162	997	578
1988	0	1999	2202	2299	2186	2113	2332	2188	766
1988	45	2657	2828	2730	2730	2657	2397	2666	1082
1988	90	3104	2169	3055	2616	1942	2665	2592	1116
1988	145	2373	2706	2819	2868	2364	2576	2618	1176
1988	180	2852	2925	2868	2373	2348	2860	2704	1203
1987	0	943	1219	772	861	780	1073	941	262
1987	45	1089	691	878	967	1040	3250	1319	175
1987	90	642	1203	829	1016	1105	1170	994	34
1987	145	878	1398	1129	1113	1105	1105	1121	108
1987	180	951	829	1129	1008	902	1259	1013	134
1986	0	1089	1138	1398	1040	569	1056	1048	470
1986	45	1284	1536	991	1316	967	829	1154	538
1986	90	1438	1251	1414	926	691	837	1093	591
1986	145	1235	1016	853	837	731	748	903	632
1986	180	1235	1373	1129	926	577	488	955	659
1985	0	1316	1430	1381	1349	1568	1812	1476	833
1985	45	2113	2340	2413	1958	1909	2048	2130	1505
1985	90	2218	2324	2056	2153	1828	1909	2081	1861
1985	145	2015	2056	2194	2129	1755	1706	1976	1976
1985	180	2137	2007	2088	2121	1901	2031	2048	2029

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Avg.	Model
1984	0	1146	1276	1292	3713	999	1032	1576	121
1984	45	1178	1389	1259	951	902	1056	1123	121
1984	90	1138	1544	1178	1146	1008	1146	1193	74
1984	145	1194	1487	1284	1284	902	1016	1194	40
1984	180	1333	1316	1479	1219	878	1381	1268	47
1983	0	1544	1625	1698	1259	1381	1259	1461	114
1983	45	2616	2624	2137	2397	1674	2104	2259	188
1983	90	2884	2722	2689	2153	1950	2072	2412	323
1983	145	2511	2421	2316	2194	2226	2169	2306	410
1983	180	2901	2202	2568	2202	2039	2844	2459	450
1982	0	1867	1691	2143	2827	1076	1159	1794	296
1982	45	2951	2451	2445	1933	1243	1901	2154	390
1982	90	2669	3123	2856	1698	1565	1636	2258	444
1982	145	3124	2321	1953	1433	1840	1196	1978	464
1982	180	2579	2861	2382	1620	1575	2326	2224	484
1981	0	1718	3213	1991	1376	1497	1391	1865	1062
1981	45	2886	2957	2425	2471	1739	2482	2493	1230
1981	90	3166	3713	2891	2509	2076	2248	2767	1290
1981	145	3697	2683	2847	2248	2852	1985	2719	1310
1981	180	3123	2903	2666	2295	2161	2681	2638	1317

Stillwater observed and calibrated predicted yields for each treatment.

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Model
1992	0	954	764	901	929	887	974
1992	45	2023	1645	1466	1459	1648	1384
1992	90	1867	2223	2081	1979	2037	1646
1992	135	1790	1838	2357	1734	1930	1767
1991	0	1374	935	1252	1130	1173	1351
1991	45	1878	1757	1675	1943	1813	1828
1991	90	1862	1919	2073	1740	1899	2191
1991	135	1667	2065	2179	2090	2000	2325
1990	0	878	853	943	870	886	813
1990	45	1650	1179	1260	1561	1413	1767
1990	90	1545	1667	1789	1765	1691	2587
1990	135	1041	2309	1521	1748	1655	3266
1989	0	1025	813	1097	1154	1022	995
1989	45	1521	1439	935	1244	1285	2661
1989	90	1472	1610	1415	1553	1512	3535
1989	135	1943	1910	2090	1602	1886	3938
1988	0	837	1106	1122	1382	1112	867
1988	45	1382	1431	1415	1585	1453	2103
1988	90	1309	1634	1618	1699	1565	2782
1988	135	1838	1699	2326	1529	1848	3649
1987	0	992	1057	894	797	935	249
1987	45	724	1057	894	789	866	383
1987	90	1106	894	585	789	844	383
1987	135	984	642	732	488	711	349
1986	0	894	642	756	683	744	773
1986	45	1097	919	894	821	933	2137
1986	90	960	1057	829	894	935	2809
1986	135	537	1073	561	1025	799	3004
1985	0	528	1049	1130	1041	937	934
1985	45	1748	1285	1146	1382	1390	1908
1985	90	1585	1464	1496	1634	1545	2386
1985	135	1691	2781	1910	2049	2108	2930
1984	0	1626	1537	1585	1577	1581	1055
1984	45	3326	2724	3074	2602	2931	1801
1984	90	3618	2765	2773	2212	2842	2580
1984	135	3293	3659	3586	3447	3496	3219
1983	0	293	667	667	610	559	1176
1983	45	1073	650	1293	675	923	1949
1983	90	1553	1016	1187	1220	1244	2715
1983	135	1456	1585	1675	1301	1504	3367

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Model
1982	0	1577	1781	1691	1748	1699	1095
1982	45	2846	2203	1529	1976	2138	1398
1982	90	2431	2212	2431	2618	2423	1673
1982	135	2675	2382	2171	2455	2421	1808
1981	0	1220	1025	1293	1171	1177	820
1981	45	2334	2154	2065	2146	2175	1250
1981	90	2309	2464	2545	2130	2362	1472
1981	135	2838	2854	2707	2642	2760	1646

Lahoma observed and predicted yields for each treatment using genetic coefficients calibrated for Stillwater.

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Model
1992	0	1538	1001	986	1285	1202	988
1992	22	1560	1631	2027	2236	1863	1243
1992	45	1921	2378	2534	2449	2320	1458
1992	67	2576	2267	2584	2852	2570	1606
1992	90	2569	2896	2957	2781	2801	1720
1992	112	2782	2321	2765	2547	2604	1774
1991	0	1220	1545	1667	1658	1522	887
1991	22	1513	1480	2090	2228	1828	1042
1991	45	1439	1821	2122	2179	1891	1169
1991	67	1626	2130	2017	2017	1947	1284
1991	90	1464	2098	2195	1724	1870	1331
1991	112	1585	2220	1984	2138	1982	1384
1990	0	1553	1740	1773	2041	1777	1095
1990	22	2439	2382	3211	3211	2811	1821
1990	45	2618	3187	3627	3594	3257	2439
1990	67	3033	3455	3554	3203	3311	2930
1990	90	3147	3358	3302	3171	3244	3320
1990	112	2618	2911	3171	3090	2948	3716
1989	0	1366	1065	1081	1350	1216	847
1989	22	1943	2082	2537	2773	2334	840
1989	45	2342	2553	2830	2358	2521	941
1989	67	2642	2602	2505	2878	2657	1310
1989	90	2797	3195	2943	2472	2852	1411
1989	112	2691	3066	2553	2529	2710	1465
1988	0	1675	1748	1821	2033	1819	894
1988	22	2610	2269	3049	3082	2752	1431
1988	45	2480	2976	4415	3025	3224	1908
1988	67	3838	3187	4115	4260	3850	2365
1988	90	3862	4716	4553	4359	4373	2796
1988	112	4651	4098	4058	4171	4244	3192
1987	0	1927	2220	2082	1968	2049	349
1987	22	2220	2195	2854	2691	2490	618
1987	45	2415	2757	3147	2732	2763	793
1987	67	2951	2854	2830	2830	2866	880
1987	90	2886	2959	2959	2748	2888	988
1987	112	2789	2781	2927	2659	2789	1089

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Model
1986	0	2594	2789	2618	2854	2714	497
1986	22	2984	2724	2984	2716	2852	847
1986	45	2675	2976	3098	2830	2895	1021
1986	67	3163	2878	2830	3082	2988	1075
1986	90	2943	3074	3155	3025	3049	1163
1986	112	3236	3090	3049	2992	3092	1230
1985	0	1333	1398	1456	1301	1372	665
1985	20	1919	1894	2138	2244	2049	706
1985	40	2187	2496	2261	2277	2305	773
1985	60	2521	2269	2537	1992	2329	847
1985	80	2464	2073	2407	2033	2244	907
1985	100	2187	1927	2114	1894	2031	921
1984	0	2090	2480	2041	2358	2242	900
1984	20	3033	2732	2919	3066	2937	1445
1984	40	2455	2870	2878	3236	2860	1962
1984	60	3058	3211	2529	3195	2998	2372
1984	80	2846	2683	3114	2707	2838	2782
1984	100	2838	2886	2642	2480	2712	3084
1983	0	2390	2846	2505	2618	2590	1035
1983	20	3082	3025	3391	3431	3232	1539
1983	40	2699	3504	4041	3610	3464	2050
1983	60	3342	3635	3480	3269	3431	2493
1983	80	3513	3033	3049	3203	3199	2809
1983	100	2464	2309	2261	3025	2514	3071
1982	0	1561	1968	1943	1919	1848	880
1982	20	2529	2350	2334	2480	2423	1404
1982	40	2472	2187	2277	1886	2206	1895
1982	60	2106	2618	1757	2317	2199	2379
1982	80	2001	1789	2334	1870	1998	2843
1982	100	1927	1862	1773	1910	1868	3199
1981	0	1317	1366	1439	1130	1313	504
1981	20	2171	1927	2253	2171	2131	598
1981	40	1220	2683	2586	2187	2169	726
1981	60	2854	1325	2805	2398	2346	867
1981	80	2578	2797	2358	2358	2523	1001
1981	100	2773	2838	2570	2244	2606	1068

Altus observed and predicted yields for each treatment using genetic coefficients calibrated for Stillwater.

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Avg.	Model
1992	0	648	660	649	703	793	668	687	800
1992	45	1064	1015	1345	1121	1120	1320	1164	1230
1992	90	861	1009	1107	1478	1205	1241	1150	1707
1992	145	899	1253	1517	1400	1242	1183	1249	2023
1992	180	1163	1105	946	1375	1425	1114	1188	2009
1991	0	1308	1503	1495	1276	1324	1398	1384	921
1991	45	2113	2275	1414	2088	1487	1576	1825	1075
1991	90	2316	1893	2413	1463	1528	1804	1903	1183
1991	145	2096	1828	1609	1568	1609	1658	1728	1189
1991	180	1552	2389	1788	1763	1584	1641	1786	1236
1990	0	1422	1259	1471	1235	1300	1259	1324	1485
1990	45	1869	2088	2178	2316	2096	2308	2142	2500
1990	90	2064	2048	1983	2324	1974	2007	2066	2137
1990	145	1918	2356	1999	1901	2275	2397	2141	2460
1990	180	1828	2072	2259	2121	2072	1869	2037	2634
1989	0	609	618	723	512	788	634	647	739
1989	45	910	1186	967	1081	861	926	989	914
1989	90	1178	1024	1300	1016	943	918	1063	1042
1989	145	1008	959	967	1008	1024	943	984	1062
1989	180	926	1105	1016	837	934	1162	997	1042
1988	0	1999	2202	2299	2186	2113	2332	2188	934
1988	45	2657	2828	2730	2730	2657	2397	2666	1156
1988	90	3104	2169	3055	2616	1942	2665	2592	1270
1988	145	2373	2706	2819	2868	2364	2576	2618	1310
1988	180	2852	2925	2868	2373	2348	2860	2704	1337
1987	0	943	1219	772	861	780	1073	941	430
1987	45	1089	691	878	967	1040	3250	1319	255
1987	90	642	1203	829	1016	1105	1170	994	181
1987	145	878	1398	1129	1113	1105	1105	1121	202
1987	180	951	829	1129	1008	902	1259	1013	222
1986	0	1089	1138	1398	1040	569	1056	1048	491
1986	45	1284	1536	991	1316	967	829	1154	558
1986	90	1438	1251	1414	926	691	837	1093	632
1986	145	1235	1016	853	837	731	748	903	679
1986	180	1235	1373	1129	926	577	488	955	679
1985	0	1316	1430	1381	1349	1568	1812	1476	2278
1985	45	2113	2340	2413	1958	1909	2048	2130	3078
1985	90	2218	2324	2056	2153	1828	1909	2081	3508
1985	145	2015	2056	2194	2129	1755	1706	1976	3851
1985	180	2137	2007	2088	2121	1901	2031	2048	4153

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Avg.	Model
1984	0	1146	1276	1292	3713	999	1032	1576	222
1984	45	1178	1389	1259	951	902	1056	1123	222
1984	90	1138	1544	1178	1146	1008	1146	1193	222
1984	145	1194	1487	1284	1284	902	1016	1194	202
1984	180	1333	1316	1479	1219	878	1381	1268	181
1983	0	1544	1625	1698	1259	1381	1259	1461	437
1983	45	2616	2624	2137	2397	1674	2104	2259	874
1983	90	2884	2722	2689	2153	1950	2072	2412	1042
1983	145	2511	2421	2316	2194	2226	2169	2306	1102
1983	180	2901	2202	2568	2202	2039	2844	2459	1122
1982	0	1867	1691	2143	2827	1076	1159	1794	974
1982	45	2951	2451	2445	1933	1243	1901	2154	1163
1982	90	2669	3123	2856	1698	1565	1636	2258	1304
1982	145	3124	2321	1953	1433	1840	1196	1978	1364
1982	180	2579	2861	2382	1620	1575	2326	2224	1364
1981	0	1718	3213	1991	1376	1497	1391	1865	981
1981	45	2886	2957	2425	2471	1739	2482	2493	1210
1981	90	3166	3713	2891	2509	2076	2248	2767	1284
1981	145	3697	2683	2847	2248	2852	1985	2719	1317
1981	180	3123	2903	2666	2295	2161	2681	2638	1337

Lahoma observed and calibrated predicted yields for each treatment.

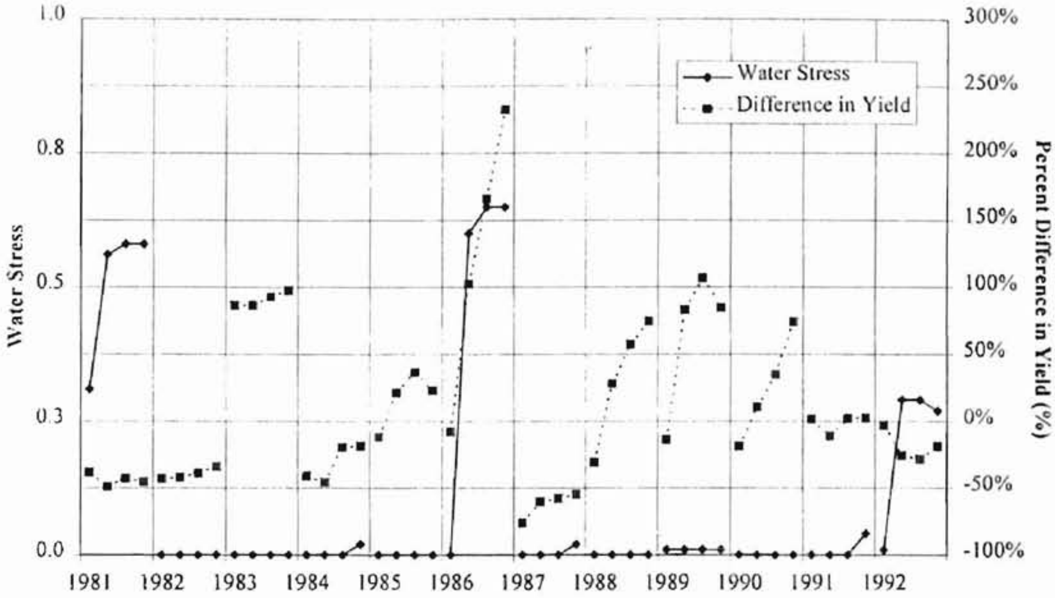
Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Model
1992	0	1538	1001	986	1285	1202	1310
1992	22	1560	1631	2027	2236	1863	1653
1992	45	1921	2378	2534	2449	2320	1935
1992	67	2576	2267	2584	2852	2570	2130
1992	90	2569	2896	2957	2781	2801	2278
1992	112	2782	2321	2765	2547	2604	2352
1991	0	1220	1545	1667	1658	1522	1169
1991	22	1513	1480	2090	2228	1828	1378
1991	45	1439	1821	2122	2179	1891	1552
1991	67	1626	2130	2017	2017	1947	1693
1991	90	1464	2098	2195	1724	1870	1761
1991	112	1585	2220	1984	2138	1982	1835
1990	0	1553	1740	1773	2041	1777	1452
1990	22	2439	2382	3211	3211	2811	2412
1990	45	2618	3187	3627	3594	3257	3232
1990	67	3033	3455	3554	3203	3311	3877
1990	90	3147	3358	3302	3171	3244	4442
1990	112	2618	2911	3171	3090	2948	4919
1989	0	1366	1065	1081	1350	1216	1122
1989	22	1943	2082	2537	2773	2334	1116
1989	45	2342	2553	2830	2358	2521	1243
1989	67	2642	2602	2505	2878	2657	1734
1989	90	2797	3195	2943	2472	2852	1868
1989	112	2691	3066	2553	2529	2710	1935
1988	0	1675	1748	1821	2033	1819	1183
1988	22	2610	2269	3049	3082	2752	1888
1988	45	2480	2976	4415	3025	3224	2520
1988	67	3838	3187	4115	4260	3850	3125
1988	90	3862	4716	4553	4359	4373	3696
1988	112	4651	4098	4058	4171	4244	4213
1987	0	1927	2220	2082	1968	2049	464
1987	22	2220	2195	2854	2691	2490	813
1987	45	2415	2757	3147	2732	2763	1048
1987	67	2951	2854	2830	2830	2866	1163
1987	90	2886	2959	2959	2748	2888	1304
1987	112	2789	2781	2927	2659	2789	1438

Year	Trt	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Model
1986	0	2594	2789	2618	2854	2714	659
1986	22	2984	2724	2984	2716	2852	1122
1986	45	2675	2976	3098	2830	2895	1344
1986	67	3163	2878	2830	3082	2988	1425
1986	90	2943	3074	3155	3025	3049	1532
1986	112	3236	3090	3049	2992	3092	1626
1985	0	1333	1398	1456	1301	1372	880
1985	20	1919	1894	2138	2244	2049	934
1985	40	2187	2496	2261	2277	2305	1021
1985	60	2521	2269	2537	1992	2329	1122
1985	80	2464	2073	2407	2033	2244	1196
1985	100	2187	1927	2114	1894	2031	1223
1984	0	2090	2480	2041	2358	2242	1196
1984	20	3033	2732	2919	3066	2937	1908
1984	40	2455	2870	2878	3236	2860	2594
1984	60	3058	3211	2529	3195	2998	3145
1984	80	2846	2683	3114	2707	2838	3689
1984	100	2838	2886	2642	2480	2712	4079
1983	0	2390	2846	2505	2618	2590	1371
1983	20	3082	3025	3391	3431	3232	2036
1983	40	2699	3504	4041	3610	3464	2715
1983	60	3342	3635	3480	3269	3431	3293
1983	80	3513	3033	3049	3203	3199	3709
1983	100	2464	2309	2261	3025	2514	4066
1982	0	1561	1968	1943	1919	1848	1163
1982	20	2529	2350	2334	2480	2423	1861
1982	40	2472	2187	2277	1886	2206	2513
1982	60	2106	2618	1757	2317	2199	3152
1982	80	2001	1789	2334	1870	1998	3763
1982	100	1927	1862	1773	1910	1868	4234
1981	0	1317	1366	1439	1130	1313	665
1981	20	2171	1927	2253	2171	2131	793
1981	40	1220	2683	2586	2187	2169	961
1981	60	2854	1325	2805	2398	2346	1149
1981	80	2578	2797	2358	2358	2523	1290
1981	100	2773	2838	2570	2244	2606	1418

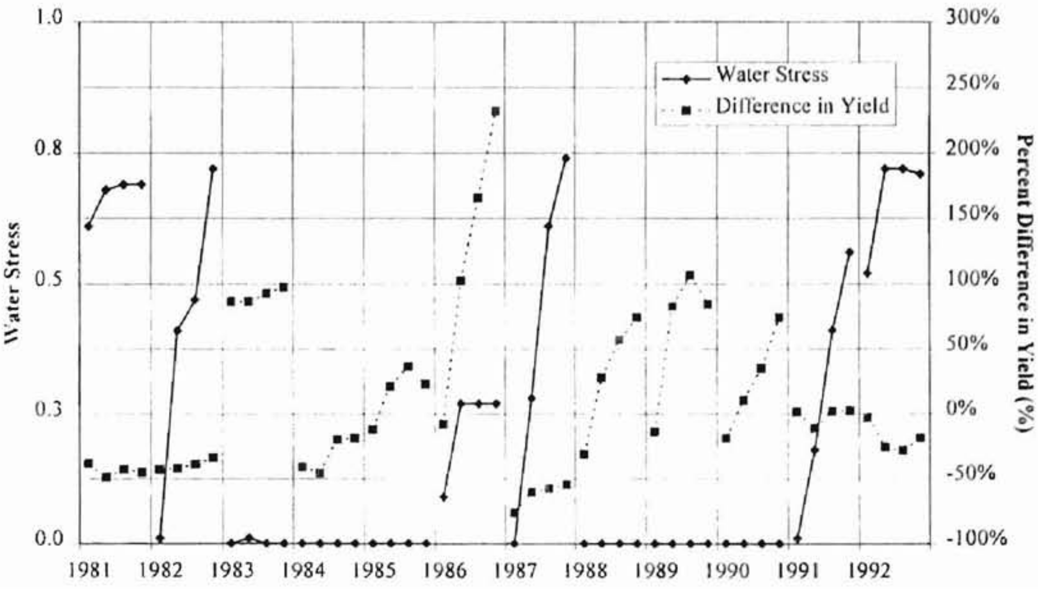
APPENDIX D

Water Stress Plots

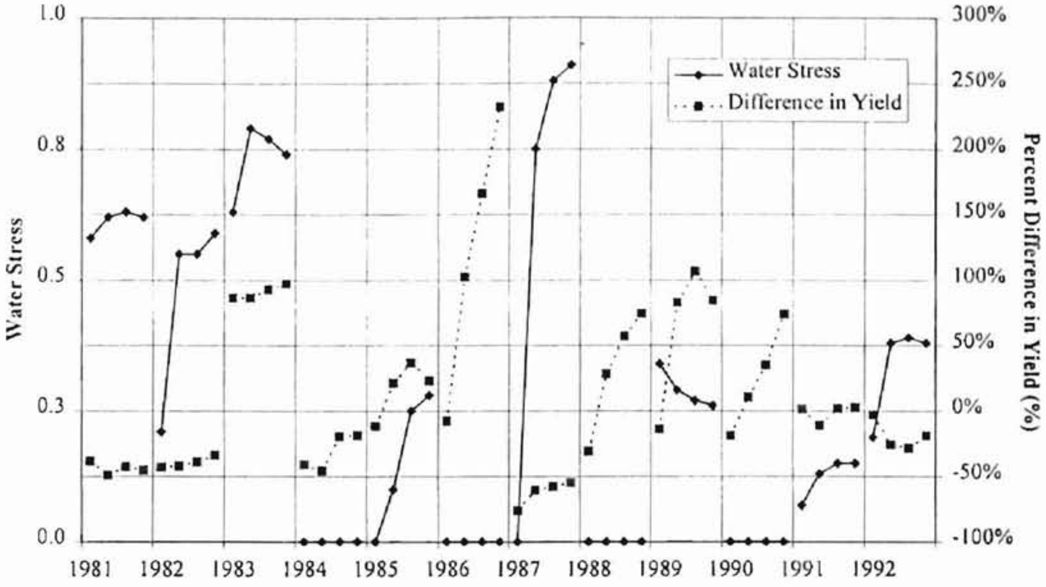
Water Stress in the Vegetative Growth Stage and Percent Difference from Observed Yield for Stillwater



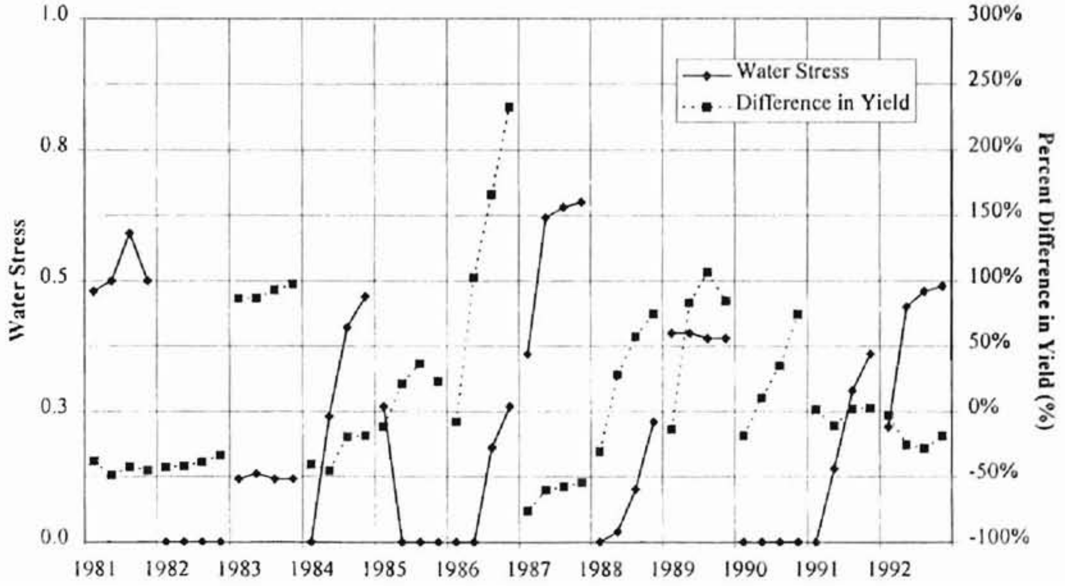
Water Stress in the Ear Growth Stage and Percent Difference from Observed Yield for Stillwater

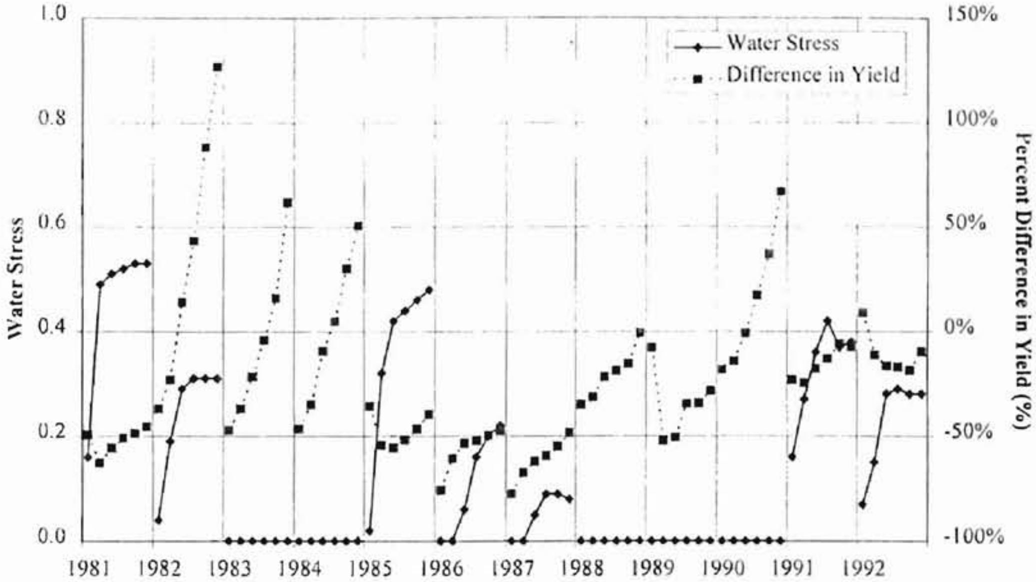


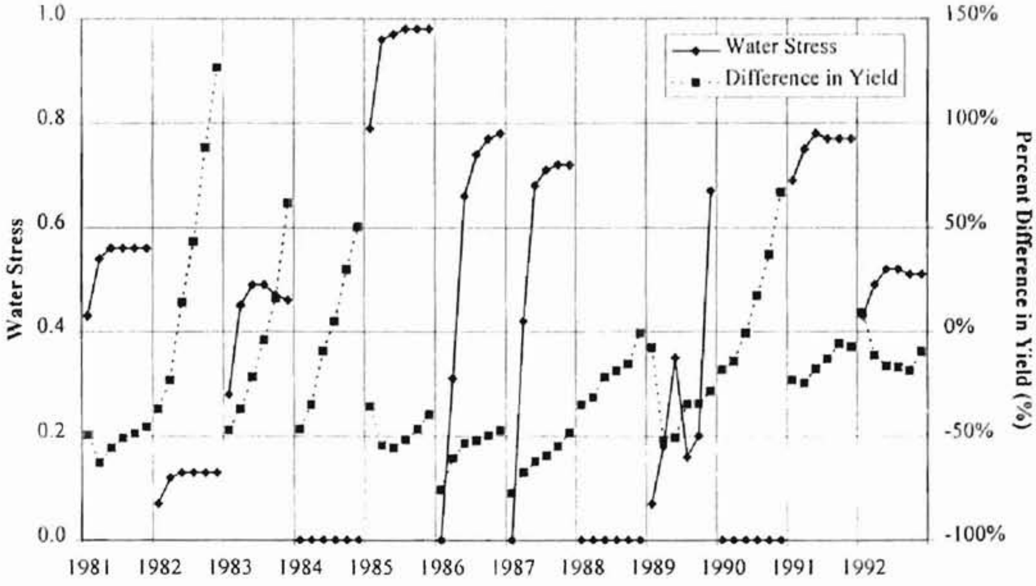
Water Stress in the Grain Fill Stage and Percent Difference from Observed Yield for Stillwater



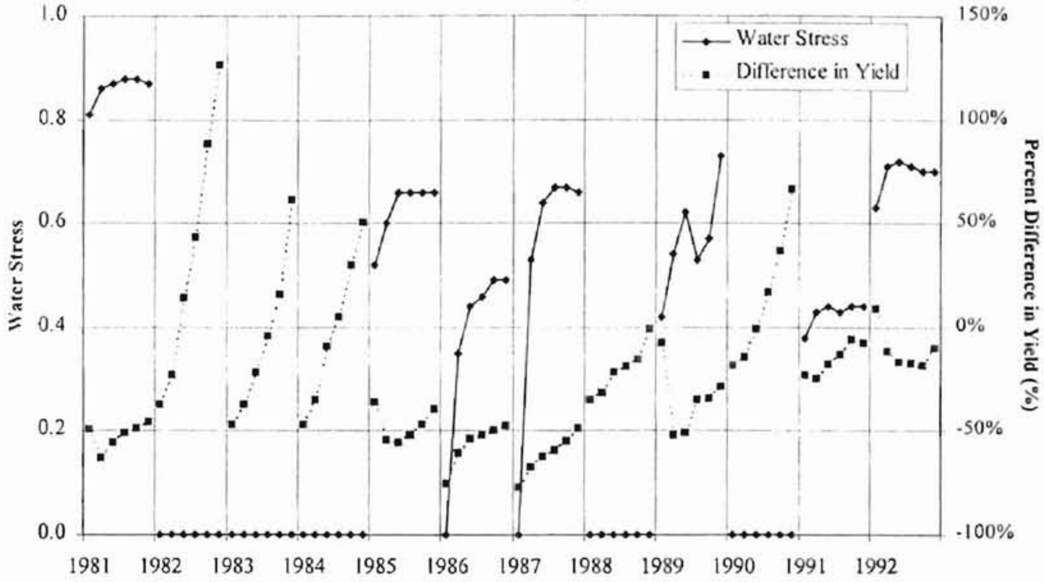
Water Stress in the Maturity Stage and Percent Difference from Observed Yield for Stillwater



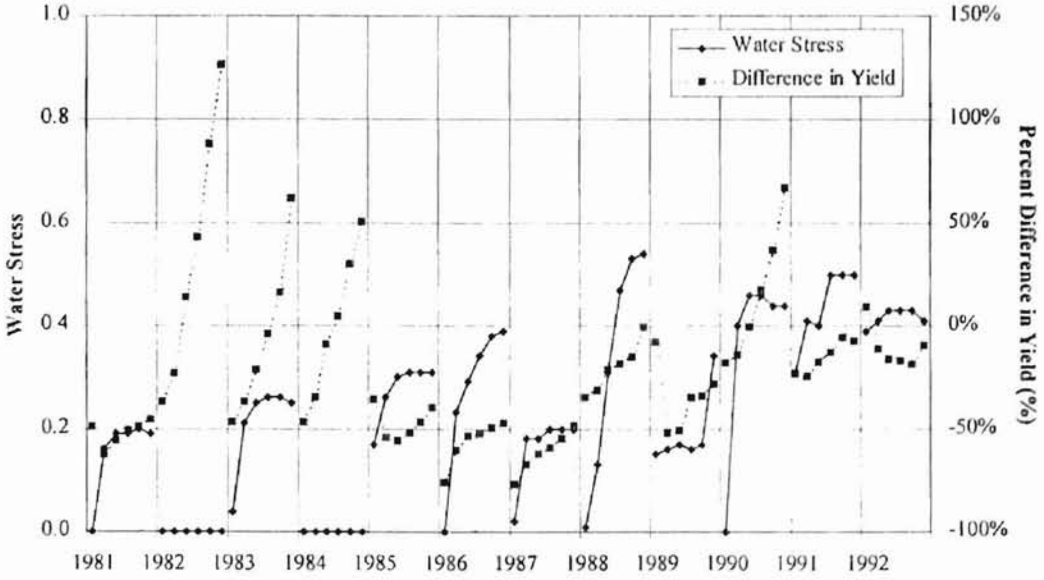

Water Stress in the Vegetative Growth Stage and Percent Difference from Observed Yield for Lahoma


Water Stress in the Ear Growth Stage and Percent Difference from Observed Yield for Lahoma

Water Stress in the Grain Fill Stage and Percent Difference from Observed Yield for Lahoma



Water Stress in the Maturity Stage and Percent Difference from Observed Yield for Lahoma



VITA

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