Sink-pulled simulation of the maize crop

Samiha Abou El-Fetouh Hamed Ouda

Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/rtd

Part of the Agricultural Science Commons, Agriculture Commons, Agronomy and Crop Sciences Commons, Botany Commons, and the Plant Biology Commons

Recommended Citation


This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6” x 9” black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
Sink-pulled simulation of the maize crop

by

Samiha Abou El-Fetouh Hamed Ouda

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Crop Physiology and Production

Major Professor: Ricardo Salvador

Iowa State University
Ames, Iowa

1998
Graduate College
Iowa State University

This is to certify that the Doctoral dissertation of

Samiha Abou El-Fetouh Hamed Ouda

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Committee Member
Signature was redacted for privacy.

Committee Member
Signature was redacted for privacy.

Committee Member
Signature was redacted for privacy.

Major Professor
Signature was redacted for privacy.

For the Major Program
Signature was redacted for privacy.

For the Graduate College
**TABLE OF CONTENTS**

**INTRODUCTION**
- Objectives and Purpose

**LITERATURE REVIEW**
- Crop Modeling and Simulation
- Maize Vegetative Development
- Maize Reproductive Development

**MATERIALS AND METHODS**
- Model Description
  - Simulation of maize vegetative growth
  - Germination and seedling emergence
  - Emergence to silking phase
  - Simulation of maize reproductive growth
  - Grain filling period
  - Physiological maturity
- Validation Procedure and Sensitivity analysis
  - Model validation
  - Sensitivity analysis
  - Effect of defoliation

**RESULTS AND DISCUSSION**
- Model validation
  - Vegetative growth
  - Reproductive growth
  - Physiological implication of Maize-S
    - Effect of temperature changes on maize growth
    - Effect of solar radiation change on maize growth
    - Effect of defoliation on maize yield

**SUMMARY AND CONCLUSION**

**APPENDIX A. LISTING OF MAIZE-S**

**APPENDIX B. PROGRAM DISK AND USER INSTRUCTION**

**APPENDIX C. ADDITIONAL FLOW CHARTS**
- Figure 1. Flow chart of the procedures simulating seedling emergence stage.
- Figure 2. Flow chart of the procedures simulating the phase after seedling emergence to the end of juvenile phase.
Figure 3. Flow chart of the procedures simulating tassel initiation phase.

Figure 4. Flow chart of the procedures simulating the phase after tassel initiation to silking.

Figure 5. Flow chart of the procedures simulating grain filling period.

Figure 6. Flow chart of the procedures simulating physiological maturity.

REFERENCES

ACKNOWLEDGMENTS
LIST OF TABLES

Table 1. The inputs required to operate Maize-S. 26

Table 2. Effect of leaf temperature on the maximum rate of leaf photosynthesis in maize. 30

Table 3. Daily percentage of silk emerged and ovule position from the base of the ear in maize. 37

Table 4. Genetic coefficients for Pioneer 3394, and Pioneer 3489. 40

Table 5. Soil types and latitude for Ames and Armstrong locations. 40

Table 6. The mean difference between predicted and observed values averaged over time (RMSE) and the average percent difference between predicted and observed values averaged over time (PE) for leaf weight (kg/ha) for both Maize-S and CERES-Maize for Pioneer 3394 and Pioneer 3489 planted at Ames and Armstrong 1995 and Ames 1996. 43

Table 7. The mean difference between predicted and observed values averaged over time (RMSE) and the average percent difference between predicted and observed values averaged over time (PE) for stem weight (kg/ha) for both Maize-S and CERES-Maize for Pioneer 3394 and Pioneer 3489 planted at Ames and Armstrong 1995 and Ames 1996. 44

Table 8. The mean difference between predicted and observed values averaged over time (RMSE) and the average percent difference between predicted and observed values averaged over time (PE) for kernel number (kernel/m²) for both Maize-S and CERES-Maize for Pioneer 3394 and Pioneer 3489 planted at Ames and Armstrong 1995 and Ames 1996. 46

Table 9. The mean difference between predicted and observed values averaged over time (RMSE) and the average percent difference between predicted and observed values averaged over time (PE) for kernel weight (kg/ha) for both Maize-S and CERES-Maize for Pioneer 3394 and Pioneer 3489 planted at Ames and Armstrong 1995 and Ames 1996. 47
LIST OF FIGURES

Figure 1. Flow chart of the procedures simulating maize vegetative and reproductive growth. 25

Figure 2. Maize-S predictions for aboveground nongrain biomass using normal temperature, normal temperature + 5° C, and normal temperature - 5° C. 49

Figure 3. Maize-S predictions for grain yield using normal temperature, normal temperature + 5° C, and normal temperature - 5° C. 49

Figure 4. Maize-S predictions for leaf area index using normal temperature, normal temperature + 5° C, and normal temperature - 5° C. 50

Figure 5. Maize-S predictions for aboveground nongrain weight using normal radiation, and normal radiation + 5%. 52

Figure 6. Maize-S predictions for grain weight using normal radiation, and normal radiation + 5%. 52

Figure 7. Maize-S predictions for grain weight under 100% defoliation imposed in weekly intervals after silking. 54

Figure 8. Maize-S predictions for weight per kernel under 100% defoliation imposed in weekly intervals after silking. 54

Figure 9. Maize-S predictions for kernel number under 100% defoliation imposed in weekly intervals after silking. 55
INTRODUCTION

Maize occupies a unique position in science and agriculture, in addition of being a crop of enormous economic significance worldwide. Potential biomass of maize is the product of dry matter accumulation throughout the growing season, and it is driven by the amount of solar radiation intercepted by plants over a range of time coinciding with optimum temperature distribution. Early in the vegetative phase of maize, after seedling emergence, leaves are a stronger sink than the roots and the stem. Therefore, leaves have the ability to attract assimilate more than the stem and root. After pollination and before the onset of the grain filling phase, substantial quantities of reserve carbohydrate are stored in the stem because it becomes a very strong sink. Grain becomes the main physiological sink on the plant after the lag phase between pollination and the onset of linear phase of grain growth. Yield formation in maize is the product of the interaction between supply and demand for assimilates and nutrients, conditioned by the genetic potential of the specific cultivar. Under well-watered conditions and ample nutrition, in the absence of pests and diseases, maize yield has been shown to be closely related to the amount of radiation intercepted by the crop (Warrington and Kanemasu, 1983a).

Recently, there is a growing demand for maize growth models for inclusion in system management models on the farm level. During the past four decades, there has been great progress in modeling of agricultural production systems. The fundamental goals of crop simulation models are: to provide improved qualitative and quantitative interpretations of the behavior of crops, in addition to providing better predictions of that behavior for immediate use in improving crop management (Jones et al., 1987).

The simulation of maize growth should involve modeling three general processes: interception of solar radiation, dry-matter production, and assimilate translocation to the different growing sinks. The rate and duration of development processes and to the time when those processes initiate and terminate is another important factor in physiological simulation of maize.
Purpose and Objectives

Despite the extensive literature on the effect of the environment and genetics on maize growth, the accurate prediction of developmental events, and physiological processes remains one of the major obstacles to the simulation of the yield. Current maize simulation models, such as CORNF (Stapper and Arkin, 1980) and CERES-Maize (Jones and Kiniry, 1986) predict maize growth and development stages to a varying degree of detail. These models simulate the performance of the whole plant throughout the growing season, sometimes using simple empirical functions, with a daily time step. Furthermore, these models are "source-oriented", which utilize a predetermined value to partition assimilate to different competing sinks. Although these models show sound physiological simulation of the vegetative phase; processes such as seedling emergence, vegetative growth stages, leaf area growth, and leaf, root, and stem weight increase are all well predicted by these models. However, this is not the case for the simulation of the reproductive growth of maize. There is a lack of sufficient understanding of the mechanisms of the reproductive phase in these models, in which kernel weight is predicted without simulating sink demand of each kernel. In such models, the assumption was made that the rate of dry matter accumulation in the kernels is the same for all kernels on the ear. However, dry matter accumulation in the basal kernels on the ear start earlier than the tip-kernels. As a result, at physiological maturity, the tip-kernels usually have less weight than the basal kernels (Tollenaar and Daynard, 1978b). In other words, the strength of basal kernels to pull assimilates is greater than tip-kernels. Predicting maize yield should account for these phenomena because of its impact on individual kernel weight as well as the final yield weight.

From the physiological point of view, grain development simulation should be based on a response to sink strength (the ability to import assimilate), which is defined on the basis of sink size and sink activity. In maize, at kernel levels, sink size may be considered kernel weight and kernel number per unit area (Tollenaar, 1977) whereas, at cell level, sink size may be considered to be the number of endosperm cells and the number of starch granules per unit area (Reddy and Daynard, 1983). Sink activity, at kernel level, may be considered the rate of uptake of assimilates per unit weight of sink tissue (Taiz and Zeiger, 1991)
whereas, at cell level, sink activity may be considered to be the efficiency of starch accumulation (Shannon et al., 1993).

Studies involving genotypic variation (Capitanio et al., 1983) and environmental treatments (Jones et al., 1985) have indicated that in maize, mature kernel weight is well correlated with endosperm cell number. During endosperm cell division, potential sink capacity or sink strength potential (or both) are established, and it may be determined by the number or size (or both) of endosperm cells or starch granules formed. Both the number and the size of starch granules are highly correlated with mature kernel mass (Capitanio et al., 1983; Reddy and Daynard, 1983). Because mature kernel weight is well correlated with endosperm cell number, the extent of cell division may place an upper limit on the amount of storage material synthesized at subsequent stages of endosperm development (Setter and Flannigan, 1989).

Salvador (1988) developed a simulation model called CENTLI to simulate maize kernel development and final kernel weight in a sink-pulled fashion, while accounting for the fact that basal kernels have more strength to attract assimilate than the tip-kernels. Furthermore, CENTLI includes simulation of endosperm differentiation and starch accumulation at the cell level. In other words, CENTLI provides estimation of sink demand at the cell level during the grain filling period. However, the model has several weak points. Because CENTLI does simulate for the vegetative growth of maize neither leaf area index nor kernel number are estimated by the model, instead they are required as input. The former is important for photosynthesis simulation and the latter is one of the two major constituents of yield determination. Furthermore, in CENTLI, simulation begins with silking and ends when growth substrate is exhausted therefore; the model does not determine the time of physiological maturity. The model assumes that the plant is grown under nonstress conditions, which rarely occurs under non-irrigated cultivation. The exposure of maize plants to stress, such as drought and/or high temperature can reduce yield dramatically. The number of ovules that are fertilized and developed into grains decreases rapidly when drought or high temperature conditions occur during flowering (Classen and Shaw, 1970). When maize ears were exposed to temperature higher than 25°C, starch synthesis decreased (Keeling et al., 1994). Moreover, silk emergence is often cited as being responsible for the
decrease in kernel number (Herrero and Johnson, 1981). Pollen viability and capability of
the pistillate flower to produce seed after being pollinated may be factors that determine seed
production when drought or high temperature conditions occur. Under water stress for as
long as four days, silk water potential drops to -1.2 MPa and no grain develops even when
pollination occurs (Westgate and Boyer, 1986a). Furthermore, CENTLI assumes that all
kernels initiate growth synchronously and there is no time lag due to silk development and
pollen tube growth delays, which is not the case for maize plant. Bassetti and Westgate
(1993a) concluded that a period of 4 to 8 days is required for all silks to emerge from husks.
Whereas, CENTLI accounts for mobilization of soluble carbohydrate form the stem, it does
not remobilize reserve from the leaves. At the end of growing season when assimilate
reserves are completely exhausted from the stem, mobilization from the leaf occurs resulting
in leaf senescence (Grant, 1989b).

The major goal of this research is to develop a physiologically sound model to
simulate both vegetative and reproductive growth of maize by utilizing published
information from the literature. For sound simulation of vegetative growth, seedling
emergence, leaf area development and weight growth, stem weight growth, production of
reproductive organs (tassel and ear), and kernel set simulation should be included in the
model. Furthermore, for accurate prediction of the maize yield, sink demand of kernels should
be simulated.

The objectives of this study were: 1) to develop a subroutine to predict maize
vegetative development; 2) to develop mechanisms to calculate silk growth, fertilization of
the silk, and kernel set; 3) to address some of the problems that CENTLI has and use the
model to simulate grain filling period; 4) to develop a mechanism to predict the impact of
both temperature and water stresses on maize growth and development; 5) to test the
physiological implication of the developed model.
LITERATURE REVIEW

The main goal of this research is to develop a physiologically sound model to simulate both vegetative and reproductive growth of maize. For this reason, this section is divided into three major parts. The first part includes a review of terminology and concepts concerning simulation methods and techniques. The second part contains a description of the vegetative development of the maize plant. The third part describes the reproductive phase. The effect of both temperature and water stresses on vegetative and reproductive phases of maize are also discussed in these sections.

Crop Modeling and Simulation

Modeling is a process of developing a mathematical representation of a system, whereas simulation is a representation of all relevant processes of the system, usually embodied in the form of a computer program (Penning de Vries et al., 1989). At the same time, a simulation model should be a simple representation of a system. A physiological simulation model should act like a real plant: fixing CO$_2$, respiring, and translocating assimilate to leaves, stem, root, and fruits. There are two approaches used in crop simulation: “source-driven” and “sink-pulled”. Source-driven simulation is usually done by partitioning a predetermined amount of photosynthate to different growing sinks on the plant, whereas sink-pulled simulation depends on creating the need or capacity to consume or store carbohydrate in a sink before the carbohydrate is allocated to it. Crop models can be classed into different types. Penning de Vries et al. (1989) described crop models as either descriptive or explanatory. A descriptive model defines the behavior of a system in a simple manner. It reflects little or nothing of the mechanisms that are responsible for behavior. In contrast, an explanatory model consists of a quantitative description of the mechanisms and processes that cause the behavior of a system.

Thornley and Johnson (1990) defined “empirical models” as directly describing observational data, while containing no information beyond the original data. On the other hand, “processes-oriented models” embody each process accounted for in the system and the factors that influence such processes. A “deterministic model” can predict the future state of a system given the initial condition. Closed systems can be simulated in such fashion.
“Mechanistic models” are suitable for simulating more complex situations than can empirical models. Mechanistic models tend to explain phenomena by referring to their biological and physical causes.

Thornley and Johnson (1990) also contrast “research models” and “production models”. Research models have speculative hypotheses, have tenuous connections to observational data, and give variable predictions. Furthermore, they are complex and mechanistic. Production models have well-accepted hypotheses, good connections to observational data, and give good predictions. Moreover, production models tend to be simple and empirical.

According to Penning de Vries and van Laar (1982), crop production systems can be classified based on major growth limiting factors into four distinct levels. “Production-level-one” indicates that a crop has ample water and nutrients, and its growth rate depends only upon the current state of the crop and current weather, particularly on radiation and temperature levels. “Production-level-two” indicates that crop growth rate is limited only by the availability of water for at least part of the growing season. “Production-level-three” indicates that crop growth rate is limited by nitrogen shortage for at least part of the growing season and by water shortage or poor weather for the remainder of the season. “Production-level-four” indicates that crop growth rate is restricted by phosphorus and other mineral shortages in the soil for at least part of the growing season.

Developing a simulation model requires the implementation of several steps. Firstly, selection of state variables, processes, inputs and the parameters of modeling are critical (Jones and Boote, 1987). State variables describe the conditions of the components of systems, taking on different values with time as these components interact with the environment and with each other. A crop model is a set of mathematical relationships describing the changes in state variables over time as a result of various processes. The environmental factors that influence the behavior of the system are called inputs. Parameters are characteristics of the components of the model that are constant throughout the simulation time (Jones et al., 1987).

Secondly, consideration must be given to the rate and duration of developmental processes of the plant and the time when these processes are initiated and terminated. In
modeling species with determinate growth habit, such as maize where leaf differentiation is
terminated by reproductive primordial production, prediction of floral initiation is essential to
aid in leaf number prediction. Moreover, the time of anthesis must be accurately predicted to
define the termination of leaf, and stem growth and to determine the start of the grain-filling
phase. The simulation of leaf area development is important in determining the percentage
of solar radiation intercepted by the crop canopy. Crop photosynthesis, respiration,
transpiration, dry matter production, plant growth and final yield are all influenced by leaf
surface area and angle within the canopy (Warrington and Kanemasu, 1983b).
Environmental factors, such as temperature and photoperiod can control both the rate and the
duration of many of these developmental events. Accordingly, their effects must be defined
quantitatively if a mechanistic simulation model is to be developed.

CERES-Maize is one of the most important models that simulate maize growth and
development. The model has gained widespread use because it can be used with many
hybrids and on many different soil types. CERES-Maize was developed by the United States
Department of Agriculture, Agriculture Research Service Group, at the Grassland, Soil, and
Water Research Laboratory at Temple, Texas. CERES-Maize requires two input files: the
parameters input file and the weather-input file. The parameters input file contains variables
for sowing date, plant population, latitude, planting depth, model output switches, irrigation
switch, initial soil water status, soil water balance switch, soil parameters, irrigation dates
and amounts, and genetic inputs. The genetic inputs are of three types: the relationship of
growing degree days to phenological events, a photoperiod sensitivity coefficient, and yield
estimates in terms of potential kernel number and potential kernel growth rate. The weather-
input file contains the variables: year, day of the year, daily values of total incoming solar
radiation, maximum and minimum air temperature, and precipitation (Jones and Kiniry,
1986).

Maize Vegetative Development

The state of a plant is determined by both growth and development. Growth is the
increase in weight, length, or area of the plant. Development is the sequencing of
phenological events in the plant life cycle (Ritchie and NeSmith, 1991). The maize plant
develops 20-21 total leaves in central Iowa, silks about 65 d after emergence, and matures about 125 d after emergence. All corn plants follow this same general pattern of development, but the specific time intervals between stages and total leaf numbers developed vary between hybrids, season, dates of planting, and locations. (Ritchie et al., 1993). The maize shoot produces a limited number of structures in a regular and highly predictable pattern. In the beginning of the vegetative phase, internodes elongate slowly and the entire above ground part of the shoot consists solely of leaves (Poethig, 1993). Leaf initiation continues until floral initiation occurs at the apex, after which reproductive primordial production commences (Warrington and Kanemasu, 1983a). With the initiation of the tassel, all but the basal five or six internodes begin to elongate rapidly and push through the enclosing leaf sheaths (Poethig, 1993). The basal 5-6 internodes remain below ground, where they give rise to the root system (Feldman, 1993). A system is used to identify stage of development (Vn) according to the uppermost leaf whose leaf collar is visible. "V" represents the vegetative stage and "n" represents the current leaf stage. All leaves and ear shoots that the plant will eventually produce are initiated by the V4 stage. At about V5, leaf and ear shoot initiation is completed (Ritchie et al., 1993). The duration of the period from seedling emergence to silking is closely associated with the number of leaves initiated by the plant (Chase and Nanda, 1967). This number is determined by the duration of the juvenile and inductive phases. The duration of the juvenile phase is genotype-specific and could be used to estimate cultivar maturity requirements (Kiniry et al., 1983a). Duration of the inductive phase, which may also be genotype-specific, is determined by the timing of tassel initiation, and is usually 4 to 8 days (Kiniry et al., 1983b). The inductive phase is influenced by temperature and photoperiod (Kiniry et al., 1983b; Tollenaar and Hunter, 1983), but photoperiod sensitivity ends with tassel initiation (Kiniry, 1991). Furthermore, tassel initiation is delayed by an increase in leaf number (Chase and Nanda, 1967; Hunter et al., 1974; Hunter et al., 1977).

**Leaf production**

The number of leaves formed on the plant depends upon two developmental processes. Firstly, it is determined by the rate of leaf production at the apical meristem, and
secondly by the duration of the period between seedling emergence and floral initiation (Warrington and Kanemasu, 1983c). Both of these processes are in turn influenced by environmental factors such as temperature and photoperiod (Warrington and Kanemasu, 1983a,b). Juvenile and adult maize leaves differ in shape and size (Freeling and Lane, 1993). Warrington and Kanemasu (1983b) reported that leaf collar appearance in a 12-hour photoperiod, with total photosynthetically active radiation of $8.7 \text{ MJ/m}^2/\text{day}$, was 16 to 20% lower than the rate in a 16-hour photoperiod with total photosynthetically active radiation of $11.5 \text{ MJ/m}^2/\text{day}$ under the same temperature. Furthermore, for every degree increase in temperature over $26^\circ \text{C}$, leaf appearance rate increased by 0.23 leaf/day/$^\circ \text{C}$.

Leaf area development is dependent on leaf number, on the rate at which leaves are initiated and subsequently emerge from the whorl, and on the rate and duration of expansion of individual leaves (Warrington and Kanemasu, 1983b). Leaf area is correlated with dry matter production by a plant and it therefore influences plant growth and final yield (Sinclair, 1984). There is a linear relationship between incident solar radiation absorbed by the leaves and the rate of crop dry matter accumulation when nutrient and water supply are not limiting to crop growth (Tollenaar and Bruulsema, 1988). Canopy structure also has an effect on the amount of incident solar radiation absorbed by the leaves (Williams et al., 1968). Canopy light interception and photosynthesis are closely related to leaf area index (LAI; the ratio between leaf area to ground area) up to a 'critical' LAI, the level required to intercept 95% of incident radiation (Pearce et al., 1965). Under stress conditions such as drought, leaf photosynthesis tends to decrease. Dwyer et al. (1992) used a curve fitting method to divide photosynthesis data into "stressed" and "unstressed" groupings to quantitatively separate the reduction in photosynthetic rates resulting from water stress and the time of the stress.

**Leaf area prediction**

Mathematical functions that simulate leaf development are a critical part of crop simulation models. Several approaches have been taken in analyzing and predicting leaf area development as a function of air temperature (Stapper and Arkin, 1980; Dwyer and Stewart, 1986; Jones and Kiniry, 1986). Other approaches focus on the activity at the apical meristem (Kiniry et al., 1983a; Tollenaar and Hunter, 1983). Grant (1989a) used soil temperature to
predict the rate of both leaf initiation and leaf tip appearance. CERES-Maize uses daily thermal time units to calculate the rate of both leaf initiation and leaf tip appearance, with the assumption that leaf development rate is the same among all hybrids.

The production of reproductive organs

In addition to the important role of the main stem apex of maize in the production of leaf primordia and in the control of development of the whole plant, it also has an important role in the production of reproductive organs. The growth and development of the terminal (male) apex and the two uppermost axially (female) apices follow similar patterns, with apex volumes increasing curvilinearly with increase in number of leaf or husk primordia. The axially apices of maize (the potential grain bearing inflorescence) follow a pattern of growth and development similar to that of the main stem apex. Furthermore, there is no difference in growth and development between the first and the second ear before silking. Other factors, such as accumulation of dry weight rather than primordia production might be responsible for a given ear's potential to bear grain (Jacobs and Pearson, 1992a). The accumulation of dry matter and nitrogen within axially branches always favors the ear over the husk and shank. Dry matter and nitrogen accumulate faster in the first ear than in the tassel or second ear (Jacobs and Pearson, 1992b).

Prolificacy

Prolificacy is the ability of some maize cultivars to produce more than one ear under favorable conditions. However, under unfavorable conditions, many prolific hybrids produce only one ear. The number of ears per plant is generally determined by the supply of carbon and nitrogen near flowering (Tollenaar, 1977). Furthermore, there is a certain combination of nitrogen level by plant density required to promote prolificacy (Carlone and Russell, 1987). At high population densities, prolific hybrids have fewer barren stalks (Russell, 1968). Moreover, prolific hybrids have a superior ability to remobilize nitrogen from other plant parts to grain after silking (Pan et al., 1984).
Kernel set

Kernel set occurs in the period from approximately 15 days before to 15-20 days after silking. In the absence of drought stress problems, seed number per plant in maize can vary greatly among hybrids, environments and planting density (Hawkins and Cooper, 1981; Cirilo and Andrade, 1994a,b). Initial kernel number is strongly associated with assimilate availability at flowering (Tollenaar, 1977). Factors that affect either growth rate per plant (e.g. plant population), or development rate (e.g. temperature), have a corresponding effect on grain number at harvest (Hawkins and Cooper, 1981). Crop growth rate during the 30-day period bracketing silking is highly associated with initial kernel number and kernel yield (Tollenaar, 1977; Tollenaar et al., 1992).

Kernel number prediction

Several methods have been used in predicting seeds per plant. CERES-Maize (Jones and Kiniry, 1986) predicts seeds per plant using cultivar specific potential number, modified by the nonlinear stress yield-reduction function of Edmeades and Daynard (1979). The predicted seed number is based on plant growth rate soon after anthesis. In their method, Edmeades and Daynard (1979) fitted a rectangular hyperbola to the relationship between kernels per plant and plant photosynthesis at one day post anthesis for plants subjected to varying level of stress. This relationship had a positive x-axis intercept, which can be interpreted as a threshold plant photosynthetic level required to produce kernels. Moreover, a nonlinear response was found by Tollenaar et al. (1992) where seed per plant is a function of plant growth rate during the period between one week before silking and three weeks after silking. In contrast, a linear response between plant growth rate and seed number was observed by Hawkins and Cooper (1981) and Grant (1989b) in the period of 10 days after tassel initiation to one week before silking. Another approach was used to quantify kernel number by relating plant biomass to intercepted photosynthetically active radiation under non-stress conditions (Monteith, 1965; Kiniry et al., 1989; Kiniry and Knievel, 1995).
Temperature effect on vegetative growth

The summing of degree days is one approach used for defining the developmental response to temperature, assuming a linear response between rate of development and mean temperature. Temperature plays an important role in maize seedling emergence. Blacklow (1972) identified 10 to 40° C as the range of temperature driving physiological activity in maize. Temperatures greater than 40° C have a detrimental effect on maize germination and emergence (Riley, 1981). In contrast, Warrington and Kanemasu (1983a) found that the response of seedling emergence to mean temperature is curvilinear. When seedlings are grown under cool temperature conditions (16/6° C) they take 16 days to emerge, while those grown under high temperature conditions (30/30° C) take only 3 days.

An increase in leaf number in response to an increase in mean daily temperature from 15 to 30° C has been reported in several studies (Hunter et al., 1974; Tollenaar et al., 1979), whereas an increase in leaf number with decreasing mean temperature from 20 to 10° C has been reported in other studies (Stevenson and Goodman, 1972; Hunter et al., 1974).

High temperatures affect growth and development aspects of reproductive organs, such as tassel initiation, time of flowering (Ellis et al., 1992), pollination and fertilization (Dupuis and Dumas, 1990). In addition, high temperature causes pollen sterility (Saini and Aspinall, 1982) and might causes asynchronous silking of the ears relative to pollen shed (Jacobs and Pearson, 1991).

Vegetative growth simulation

Weach et al. (1996) developed a model to predict maize seedling emergence by using an exponential function to predict coleoptile and first internode growth rates as a function of temperature, and summing the output to predict shoot length. CERES-Maize predicts seedling emergence and the subsequent phenological stages using growing degree days (the sum of average daily temperature above base temperature) because of the effect of temperature on developmental stages in maize. On the other hand, Grant (1989a) predicted emergence date by assuming that the accumulated degree days required for germination is a constant value of 62.5.
Accurate simulation of maize vegetative growth after seedling emergence should involve modeling three general processes: interception of solar radiation, dry matter production and dry matter distribution. CERES-Maize calculates dry matter production by calculating potential dry matter production at optimum temperature and soil water using Beer’s Law to intercept photosynthetically active radiation with an extinction coefficient of 0.65. It also assumes that 5.0 g of dry biomass is produced per each MJ of intercepted photosynthetically active radiation under nonstressful conditions (Jones and Kiniry, 1986). As a result, there is no calculated value for gross photosynthesis, growth and maintenance respiration or net photosynthesis. Furthermore, leaf, root, and stem weight are calculated without taking into account dry matter partitioning to these sinks. On the other hand, in the model that was developed by Grant (1989b), dry matter partitioning coefficients for leaf, stem, root, and soluble reserves were calculated and used in predicting the weight of these organs. Moreover, the model uses soil temperature, instead of air temperature, to predict maize phonology during vegetative growth.

**Maize Reproductive Development**

Sexual reproduction in plants requires gamete transport in an aqueous medium. Plants solve this problem by enclosing the male gametes in the aqueous medium of a much reduced gametophyte, the pollen, which can be dispersed through the air. The egg is enclosed in a highly modified ovary having an extended style with pollen-receptive tissue (stigmas). At the time of pollination, the nucleus, pericarp, and associated maternal tissues that surround the embryo sac contain reserve carbohydrates (Setter and Flannigan, 1989). Nevertheless, reproduction remains sensitive to limited supplies of water, which can cause severe losses in the productivity of the crop (Westgate and Boyer, 1986a).

**Post silking growth**

Reproductive growth of maize starts with silk emergence. The pistillate flowers of maize are protected from the environment by several layers of husks. Bassetti and Westgate (1993a) concluded that the first silks to emerge from the husks were from flower positions 6 to 15 from the base of the ear. Silks from the remaining flower positions appeared over the
following 4 to 8 days. The first senesced silks were observed 7 to 8 days after first silks appeared, and all silks were senesced within 4 to 6 days. Under favorable growing conditions, rate of silk emergence and development do not present a serious limitation to seed formation in maize.

For fertilization to occur, the stigmatic tissues (silks) of these flowers must elongate beyond the husks, intercept air-borne pollen, support pollen germination and pollen tube growth, and deliver the male gametes to the ovary (Bassetti and Westgate, 1993a). Pollen is produced by the tassel and is available in excess of the requirements for pollination and fertilization of the silks. Even under water stress, pollen production appears to be less limiting to grain yield than the effect of delayed development of axially branches (Hall et al., 1982). In addition, under extremely low pollen water potential, pollination is successful (Westgate and Boyer, 1986b). Maximum kernel set occurs when pollination is 4 to 6 days after silks first appear. Delayed pollination after silk emergence decreases seed set in maize (Bassetti and Westgate, 1993b).

Maize production in temperate zones is characterized by the existence of a greater number of potential ears per plant and kernels per ear at flowering time than are observed at maturity, and both of these yield components are sensitive to environmental stresses. Low nitrogen has been shown to influence the number of florets per ear and the fraction of those florets that form kernels (Jacobs and Pearson, 1991), whereas drought or shading immediately after flowering have their primary effect on the number of aborting kernels (Kiniry and Ritchie, 1985; Schussler and Westgate, 1991a). A smaller ear biomass per floret at flowering has been associated with high levels of abortion of tip kernels in maize. High levels of abortion of tip kernels can be attributed to several days delay in the development and pollination of these kernels compared with basal florets (Reed and Singletary, 1989), and low nitrogen supply can reduce ear biomass per floret (Lemcoff and Loomis, 1986).

The period between silking and the beginning of effective grain filling is also characterized by increased dry matter storage in the stem. In this period, the stalk appears to be more effective than the ear in competing for available photosynthate (Edmeades and Daynard, 1979; Setter and Meller, 1984; Schussler and Westgate, 1991b). Zinselmeier et al. (1995b) stated that during the early reproductive phase the stalk is a major sink for
assimilates, accumulating 20 to 40 g of dry matter from silking through early kernel development.

**Effect of water stress on post silking phase**

Anthesis is particularly vulnerable to water stress because low water potential can cause asynchronous development of the staminate and pistillate inflorescence, disrupting pollination (Westgate and Boyer, 1985b; Herrero and Johnson, 1981). A number of workers have suggested that yield losses associated with low water potential at pollination is caused by silk and pollen desiccation (Tatum and Kehr, 1951). Slight decreases in silk water potential cause large losses in grain production (Westgate and Boyer, 1986c). Low silk water potential decreases kernel-set in hand-pollinated plants (Schop et al., 1987; Schussler and Westgate, 1991b; Westgate and Boyer, 1986b). Furthermore, low silk water potential can inhibit ear development, silk emergence (Herrero and Johnson, 1981; Hall et al., 1982), and silk growth (Herrero and Johnson, 1981; Westgate and Boyer, 1985b). Silk elongation rate was completely inhibited when silk water potential was held below -0.8 MPa by Bassetti and Westgate (1993b). Moreover, under water stress, the potential yield of maize is reduced because growth of axially apices (potential ears) and the number of kernels formed on an ear are reduced as a result of lack of assimilate supply to the developing ear (Pearson and Jacobs, 1987; Jacobs and Pearson, 1991; Schussler and Westgate, 1991b). Under water stress, biomass accumulation in the stalk was severely inhibited when water was withheld between 0 and 2 days after pollination, but recovered upon rehydration. Westgate and Grant (1989) reported that total extractable carbohydrates in the stalk were reduced when water was withheld for 6 days after pollination, as a result of remobilization of carbohydrate to the growing ovaries.

In summary, decreased grain production due to water stress around anthesis is associated with at least three developmental events. First, low water potential just prior to anthesis may disturb megasporogenesis (Moss and Downey, 1971). Second, the tassel may fail to emerge, the anther may not exert, or silks may not elongate, leading to asynchrony in flower development and reduced pollination (Westgate and Boyer, 1985b). Third, embryos
may not grow in flowers that otherwise have developed normally (Westgate and Boyer, 1986b).

Post silking simulation

Although accurate modeling of the post silking phase, including silk growth and emergence, pollination, and fertilization is important for accurate prediction of maize yield, CERES-Maize does not contain any routine to simulate this stage. Only two published papers have addressed post silking simulation of maize. The first is by Sadras et al. (1985) where a simulation model was developed to determine kernel set under water stress conditions. The model deals with pollen production, dispersion, and interception by the silk. The second one was by Salvador (1988), where an equation was developed to calculate the rate of pollen tube growth as a function of maximum temperature.

Grain filling phase

Maize yield is the product of two principal components: kernel weight and number per unit area. Of these two, kernel weight is the more stable. Maize has been found to show no significant change in seed weight due to a decrease in seed number. Removal of 20 seeds per ear 10 to 18 days after silking did not alter the weight of the remaining seed (Tollenaar and Daynard, 1978b). Kiniry et al. (1990) reported that as a result of decreased kernel number per ear, seed weight can either increase, decrease, or be unaffected, depending on the timing of reduction in kernel number, or on the cultivar used. Two possible constraints to potential seed weight are the number of endosperm cells and seed volume. The former has been shown to be correlated with seed weight of maize (Jones and Simmons, 1983).

Maize endosperm occupies 83% of the mature kernel and is composed of 88% starch and 8% protein. Starch and protein synthesis are regulated and interrelated (Singletary and Below, 1989). Kernel dry weight and protein content often increase concomitantly in response to nitrogen fertilization (Tsai et al., 1978). Protein accumulation is not dependent upon the supply of carbohydrate provided to the kernels, although the same is not true for starch synthesis (Singletary and Below, 1989). From the point of view of the production agronomist, starch accumulation in endosperm cells is the most significant activity in maize
grain (Salvador and Pearce, 1995). Starch is the principal reserve carbohydrate of maize kernels. Within amyliferous or starch producing endosperm cells, starch is always found in the form of granules contained within plastids. Starch is a polysaccharide constructed from glucose as the basic building block. It is a mixture of two polymers: amylose, in which the glucosyl units are joined by α-1,4 linkages to form unbranched molecules up to several thousand units long, and amylopectin, in which shorter α-1,4 chains are connected by α-1,6 linkages to form larger, highly branched molecules (John, 1992).

The primary source of carbon skeletons for starch synthesis is sucrose translocation to the endosperm (Nelson and Pan, 1995). Most of the sucrose is hydrolyzed as it enters the endosperm, but then resynthesized within the endosperm (Shannon, 1968). During rapid kernel growth sucrose is unloaded passively from the phloem into the apoplast of the pedicel parenchyma (Zinselmeier et al., 1995a) and inverted to hexose sugar by a cell-wall-bound acid invertase (Shannon and Dougherty, 1972). Some sucrose can enter maize endosperm without being hydrolyzed, but it has been proposed that the monosaccharide gradient between pedicel apoplasm and endosperm cells is a driving force in assimilate movement into the endosperm (Shannon et al., 1993).

Large differences in maize yield are usually the result of fluctuations in grain number. The number of embryonic grain sites, or spikelets, which survive to become mature grains in maize is the major yield component, rather than the number of spikelets formed. Determination of the number of final kernels per ear occurs during the lag phase of grain growth, after which the rate of accumulation of grain biomass is constant with time. Grain sink strength varies with changes in source strength during reproductive development (Tollenaar and Daynard, 1982). The observation that high plant population density decreases grain number by increasing the number of fertilized kernels that abort (Daynard and Duncan, 1969; Iremiren and Milbourn, 1980) indicates that an inadequate assimilate supply may limit the growth of these kernels. Frey (1981) presented evidence that the numbers of kernels that cease dry matter accumulation within two or three weeks of pollination is related to carbohydrate supply. When kernels from the middle of an ear are cultured in vitro, about 60% of the kernels abort (Hanft and Jones, 1986a). Carbohydrate concentration patterns in the pedicel and endosperm of these aborting kernels indicate that the amount of sucrose
reaching the pedicel is inadequate to sustain growth beyond 8 to 10 days in culture (Hanft and Jones, 1986b).

Kernels at the tip of maize ears often abort prior to the onset of linear dry matter accumulation (Daynard and Duncan, 1969; Tollenaar and Daynard, 1978a,b). These kernels have reduced mass and fail to contribute to the yield of harvested grain (Hanft and Jones, 1986a). Hanft et al. (1986) found that tip kernels synthesized less starch in the endosperm, which in general appeared to lag slightly compared to the development of other kernels. This might be a result of negative feedback regulation delaying the initiation of starch synthesis or of an inadequate sucrose concentration. The kernels at the tip of the ear that do enter a period of linear dry matter accumulation are usually pollinated 2 to 4 days later than are kernels towards the middle and base of the ear (Hanft et al., 1986). Since they have a reduced rate of growth and a shorter period of dry matter accumulation, tip kernels have a lower mass at maturity (Tollenaar and Daynard, 1978a). When apical regions of field-grown maize ears were exposed to 25±3°C from 7 days after pollination to maturity, tip kernels increased in size, whereas the basal and middle position kernels decreased in size as a result of restricted photosynthate supply or perhaps due to restricted supply of other nutrients (Ou-Lee and Setter, 1985). Defoliation prior to the onset of linear dry matter accumulation also increases the number of tip kernels that abort (Egharevba et al., 1976; Jones and Simmons, 1983).

**Effect of environmental stress on maize yield**

Both water and heat stresses during the grain filling period in maize have a great impact on yield. Water deficit imposed during grain filling causes a large decrease in final endosperm and embryo mass. Dry matter accumulation in the endosperm and embryo ceases prematurely (Westgate, 1994). The rate of cell division between 8 and 10 days after pollination decreases when water potential falls below -1.1 MPa (Myers et al., 1992). The decrease in endosperm cell number is concomitant with a rise in ABA (Ober et al., 1991). Low ovary water potential reduces ovary development as a result of reduced capacity to attract assimilates required for continued growth (Schussler and Westgate, 1991b). Zinselmeier et al. (1995a) discovered that the delivery and metabolism of carbohydrate
within maize ovaries is disrupted at low ovary water potential as a result of the inhibition of soluble and insoluble acid invertases, which causes sucrose to accumulate within the ovary while starch is depleted. The increase in ovary sucrose ultimately leads to a decrease in effective sink demand. Water deficit during rapid grain filling has less effect on grain development, which continues even when photosynthesis is inhibited (Jurgens et al., 1978; Westgate and Boyer, 1985a; Ouattar et al., 1987a), and sucrose is mobilized rapidly from the stem to support kernel growth (Jones and Simmons, 1983; Westgate and Boyer, 1985a; Westgate, 1994). Yet, mobilization of sucrose reserves alone is inadequate to meet sink demand during linear grain filling, since the rate of dry matter accumulation decreases if photosynthesis is rapidly and completely inhibited (Jurgens et al., 1978; Jones and Simmons, 1983; Westgate and Boyer, 1985a). It has been suggested that lack of response of grain development to water stress during rapid grain filling period may be due to vascular discontinuities within the caryopses (Brooks et al., 1982), large hydraulic resistance within the grain (Westgate and Boyer, 1986c), or a favorable water status in the stem (Ouattar et al., 1987b).

During reproductive development, temperature is often higher than optimum for maximum grain yield. High temperature can reduce kernel sink capacity and limit subsequent kernel development and grain yield (Cheikh and Jones, 1994). Long-term heat stress during early stages of kernel development disrupts endosperm development and leads to abortion or premature cessation of growth, even if the stress lasts for a brief period (i.e. a few days at 35° C) (Cheikh and Jones, 1994). High temperature stress during the phase of endosperm cell division and amyloplast biogenesis in maize kernel results in reduction of the rate and duration of endosperm cell division, reducing the number of cells formed. At 30° C, endosperm cell division ceases approximately 10 days earlier, and the final number of cells is reduced by 34%. Furthermore, the number of starch granules initiated at 15 and 35° C are reduced by 70 and 97%, respectively (Jones et al., 1985).

The responses of both rate and duration of kernel dry matter accumulation to temperature variation are important inputs for simulation models. However, these responses are not conclusive. Badu-Apraku et al. (1983) reported no effect of temperature on the rate of kernel dry matter accumulation over a range of day/night temperature regimes from 25/15
to 35/25°C for maize grown under controlled-environment conditions. Setter and Flannigan (1986) also found no differences in kernel growth rate when ear temperatures were controlled over a temperature range from 6 to 32°C for a 10-day period for field-grown maize. In contrast, Duncan et al. (1965) reported a significant correlation between daily temperature and daily increments in dry matter of field-grown maize. Jones et al. (1981) reported that temperature during kernel development appears to be a major factor determining the rate and duration of grain filling, possibly through its effect on the duration of the endosperm cell division stage and the initiation of rapid starch deposition of starch into the endosperm.

Potential kernel growth rate in maize appears to be established at, or soon after the onset of linear dry matter accumulation of the kernels (Reddy and Daynard, 1983) and, consequently, will not be influenced by temperature after this stage of development (Tollenaar and Bruulsema, 1988). Temperature may also exert an influence on kernel dry matter accumulation by its effect on potential kernel growth rate, assimilate supply to kernels and rate of assimilate translocation (Tollenaar and Bruulsema, 1988). Furthermore, high temperature causes kernel abortion, possibly through inhibition of starch synthesis and/or sucrose unloading (Jones et al., 1981). Duncan et al. (1965) indicate that kernel growth rate is lower when reserve carbohydrates are the exclusive source of assimilate for kernel growth. Hence, rate and duration of kernel growth can be influenced by effects of temperature on assimilate supply (Tollenaar and Bruulsema, 1988). In contrast, kernel growth occurs at a greatly reduced rate under extremely cool temperature. Jones et al. (1981) stated that kernel growth rate was 0.65 mg/kernel/day, when kernels were cultured in vitro at 15°C, whereas kernel growth rate was 6.25 mg/kernel/day at 30°C. The higher rate of kernel growth at 30°C was negated by pronounced shortening of the duration of grain filling period. He also added that a three-fold increase in duration of grain filling period at 15°C was not adequate to compensate for the 90% reduction in kernel growth rate that occurred. Badu-Apraku et al. (1983) reported that high temperature during the grain filling period reduced both total dry matter and grain yield. Reduction in total dry matter production was associated with lower leaf area duration and lower rate of dry matter accumulation. Reduced grain yield was associated with a shorter duration of the grain-filling period.
Grain yield prediction

CERES-Maize simulates the grain filling period in maize by using an empirical method. Daily grain growth rate is calculated by estimating a zero-to-unity relative rate of grain fill, which scales potential kernel growth rate and is affected by temperature, the number of kernels per plant, and a cultivar specific coefficient (potential kernel growth rate, mg/kernel/day). The daily biomass production is then compared with daily grain growth rate. If the latter is less than the former, a limited amount of dry weight is translocated from the stem and the leaves until reaching the minimum weight. CERES-Maize assumes that leaf minimum weight is equal to 85% of leaf weight at silking and minimum stem weight is equal to 80% of stem weight at silking (Jones and Kiniry, 1986). Another approach was used by Grant (1989b) to calculate maize final yield. In this method, all net photosynthesis is allocated to the grain during the grain filling period. An empirical value for maximum grain fill rate at optimum temperature (26°C) of 0.0005 g/kernel/hour is multiplied by a temperature function adjusted for current temperature. If the hourly growth increments allocated to the grain exceed the maximum filling rate, the excess is allocated to the soluble reserve in the stalk (CERES-Maize does calculate a value for the reserve in the stalk). If the stalk reserve is close to depletion, the difference may be translocated to the grain from the leaves at 1 g CH₂O per 4 g leaf dry matter causing leaf senescence. Both models use a predetermined value for maximum grain filling rate and a predetermined value for remobilization from both the stem and the leaves. Therefore, both models are source-driven in both vegetative and reproductive growth.

Because final kernel weight is highly correlated with endosperm cell number (Jones et al., 1985), and the sink strength of the kernels is established during endosperm cell division (Capitanio et al., 1983), it would be more accurate, from the physiological point of view, to simulate the grain filling period in a sink-pulled fashion. Only one model, called CENTLI, has such a characteristic. CENTLI simulates the actual demand for assimilate by the kernels during the grain filling period. After pollination, the model first simulates endosperm cell division for each kernel at every position on the ear and estimates the final endosperm cell number after cell division is completed. Then the model calculates the number of amyloplasts for each amyliferous cell and for each aleurone cell. After amyloplast initiation
has ceased, the model simulates starch synthesis. At this point the strength of the kernel sink is established and the model calculates a daily value of both new dry matter produced and sink demand from each kernel on the ear. New dry matter consists of the flux of dry matter due to the activity of granules in amyliferous cells, the flux of dry matter due to the activity of granules in aleurone cells, and carbon that goes toward protein synthesis. Kernel sink demand consists of the metabolic cost of making amyloplasts in amyliferous cells, amyloplasts in aleurone cells, and protein synthesis. As long as sink demand is less than net photosynthesis, kernel weight is calculated by the accumulation of the value of daily new dry matter. If sink demand is greater than net photosynthesis, the difference is made by remobilization of stored carbohydrates from the stalk. Therefore, CENTLI does not use any predetermined value for grain growth rate and remobilization rate and this can be considered the main difference between CENTLI and CERES-Maize approaches in calculating grain weight.

In summary, some of the limitations of crop simulation models result because some models include empirical data that require calibration and testing for site-specific application. Furthermore, it is difficult to include all the factors that influence plant growth in a single model.

For accurate prediction of maize yield to occur, the biology of maize should be simulated in a way that includes as much detail of all the metabolic activities in the plant as possible. Source-oriented simulation might be appropriate to simulate vegetative growth. However, modeling of reproductive growth should be sink-driven because mature kernel weight is highly correlated with endosperm cell number. More research is needed to overcome the limitations of current simulation models and improve their general applicability.
MATERIALS AND METHODS

The major goal of this research is to develop a physiologically sound model to simulate both vegetative and reproductive growth of maize by utilizing published information from literature. During the development of the model, the main intention was for the model to simulate the biology of maize as much as possible. For that reason, several whole-plant simulation models were examined, such as CERES-Maize (Jones and Kiniry, 1986), CORNF (Stapper and Arkin, 1980), and MACROS (Penning de Vries et al., 1989). In addition, other published papers that deals with simulation of single process in maize, such as seedling emergence, were examined.

Model Description

The developed model is called Maize-S. The ‘S’ is an abbreviation of ‘simulation’. Maize-S is a research model, written in Pascal. It is source-driven in the vegetative phase and sink-pulled in the reproductive phase. It is a production-level-two model, which is capable of simulating the effect of water deficit (Penning de Vries, 1982). Moreover, the model responds to temperature stress.

The state variables in the vegetative part of the model are: leaf, root and stem biomass, leaf area index, and total number of leaves. For the reproductive part of the model, the state variables are: cell number per endosperm, starch granule per cell, starch granule per endosperm, final kernel number, and kernel weight.

In summary, the developed model simulates seedling emergence using the method of Weaich et al. (1996). During vegetative growth, the model uses heat sums based on the average daily temperature and base temperature (lowest temperature under which growth occurs) to determine the time of each development stage. Leaf area growth was simulated using the method presented in CERES-Maize (Jones and Kiniry, 1986). To calculate photosynthesis, the method of Goudriaan and van Laar (1978) was used. Then, it was modified to account for the effect of temperature on maximum leaf photosynthesis using published data from the literature and the method of Penning de Vries et al. (1989). Growth and maintenance respiration were calculated according to the method of Penning de Vries et al. (1989). Dry matter partitioning to the different competing sinks during vegetative growth
is predicted according to the method of Grant (1989b). Using field data, kernel number per ear was calculated as a function of plant growth rate. Silk growth was calculated by using published data (Sadras et al., 1985; Ritchie et al., 1993). Grain filling period is simulated by using a method presented in CENTLI (Salvador, 1988). Both water and temperature stresses were simulated using the method of CERES-Maize (Jones and Kiniry, 1986).

The main program of Maize-S consists of several procedures simulating various components of maize biology (Fig 1). The main routine of the Maize-S can be divided into three sections. The first section consists of four procedures: InitialValues, GetInformation, OpenSfile, GetPlantingDate. These procedures are utilized to set the initial conditions for the model. The second section consists of four procedures: GermToEmerg, EmerToJuvenile, JuvenileToTassel and TasselToSilk. These procedures simulate maize vegetative development. The third section, which simulates reproductive development, is composed of two procedures: GrainFill, and PhysiologicalMaturity (see APPENDIX C for flow charts representing the procedure simulating each growth stage). In each procedure, the program simulates the physiological processes of the growing maize plant. In summary, on a daily basis, the program simulates leaf area growth, photosynthesis, respiration, dry matter partitioning to different plant parts, and evapotranspiration.

On execution, the program initializes variables and constants, then calls procedure GetInformation to ask for input. The input required is: weather data, planting month, planting day, planting density (plant/m²), planting depth (cm), latitude, P1 (cumulative growing degree days from seedling emergence to the end of juvenile phase), P2 (photoperiod sensitivity coefficient), and the number of kernel rows per ear (Table 1). The third procedure called by the main program is OpenSfile. Procedure OpenSfile in turn calls procedure GetSoilInformation, which reads the file that contains soil parameters (Table 1). The program then calls procedure GetPlantingDate, which reads the weather file. Calendar day, daily values of average solar radiation, maximum temperature, minimum temperature and precipitation are the variables read from the weather files (Table 1). Afterwards, procedure GetPlantingDate calls procedure WaterTableInitial to calculate initial soil water status in each layer of soil profile by using the value of precipitation starting from the first day of the year until the input planting date.
Figure 1. Flow chart of the procedures simulating maize vegetative and reproductive growth
Table 1. The inputs required to operate Maize-S.

<table>
<thead>
<tr>
<th>Soil Parameters</th>
<th>Weather Data</th>
<th>Management Data</th>
<th>Genetic Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil water in the upper limit (cm/cm)</td>
<td>Solar radiation (MJ)</td>
<td>Planting date</td>
<td>P1*</td>
</tr>
<tr>
<td>Soil water in the most limit (cm/cm)</td>
<td>Maximum temperature (°C)</td>
<td>Planting depth (cm)</td>
<td>P2**</td>
</tr>
<tr>
<td>Drainage rate per day (1/day)</td>
<td>Minimum temperature (°C)</td>
<td>Planting density (plant/m²)</td>
<td>Number of kernel rows per ear</td>
</tr>
<tr>
<td>Root growth weight factor (unitless)</td>
<td>Precipitation (cm)</td>
<td>Latitude</td>
<td></td>
</tr>
<tr>
<td>Bare soil albedo (unitless)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* P1: cumulative growing degree days from seedling emergence to the end of juvenile phase using base temperature of 8° C.
** P2: photoperiod sensitivity coefficient.
Maize-S output can be stated as follows:

1- days to seedling emergence
2- days to end of juvenile phase
3- days to tassel initiation
4- days to silking
5- days to physiological maturity
6- leaf weight, root weight, stem weight, and grain weight (kg/ha)
7- total number of leaves at tassel initiation
8- leaf area index at silking (m² leaf/m² land)
9- kernel number per ear (kernel/m²)

Simulation of maize vegetative growth

Simulation of vegetative growth in maize involves different growth stages and physiological processes. Growth stages include: germination of maize seed and seedling emergence, juvenile phase, tassel initiation and silking. Physiological processes include leaf area growth, photosynthesis, respiration, allocation of assimilate to different plant components, kernel set, and evapotranspiration.

Germination and seedling emergence

Under adequate field conditions, the planted maize seed absorbs water and begins growth. The radical is the first to begin elongation from the swollen kernel, followed by the coleoptile. Emergence is attained by rapid mesocotyl (first internode) elongation, which pushes the growing coleoptile to the soil surface (Ritchie et al., 1993). Prediction of seedling emergence is an important first step in predicting crop establishment (Weaich et al., 1996). CERES-Maize predicts seedling emergence using heat sums and planting depth. However, when temperature is lower than 10° C (base temperature for germination) or higher than 40° C, the previous method may overestimate emergence.
date because no growth occurs under these two extreme temperatures. Moreover, the previous method does not simulate germination of maize seed; it only predicts emergence date. Weaich et al. (1996) developed a model to simulate maize germination by predicting coleoptile and first internode growth rates as a function of temperature, and sums the output to predict shoot length. For more realistic simulation of germination, I decided to use this second method in Maize-S. To determine the time of seedling emergence, both coleoptile length and first internode length are calculated and summed. When the sum of coleoptile and first internode length equals to or exceeds planting depth, emergence occurs.

**Emergence to silking phase**

Temperature is often the dominant factor influencing plant development in temperate climates. Development stages can then be predicted on the basis of temperature sums (Warrington and Kanemasu, 1983a). By calculating growing degree days, Maize-S determines the dates for each growth stage during vegetative growth. The exception is tassel initiation, which is controlled by day length (Jones and Kiniry, 1986). Daily growing degree days are calculated from daily maximum temperature, daily minimum temperature, and a base temperature of 10° C before seedling emergence, and 8° C after emergence according to the method of CERES-Maize (Jones and Kiniry, 1986).

Maize-S simulates leaf area growth (cm²/plant), total leaf area (cm²/plant), leaf senescence (cm²/plant), leaf area index (m² leaf/ m² land), and leaf number from seedling emergence until silking using the method presented in CERES-Maize (Jones and Kiniry, 1986). This method assumes that the rate of leaf tip appearance is faster for the first four leaves. The cumulative number of fully expanded leaves is calculated as a function of daily growing degree days and used to calculate leaf area growth rate. Leaf area growth rate is then accumulated to predict total leaf area. Leaf senescence resulting from normal phenological development is calculated as a function of growing degree days and total leaf area. Leaf area index is a ratio of leaf area to the ground area (Gardner et al., 1985). Leaf area index is calculated by subtracting the value of leaf senescence from the value of total leaf area and divided it by land area. Total leaf number that will eventually emerge is calculated using accumulated growing degree days from emergence to silking divided by 21.
which is the number of growing degree days required for leaf tip appearance (Warrington and Kanemasu, 1983b) plus 6 (number of leaf primordia present at seedling emergence; Ritchie et al., 1993).

Photosynthesis is a process by which light energy is converted to chemical energy (Taiz and Zeiger, 1991). The three most important factors in photosynthesis are: the photosynthetic light response curve of leaves, the radiation intercepted by the leaf canopy, and the distribution of light within a canopy. Maize-S simulates photosynthesis using the method of Goudriaan and van Laar (1978). In this method, gross photosynthesis rate per unit of leaf area (kg CO₂/plant/d) is assumed to increase according to a rectangular hyperbolic response, as a function of absorbed photosynthetically active radiation. Only radiation from a part of the light spectrum (400-700 nm) is effective for photosynthesis. The photosynthetically active radiation is about 50% of solar radiation (Penning de Vries et al., 1989). Canopy photosynthesis should be the sum of the rates of photosynthesis of all leaves. Therefore, in this method gross photosynthesis of sunlit and shaded leaves is estimated and summed to calculate canopy photosynthesis. In addition, this method uses an empirical measurement of light use efficiency for incoming radiation (12.90E-09 Kg CO₂/J). Because maximum rate of leaf photosynthesis is strongly related to temperature, a routine was added to this method to calculate maximum rate of leaf photosynthesis at light-saturated levels using the method presented in MACROS (Penning de Vries et al., 1989). Values for the effect of leaf temperature on the maximum rate of leaf photosynthesis were obtained from the literature by Penning de Vries et al. (1989) (Table 2). To calculate values of maximum rate of leaf photosynthesis with temperatures other than those in Table 2, I developed a function called TLeafPs. First, function TLeafPs checks if maximum temperature, which is read from the weather file on a daily basis, exists in Table 2. If so, the value of maximum rate of leaf photosynthesis is read from the table and used to calculate photosynthesis. If the value of maximum temperature is not in the table, the temperature and maximum rate of leaf photosynthesis values that bracket the specific temperature are read, and used in equation [1] to estimate the corresponding value of maximum rate of leaf photosynthesis under that specific temperature.
Table 2. Effect of leaf temperature on the maximum rate of leaf photosynthesis in maize.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Maximum rate of leaf photosynthesis (kg/CO₂/m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.01</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>20</td>
<td>0.8</td>
</tr>
<tr>
<td>25</td>
<td>1.0</td>
</tr>
<tr>
<td>35</td>
<td>1.0</td>
</tr>
<tr>
<td>40</td>
<td>0.9</td>
</tr>
<tr>
<td>45</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Source: Table 5, Penning de Vries et al. (1989)

[1] \( Y = Y_1 + \frac{(X-X_1)}{(X_2-X_1)} \times (Y_2-Y_1) \)

where:

\( Y \) = the calculated value of maximum rate of leaf photosynthesis

\( X_1 \) = temperature value from Table 2 which is lower than the input value.

\( X_2 \) = temperature value from Table 2 which is higher than the input value.

\( Y_1 \) = the value of maximum rate of leaf photosynthesis with \( X_1 \)

\( Y_2 \) = the value of maximum rate of leaf photosynthesis with \( X_2 \)

\( X \) = the input value of temperature

Following the calculation of gross photosynthesis, maintenance and growth respiration (kg/ha) are calculated. Both occur at different rates with their own regulation, but they have CO₂ production in common (Taiz and Zeiger, 1991). Respiration is calculated according to the method of MACROS (Penning de Vries et al., 1989). Temperature has a direct effect on the rate of maintenance respiration. It corresponds to a doubling of the rate for each 10° C rise in temperature up to the temperatures that will kill plants (higher than 45°...
C). This dependence between temperature and rate of maintenance respiration corresponds with the biological concept of Q10 with a value of 2.0 (Penning de Vries et al., 1989). The calculation of maintenance respiration involves calculations of effect of temperature on maintenance respiration using mean temperature and reference temperature for maintenance respiration equal to 18°C. Then this value is multiplied by the weight of different plant part to calculate energy cost for maintenance. Furthermore, in this method, growth respiration is defined as the CO₂ evolution resulting from growth processes. Penning de Vries et al. (1989) calculated weight of CO₂ produced during formation of leaf, root, stem, and cob dry matter for maize. These values are used in Maize-S to calculate growth respiration. In addition, growth rate of leaves, root, stem, and cob (kg/ha/day) are calculated as a gain in weight per unit of time (Gardner et al., 1985). Total respiration is calculated after that by summing the values of growth respiration and maintenance respiration.

Net Photosynthesis is then calculated by subtracting total respiration from gross photosynthesis. Maiz-S accounts for the effects of both water and temperature stresses on net photosynthesis. A zero-to-unity temperature stress factor is calculated according to the method of CERES-Maize (Jones and Kiniry, 1986). The temperature stress factor is calculated from minimum temperature and maximum temperature, as a weighted daily average with an optimum temperature of 26°C. The calculation of water stress factors will be discussed under the discussion of the calculations of soil-plant water balance. Net photosynthesis is reduced by the minimum of these two stress factors (Jones and Kiniry, 1986).

Any glucose produced by the plant during the day and remaining after respiration processes is usually used for growth. Maize-S calculates leaf weight (kg/ha), root weight (kg/ha), stem weight (kg/ha), soluble reserve weight in the stem (kg/ha), and cob weight, (kg/ha) according to the method of Grant (1989b). In this method, prior to tassel initiation the fraction of fixed carbon translocated to the shoot is 0.67 and the rest is translocated to the root. After tassel initiation, partitioning coefficients to different plant parts were used to calculate the weight.

The number of ovule sites set by maize plant is determined during the period of ear formation, which begins about 10 days after tassel initiation and continues until about one
week before silking (Grant, 1989b). Final kernel number per plant in maize is positively related to plant growth rate (Hawkins and Cooper, 1981). To simulate kernel set, field data were collected for maize hybrid Pioneer 3279 planted at Ames, Iowa in the spring of 1995, at four different planting dates (May 14, May 21, May 28, and June 4). Weekly samples of five bordered plants were collected for each planting date when 9 leaves existed on the plant, which is consider to be the onset of kernel set (Grant, 1989b). For each plant, leaves counted, ear shoots were separated, and ovule sites were counted under the microscope and left to air dry. The reminder of each plant was left to air dry. Both the ear shoots and the reminder parts of the plants were weighed. An average of five plants was used for calculations. A spreadsheet was used to sort the collected data according to leaf number. Plant growth rate was calculated from the following formula:

\[
\text{[2] Plant growth rate} = \frac{\text{Change of plant weight}}{\text{Change of time}}
\]

To determine time interval to use in calculating plant growth rate, the time between leaf stages was thought to be most appropriate. Because of the different planting dates, sorting the data according to leaf number made it easy to handle the data. According to Ritchie et al. (1993), at V9-V15 the interval between the appearance of new leaf stages is generally two to three days. Therefore, The change of plant weight was divided by 3 (time interval) to calculate plant growth rate. A regression equation was developed to predict the daily production of kernel sites as a function of plant growth rate as follows:

\[
\text{[3] } Y = 8.012947 + 1.767148 \times X \quad (r^2=0.94)
\]

where:

\[Y = \text{kernel number per plant}\]
\[X = \text{plant growth rate}\]
Under non-irrigated cultivation, water stress often exists, therefore the estimation of soil-plant water balance should be a part of any simulation model. Water stress affects metabolic activity, morphology, plant development, and yield potential. Under water stress, photosynthetic rate is reduced as well as most enzyme activity, such as nitrate reduction. In addition, protein synthesis, cell wall synthesis, and cell enlargement are reduced causing smaller leaves and smaller leaf area index (Gardner et al., 1985). Furthermore, moisture stress may lengthen the time between vegetative stages but shorten the time between reproductive stages (Ritchie et al., 1993). The method that was presented in CERES-Maize (Jones and Kiniry, 1986) is used in Maize-S to simulate soil-plant water balance. The estimation of water balance in Maize-S consists of calculating the value of daily evapotranspiration, the status of soil water in each soil layer, root growth in each soil layer, the daily value of total root water uptake in order to update volumetric soil water, and two soil water stress factors.

Potential evapotranspiration is calculated because under field conditions water is lost from plants by the transpiration stream and from the soil by evaporation. Transpiration provides the major driving force for plant water absorption against the gravitational pull and frictional resistance in the water pathway through the plant. Evaporation is an energy dependent process involving a change in state from liquid to vapor phase. The environmental effects on evapotranspiration is called atmospheric demand. The greater the atmospheric demand the faster water can be evaporated from a free water surface. The major environmental factors that affect evapotranspiration are temperature and solar radiation. High temperature increases the capacity of air to hold water, which in turn increases evapotranspiration. In addition, solar radiation increases atmospheric demand (Gardner et al., 1985). Potential evapotranspiration (mm/day) is calculated from three variables: mean temperature during daylight hours (°C), the integrated crop and soil albedo (unitless) and the equilibrium evaporation rate (mm/day). The mean temperature during daylight hours is a weighted mean of air temperature during the day when both soil and plant evaporation are greatest. The integrated crop and soil albedo is calculated from bare soil albedo, which is read from the soil file, and from leaf area index. The equilibrium evaporation rate is calculated from solar radiation, mean temperature during daylight hours, and the integrated...
crop and soil albedo. The potential rate of soil evaporation (mm/day) is calculated as a function of potential evapotranspiration and leaf area index. Crop transpiration (mm/day) is calculated also from potential evapotranspiration and leaf area index.

The availability of soil moisture is affected by colloidal properties (Gardner et al., 1985). As a result, different soil types have different ability to hold water. Under field conditions, when precipitation or irrigation occurs part of the water penetrates the soil and the rest is lost due to surface run off. When water penetrates the first soil layer, part of it is held in that layer between the current volumetric water content and saturation. The rest of the water infiltrates to the following layer. Then, the above mentioned occurs in all successive soil layers. Soil water content in each soil layer is calculated according to the method presented in CERES-Maize (Jones and Kiniry, 1986). To calculate downward water movement through successive soil layers, runoff (cm), potential infiltration (cm), the value of drainage (cm) and soil water redistribution in each soil layer are calculated. If infiltration occurs, the amount of water held by the layer between current volumetric water content is calculated and compared to the value of potential infiltration. If it is less than or equal to the amount of water held by that layer, a new value of soil water content in each soil layer is calculated. No drainage occurs if the new value of water content is less than the drained upper limit of volumetric soil water in the layer (cm/cm), which is read from the soil file. Drainage by nonsaturated flow from that layer is calculated, as well as a new post-drainage value of soil water content in each soil layer. Then, the new value of potential infiltration is set equal to the value of drainage by nonsaturated flow from the layer. If the value of potential infiltration is greater than the amount of water held by the layer, the water in excess of the amount of water held by that layer is passed to that layer below. Then, a new value of drainage by nonsaturated flow from that layer is calculated.

Root length density and root water uptake for each soil layer is calculated according to the method of CERES-Maize (Jones and Kiniry, 1986). A factor that distribute newly formed root length throughout the soil profile is calculated and used to calculate root depth. The new root length is added to total root weight (cm$^2$ root/cm$^2$ soil surface) is calculated by converting daily root growth to root length. Plant-extractable soil water for each layer (cm/cm) is calculated and used to calculate a zero-to-unity soil water deficit factor for root
growth in each layer, which in each soil layer is equal to 1 unless the volumetric soil water declines below 0.25 of plant-extractable soil water for each layer. In turn, the zero-to-unity soil water deficit factor for root growth in each layer is used with the root growth weighting factor (read from the soil file) to calculate a zero-to-unity root length density factor for root growth in each layer. To account for the effect of air temperature and soil profile water content on the daily increase in root depth, the root depth is calculated. The zero-to-unity root length density factor for root growth in each layer is adjusted for the fraction of that layer that has been explored by the root by subtracting root depth from the depth of soil profile and summed to calculate a total root density factor for root growth. The distributions of newly formed root length throughout the soil profile is calculated from the amount of new root length per unit area of soil and total root density factor for root growth.

Root water uptake from each soil layer is also calculated. According to the method of CERES-Maize (Jones and Kiniry, 1986), the amount of water removed from the profile is the minimum of total potential root water uptake from all layers (cm) or the potential transpiration (cm/day). Potential root water uptake for each layer is calculated as units of cm uptake/layer. At this point, Maize-S calculates two zero-to-unity soil water deficit factors are calculated. The first water deficit factor calculates the affect of water stress on photosynthesis. A more sensitive soil water deficit factor affecting cell expansion is also calculated.

**Simulation of maize reproductive growth**

Simulating maize reproductive growth involves accounting for two growth stages: the grain filling period and physiological maturity. During grain filling period, several events take place, such as silk growth, fertilization of the silk, endosperm cell division, and starch accumulation.

**Grain filling period**

Under field conditions, the reproductive stage begins when silks are visible outside the husk (Ritchie et al., 1993). Maize-S accounts for the effect of leaf senescence on leaf area index after silking using the method of Salvador (1988). Fertilization of the silks is
simulated by calculating daily percentage of silk emerged, silk length, and pollen tube length. Silk elongation starts at V18 where the silks of basal ovules elongate first, followed by the silks of tip ovules (Ritchie et al., 1993). Maize-S assumes that ear length at silking equals 21 cm (actual cob length = 13 cm plus the length of the husk at the tip of the ear; Ritchie et al., 1993). The daily percentage of emerged silks (SilkEmerged) is calculated according to the method of Sadras et al. (1985) as follows:

\[ \text{SilkEmerged} = 100 - \exp(4.57 - 0.88 \times \text{TimeStep}) \]

where:

\( \text{TimeStep} = \) calendar day

According to equation [4], 6 days are required for 100% of silk emergence (Table 3). On a daily basis, the length of the percentage of emerged silks should be less than the group that had emerged on the previous day because silks emerge from higher positions each day. Therefore, silks length of the group that is will emerge the following days can be calculated by estimating the part of the ear where the silks have already emerged and using this to estimate the distance that the silks need to grow to escape the tip of the husks and emerge as follows:

\[ \text{SilkLength} = (\text{EarLength} + (\text{EarElongationRate} \times \text{TimeStep})) - ((\text{EarLength} + (\text{EarElongationRate} \times \text{TimeStep})) \times \text{SilkEmerged}) / 100 \]

where:

\( \text{EarLength} = \) ear length at silking (cm)

\( \text{EarElongationRate} = \) ear elongation rate \( (0.5 \text{ mm/day}, \text{Ritchie et al., 1993}) \)

\( \text{TimeStep} = \) calendar day after silking
Table 3. Daily percentage of silk emerged and ovule position from the base of the ear in maize.

<table>
<thead>
<tr>
<th>Days after silking</th>
<th>% silk emerged</th>
<th>ovule position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (silking)</td>
<td>60.95</td>
<td>1-32</td>
</tr>
<tr>
<td>2</td>
<td>84.39</td>
<td>32-46</td>
</tr>
<tr>
<td>3</td>
<td>94.11</td>
<td>46-53</td>
</tr>
<tr>
<td>4</td>
<td>98.14</td>
<td>53-57</td>
</tr>
<tr>
<td>5</td>
<td>99.81</td>
<td>57-60</td>
</tr>
<tr>
<td>6</td>
<td>100.58</td>
<td>60</td>
</tr>
</tbody>
</table>

Equation [4] accounts for the increase in ear length by elongation in the six-day period required for 100% silk emergence. Ear length is multiplied by the percentage of silk emerged to convert the percentage of silk emergence to length in centimeters, then this is subtracted from the actual ear length to determine the new value of silk length. As soon as silks are visible outside the husks, pollination occurs. A pollen grain captured by moist silks grows down the silks to the ovule, where fertilization occurs and the ovule becomes a kernel (Ritchie et al., 1993). To determine the time when fertilization occurs, pollen growth rate (mm/day) is calculated and summed to calculate pollen tube length according to the method of (Salvador, 1988).

\[
[5] \text{TubeGrowthRate} = (((-0.005*\text{Position})+0.48)*((0.1*\text{MaxTemp})- 0.5))*24
\]

where:
Position = ovule location on the ear
MaxTemp = maximum temperature
Equation [5] uses single ovule position from ear base to apex. Because Maize-S calculates the percentage of silk emergence, therefore, until all emerged silks are fertilized, the variable position is calculated from ear length and the percentage of emerged silks (Table 3) and multiplied by 4, which represent the number of ovules per one centimeter of ear at silking (Ritchie et al., 1993) as follows:

\[
\text{Position} = \frac{(\text{EarLength} + (\text{EarElongationRate} \times \text{TimeStep}) \times \text{SilkEmerged})}{100} \times 4
\]

When the length of pollen tube reaches or exceeds silk length, fertilization occurs.

Grain weight is calculated according to the method of CENTLI (Salvador 1988). In this method, each kernel on the ear from base to apex is checked for fertilization. If it was fertilized, the model updates a complex data structure that represents the maize ear. First, the differentiation of the endosperm is simulated on the basis of empirical growth curve synthesized from various published sources. A phase of coenocytic division precedes a phase of cellular growth. Depending on the number of cells present, different developmental phases can be recognized. When number of cells is greater than 1024, differentiation of the meristematic cells in the aleurone layer begins. If number of cells exceeds 111000, amyliferous cells start differentiation. Endosperm development is completed, when number of new cells generated on a given day is less than 5. The synthesis of amyloplasts per aleurone cell is also simulated. After it ceases, the simulation of starch synthesis begins.

Sink demand is calculated next by calculating the new number of amyloplasts per amyliferous cell, the new number of amyloplasts per aleurone cell, the total number of starch granules, the number of amyloplasts per amyliferous cell, the number of amyloplasts per aleurone cell, the flux of dry matter due to the activity of granules in amyliferous cells, and growth respiration associated with this process. Equivalent calculations are carried out for starch granules produced in the aleurone layer, taking into account that the rate of starch accumulation of these granules is approximately one third of that of granules in amyliferous cells. In order to estimate the total flux of carbohydrate established by sink demand, it is necessary to account for carbon that goes toward protein synthesis by calculating carbon that
is used in nitrogen synthesis. The source of N is taken into account in estimating protein construction cost, where growth respiration associated with this process is estimated. Then the value of new dry matter is calculated.

On a daily basis, Maize-S calculates grain weight by summing the value of new dry matter. After partitioning assimilate to growing grain, any leftover is allocated to the stem for storage, where it will be available for remobilization later in the season. Whereas, if the available assimilate fail to meet sink demand, remobilization of stored carbohydrates from the stem occurs. When the stored carbohydrate in the stem is exhausted, dry matter translocation from the leaves to the grain occurs, where the value of grain sink demand is subtracted from the leaves weight and added to the grain weight causing leaf senescence. Leaf weight decreases down to the minimum leaf weight, of 85% of the weight at silking (Jones and Kiniry, 1986). The end of the grain filling period occurs when dry matter translocation from both stem and leaves is completely exhausted.

**Physiological maturity**

After the grain filling period ends, physiological maturity is detected by Maize-S when the daily growing degree days become less than 2 (Jones and Kiniry, 1986).

**Validation Procedure and Sensitivity Analysis**

**Model validation**

Validation is the process of comparing simulated results to real system data not used in the parameter estimation process. The purpose of validation is to determine if the model is sufficiently accurate for its applications (Jones et al., 1987). Field data from two locations in 1995 (Ames, and Armstrong farm, Iowa) and one location in 1996 (Ames, Iowa) were used to validate Maize-S. Two maize hybrids were used in the validation (Pioneer 3394, and Pioneer 3489). Each hybrid was planted at two different planting dates (early in May and late in May). All experiments were grown under typical management conditions in Iowa with no irrigation, with no tillage and with optimum nitrogen application. The data were obtained from Edward M. Allen (Agriculture and Biosystem Engineering Department) at Iowa State University. The input required by Maize-S for the above conditions are shown in
Tables 4 and 5. Soil data required to run the model were derived from the SCS county soil survey for each soil type found at these two locations. In addition, CERES-Maize was run for the previous locations. Both CERES-Maize and Maize-S predictions were compared. Predicted leaf weight, stem weight, kernel weight and kernel number were compared to field data.

Table 4. Genetic coefficients for Pioneer 3394, and Pioneer 3489.

<table>
<thead>
<tr>
<th>Hybrid</th>
<th>Pioneer 3394</th>
<th>Pioneer 3489</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>246.5</td>
<td>244</td>
</tr>
<tr>
<td>P2</td>
<td>0.61</td>
<td>0.7</td>
</tr>
<tr>
<td>Kernel rows/ear*</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

* personal communication

Table 5. Soil type and latitude for Ames and Armstrong locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil Type</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ames</td>
<td>Clarion</td>
<td>42</td>
</tr>
<tr>
<td>Armstrong</td>
<td>Marshall</td>
<td>41</td>
</tr>
</tbody>
</table>

To evaluate accuracy of both Maize-S and CERES-Maize predictions, the mean root square error (RMSE) and percent error averaged (PE) over time were calculated for leaf, stem, grain weight, and grain number. The RMSE statistic reflects the magnitude of the mean difference between predicted and observed values over time (Allen et al., 1996).

\[ \text{RMSE} = \sqrt{\frac{\sum_{j=1}^{n} \sum_{i=1}^{m} (y_i - y_j)^2}{n \times m}} \]
where:

\[ m = \text{number of observations per experiment} \]

\[ n = \text{number of experiments} \]

\[ y = \text{measured value} \]

\[ y^\wedge = \text{predicted value} \]

The PE is a measure of average percent difference between predicted and measured values, averaged over all observations for an experiment. This determines the average percentage error for a plant growth component for an entire season (Allen et al., 1996).

\[
\text{PE} \% = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} \frac{|y - y^\wedge|}{y}}{n \times m}
\]

**Sensitivity analysis**

Sensitivity analysis involves exploring the behavior of the different values of parameters. This is done to determine how much a change in the value of a parameter influences the important outputs from the model (Jones et al., 1987). Maize-S was examined by changes in both temperature and solar radiation inputs. The change in temperature was +5°C and -5°C, and all other climatic inputs remained the same as before. Solar radiation was increased by 5% and all other climatic inputs remained the same as before. This allowed study of the effect of each individual change in the inputs on total aboveground nongrain biomass, leaf area, and grain yield.

**Effect of defoliation**

The response of Maize-S to 100% defoliation also was tested. After silking, on a weekly interval, 100% defoliation was imposed on the model. Three variables were studied: grain yield, weight per kernel, and kernel number. The results are presented in the following section.
RESULTS AND DISCUSSION

Model validation

During data collection in 1995, leaf sheaths were mistakenly left on the stem as they were weighted. Therefore, the recorded stem weight was higher than actual weight and recorded leaf weight was lower than actual weight. For that reason, leaf weight was calibrated by subtracting 25% of stem weight and adding it to leaf weight in this particular year. In addition, some nitrogen stress was detected at Ames 1996. Both Maize-S and CERES-Maize were run for these locations and its predictions were compared to the field data.

Vegetative growth

Both Maize-S and CERES-Maize were validated for three variables in the vegetative phase: leaf weight, stem weight and kernel number. Leaf weight was well predicted by Maize-S except for late planting date in Ames 1996 for Pioneer 3394. In this particular year, the observed leaf weight was considerably lower as a result of nitrogen stress (Table 6).

Maize-S predictions for stem weight were accurate except for four locations. In both Ames and Armstrong 1995 for Pioneer 3489 at early late planting date and for both cultivars in Ames 1996 at late planting date (Table 7). For Ames 1996, observed stem weight was considerably low for late planting date for both cultivars, which might also be a result of nitrogen stress.

Maize-S predictions for leaf and stem weight were more accurate than CERES-Maize (Table 6, and 7). The reason for the overprediction of CERES-Maize could be that the data used to develop the partitioning algorithms in the model were from experiments conducted during the 1960's and 1970's (Allen et al., 1996).

Accurate prediction of kernel number is important for accurate yield prediction. Maize-S predictions for kernel number were also accurate, except for two locations: at Armstrong in 1995 for Pioneer 3394 at late planting date, and at Ames 1996 for Pioneer 3394 at early planting date (Table 8). The observed kernel numbers was low at Ames 1996. CERES-Maize predictions for kernel number were more accurate than Maize-S predictions in four locations (Table 8). This might be attributed to the method that CERES-Maize
Table 6. The mean difference between predicted and observed values averaged over time (RMSE) and the average percent difference between predicted and observed values averaged over time (PE) for leaf weight (kg/ha) for both Maize-S and CERES-Maize for Pioneer 3394 and Pioneer 3489 planted at Ames and Armstrong 1995 and Ames 1996.

<table>
<thead>
<tr>
<th>Hybrid</th>
<th>Plot Name</th>
<th>Maize-S</th>
<th></th>
<th>CERES-Maize</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RMSE</td>
<td>PE</td>
<td>RMSE</td>
<td>PE</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Ames (1995) Early</td>
<td>300.95</td>
<td>8.70</td>
<td>910.5</td>
<td>26.34</td>
</tr>
<tr>
<td></td>
<td>Ames (1995) Late</td>
<td>342.22</td>
<td>12.00</td>
<td>482.91</td>
<td>17.17</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Ames (1995) Early</td>
<td>181.70</td>
<td>9.07</td>
<td>971.80</td>
<td>45.39</td>
</tr>
<tr>
<td></td>
<td>Ames (1995) Late</td>
<td>333.40</td>
<td>7.48</td>
<td>386.20</td>
<td>30.21</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Armstrong (1995) Early</td>
<td>183.32</td>
<td>4.89</td>
<td>1267.50</td>
<td>33.86</td>
</tr>
<tr>
<td></td>
<td>Armstrong (1995) Late</td>
<td>218.50</td>
<td>7.05</td>
<td>1357.49</td>
<td>43.83</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Armstrong (1995) Early</td>
<td>222.82</td>
<td>5.89</td>
<td>1099.20</td>
<td>29.07</td>
</tr>
<tr>
<td></td>
<td>Armstrong (1995) Late</td>
<td>276.47</td>
<td>9.41</td>
<td>1776.50</td>
<td>60.57</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Ames (1996) Early</td>
<td>252.42</td>
<td>8.30</td>
<td>1552.90</td>
<td>63.06</td>
</tr>
<tr>
<td></td>
<td>Ames (1996) Late</td>
<td>771.40</td>
<td>26.90</td>
<td>1562.6</td>
<td>84.26</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Ames (1996) Early</td>
<td>426.21</td>
<td>13.51</td>
<td>1135.00</td>
<td>40.78</td>
</tr>
<tr>
<td></td>
<td>Ames (1996) Late</td>
<td>143.40</td>
<td>6.24</td>
<td>1092.00</td>
<td>78.54</td>
</tr>
</tbody>
</table>
Table 7. The mean difference between predicted and observed values averaged over time (RMSE) and the average percent difference between predicted and observed values averaged over time (PE) for stem weight (kg/ha) for both Maize-S and CERES-Maize for Pioneer 3394 and Pioneer 3489 planted at Ames and Armstrong 1995 and Ames 1996.

<table>
<thead>
<tr>
<th>Hybrid</th>
<th>Plot Name</th>
<th>Maize-S</th>
<th></th>
<th>CERES-Maize</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RMSE</td>
<td>PE</td>
<td>RMSE</td>
<td>PE</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Ames (1995) Early</td>
<td>0.96</td>
<td>0.02</td>
<td>895.50</td>
<td>26.88</td>
</tr>
<tr>
<td></td>
<td>Ames (1995) Late</td>
<td>427.67</td>
<td>10.50</td>
<td>850.02</td>
<td>61.11</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Ames (1995) Early</td>
<td>766.3</td>
<td>25.70</td>
<td>687.50</td>
<td>34.81</td>
</tr>
<tr>
<td></td>
<td>Ames (1995) Late</td>
<td>451.4</td>
<td>15.40</td>
<td>859.90</td>
<td>43.83</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Armstrong (1995) Early</td>
<td>128.03</td>
<td>3.36</td>
<td>904.50</td>
<td>23.71</td>
</tr>
<tr>
<td></td>
<td>Armstrong (1995) Late</td>
<td>157.00</td>
<td>6.19</td>
<td>1719.04</td>
<td>67.89</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Armstrong (1995) Early</td>
<td>1160.00</td>
<td>30.69</td>
<td>1824.00</td>
<td>70.89</td>
</tr>
<tr>
<td></td>
<td>Armstrong (1995) Late</td>
<td>125.19</td>
<td>4.87</td>
<td>1712.50</td>
<td>94.04</td>
</tr>
<tr>
<td></td>
<td>Ames (1996) Late</td>
<td>1093.9</td>
<td>72.99</td>
<td>1794.40</td>
<td>127.20</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Ames (1996) Early</td>
<td>124.14</td>
<td>6.94</td>
<td>1345.00</td>
<td>81.66</td>
</tr>
<tr>
<td></td>
<td>Ames (1996) Late</td>
<td>493.4</td>
<td>36.62</td>
<td>1992.00</td>
<td>139.30</td>
</tr>
</tbody>
</table>
Table 8. The mean difference between predicted and observed values averaged over time (RMSE) and the average percent difference between predicted and observed values averaged over time (PE) for kernel number (kernel/m²) for both Maize-S and CERES-Maize for Pioneer 3394 and Pioneer 3489 planted at Ames and Armstrong 1995 and Ames 1996.

<table>
<thead>
<tr>
<th>Hybrid</th>
<th>Plot Name</th>
<th>Maize-S</th>
<th>CERES-Maize</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE</td>
<td>PE</td>
<td>RMSE</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Ames (1995) Early</td>
<td>207.57</td>
<td>5.51</td>
</tr>
<tr>
<td></td>
<td>Ames (1995) Late</td>
<td>661.73</td>
<td>15.44</td>
</tr>
<tr>
<td></td>
<td>Ames (1995) Late</td>
<td>534.30</td>
<td>13.30</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Armstrong (1995) Early</td>
<td>605.79</td>
<td>12.96</td>
</tr>
<tr>
<td></td>
<td>Armstrong (1995) Late</td>
<td>712.10</td>
<td>18.93</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Armstrong (1995) Early</td>
<td>173.00</td>
<td>4.08</td>
</tr>
<tr>
<td></td>
<td>Armstrong (1995) Late</td>
<td>457.80</td>
<td>13.15</td>
</tr>
<tr>
<td></td>
<td>Ames (1996) Late</td>
<td>393.39</td>
<td>11.15</td>
</tr>
<tr>
<td></td>
<td>Ames (1996) Late</td>
<td>435.00</td>
<td>16.51</td>
</tr>
</tbody>
</table>
uses to calculate kernel number, wherein a stress factor is used to reduce kernel number.
Maize-S does not account for any stress during kernel set.

**Reproductive growth**

Kernel weight was well predicted by Maize-S at all locations except for Ames 1995 for late planting date for Pioneer 3394 and late planting date for Pioneer 3489 and for Ames 1996 for the same hybrid at early and late planting dates (Table 9). These locations had low observed grain yield. CERES-Maize predictions were more accurate than Maize-S at two locations (Table 9). The overpredictions in grain weight might occur because Maize-S does not account for the effect of water stress during the phase of endosperm cell division which otherwise might cause reduction in the number of cells formed, reduction in starch granule number and reduction in grain yield.

Comparing Maize-S with CERES-Maize, the former simulates vegetative growth of maize in a source-oriented fashion and simulates reproductive growth in a sink-pulled fashion whereas the latter is a source-oriented model in both vegetative and reproductive phases. CERES-Maize uses heat sums to predict seedling emergence, whereas Maize-S calculates coleoptile and first internode length and sums them to predict seedling emergence. CERES-Maize predicts vegetative growth by using an empirical approach to partition carbon between leaves, stalk, and roots. CERES-Maize is known to overpredict total plant weight in vegetative development. Maize-S predicts weight using partitioning coefficients to allocate carbon between leaf, stem, and roots. CERES-Maize does not contain simulation of the post silking phase, whereas silk growth and fertilization are simulated by Maize-S. CERES-Maize calculates kernel number using cultivar specific potential numbers, modified by the nonlinear stress yield-reduction. Whereas, Maize-S simulates kernel set as a function of plant growth rate. CERES-Maize calculates kernel weight from daily grain growth rate, the number of kernels per plant, and a cultivar specific coefficient (potential kernel growth rate). Whereas Maize-S simulates the actual demand for assimilate by the kernels during the grain filling period.
Table 9. The mean difference between predicted and observed values averaged over time (RMSE) and the average percent difference between predicted and observed values averaged over time (PE) for kernel weight (kg/ha) for both Maize-S and CERES-Maize for Pioneer 3394 and Pioneer 3489 planted at Ames and Armstrong 1995 and Ames 1996.

<table>
<thead>
<tr>
<th>Hybrid</th>
<th>Plot Name</th>
<th>Maize-S RMSE</th>
<th>Maize-S PE</th>
<th>CERES-Maize RMSE</th>
<th>CERES-Maize PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pioneer 3394</td>
<td>Ames (1995) Early</td>
<td>550.37</td>
<td>5.63</td>
<td>1425.00</td>
<td>15.10</td>
</tr>
<tr>
<td></td>
<td>Ames (1995) Late</td>
<td>1436.60</td>
<td>17.12</td>
<td>1830.00</td>
<td>22.90</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Ames (1995) Early</td>
<td>307.50</td>
<td>4.42</td>
<td>1040.00</td>
<td>11.00</td>
</tr>
<tr>
<td></td>
<td>Ames (1995) Late</td>
<td>1139.00</td>
<td>13.60</td>
<td>1712.00</td>
<td>27.20</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Armstrong (1995) Early</td>
<td>424.51</td>
<td>6.02</td>
<td>1722.00</td>
<td>19.40</td>
</tr>
<tr>
<td></td>
<td>Armstrong (1995) Late</td>
<td>1483.00</td>
<td>14.57</td>
<td>2407.00</td>
<td>32.70</td>
</tr>
<tr>
<td>Pioneer 3489</td>
<td>Armstrong (1995) Early</td>
<td>764.30</td>
<td>5.38</td>
<td>1582.00</td>
<td>19.00</td>
</tr>
<tr>
<td></td>
<td>Armstrong (1995) Late</td>
<td>4973.00</td>
<td>7.88</td>
<td>1433.00</td>
<td>21.90</td>
</tr>
<tr>
<td>Pioneer 3394</td>
<td>Ames (1996) Early</td>
<td>1754.00</td>
<td>21.96</td>
<td>1529.50</td>
<td>16.34</td>
</tr>
<tr>
<td></td>
<td>Ames (1996) Late</td>
<td>3322.30</td>
<td>48.42</td>
<td>398.00</td>
<td>5.80</td>
</tr>
<tr>
<td></td>
<td>Ames (1996) Late</td>
<td>994.80</td>
<td>12.99</td>
<td>1739.00</td>
<td>22.72</td>
</tr>
</tbody>
</table>
Physiological implication of Maize-S

Being a mechanistic model, Maize-S should reflect the behavior of a maize plant under changes in external factors, such as changes in temperature and solar radiation or internal factors, such as reduction in assimilate supply by defoliation.

Effect of temperature changes on maize growth

Temperature is the major environmental factor controlling plant development. The potential biomass yield of a crop can be thought of as the product of the rate of biomass accumulation multiplied by the duration of growth (Ritchie and NeSmith, 1991). Sensitivity analysis using Maize-S with the conditions of + 5 or - 5°C from the observed air temperatures reveals major changes in the length of the life cycle of the plant. High temperature decreases the length of the growth season as a result of acceleration of plant growth rate. The acceleration in plant growth rate can be attributed to the effect of temperature on photosynthesis and synthesis of new tissues. Both these processes are enzymatically controlled reactions, which increases with temperature until temperature reaches a level causes enzymatic denaturization (Gardner et al., 1985). As a result, plants progress through the different growth stages faster than normal resulting in less accumulation of assimilate in different plant parts per unit of time. Maize-S output shows a reduction in aboveground nongrain weight (Fig 2), grain weight (Fig 3), and leaf area index (Fig 4) at higher temperature. A reduction in the duration of the seed germination and seedling emergence phase and number of days from seedling emergence to silking were also observed since Maize-S predicts the date of these two phases as a function of temperature. Silking occurred earlier than normal by an average of 3.2 days for each 1°C increase in temperature. High temperature also decreased the number of days from silking to the end of the grain filling period causing reduction in grain weight. In Maize-S, the end of grain filling period is not controlled by the daily accumulated growing degree days, but by the amount of growth substrates available for grain (net photosynthesis, and mobilization of carbohydrates from stem and leaves). When these growth substrates are completely exhausted, the end of grain filling period occurs. Therefore, the observed reduction of the grain filling as a result
Figure 2. Maize-S predictions for aboveground nongrain biomass using normal temperature, normal temperature + 5° C, and normal temperature - 5° C.

Figure 3. Maize-S predictions for grain yield using normal temperature, normal temperature + 5° C, and normal temperature - 5° C.
Figure 4. Maize-S predictions for leaf area index using normal temperature, normal temperature + 5° C and normal temperature - 5° C.

of high temperature can be attributed to a reduction of the amount of carbohydrates available for remobilization either from the stem or from the leaves.

The shortening of the growing season is usually associated with reduction in total leaf area. In Maize-S, leaf area prediction is a function of temperature. Low total leaf area means low leaf area index (Fig 4), decreased photosynthesis and reduction in aboveground nongrain biomass (Fig 2), and grain yield (Fig 3). The reduction in these variables can also be attributed to the effect of high temperature on evapotranspiration rate calculated by Maize-S. Transpiration from the plant and evaporation from the field increase under temperature stress. High transpiration rate might cause stomatal closure, which increases stomatal resistance to CO₂ diffusion, and reduces photosynthesis (a temperature stress factor is calculated by Maize-S and is used to reduce the value of net photosynthesis). High temperature also increases maintenance respiration (it is accounted for in the calculation of maintenance respiration by Maize-S), which in turn reduces the amount of assimilate translocated to different plant parts and reduces accumulated weight (Taiz and Zeiger, 1991). Higher temperature increases the capacity of air to hold water, which increases atmospheric demand for water and leads to water loss from the field (Gardner et al., 1985). Maize-S calculates two water deficit factors. The first one calculates the effect of
water stress on photosynthesis, and the second one calculates the effect of water stress on cell expansion.

On the other hand, sensitivity analysis using Maize-S with the condition of -5°C from the normal air temperatures shows an increased length of the life cycle, where cool temperature prolongs the growing season causing both silking and physiological maturity to occur later in the season than normal. Jong et al. (1982) concluded that when maize was grown under low temperature, a decrease of 1°C was accompanied with an increase of 3.4 days of number of days to silking. Cool temperature leads to higher total leaf area and consequently to higher leaf area index (Fig 4). This in turn is reflected on photosynthesis. Net photosynthesis increases as a result of increasing gross photosynthesis, and decreased maintenance respiration. Furthermore, cool temperature decreases water loss from both the crop and soil, increases translocation of assimilates to different plant parts and consequently increases both aboveground non-grain weight and grain weight (Fig 2 and 3).

**Effect of solar radiation change on maize growth**

Solar radiation was found to be the single most influential climatic factor affecting maize yield (Jong et al., 1982). The rate of biomass accumulation is principally influenced by the amount of light intercepted by the canopy (Ritchie and NéSmith, 1991). Sensitivity analysis using Maize-S with the condition of 5% increase in daily solar radiation did not affect number of days from planting to silking, but increased number of days from planting to the end of grain filling period, which increased by an average of 6 days (Fig 5 and 6). Because Maize-S used accumulated growing degree days to predict the date of silking, solar radiation increase does not have any effect on this factor. In contrast, the end of the grain filling period is predicted by the full exhaustion of growth substrates. Being a C₄ plant, maize does not reach light saturation levels even under light levels equal to full sunlight (Gardner et al., 1985). Maize-S output shows that aboveground non-grain biomass and grain weights were increased (Fig 5 and 6), while leaf area index was not affected. The increase in aboveground non-grain biomass and grain weight can be attributed to higher photosynthetic rate causing more assimilate translocation to different plant parts. In addition, higher levels of assimilate storage in the stem for further use by the grain, prolonged grain filling period.
Figure 5. Maize-S predictions for aboveground nongrain weight using normal radiation, and normal radiation + 5%.

Figure 6. Maize-S predictions for grain weight using normal radiation, and normal radiation + 5%.
Jong et al. (1982) concluded that as solar radiation increased by 100 calories, there was an increase in maize grain yield of 2.3 metric ton/ha. As mentioned earlier, Maize-S predicts leaf area as a function of growing degree days. For this reason, leaf area index was not affected by solar radiation increase.

**Effect of defoliation on maize yield**

Reduction of assimilate supply to the developing grain by defoliation reduces kernel yield (Jones and Simmons, 1983). Maize-S output shows that when defoliation occurs on weekly intervals after silking for three weeks, great reductions of kernel yield (Fig 7), weight per kernel (Fig 8), and kernel number (Fig 9) were observed. Tollenaar and Daynard (1978a,b) suggested that maize does not alter the number of kernels per ear in order to compensate for reduction in assimilate supply occurring during the first three weeks after mid-silking. Instead, reduction in kernel growth rate and duration of grain filling period with enhanced remobilization from the stem is observed. In addition, weight per kernel especially at the tip of the ear, could be reduced to the point where during mechanical harvest these kernels could be left on the ear, which leads to reduction in kernel number per ear at harvest. Maize-S output shows reduction in the duration of grain filling period from 65 days with no defoliation to 19 days when defoliation was imposed at the first week after silking. During that time, the source of assimilates for developing grain is only mobilization of soluble carbohydrates from the stem. Maize-S output also shows that defoliation imposed at fourth week after silking did not affect grain yield, weight per kernel, or kernel number. At this time, the source for assimilates needed for developing grain is mainly remobilization of both the stem and leaves with little contribution from photosynthesis because of leaf senescence.
Figure 7. Maize-S predictions for grain weight under 100% defoliation imposed in weekly intervals after silking.

Figure 8. Maize-S predictions for weight per kernel under 100% defoliation imposed in weekly intervals after silking.
Figure 9. Maize-S predictions for kernel number under 100% defoliation imposed in weekly intervals after silking.
SUMMARY AND CONCLUSION

The major goal of this research was to develop a physiologically sound model to simulate both vegetative and reproductive growth of maize. This required incorporation of parts of several published models, such as CERES-Maize (Jones and Kiniry, 1986), MACROS (Penning de Vries et al., 1989), and CENTLI (Salvador, 1988), in addition to data from the literature and field data to develop regression equations. The developed model is called Maize-S. It is a research model, written in Pascal. It is source-driven in the vegetative phase and sink-pulled in the reproductive phase. It is a production-level-two model, which is capable of simulating the effect of water deficit. Moreover, the model responds to temperature stress.

Maize-S simulates seedling emergence according to the method of Weaich et al. (1996), leaf area growth according to the method of CERES-Maize (Jones and Kiniry, 1986), gross photosynthesis according to the method of Goudriaan and van Laar (1978). This method was modified to account for the effect of temperature on maximum leaf photosynthesis according to the method that is used in MACROS (Penning de Vries et al., 1989). Growth and maintenance respirations also were calculated according to the method used in MACROS (Penning de Vries et al., 1989). Dry matter partitioning to the different competing sinks during vegetative growth was predicted according to the method of Grant (1989b). Using field data, kernel number per ear was calculated as a function of plant growth rate during the period of 10 days after tassel initiation to one week before silking. Silk growth was simulated by using published data (Herrero and Johnson 1981; Sadras et al., 1985; Ritchie et al., 1993). The beginning of endosperm cell division phase, and starch accumulation in the grain and grain weight were simulated using the method of Salvador (1988). The effect of water stress on photosynthesis and cell expansion was simulated using the water balance routines of CERES-Maize. However, no attempt was made to simulate the effect of water stress on kernel set or on starch synthesis.

The main routine of Maize-S consists of procedures simulating various components of maize biology. It can be divided into three sections. The first section consists of four procedures that are utilized to set the initial conditions for each module. The second section consists of four procedures simulating maize vegetative development that include: seedling
emergence, end of juvenile phase, tassel initiation and silking. The third section, which simulates reproductive development, is composed of two procedures that include pollination and grain filling in one procedure, and physiological maturity in the second procedure.

To operate the model, four sets of input are required: weather data, management data, genetic coefficients, and soil parameters. Weather data consists of daily radiation, daily maximum and minimum temperature, and precipitation. Management data consists of planting date, planting depth, planting density, and latitude. Cultivar genetic coefficients consist of P1 (cumulative growing degree days from seedling emergence to the end of juvenile phase), P2 (photoperiod sensitivity coefficient), and number of kernel rows per ear. Soil parameters consist of runoff curve number, soil water in the upper limit, drainage rate per day, root growth weight factor, bare soil albedo, soil depth, and soil water in the lower limit.

Both Maize-S and CERES-Maize were validated against field data collected from two locations in 1995 (Ames, and Armstrong farm, Iowa) and one location in 1996 (Ames, Iowa). Two maize hybrids were used in the validation (Pioneer 3394, and Pioneer 3489). Each hybrid was planted at two different planting dates (early in May and late in May) and were grown under typical management conditions in Iowa with no irrigation, no tillage and with optimum nitrogen application. The mean root square error (RMSE) and percent error averaged (PE) over time were calculated for leaf, stem, and grain weight and grain number. The RMSE statistic reflects the magnitude of the mean difference between predicted and observed values over time. The value of PE is a measure of average percent difference between predicted and measured values, average over all observations for an experiment. This determines the averaged percentage error for a plant component for entire season.

Leaf weight was well predicted by Maize-S except for one location. Stem weight predictions were accurate except for four locations. Maize-S predictions for kernel number were also accurate except for two locations. Kernel weight was well predicted by Maize-S at all locations except for three locations. Most of the overpredictions were in Ames 1996 where nitrogen stress existed.

Maize-S predictions for leaf and stem weight were more accurate than CERES-Maize. CERES-Maize predictions for kernel number were more accurate than Maize-S
predictions in four locations. This might be attributed to the method that CERES-Maize uses to calculate kernel number, wherein a stress factor is used to reduce kernel number. Maize-S does not account for any stress during kernel set. CERES-Maize predictions for kernel weight were more accurate than Maize-S at two locations.

Sensitivity analysis using Maize-S with conditions of +5 or -5°C from observed air temperatures revealed major changes in maize plant behavior. High temperatures caused the plant to progress through the different growth stages faster than normal resulting in less accumulation of assimilates in different plant parts. The output of the model showed that silking occurred earlier than normal with an average of 3.2 days for each 1°C increase in temperature. The shortening of the growing season was also associated with reduction in total leaf area. On the other hand, Maize-S output shows that cool temperature prolonged the growing season, causing both silking and physiological maturity to occur latter than normal in the season and consequently increasing both aboveground nongrain weight and grain weight. Cool temperature also leads to higher total leaf area and consequently to higher leaf area index.

Sensitivity analysis using Maize-S with the condition of 5% increase in daily solar radiation did not affect number of days from planting to silking, but increased the number of days from planting to the end of grain filling period, by an average of 6 days. Furthermore, aboveground nongrain biomass and grain weight were increased whereas leaf area index was not affected.

Furthermore, Maize-S output shows that when defoliation occurs on weekly intervals after silking up to three weeks, kernel yield, weight per kernel, and kernel number were greatly reduced. Maize-S output also showed reduction in grain filling period from 65 days with no defoliation to 19 days when defoliation was imposed one week after silking.

**Weak Points of The Model**

Further improvement in estimating water stress on kernel set, silk growth, endosperm cells differentiation and starch accumulation is recommended. The model needs to be modified to simulate maize vegetative development in a sink-pulled fashion, wherein the sink strength of leaves, stem, and root is simulated. Another improvement in Maize-S would be
the capability to simulate prolificacy. This can be done by predicting the time of ear shoot
emergence, the rate of development of secondary ear, including silk emergence and growth.
fertilization of the silk and the establishment of secondary ear sink demand. Maize-S
currently assumes sufficient nitrogen for whole plant development. However, nitrogen stress
has a great effect on both photosynthesis and kernel set. Adding a routine to estimate
nitrogen stress effects on final yield would significantly improve Maize-S predictions.
Program MAIZE_S(input, Output, dfile);
Uses crt;
Const
  Pi=3.1415;
  name_length=10;
  AmmoniumN=True;
  Base=1;
  DevelopMachinery=10;
  GranuleRate=2.07E-9;
  PreAlRatio=0.3779;
  PostAlRatio=0.2970;
  Tip=70;
  TotalGranules=270;
  RefTemp=30;

Type
  AgeGroup = record
    CellsExist,MakingStarch : Boolean;
    AmylGranules,MerisGranules,Amyliferous,Meristematic : real;
  end;

  Traits = record
    CellComponents : array[1..25] of AgeGroup;
    Aleurone,CellMax : boolean;
    CellNo,CountOfCells,Weight : real;
  end;

Var
  Kernel : array[Base..Tip] of Traits;
  SW,SLLL,SDLUL,ESW,SLB,SSAT,SLOR,RLDF,RLV,RWU:ARRAY[1..15] of real;
  SRGF,SSKS,SBMD,SL0C,SLCL,SLSI,SLCF,SLMH:ARRAY[1..15] of real;
  PsTemp:array [5..45] of real;
  Fertilized,germination,match,not_done.Pollinated,ThereIsLeafArea:boolean;
  char_var,name:char;
  a,Apex,Age,CriticalAge,d,day,DaysFromPlanting,DaysToGrainFill:integer;
  DaysFromTasselToSilk,GranulesPerDay,H,I,i,j,k,l,m,MaxAge,number,Nday,:integer;
  PlantingDepth,Position,Time,TimeStep,Year,DaysFromJuvenileToTasse:integer;
  SilkLength,Pollen TubeLength,EarLength,EarElongationRate,MaxLAI:real;
  EarHuskLength,SilkElongationRate,RankArea,SilkLengthDecrease,NetPs1:real;
CobResM, CobResG, MinRootW, TotalLeafArea, LeafWeight, LeafWeightGrowth: real;
LeafAreaGrowth, Declination, Latitude, EffDayLength, XLeafW, P1, P2: real;
P3, DTT, LeafFracEmerg, c, SIND, TotalResM, TotalResG, Temp1, Temp2, Temp3: real;
MinLeafW, MinStemW, MaxTemp, MinTemp, Tbase, LeafAreaGrowth1, CobWeight: real;
PlantingDensity, GrossPs, TotalPs, LAI, DailyCobGrowth, DayLength: real;
ShootL, CumDTT, MeanTemp, Radiation, OldLeafNum, LeafPs, TempResM: real;
DailyRootGrowth, DailyStemGrowth, NetPs, LeafSenesc. TotalRes: real;
RootWeight, RootWeight1, StemWeight1, LeafWeight1, SolubleReserveWeight: real;
StemWeight, TotalLeavesNum, LeafWeightT, CobWeight1, TubeGrowthRate: real;
TestMinTemp, TestMaxTemp, TestRad, Prec, WeightReductionFactor, HuskL: real;
KernelNumER1, KernelNum1, PlantGR1, PlantGR, SenescenceFactor: real;
SolubleReserveWeight1, TempStress, TRWU, EP1, RTDEP, SWDF1, SWDF2: real;
Labile, NewDryMatter, GrainWt, GranuleSum, Adjust.Exponent: real;
SinkDemand, Stalk, TotalRate, TRLDF, SALB, SLDR, SLRO, PRECrP, g: real;
Sname, SfileName, OutToFile, fname, Hname: string;
dfile, sfile, OutFile: text;
{ ----------------------------------------------- }
Procedure InitialValues;
begin
  clrscr;
  PsTemp[5] := 0.01;
  PsTemp[10] := 0.1;
  PsTemp[15] := 0.5;
  PsTemp[20] := 0.8;
  PsTemp[25] := 1.0;
  PsTemp[30] := 1.0;
  PsTemp[35] := 1.0;
  PsTemp[40] := 0.9;
  PsTemp[45] := 0.75;
  OldLeafNum := 0;
  ShootL := 0;
  SIND := 0;
  TimeStep := 1;
  RootWeight1 := 0;
  LeafWeightT := 0;
  StemWeight1 := 0;
  DaysFromPlanting := 0;
  DaysToGrainFill := 0;
  not_done := true;
  RTDEP := 0;
  TRLDF := 0;
  CumDTT := 0;
LeafWeight:=0;
TotalLeafArea:=0;
SolubleReserveWeight1:=0;
CobWeight:=0;
ThereIsLeafArea:=true;
NetPs:=0;
PollenTubeLength:=0;
KernelNumEI=0;
EarLength:=210; {mm}
EarElongationRate:=5; {mm}
HuskL:=90;{mm}
end;

{ Procedure Initialize; begin
  Apex:=Round(KemelNumERl/KemelRows);
  Exponent:=0;
  GrainWt:=0;
  GranulesPerDay:=Trunc(TotalGranules/DevelopMachinery); 
  Labile:=0;
  SinkDemand:=0;
  Stalk:=SolubleReserveWeight;
  TotalRate:=0;
  Time:=0;
  Fertilized:=false;
  Day:=1;

  For Position:=Base to Apex do
    begin
      With Kemel[Position] do
        begin
          Aleurone:=false;
          CellMax:=false;
          CellNo:=0;
          CountOfCells:=0;
          Weight:=0;
        end;

    For Age := 1 to 25 do
      begin
        With CellComponents[Age] do
          begin
            AmylGranules:=0;
            Amyliferous:=0;
          end;
CellsExist:=false;
MakingStarch:=false;
MerisGranules:=0;
Meristematic:=0;
end;
end;
end;
end;
end;

{ } Procedure GetInformation;
Begin
assign(OutFile,'C:\OutToFile.pas');
rewrite(OutFile);

Writeln('Enter the name of weather file to use');
Readln(fname);
Writeln(OutFile,'weather file:',fname);

Writeln('What is planting month');
Readln(m);
Writeln(OutFile,'planting month:',m:4);

Writeln('What is planting day');
Readln(d);
Writeln(OutFile,'planting day:',d:5);

Writeln('What is planting density (plant/m2)');
Readln(PlantingDensity);
Writeln(OutFile,'planting density:',PlantingDensity:4:1);

Writeln('What is planting depth (cm)');
Readln(PlantingDepth);
Writeln(OutFile,'planting depth:',PlantingDepth:4);

Writeln('What is the latitude');
Readln(Latitude);
Writeln(OutFile,'Latitude:',Latitude:4:2);

Writeln('What is the name of the hybrid');
Readln(Hyname);
Writeln(OutFile,'Hybrid name:',Hyname);
Writeln('Enter PI');
Readln(P1);
Writeln(OutFile,'PI:', P1:4:2);

Writeln('Enter P2');
Readln(P2);
Writeln(OutFile,'P2:', P2:4:2);

Writeln('Enter kernel rows per ear');
Readln(KernelRows);
Writeln(OutFile,'Enter kernel rows per ear one:', KernelRows:8);
end;

----------------------------------------------------------------------------
Procedure GetSoilInformation;
begin
  Writeln('Enter the name of soil type to use');
  readln(Sname);
  Writeln(OutFile,'Soil type:', Sname);

  Writeln('How many soil layers are included in the profile');
  Readln(j);
  Writeln(OutFile,'Number of soil layers:', j:8);
end;

----------------------------------------------------------------------------
Procedure OpenSFile;
var
  SCOM,b,e,f:real;
  n:integer;
  IBO01:string;
begin
  GetSoilInformation;
  Sfilename:='a:\Sfile';
  assign(Sfile,Sfilename);
  reset(Sfile);
  while (not done) and not eof (Sfile) do
  begin
    read(Sfile,char_var);
    if char_var='*' then
    begin
      for n:=1 to name_length do
      begin
        read(sfile,name);
        read(sfile,name);
        if name=Sname[n] then
          begin
            \/* code continues */
          end;
    end;
  end;
end;
match:=true
else
match:=false;
end;
if match=true then
begin
readln(Sfile);readln(Sfile);readln(Sfile);
readln(Sfile);readln(Sfile);
readln(Sfile,SCOM,SALB,e,SLDR,SLRO,b,f,IB001,IB001,IB001);
readln(Sfile);
readln(Sfile,SLB[1],SLMH[1],SLLL[1],SDUL[1],SSAT[1],SRGF[1],SSKS[1],SBMD[1],SLOC[1],SLCL[1],SLSI[1],SLCF[1]);
For I:=2 to j do
begin
readln(Sfile,SLB[I],SLMH[I],SLLL[I],SDUL[I],SSAT[I],SRGF[I],SSKS[I],SBMD[I],SLOC[I],SLCL[I],SLSI[I],SLCF[I]);
end;
not_done:=false;
end;
end;
end;
end;

Procedure WaterTablelnitial;
Var
CN1,SMX,PB,RunOff,HOLD,PINF,DRAIN:real;
begin
for I:=1 to j do
begin
SW[I]:=(SDUL[I]-SLLL[I])/2;
end;
repeat
readln(dfile,Year,Nmonth,Nday,Testrad,TestMaxTemp,TestMinTemp,prec);
if prec > 0.0 then
begin
CN1:=-16.91+1.348*SLRO-0.01379*SLRO*SLRO+0.0001172*
SLRO*SLRO*SLRO;
SMX:=100/CN1-1;
PRECIp:=prec*25.4;
PB:=PRECIp-0.2*SMX;
if PRECIP < 0.508 then
  RunOff:=0
else
  RunOff:=PB*PB/(PRECIP+(0.8*SMX));
  PINF:=PRECIP-RunOff;
  if PINF < 0 then
    PINF:=0;
  for I:=1 to j do
    begin
      if PINF > 0 then
        begin
          HOLD:=(SSAT[I]-SW[I])*(SLB[I+1]-SLB[I]);
          if PINF <= HOLD then
            begin
              SW[I]:=SW[I]+PINF/(SLB[I+1]-SLB[I]);
              if SW[I] > (SDUL[I]+0.003) then
                DRAIN:=0
              else
                if SW[I] > (SDUL[I]+0.003) then
                  begin
                    DRAIN:=(SW[I]-SDUL[I])*SLDR*(SLB[I+1]-SLB[I]);
                    SW[I]:=SW[I]-DRAIN/(SLB[I+1]-SLB[I]);
                  end;
            end;
          else
            if PINF > HOLD then
              begin
                DRAIN:=SLDR*(SSAT[I]-SDUL[I])*(SLB[I+1]-SLB[I]);
                SW[I]:=SW[I]-DRAIN/(SLB[I+1]-SLB[I]);
                PINF:=DRAIN;
              end;
        end;
    end;
  end;
until ((Nmonth=n) and (Nday=d));
end;
{--------------------------------------------------}
Procedure GetPlantingDate;
begin
  assign(dfile,fname);
  Reset(dfile);
  Nmonth:=0;
Nday:=0;
WaterTableInitial;
end;

{-------------------------------------------------------------}
Procedure GetWeatherData;
begin
if Testrad <> -99 then
  Radiation:=Testrad*1000000;
if TestMaxTemp <> -99 then
  MaxTemp:=TestMaxTemp;
if TestMinTemp <> -99 then
  MinTemp:=TestMintemp;
Readln(dfile,Year,Nmonth,Nday,Testrad,TestMaxTemp,
        TestMinTemp,prec);
end;
{-------------------------------------------------------------}
Procedure GDD_Correction;
var
  I: integer;
  TFac,TTMP,SUM:real;
begin
  SUM:=0;
  for I:=1 to 8 do
  begin
    TFac:=0.931+0.114*I-0.0703*I*I+0.0053*I*I*I;
    TTMP:=MinTemp+TFac*(MaxTemp-MinTemp);
    if (TTMP > Tbase) and (TTMP < 34) then
    begin
      DTT:=TTMP-Tbase;
      if (TTMP < Tbase) or (TTMP >= 44) then
        DTT:=0
      else
        if (TTMP > 34) and (TTMP < 44) then
          DTT:=(34-Tbase)*(1-(TTMP-34)/10);
        SUM:=SUM+DTT;
    end;
  end;
  DTT:=SUM/8;
end;
{-------------------------------------------------------------}
procedure GDD;
begin
  MeanTemp:=0;
if not germination then
  Tbase:=8
else
  Tbase:=10;
if (((MinTemp >= Tbase) and (MaxTemp <= 34)) then
  begin
    MeanTemp:=(MaxTemp+MinTemp)/2;
    DTT:=MeanTemp-Tbase;
  end
else
  begin
    if (((MinTemp < Tbase) and (MaxTemp > 34)) then
      GDD_Correction;
    end;
    CumDTT:=CumDTT+DTT;
    GetWeatherData;
    TempStress:=1-0.0025*(((0.25*MinTemp+0.75*MaxTemp)-26)*
                          ((0.25*MinTemp+0.75*MaxTemp)-26));
  end;

{--------------------------------------------------------------------------}
Procedure Expanded_5_Leaves;
var
  pc:real;
begin
  repeat
    pc:=0.66+0.068*OldLeafNum;
    LeafFracEmerg:=DTT/(38.9*pc);
    OldLeafNum:=OldLeafNum+LeafFracEmerg;
    if OldLeafNum < 4 then
      LeafAreaGrowth:=3*OldLeafNum*LeafFracEmerg
    else
      LeafAreaGrowth:=3.5*OldLeafNum*OldLeafNum*LeafFracEmerg;
    until OldLeafNum >= 5;
  end;
{--------------------------------------------------------------------------}
Procedure ExpandedLeaves;
begin
  if SWDF2=0 then
    SWDF2:=1;
  LeafFracEmerg:=DTT/38.9;
  OldLeafNum:=OldLeafNum+LeafFracEmerg;
  LeafAreaGrowth:=3*OldLeafNum*OldLeafNum*LeafFracEmerg*SWDF2;
end;
Function power (a,b:real):real;
begin
  c:=b*ln(a);
  power:=exp(c);
end;

Procedure LeafAreaIndex;
begin
  LAI:=(TotalLeafArea-LeafSenesc)*PlantingDensity*0.0001;
end;

Procedure TasselLeafGrowth;
begin
  if NetPs > 0 then
    begin
      if OldLeafNum < 12 then
        begin
          LeafAreaGrowth:=3.5*OldLeafNum*OldLeafNum*LeafFracEmerg*SWDF2
        end
      else
        if (OldLeafNum >= 12) and (OldLeafNum <= (TotalLeavesNum-3)) then
          LeafAreaGrowth:=3.5*170*LeafFracEmerg*SWDF2
        else
          if (OldLeafNum > (TotalLeavesNum-3)) then
            LeafAreaGrowth:=170*3.5/(power((OldLeafNum+5)-TotalLeavesNum,0.5))
            *LeafFracEmerg*SWDF2;
      end;
      TotalLeafArea:=TotalLeafArea+LeafAreaGrowth;
      LeafSenesc:=TotalLeafArea/1000;
      LeafAreaIndex;
    end;
end;

Procedure LeafPostSilking;
begin
  TotalLeafArea:=TotalLeafArea+LeafAreaGrowth;
  LeafSenesc:=TotalLeafArea*(0.05+CumDTT/170*0.05);
  LeafAreaIndex;
end;

Procedure LeafGrowth;
begin
  TotalLeafArea:=TotalLeafArea+LeafAreaGrowth;
  LeafSenesc:=CumDTT*TotalLeafArea/10000;
  LeafAreaIndex;
Function ArcSin(value: real): real;
begin
  value := arctan(value / sqrt(-sqr(value) + 1));
  ArcSin := value * 180 / Pi;
end;

Function radians(value: real): real;
begin
  radians := (value * Pi / 180);
end;

Procedure PhotoPeriod;
begin
  var
    SinLatitude, CosLatitude: real;
  begin
    Declination := -23.45 * cos(2 * Pi * (Nday + 10) / 365);
    SinLatitude := sin(radians(Declination * Pi / 180)) *
      sin(radians(Latitude * Pi / 180));
    CosLatitude := cos(radians(Declination * Pi / 180)) *
      cos(radians(Latitude * Pi / 180));
    DayLength := (43200 * (Pi + 2 * ArcSin(SinLatitude / CosLatitude)) / Pi) / 3600;
    EffDayLength := (43200 * (Pi + 2 * ArcSin((-sin(radians(8 * Pi / 180)) + SinLatitude) / CosLatitude)) / Pi);
  end;
end;

Procedure CalculateLAI;
begin
  Time := Time + 1;
  SenescenceFactor := 0.98 + (3.06E-03 * Time) - (3.03E-04 * sqr(time));
  LAI := LAI * SenescenceFactor;
  if LAI <= (MaxLAI * 0.25) then
    begin
      LAI := MaxLAI * 0.25;
      NetPs := 0;
      ThereIsLeafArea := false;
    end;
end;

Function TLeafPs(MaxTemp: real): real;
begin
  i := integer;
  if

Ps1,Ps2:real;
begin
index:=5;
for I:= 1 to 8 do
begin
Ps1:=PsTemp[index];
Ps2:=PsTemp[index+5];
MaxTemp:=round(MaxTemp);
if (MaxTemp > index) and (MaxTemp < index+5) then
LeafPs:=(60*(Ps1+((MaxTemp-Index)/5)*(Ps2-Ps1)))/36000000
else
if (MaxTemp=index) then
LeafPs:=(60*PsTemp[index])/36000000
else
if MaxTemp=index+5 then
LeafPs:=(60*PsTemp[index+5])/36000000
else
if MaxTemp > (index+5) then
index:=index+5;
end;
TLeafPs:=LeafPs;
end;
{--------------------------------------------------------}
Procedure TotalLeavesNumber;
begin
TotalLeavesNum:=CumDTT/21+6;
end;
{--------------------------------------------------------}
Procedure Photosynthesis;
var
SunLitLeafArea,AveRadiation,X,LightUseEff,Xprime:real;
ShadedLeafPs,SunLitLeafPs:real;
begin
LightUseEff:=12.90E-09;
PhotoPeriod;
SunLitLeafArea:=sin(radians(90+Declination-Latitude));
AveRadiation:=(Radiation*0.5)/EffDayLength;
X:=0.45*LightUseEff*AveRadiation/(SunLitLeafArea*TLeafPs(MaxTemp));
Xprime:=Ln(1+X);
GrossPs:=Xprime/(1+Xprime);
SunLitLeafPs:=SunLitLeafArea*EffDayLength*TLeafPs(MaxTemp)*GrossPs;
if SunLitLeafArea < LAI then
begin
\[ X = 0.55 \times \text{LightUseEff} \times \text{AveRadiation} / ((\text{LAI-SunLitLeafArea}) \times \text{TLeafPs}(\text{MaxTemp})) \]

\[ X' = \ln(1 + X) \]

\[ \text{GrossPs} = X' / (1 + X') \]

\[ \text{ShadedLeafPs} = (\text{LAI-SunLitLeafArea}) \times \text{EffDayLength} \times \text{TLeafPs}(\text{MaxTemp}) \times \text{GrossPs}; \]

end

else

\[ \text{ShadedLeafPs} = 0; \]

if LAI <= 0 then

begin

\[ \text{ShadedLeafPs} = 0; \]

\[ \text{SunLitLeafPs} = 0; \]

\[ \text{TotalPs} = 0; \]

end

else

if LAI > 0 then

\[ \text{TotalPs} = (\text{SunLitLeafPs} + \text{ShadedLeafPs}) \times 10000 \times (30/44); \]

end;

{---------------------------------------------------------------------}

procedure GrowthRate;

begin

\[ \text{LeafWeightGrowth} = \text{abs}(\text{LeafWeight} - \text{Temp1}) \times \text{SWDF2}; \]

\[ \text{DailyRootGrowth} = \text{abs}(\text{RootWeight} - \text{Temp2}); \]

if Stem Weight > 0 then

\[ \text{DailyStemGrowth} = (\text{Stem Weight} - \text{Temp3}) \times \text{SWDF2}; \]

if Cob Weight > 0 then

\[ \text{DailyCobGrowth} = (\text{Cob Weight} - \text{Temp4}) \times \text{SWDF2}; \]

end;

{---------------------------------------------------------------------}

procedure Juvenile Weight;

begin

\[ \text{LeafWeight} = \text{NetPs} \times 0.67; \]

\[ \text{RootWeight} = \text{NetPs} \times 0.33; \]

\[ \text{StemWeight} = 0; \]

\[ \text{CobWeight} = 0; \]

\[ \text{RootWeight1} = \text{RootWeight} + \text{RootWeight}; \]

\[ \text{LeafWeightT} = \text{LeafWeightT} + \text{LeafWeight}; \]

end;

{---------------------------------------------------------------------}

Procedure PreSilking Weight;

begin

\[ \text{LeafWeight} = (0.8 - \text{LeafFracEmerg}) \times \text{NetPs} \times 0.925; \]
LeafWeightT:=LeafWeightT+LeafWeight;
RootWeight:=NetPs*0.075;
RootWeight1:=RootWeight1+RootWeight;
SolubleReserveWeight:=NetPs*(0.9-0.6*exp(LeafFracEmerg))*0.925;
SolubleReserveWeight1:=SolubleReserveWeight1+SolubleReserveWeight;
StemWeight:=1.1*LeafFracEmerg*NetPs*0.925;
StemWeight1:=StemWeight1+StemWeight+SolubleReserveWeight;
CobWeight:=NetPs*(exp(-8.4+7*LeafFracEmerg))*0.925;
CobWeight1:=CobWeight1+CobWeight;
end;

{------------------------------------------------------------------------------}
Procedure PostSilkingWeight;
begin
  CobWeight:=NetPs*(exp(-8.4+7*LeafFracEmerg))*0.925;
  CobWeight1:=CobWeight1+CobWeight;
  if LAI <= 0.1 then
    StemWeight1:=StemWeight1*0.998;
    RootWeight1:=RootWeight1*0.999;
  if LAI > (MaxLAI*0.25) then
    LeafWeightT:=LeafWeightT*0.999
  else
    if LAI < (MaxLAI*0.25) then
      LeafWeightT:=LeafWeightT*0.996;
    if LeafWeightT <= MinLeafW then
      LeafWeightT:=MinLeafW;
    if StemWeight1 < MinStemW then
      StemWeight1:=MinStemW;
    if RootWeight1 < MinRootW then
      RootWeight1:=MinRootW;
end;
{------------------------------------------------------------------------------}
Procedure Respiration;
var
  Q10:integer;
begin
  Q10:=2;
  RefTempResM:=18;
  CoefLeafResM:=0.032;
  CPGLV:=0.461;
  CPGST:=0.408;
  CPGRT:=0.406;
  CPGSO:=0.384;
if DaysFromPlanting > 1 then
  GrowthRate;
  TempResM:=power(10,((MeanTemp-RefTempResM)/10));
  LeafResM:=LeafWeight*CoefLeafResM*TempResM*0.75;
  RootResM:=0.015*RootWeight*TempResM;
  StemResM:=0.01*StemWeight*TempResM;
  CobResM:=0.015*CobWeight*TempResM;
  StemResG:=DailyStemGrowth*CPGST;
  LeafResG:=LeafWeightGrowth*CPGLV;
  RootResG:=DailyRootGrowth*CPGRT;
  CobResG:=DailyCobGrowth*CPGSO;
  TotalRes:=TotalResM+TotalResG;
end;
{---------------------------------------------------------------}
Procedure NetPhotosynthesis;
var
  NetPs1:real;
begin
  NetPs1:=(TotalPs-TotaiRes);
  if SWDF1 <= TempStress then
    NetPs:=NetPs1*SWDF1
  else
    NetPs:=NetPs1*TempStress;
  if LAI <= (MaxLAI*0.25) then
    NetPs:=0;
end;
{---------------------------------------------------------------}
Procedure InitialKernelNumber;
begin
  PlantGR:=(LeafWeightGrowth+DailyStemGrowth)/PlantingDensity;
  KernelNum1:=((8.012947+1.767148*PlantGR)*PlantingDensity/8);
  KernelNumERl:=KernelNumERl+KernelNum1;
end;
{---------------------------------------------------------------}
Procedure RootDensity;
Var
  RLNEW,RNL,RTDEP1,TRLDF:real;
  SWDF,RLDF,RLV1:array[1..15] of real;
begin
  RLNEW:=RootWeight*PlantingDensity;
  for I:=1 to J do

begin
  ESW[I]:=SDUL[I]-SLLL[I];
  if SW[I] < 0.25 then
    SWDF[I]:=(4*(SW[I]-SLLL[I])/ESW[I])
  else
    if SW[I] > 0.25 then
      SWDF[I]:=1;
      RTDEP1:=DTT*0.22*SWDF[I]*0.2;
      RTDEP:=RTDEP+RTDEP1;
      if RTDEP > SLB[j] then
        RTDEP:=SLB[j];
    RLDF[I]:=SWDF[I]*SRGF[I];
    RLDF[I]:=(RLDF[I]*(1-SLB[j]-RTDEP)/(SLB[I+1]-SLB[I]));
    TRLDF:=TRLDF+RLDF[I];
end;
RNLF:=RLNEW/TRLDF;
for I:=1 to j do
  begin
    RLV[I]:=RLDF[I]*(RNLF/(SLB[I]-SLB[I]));
    if RLV[I] > 5.0 then
      RLV[I]:=5.0;
  end;
end;
procedure RootWaterUptake;
var
  WUF: real;
begin
  For I:=1 to j do
    begin
      RWU[I]:=(2.67e-3*EXP((SW[I]-SLLL[I]))*62);
      if RWU[I] > 0.03 then
        RWU[I]:=0.03;
      RWU[I]:=RWU[I]*(SLB[I+1]-SLB[I])
      TRWU:=TRWU+RWU[I];
    end;
    if EPI <= TRWU then
      begin
        WUF :=EPI/TRWU;
        RWU[I]:=RWU[I]*WUF;
    end;
    SW[I]:=SW[I]-(RWU[I]/(SLB[I+1]-SLB[I]));
SWDF1:=TRWU/EP1;
IF (SWDF1 >= 1) AND (SWDF1 <= 1.5) THEN
SWDF2:=0.67*SWDF1
END;
{ ----------------------------------------------- }

Procedure WaterTable;
var
CN1,SMX,PB,RunOff,HOLD,PINF,DRAIN:real;
begin
if prec > 0.0 then
begin

CN1:=-16.91+1.348*SLRO-0.01379*SLRO*SLRO+0.0001172*SLRO*SLRO*SLRO;
SMX:=100/CN1-1;
PRECIP:=prec*25.4;
PB:=PRECIP-0.2*SMX;
if PRECIP < 0.508 then
RunOff:=0
else
RunOff:=PB*PB/(PRECIP+(0.8*SMX));
PINF:=PRECIP-RunOff;
for I:=l to j do
begin
if PINF > 0 then
begin
HOLD:=(SSAT[I]-SW[I])*(SLB[I+1]-SLB[I]);
if PINF <= HOLD then
begin
SW[I]:=SW[I]+PINF/(SLB[I+1]-SLB[I]);
if SW[I] < (SDUL[I]+0.003) then
DRAIN:=0
else
if SW[I] > (SDUL[I]+0.003) then
begin
DRAIN:=(SW[I]-SDUL[I])*SLDR*(SLB[I+1]-SLB[I]);
SW[I]:=SW[I]-DRAIN/(SLB[I+1]-SLB[I]);
end;
end
else
if PINF > HOLD then
begin
DRAIN:=SLDR*(SSAT[I]-SDUL[I])*(SLB[I+1]-SLB[I]);
SW[I]:=SW[I]-DRAIN/(SLB[I+1]-SLB[I]);
PINF:=DRAIN;
end;
end;
end;
end
else
  if PINF <= 0.0 then
    begin
      PINF := 0.0;
      SW[I] := SW[I] - SLDR;
    end;
  end;
else
  if prec = 0.0 then
    begin
      for I := 1 to j do
        SW[I] := SW[I] - SLDR;
    end;
  for I := 1 to j do
    begin
      if SW[I] < 0.0 then
        SW[I] := 0.0
    end;
RootDensity;
RootWaterUptake;
end;

{ ------------------------------- }
Procedure Transpiration;
var
  TD, ALBEDO, EQ, EO, EP: real;
begin
  if DaysToGrainFill > 0 then
    begin
      if (LAI <= MaxLAI * 0.25) and (LAI > 0.1) then
        begin
          Time := Time + 1;
          SenescenceFactor := 0.98 + (3.06E-03 * Time) - (3.03E-04 * sq(time));
          LAI := LAI * SenescenceFactor;
        end
      else
        if LAI <= 0.1 then
          LAI := 0.1;
      TD := 0.6 * MaxTemp + 0.4 * MinTemp;
      ALBEDO := 0.23 - (0.23 - SALB) * EXP(-0.75 * LAI);
      EEQ := Radiation * (2.04E-4 - 1.83E-4 * ALBEDO) + (TD + 29);
IF (MaxTemp >= 5) and (MaxTemp <= 35) then
   EO := EEQ*1.1
ELSE
   IF MaxTemp > 35 then
      EO := EEQ*((MaxTemp-35)*0.05+1.1)
   else
      IF MaxTemp < 5 then
         EO := EEQ*0.01*EXP(0.18*(MaxTemp+20));
      IF LAI <= 3 then
         EP := EO*(1-EXP(-LAI))
      else
         IF LAI > 3 then
            EP := EO;
      EP1 := EP*0.1;
   END;
Procedure Partition;
   begin
      Stalk := Stalk + NetPs;
      if LAI > 0.1 then
         StemWeight1 := StemWeight1 + NetPs;
   end;
procedure Remobilize;
   begin
      if Stalk > 0 then
         begin
            Labile := SinkDemand - NetPs;
            Stalk := Stalk - Labile;
            StemWeight1 := StemWeight1 - Labile;
         end
      else
         if Stalk < 0 then
            begin
               Adjust := abs(Stalk);
               Labile := Labile - Adjust;
               Stalk := 0;
            end
         else
            if (Stalk=0) and (LeafWeightT > MinLeafW) then
               begin
                  Labile := SinkDemand;
                  GrainWt := GrainWt + Labile;
end;
end;
{------------------------------

procedure Coenocytosis;
Var
NucellusReduction:real;
begin
NucellusReduction:=1.0073-0.0073*Position;
with kernel[Position] do
begin
Exponent:=1/power(CellNo,0.1879561)*3.128945;
TotalRate:=power(CellNo,Exponent)*NucellusReduction;
CellNo:=(CellNo+TotalRate);
with CellComponents[Time] do
begin
Meristematic:=TotalRate*PreAlRatio;
Amyliferous:=TotalRate-Meristematic;
CellsExist:=true;
end;
end;
end;
{------------------------------

Procedure PreAleurone;
begin
with kernel[Position],CellComponents[Time] do
begin
Exponent:=1.271845-(3.542972E-05*CountOfCells)+(3.190904E-09*
Sqr(CountOfCells)-(1.21275E-13*(CountOfCells*CountOfCells
*CountOfCells))+(-1.464094E-18*(CountOfCells*CountOfCells
*CountOfCells*CountOfCells));
end;
end;
{------------------------------

Procedure PostAleurone;
var
Patch:real;
begin
Patch—Exponent;
with Kernel[Position] do
begin
Aleurone:=true;
with CellComponents[Time] do
begin

Exponent:=107.2514-(6.888879E-03*CountOfCells)+
(1.488854E-07*Sqr(CountOfCells))-
(1.073883E-12*(CountOfCells*CountOfCells
*CountOfCells));
end;
end;
if Exponent > Patch then
Exponent:=Patch-5.42E-05;
end;
{
{----------------------------------------}
Procedure DecayGrowth;
var
Patch:real;
begin
Patch:=Exponent;
with Kernel[Position],CellComponents[Time] do
begin
Exponent:=-16580.19+(0.637903*CountOfCells)-
(6.135381E-06*Sqr(CountOfCells));
end;
if Exponent > Patch then
Exponent:=Patch-5.42E-05;
end;
{
{----------------------------------------}
Procedure DevelopEndosperm;
Var
NucellusReduction:real;
begin
NucellusReduction:=1.0073-0.0073*Position;
with Kernel[Position] do
begin
if Fertilized and (CellNo=0) then
begin
CellNo:=2;
CellComponents[Time].Meristematic:=2;
CellComponents[Time].CellsExist:=true;
end;
if CellNo <= 1024 then
Coenocytosis
else
begin
if CellNo <111000.0 then
PreAleurone

else
begin
PreAleurone

end;
else
    if CellNo <= 174600.0 then
      PostAleurone
    else
      DecayGrowth;
    end;

  TotalRate := (power(CountOfCells, Exponent)) * NucellusReduction;
  CellNo := (CellNo + TotalRate);
with CellComponents[Time] do
begin
  if Aleurone then
    Meristematic := CellNo * PostAlRatio
  else
    Meristematic := CellNo * PreAlRatio;
  Meristematic := Meristematic - CountOfCells;
  Amyliferous := abs(TotalRate - Meristematic);
  CellsExist := true;
end;
  if TotalRate < 5 then
    CellMax := True;
  if CellMax and (Position = Apex) then
end;
end;

{--------------------------------------------------------------------------}

Procedure MakeGranules;
  Var
    NucellusReduction: real;
begin
  with Kernel[Position], CellComponents[Age] do
begin
    NucellusReduction := 1.005 - 0.005 * Position;
    AmylGranules := Trunc(AmylGranules + (GranulesPerDay * 
      NucellusReduction * TempResM));
    if Aleurone then
      MerisGranules := Trunc(MerisGranules + (((GranulesPerDay * 
        NucellusReduction)/2) * TempResM));
    CriticalAge := Trunc(DevelopMachinery - ((DevelopMachinery 
      * 0.12) * (abs(MeanTemp - RefTemp))));
    if (Time - (Age - 1)) >= CriticalAge then
      MakingStarch := True;
end;
end;
{--------------------------------------------------------------------------}
Procedure CalculateSinkDemand(AmylGranules, Amyliferous, MerisGranules, Meristematic: real);

Var
AmylDryMatter, AmylCost, AmylNew, AmylSink, GramsN, ProteinCost: real;
GramsProtein, MerisCost, MerisDryMatter, MerisNew, MerisSink: real;

begin
AmylNew := AmylGranules * Amyliferous;
MerisNew := MerisGranules * Meristematic;
GranuleSum := GranuleSum + AmylNew + MerisNew;
AmylSink := AmylGranules * Amyliferous;
MerisSink := MerisGranules * Meristematic;

AmylDryMatter := AmylSink * GranuleRate;
AmylCost := AmylDryMatter * 1.173;

MerisDryMatter := MerisSink * (GranuleRate / 3);
MerisCost := MerisDryMatter * 1.173;

GramsN := (AmylCost + MerisCost) * 0.4 * 0.039;
GramsProtein := GramsN * 6.25;

If AmmoniumN then
   ProteinCost := GramsProtein * 1.762
else
   ProteinCost := GramsProtein * 2.484;

NewDryMatter := AmylDryMatter + MerisDryMatter + GramsProtein;
SinkDemand := AmylCost + MerisCost + ProteinCost;
end;

Procedure DevelopEar;
begin
if Time <= 25 then
   MaxAge := Time
else
   MaxAge := 25;
Labile := 0;
With Kernel[Position] do
   begin
      GranuleSum := 0;
      if not CellMax then DevelopEndosperm;
      For Age := 1 to MaxAge do
         begin
...
With CellComponents[Age] do
begin
  if CellsExist then
    if not MakingStarch then
      MakeGranules
    else
      CalculateSinkDemand(AmylGranules,
                           Amyliferous,
                           MerisGranules,
                           Meristematic);
  end;
end;
end;
end;

{-----------------------------------------------}
Procedure Pollination;
begin
  SilkEmerged:=101-exp(4.57-0.88*TimeStep);
  SilkLength:=(EarLength+(EarElongationRate*TimeStep))-(((EarLength+
                                                          (EarElongationRate*TimeStep))*SilkEmerged)/100);
  if TimeStep=1 then
    position:=1
  else
    if TimeStep=2 then
      Position:=32
    else
      if TimeStep=3 then
        Position:=46
      else
        if TimeStep=4 then
          Position:=53
        else
          if TimeStep=5 then
            Position:=57
          else
            if TimeStep=6 then
              Position:=60;
              TimeStep:=TimeStep+1;
              TubeGrowthRate:=((-0.005*Position)+0.48)*((0.1*MaxTemp)-0.5)*24;
              PollenTubeLength:=PollenTubeLength+TubeGrowthRate;
              if PollenTubeLength >= SilkLength then
                Fertilized:=true;
  end;
{------------------------------------------------------------}

Procedure EarOneGrowth;
begin
if SilkEmerged < 100 then
Pollination;
For Position:=Base to Apex do
begin
if Fertilized then
begin
DevelopEar;
With Kernel[Position],CellComponents[Age] do
begin
NewDryMatter:=(NewDryMatter*KernelRows*PlantingDensity*1000);
SinkDemand:=(SinkDemand*KernelRows*PlantingDensity*1000);
if NetPs >= SinkDemand then
begin
GrainWt:=(GrainWt+NewDryMatter);
end
else
if NetPs < SinkDemand then
begin
Remobilize;
GrainWt:=GrainWt+NetPs+Labile;
end;
end;
end
end;
{------------------------------------------------------------}

Procedure GermToEmerg;
Var
ColeoptileL,InternodeL,AColeoptile,BColeoptile:real;
AInternode,BInternode,SumL:real;
begin
DaysFromGermToEmerg:=0;
germination:= true;
repeat
DaysFromGermToEmerg:=DaysFromGermToEmerg+1;
DaysFromPlanting:=DaysFromPlanting+1;
GDD;
if (Maxtemp>=10) and (MaxTemp <=40) then
begin
AColeoptile:=3.1-0.16*MaxTemp+0.0031*MaxTemp*MaxTemp;
$BCoIeoptiIe:=0.065-0.014*MaxTemp+0.00089*MaxTemp*MaxTemp$  
$-0.000015*MaxTemp*MaxTemp*MaxTemp;$

$ColeoptileL:=AColeoptile*exp(BColeoptile*24);$  
$AIntemode:=0.22+0.02*MaxTemp+0.00029*MaxTemp*MaxTemp;$  
$BIntemode:=-0.07+0.013*MaxTemp-0.00092*MaxTemp*MaxTemp$  
$+0.000038*MaxTemp*MaxTemp*MaxTemp-0.00000056*MaxTemp*MaxTemp*MaxTemp$  
$MaxTemp*MaxTemp*MaxTemp*MaxTemp;$

$InternodeL:=AIntemode*exp(BIntemode*24);$  
$Until ShootL >= (PlantingDepth*10);$  
$germination:=FALSE;$

Procedure EmergToJuvenile;
  begin
    CobResG:=0;
    CobResM:=0;
    StemResM:=0;
    StemResG:=0;
    DaysFromEmergToJuvenile:=0;
    Expanded_5_Leaves;
    OldLeafNum:=6;
    writeln(OutFile,' Leaf :12,' Root ':12,' Stem ':12,' Leaf ':12,' LAI ':12,' Grain ':12);
    writeln(OutFile,' Wt :12,' Wt ':12,' Num ':12,' :12,' Wt ':12);
    writeln(OutFile,'(kg/ha):12,(kg/ha):12,(kg/ha):12,' :12,' :12,(kg/ha):12);
    repeat
      DaysFromEmergToJuvenile:=DaysFromEmergToJuvenile+1;
      DaysFromPlanting:=DaysFromPlanting+1;
      GDD;
      ExpandedLeaves;
      LeafGrowth;
      Photosynthesis;
      Respiration;
      NetPhotosynthesis;
      JuvenileWeight;
      TotalLeavesNumber;
      Transpiration;
      WaterTable;
      writeln(OutFile,LeafWeightT:12:2,RootWeight1:12:2,StemWeight1:12:2,$TotalLeavesNum:12:2,LA1:12:2,GrainWt:12:2);$  
      Until CumDTT >= P1;
end;
{---------------------------------------------------------------------}

Procedure JuvenileToTassel;
Var
  RATEIN:real;
begin
  CobResG:=0;
  CobResM:=0;
  StemResM:=0;
  StemResG:=0;
  DaysFromJuvenileToTassel:=0;
repeat
  DaysFromJuvenileToTassel:=DaysFromJuvenileToTassel+1;
  DaysFromPlanting:=DaysFromPlanting+1;
  GDD;
  ExpandedLeaves;
  LeafGrowth;
  Photosynthesis;
  Respiration;
  NetPhotosynthesis;
  JuvenileWeight;
  TotalLeavesNumber;
  Transpiration;
  WaterTable;
  RATEIN:=1/(4+P2*(DayLength-12.5));
  SIND:=SIND+RATEIN;
  writeln(OutFile,LeafWeightT:12:2,RootWeight1:12:2,StemWeight1:12:2,
    TotalLeavesNum:12:2,LAI:12:2,GrainWt:12:2);
Until SIND >= 1;
Temp1:=LeafWeight;
Temp2:=RootWeight;
Temp3:=StemWeight;
Temp4:=CobWeight;
end;
{---------------------------------------------------------------------}

Procedure TasselToSilk;
begin
  DaysFromTasselToSilk:=0;
  TotalLeavesNumber;
  P3:=(TotalLeavesNum-2)*38.9+96;
repeat
  DaysFromTasselToSilk:=DaysFromTasselToSilk+1;
  DaysFromPlanting:=DaysFromPlanting+1;

if(DaysFromTasselToSilk >= 10) then
  InitialKernelNumber;
writeln(OutFile, LeafWeight: 12:2, RootWeight: 12:2, Stem Weight: 12:2, TotalLeavesNum: 12:2, LAI: 12:2, Grain Wt: 12:2);
Until CumDTT >= P3;
MaxLAI := LAI;
Temp1 := LeafWeight;
Temp2 := RootWeight;
Temp3 := Stem Weight;
Temp4 := Cob Weight;
MinStemW := Stem Weight * 0.85;
MinRootW := Root Weight * 0.85;
MinLeafW := Leaf Weight * 0.85;
end;
==============================================================
Procedure GrainFill;
begin
  CumDTT := 0;
  repeat
    DaysToGrainFill := DaysToGrainFill + 1;
    DaysFromPlanting := DaysFromPlanting + 1;
    GDD;
    if ThereIsLeafArea then
      CalculateLAI;
    PostSilkingWeight;
    Photosynthesis;
    Respiration;
    NetPhotosynthesis;
    EarOneGrowth;
    if (NetPs > 0) then
      Partition;
    Transpiration;
    WaterTable;
    writeln(OutFile, LeafWeight: 12:2, RootWeight: 12:2, Stem Weight: 12:2,
Until (NetPs+Stalk<=0) and (LeafWeightT<=MinLeafW);
writeln(OutFile,'end');
Temp1:=LeafWeight;
Temp2:=RootWeight;
Temp3:=Stem Weight;
Temp4:=CobWeight;
end;

Procedure PhysiologicalMaturity;
  var
    DaysToMaturity:integer;
  begin
    DaysToMaturity:=0;
    CumDTT:=0;
    repeat
      DaysToMaturity:=DaysToMaturity+1;
      DaysFromPlanting:=DaysFromPlanting+1;
      GDD;
      writeln(OutFile,LeafWeightT:12:2,RootWeightl:12:2,StemWeightl:12:2
        ,TotalLeavesNum:12:2,LAI:12:2,GrainWt:l2:2);
    Until DTT >= 2.0;
    writeln(OutFile,'Days to emergence:', DaysFromGermToEmerg:4,' days');
    writeln(OutFile,'Emergence to juvenile:',DaysFromEmergToJuvenile:4,' days');
    writeln(OutFile,'Juvenile to tassel:',DaysFromJuvenileToTassel:3,' days');
    writeln(OutFile,'Tassel to silking:',DaysFromTasselToSilk:4,' days');
    writeln(OutFile,'Days to silking:',DaysFromGermToEmerg+
      DaysFromEmergToJuvenile+DaysFromJuvenileToTassel+
      DaysFromTasselToSilk:4,' days');
    writeln(OutFile,'Days to physiological maturity:',DaysFromPlanting:5,' days');
    writeln(OutFile,'Kernel Number for ear one:',KernelNumER1*
      PlantingDensity:8:2);
    writeln(OutFile,'End of the file');
    writeln(OutFile,'-----------------------------------------------');
    writeln(OutFile,'-----------------------------------------------');
    writeln(OutFile,'-----------------------------------------------');
  end;

Begin {Program}
  InitialValues;
  GetInformation;
  OpenSFile;
  GetPlantingDate;
GermToEmerg;
EmergToJuvenile;
JuvenileToTassel;
TasselToSilk;
Initialize;
GrainFill;
PhysiologicalMaturity;
end.
APPENDIX B

PROGRAM DISK AND USER INSTRUCTION

Maize-S is provided as a source code. The program should run under any Pascal compiler on an IBM computer. Three weather files are provided (Ames95.txt, Ames96.txt, and Arms95). A copy of a soil file (Sfile) is also provided. The output file (OutToFile) should be created on drive C. To run the model, execute Maize-S. When the program prompts: "Enter the name of weather file to use:", enter drive letter and file name. After you answer the rest of the questions, the program will execute. The results will be written to the output file (OutToFile).
Figure 1. Flow chart of the procedures simulating seedling emergence stage.
Figure 2. Flow chart of the procedures simulating the phase after seedling emergence to the end of juvenile phase.
Figure 3. Flow chart of the procedures simulating tassel initiation phase.
Figure 4. Flow chart of the procedures simulating the phase after tassel initiation to silking.
Figure 5. Flow chart of the procedures simulating grain filling period.
Figure 6. Flow chart of the procedures simulating physiological maturity.
REFERENCES


ACKNOWLEDGMENTS

The support and guidance of my major professor, Dr. Richard Salvador, has been gratefully appreciated. He was always available to answer questions and to provide support, encouragement and understanding.

The members of my committee of study are: Dr. Irvine C. Anderson, Dr. R. Brent Pearc, Dr. William Bachelor (Agriculture and Biosystem Engineering Department), and Dr. Kirk Moloney (Botany Department). All my committee members were very helpful and supportive, especially Dr. Irvine C. Anderson and Dr. R. Brent Perch. Dr. Bill Bachelor helped me during the development of the vegetative component of the model. He also provided me with the data I used to validate the model. I sincerely thank them for every thing they done.

The assistance of Anthony Anaele has been also appreciated. During data collection, he drove me to the farm and helped with my work in the lab.

I also want to thank my co-workers the Agriculture Research Center in Egypt for their help and support in the time when I was in Egypt from January to August of 1997, especially Dr. Samia Gouda. Special thanks to Dr. Ahmed Abed El-Haleem, my previous supervisor (Agriculture Research Center. Egypt), for his help and support during my stay in Egypt.

Thanks to everyone in the Agronomy department for making my studies at Iowa State University rewarding and memorable.