Description and performance of CERES-Wheat: A user-oriented wheat yield model

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CHAPTER 10. DESCRIPTION AND PERFORMANCE OF CERES-WHEAT: A USER-ORIENTED WHEAT YIELD MODEL

J. T. Ritchie and S. Otter[1]

INTRODUCTION

CERES-Wheat is a wheat yield model developed as a result of the ARS-Wheat Yield Project and the U. S. Government Multi-Agency AgRISTARS program. It was developed to meet the need of user agencies having primary responsibilities for making large-area yield forecasts for the U. S. and abroad. At the beginning of the ARS-Wheat Project, representatives from these agencies indicated that their present techniques, consisting mostly of statistical models, had several weaknesses that limited their reliability. They were requesting the assistance of a research group like ARS for ideas on modifying their present procedures or for developing entirely new modeling approaches to the problem.

Our early interests at Temple were modeling the soil water balance and how water deficits influence crop growth and yield. We had experienced limited success in modeling the water balance in a general way so that the model could be used successfully anywhere in the world. The problem with using the model, however, had been that the important input information on leaf area index (LAI) over the season was often not available. Our ARS group, in cooperation with Texas A&M scientists, then attempted to model the LAI of grain sorghum as a means of approximating LAI values needed in the water balance model. We demonstrated fairly good generality in a grain sorghum model, at least for the U. S. Great Plains area (Arkin et al., 1976). That model could also estimate biomass reasonably well using a simple light interception model.

From the success in modeling the soil water balance and grain sorghum LAI and biomass, it seemed only reasonable to use similar principles to develop a wheat yield model. The challenge, however, was to add genetic characteristics to the modeling concepts for global applicability and to develop relatively simple assimilate partitioning procedures so that yield components could be estimated. With the assistance primarily of H. A. Nix, R. A. Fischer, J. N. Gallagher, and H. J. Spiertz from outside the U. S., and several Federal and State scientists in the U. S., some procedures for incorporating genetic and partitioning factors into a model were developed. These procedures became the basis for parts of the CERES-Wheat Model.

The word CERES is a Greek word from which we have obtained the word cereal. It is an acronym for Crop Estimation through Resource and Environment Synthesis. The major purpose of the CERES models developed by the ARS Crop Systems Evaluation Research Unit at Temple is to provide users with an operational model that could be used for the following applications:

- --- Assistance with farm decision making
- --- Risk analysis for strategic planning
- --- Within-year management decisions
- --- Large area yield forecasting; foreign and domestic
- --- Policy analysis
- --- Definition of research needs

In order to achieve these objectives, it was necessary to become familiar

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with procedures presently being used for some of the various purposes listed above and to understand some of the limitations encountered in making a model useful for a specific purpose. The main features needed for a user-oriented model appeared to be: (1) The input information on weather, soils, and genetics should be available, (2) it should be written in a familiar computer language, and (3) the computational time should be minimal. Most of the input information needed for CERES is available from routinely collected daily weather data and soil information from standard soil classification data. The program is written in a familiar programming language, FORTRAN, and runs on a main-frame computer such as the AMDHAL 470. Simulation of a growing season uses about one second of central processing unit time.

In order to simplify the model as much as possible, many "rational empiricisms" are used to indirectly incorporate information from several levels of organization into relationships needed to make the model work for a community of plants growing in a field environment. Sometimes the empiricisms can be obtained from simplications of more complex models of certain processes. To be sufficiently general, the model must incorporate information from at least 8 levels of biological organization. These levels include molecules, cell structures, cells, tissue, organs, individuals, populations, and communities. Including all these levels of organization into a model system would be practically impossible. For example, the yield model has to directly or indirectly evaluate the uptake of CO_2 molecules through stomata on leaves of individual crop plants growing in a community of plants competing for resources over all or part of a year. To completely simulate these processes according to known principles available from each level of organization would require massive computer time and programming and almost minute-by-minute values of radiation and temperature. However, Monteith (1977) has demonstrated that a quite general empiricism to calculate biomass production for plant communities can be obtained by using total daily radiation interception, with modification for extremes in temperature or for water stress. We have found other useful empiricisms to describe the main features of other important processes that vary considerably in short-time intervals such as leaf extension growth, transpiration, infiltration, and drainage.

MAIN FEATURES OF CERES-WHEAT

Because the purpose of CERES-Wheat is to provide yield estimation to users, the main features of the model deal with the factors considered to be most influential in determining final yields. These include:

- --- Phasic development or duration of growth stages as related to plant genetics, weather, and other environmental factors
- --- Apical development as related to morphogenesis of vegetative and reproductive structures
- --- Extension growth of leaves and stems and senescence of leaves
- --- Biomass accumulation and partitioning
- --- Soil water deficit impact on growth and development
- --- Nitrogen deficit impact on growth and development

Obviously, there are many factors overlooked in the list that cause reductions in crop yields. Such limiting factors include weeds, diseases, and insects. This type of problem is not included in the general models because

the factors are more random in nature, they can usually be controlled through management, and the species are so numerous and varied that they could not be dealt with in balance with other components of the model. However, leaving out these and other known important limiting factors on yield in the general model by no means minimizes their importance nor does it imply that they are too complex to model. A particular limiting factor could be added to the general crop model for a specific application.

Although it would be desirable to discuss the scientific principles in the empirical relationships used in CERES-Wheat, this paper provides only a general description of the model. More detail is available in the preliminary model documentation (Ritchie and Otter, 1984). Also, because the nitrogen dynamics section of the model was mainly developed for management-related problems rather than large-area yield estimation, it will not be discussed here.

Inputs needed for CERES-Wheat are related to weather, soil, genetics and management. Weather inputs are restricted to daily solar radiation, maximum and minimum air temperature, and precipitation. These values are usually available at many locations with the exception of solar radiation. Solar radiation can be approximated from percent of possible sunshine data. In the future, solar radiation will likely be available in mapped form from NOAA-National Environmental Satellite Service for all the 48 contiguous states. There is presently an operational test of the solar radiation estimating program.

Soil input information needed includes drainage and runoff coefficients, evaporation and radiation reflection coefficients, soil water-holding capacity amounts, and rooting preference coefficients at several depth increments. It also requires saturated soil water content and initial soil water content for the first day of the weather data series.

Genetic input information needed are coefficients related to photoperiod sensitivity, duration of grain filling, conversion of mass to grain number, grain filling rates, vernalization requirements, stem size, and cold hardiness.

Management input information required is plant population, planting depth, and date of planting. If irrigation is used, the date of application and amount is required. Latitude of site is another needed input. The model can use different weather, soils, genetic and management information within a growing season or for different seasons in a single model execution. A few input parameters are used to control the input information for each growing season.

PHASIC DEVELOPMENT

Phasic development in CERES-Wheat deals with the duration of growth stages. The growth stages are organized around times in the plant life cycle when changes occur in partitioning of assimilate among different plant organs. For example, prior to terminal spikelet formation, all assimilate is partitioned between leaves and roots. After terminal spikelet formation, stems begin to require assimilate and later the ear becomes a major site for assimilates.

The growth stages are numbered between 1 and 9. Stages 1 through 5 are the active above-ground growing stages and the remainder are used to describe other important events in the crop cycle. The growth stages include:

Stage No.	Event	Plant Parts Growing
7	Fallow or presowing	
8	Sowing to germination	
9	Germination to emergence	roots, coleoptile
1	Emergence to terminal spikelet initiation	roots, leaves
2	Terminal spikelet to end of leaf growth	roots, leaves, stems
3	End of leaf growth to end of pre-anthesis ear growth	roots, stems, ear
4	End of pre-anthesis ear growth to beginning of grain filling	roots, stems
5	Grain filling	roots, stems, grain
6	End of grain filling to harvest	

Phasic Development Control

Both genotype and environment influence the phasic development in CERES-Wheat. The primary variable influencing development rate is temperature. We assumed that development rates are directly proportional to temperature in the range from the base temperature of 0°C to a maximum temperature of about 30°C. Thus we accumulate daily temperature above 0°C and refer to that as thermal time.

When the minimum temperature is above 0°C and the maximum is below 30°C, thermal time for a day is assumed to be the mean of the two values. If either the maximum or minimum temperature is out of that range, a separate thermal time calculation is made using the mean temperature and temperature range.

The thermal time for all growth stages is not fixed. Vernalization, photoperiod, and genetic characteristics cause total thermal time for stage 1 to vary considerably. Thermal time for stage 5 (grain fill) is variable between genotypes. In other stages, plants have fixed thermal time duration except for sowing to germination. That process is assumed to take one day where there is adequate soil water in the seed zone. Germination is delayed if the soil water is below a threshold value, or if the mean temperature is below 3°C.

Winter wheats require exposure to relatively low temperatures before spikelet formation can normally occur. The phenomenon is called vernalization. Vernalization begins at germination. Synthesis of literature and some of our own phytotron work suggests that vernalization does not occur below 0°C nor above 15°C. Optimum temperature for vernalization is assumed to be in the 0°C to 7°C range with a decreasing influence between 7°C and 15°C. Maximum and minimum temperatures are used to calculate a daily vernalization effectiveness factor between 0 and 1. The effectiveness factor is then accumulated to determine duration of effective vernalization or vernalization days. Fifty vernalization days are considered sufficient for all cultivars, but there is genetic variability in sensitivity to vernalization. Thus we use a genetic specific coefficient (PIV) to calculate the influence of vernalization on the duration of growth

stage 1. Spring wheats have a low sensitivity to vernalization. This is considered in the model through the vernalization coefficient (P1V).

In some instances devernalization can occur when young seedlings are exposed to high temperatures. In the model, if the vernalization-days are below 10 and the maximum temperature exceeds 30°C, then vernalization days decrease in proportion to the temperature above 30°C.

Photoperiod also can cause a delay in plant development in stage 1. In CERES-Wheat, daylengths shorter than 20 hours cause a delay in development somewhat proportional to the shortness of the day. The extent of the delay is dependent on a genetic-specific characteristic (P1D). Photoperiods calculated in the model include civil twilight.

Vernalization days and photoperiod are used to modify the accumulation of thermal time in stage 1. Vernalization and photoperiod factors with values between 0 and 1 are calculated using the P1V and P1D coefficients and the minimum value of the two is multiplied by the thermal time to reduce the usual thermal time calculations. When the reduced thermal time reaches 400 degree days, stage 1 ends. We believe this procedure for determining when terminal spikelet occurs can be improved, but more research will be required.

GROWTH AND ORGAN DEVELOPMENT

Dry Matter Production

In CERES-Wheat, potential dry matter production is a linear function of intercepted photosynthetically active radiation (PAR). The constant for conversion is 3.05 grams biomass per MJ of intercepted PAR. The value of PAR above the canopy is equal to 50% of the incoming solar radiation after conversion of the units from langleys to MJ per square meter. The percentage of incoming PAR intercepted by the canopy is an exponential function of leaf area index (LAI).

The actual rate of dry matter production is usually less than the potential rate due to the effects of non-optimal temperature or water stress. A weighted daytime temperature is calculated from the minimum and maximum temperatures for use in the biomass evaluation. The optimum daytime temperature is considered as 18 C. Water stress reduces dry matter production rates below the potential whenever crop extraction of soil water falls below the potential transpiration rate calculated for the crop.

Leaf and Tiller Development and Expansion Growth

Plant leaf area has an important influence on light interception and dry matter production. The rate of leaf area expansion is a component of plant growth that is quite sensitive to environmental stresses. For example, leaf growth is more sensitive to plant water deficits than photosynthesis. In addition, the optimum temperature for leaf growth is several degrees higher than for photosynthesis. Thus, cool temperatures or moderate drought stresses reduce expansion growth more than photosynthesis is reduced, causing increases in specific leaf weight and increasing the proportion of assimilate partitioned to roots. CERES-Wheat accounts for these plant responses by using separate relationships to calculate the influence of temperature and water deficits on photosynthesis and leaf growth.

The daily growth of plant leaf area is the product of the total width of expanding leaves on a plant, the maximum daily rate of length extension growth of a leaf, a reduction factor for non-optimal temperatures, and a reduction factor for water deficit. Total width of expanding leaves is the product of the number of growing leaves on a plant including tillers and the average width of a leaf. An empirical expression is used to combine leaf appearance rates with tillering rates to determine average number of growing leaves and their width. The optimum temperature for leaf expansion growth is 21°C. Soil water availability can limit leaf growth even before transpiration is reduced. Whenever maximum possible root water absorption on a day is less than 1.5 times the potential transpiration, the rate of leaf extension decreases. This important part of the model, especially for stage 1 growth, can likely be improved, but data sets available often lack details necessary to evaluate or improve the model.

Leaf Senescence

Leaf senescence is primarily coupled with crop phasic development. Senescence is initially slow, increasing as the plant approaches physiological maturity. In addition to natural senescence with normal phasic development, low temperatures and water deficits can accelerate senescence. Competition for light in dense canopies also hastens senescence. For cold temperature stresses, the degree of senescence is affected by the degree to which the crop has hardened from previous exposure to cold temperatures. Unhardened leaves are more susceptible to rapid leaf senescence than hardened leaves.

Tiller Death

Usually there are several more tillers developed and visible at terminal spikelet formation than can become full mature tillers with heads. Accounting for this loss of tiller growth has been one of the more difficult parts of wheat growth modeling. Thus it is common to make sizable errors in the final tiller numbers with the model when comparing the output with measured field data. However, this factor does not cause a serious error in the grain number or yield calculations because the number of tillers expanding stems is controlled by a source-sink balance. Thus, if tiller number estimation is low, tiller size is high and vice-versa. Tiller loss occurs in stage 2 when the stems are actively expanding. In the model, the potential growth rate of a single stem is calculated, based on a genetic-specific characteristic which distinguishes between wheat stem growth habits. The biomass allocated to stem growth of an entire plant on a given day is divided by the biomass required per individual stem to determine how many stems can expand with the available assimilate supply. A time lag factor prevents rapid decreases in tiller number due to large day to day variations in photosynthesis rates.

Root Growth

Biomass is partitioned into shoots and roots. The proportion partitioned to roots affects root density and thus the ability of the root system to supply the shoot with water and nutrients. The fraction of dry matter production partitioned to the root depends primarily on the growth stage of the crop. The fraction partitioned to roots usually declines as the plant matures. However, at all growth stages except stage 5, the fraction partitioned to roots increases with water deficits. When competition for light is high with dense canopies, the fraction partitioned to roots decreases. These compensating mechanisms are certainly real but have been difficult to quantitatively describe in the model.

The total growth of roots in a day is determined by the amount of biomass partitioned to the roots. To determine the distribution of roots in the soil, a rooting preference factor is input for each soil layer. The preference factor usually decreases rapidly with depth but root restricting factors may vary at any soil depth. The preference factor of a layer is reduced when the soil water content is below a threshold value. Thus, when a particular soil layer becomes quite dry, root growth in that layer decreases, but compensatory root growth normally occurs elsewhere in the profile where the water status is more favorable.

Grain Number and Kernel Growth Rates

In CERES-Wheat the number of grains per plant is a linear function of a genetic factor and stem plus ear weight at the end of growth stage 4. The assumption is that if conditions during stem and pre-anthesis ear growth favor large stems and ears, then grain numbers will be high. The genetic coefficient accounts for known differences between genotypes in number of grains per ear. If severe stresses occur during grain filling, some grain abortion will occur to reduce final grain numbers.

The maximum possible kernel growth rate during stage 5 is an input genetic parameter. Kernel growth rate can be reduced from the maximum when mean temperatures drop below about 17°C or when the total kernel sink demand for assimilate exceeds the available supply. The assimilate supply comes from both current assimilate and stored assimilate. The supply of stored assimilate is assumed to be equal to the amount of assimilate partitioned to the stem during stage 4 plus excess assimilate not needed for grain filling during stage 5. Plant water deficits have no effect on grain filling except indirectly through a reduction in the assimilate supply during grain filling.

Final grain yield is the product of plant population, kernels per plant and weight per kernel.

SOIL WATER BALANCE

The soil water balance is calculated in CERES-Wheat in order to evaluate the possible yield reduction caused by soil and plant water deficits. As a model option controlled by an input parameter, the soil water balance can be assumed non-limiting for all plant processes in the model. In that case, the water balance routine is by-passed.

The soil inputs set several user-selected soil depth increments where water balance calculations are made. Water contents in any layer can increase due to infiltration of rain, melted snow, irrigation water, or due to flow from an adjacent layer. Water content can decrease due to soil evaporation, root absorption or flow to an adjacent layer. The limits to which water content increase or decrease are also input for each layer as the lower limit of plant water availability, the field drained upper limit and the field saturated water content. These input limits are quite important in model runs where water availability is marginal and the traditional techniques for estimating them may not be accurate enough. Our research unit has reported on this problem and suggested possible solutions for obtaining improved input limits in 3 papers; Ritchie (1981), Ratliff, Ritchie and Cassel (1983), and Cassel, Ratliff and Ritchie (1983).

Infiltration is calculated as the difference between daily precipitation or snowfall and runoff. Runoff is estimated using a Soil Conservation Service Curve Number technique as modified for layered soil by J. R. Williams (personal communication) in other hydrology models. When irrigation inputs are encountered in the model, the runoff estimation is by-passed in order to allow all irrigation to infiltrate.

Because of the need to estimate snow depth for the cold hardening and winter killing part of CERES, an empirical approach is used to estimate snow depth. Snow accumulates when the daily maximum temperature is less than 1°C. We assume 1 cm of snow per mm rain under those conditions. Snow melts at a rate proportional to the daily maximum temperature and the rainfall amount.

Drainage is calculated as a function of the water content above the drained upper limit (DUL). A single drainage coefficient for the entire profile is input from the soils information that varies between 0 and 1. The constant is used for drainage from every soil layer under the assumption that a most limiting layer for water flow will dominate the drainage from the entire profile. The drainage coefficient represents the fraction of the water content between the DUL and field saturation that can drain in successive days after the soil is wet to saturation. Thus, if the coefficient is 0.5, half the water between DUL and saturation will drain the first day, half the remaining will drain the second day and half the remaining the third day, etc. For this example 87.5% of the difference between the DUL and saturation will have drained in three days. Drainage from the entire profile is represented by the drainage calculated from the lowest soil layer.

Evapotranspiration (ET) is calculated using procedures as primarily presented in a published model (Ritchie, 1972). The procedure separates soil evaporation (ES) from transpiration (EP) for plants growing without a shortage of soil water, primarily on the basis of energy reaching the soil, the time after the surface layer is wet and the LAI. Potential ET is calculated using an equilibrium evaporation concept as modified by Priestly and Taylor (1972). A relatively simple empirical equation was developed from several rather complex exponential equations needed to evaluate the net radiation and temperature influence on equilibrium evaporation. The equation approximates the daytime net radiation and equilibrium evaporation, assuming that stomata are closed at night and no ET occurs. The potential ET is calculated as the equilibrium evaporation times a constant (1.1) to account for unsaturated air. The constant is increased above 1.1 to account for advection when the maximum temperature is greater than 24°C. The constant is reduced for temperatures below 0°C to account for cold temperature influence on stomata closing.

The drying stage ES in the Ritchie (1972) model was altered for CERES-Wheat to further reduce ES when the soil water content in the upper soil layer reaches a low threshold value. This modification is needed for layered soils water balance evaluations to prevent the surface soil from drying

too much when root water absorption is also removing water from near the surface.

Root water uptake is calculated using an empirical evaluation of the maximum possible single root water uptake rates. The radial resistance to water flow into roots is assumed to vary with flow rates in such a way that any flow rate per unit root length can be accommodated up to a certain limiting maximum value. This maximum uptake per unit length as limited by soil water flow is calculated from a generalized hydraulic conductivity relation for each soil depth with a slight variation in the relation resulting from different root length densities. The maximum possible water uptake rate is assumed to be equal to the minimum value of the soil-limited or root-limited uptake rate.

Using estimates of root length density calculated from the root growth section of the model and soil water estimates, the maximum possible uptake per unit root length in each soil layer is then converted to the maximum uptake for the entire root system. If this maximum uptake value exceeds the calculated potential transpiration, then transpiration is assumed to occur at the potential rate. Under those circumstances, the calculated maximum uptake from each soil layer is reduced to the actual uptake by multiplying by the radio of transpiration to maximum total profile uptake. This procedure makes the total soil water uptake equal to the potential transpiration. If the maximum uptake for the entire root zone is less than potential transpiration, then the actual uptake becomes the maximum uptake, and the transpiration is reduced to that value. This reduction in transpiration, expressed as a fraction of the potential, is also used to reduce photosynthesis in the growth subroutine. When the ratio of maximum uptake to transpiration falls below 1.5, leaf and stem extension growth start to be reduced.

The potential rate of downward root growth is assumed to be proportional to the rate of plant development, and thus is controlled by temperature. The potential rate is reduced if the whole plant root absorption is less than the potential transpiration or if the soil layer where the front of new downward growth is occurring is below a threshold water content. The input root preference factor for each soil depth is used with the depth of rooting and the water content of each depth to determine the distribution of root growth in the profile. The mass of assimilate partitioned to the roots, as calculated in the plant growth section of the model, is converted to a root length, assuming a constant proportionality between root mass and length, to provide estimates of root length density. There is a small reduction in root length in each depth to account for root sloughing.

COLD HARDENING AND WINTER KILL

Under certain conditions, wheat plants can be killed or severely damaged by extremely low temperatures. The extent of the damage often is related to the hardening that has occurred prior to the low temperature event and the amount of protection the plants receive from snow cover. CERES-Wheat attempts to account for this possible loss because of its importance in large regions where wheat is grown.

The estimated crown-depth temperature is used to evaluate cold hardening and killing. Crown depth temperatures are calculated from empirical relations developed from data reported by Aase and Siddoway (1979). They found that crown depth soil temperature was proportional to air temperatures below 0°C, with the proportionality being dependent on snow depth.

Hardening is assumed to occur in two phases. In the first phase, hardening occurs when the soil mean crown temperature is between -1°C and 8°C. Ten days in this temperature range completes stage 1 hardening. Stage 2 hardening occurs after stage 1 hardening is complete and when the temperatures are below 0°C. Twelve days of this condition complete stage 2 hardening, resulting in a fully hardened plant.

The point at which tillers begin to be killed by low temperatures is a function of a hardening index that varies between 0 and 1 for stage 1 hardening and between 1 and 2 for stage 2 hardening. The threshold killing crown temperature is -6°C, -12°C and -18°C for hardening index values of 0, 1 and 2, respectively. Tiller numbers are reduced in proportion to the degree of coldness below the threshold killing temperature. If all tillers except the main stem are killed, the plant population is reduced in a similar way to the tiller loss.

Dehardening occurs when the crown temperature is 8°C. Under this condition, snow depth is assumed to be zero and the maximum temperature is used to calculate dehardening. The dehardening rate is proportional to the maximum temperature when it is above 10°C. The dehardening rate is twice as fast in stage 2 hardening than it is in stage 1 hardening. Many of the principles for the hardening and dehardening concepts used in CERES-Wheat were obtained from work of Gusta and Fowler (1976).

OUTPUT OPTIONS FOR USERS

Three types of output are available when using CERES-Wheat. A summary output is always printed. This output includes the identification of the run assigned by the user and most of the other input information on genetics, soils and management. When the development stage changes from one phase to another, the summary lists the calendar date, the day of the year, the cumulative thermal time after sowing, the above-ground biomass, and LAI. Yield and yield components are output at the end of stage 5. The summary output sheet also includes at each phase change an average of the stress coefficients for photosynthesis and extension growth during each phase of development and along with growing season cumulative values of ET, ES, EP (transpiration), and precipitation. Total potentially extractable soil water in the whole profile is also listed for each phase change. All these summary output details provide the user with information on the response of the crop for more detailed evaluation of yield response. An example summary output is shown in Figure 1.

Two optional output records are available to give greater details about the water balance components and growth components calculated with the model. For these optional output records, the frequency of output can be specified.

For the water balance, run information listed includes date of output, soil water content in each layer along with the total extractable water on that date, average daily ES, EP, ET and potential ET, solar radiation, and maximum and minimum temperatures for the period the user specifies is also


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                 *WEATHER=BUSHLD77     BUSHLAND - TEXAS    1977 - 1978  PD-2  T-4*

VARIETY NUMBER  541   VARIETY NAME    TAM W 101

LATITUDE =   35.2 , SOWING DEPTH =   11. CM , PLANT POPULATION = 230.PLANTS PER SQ METER

GENETIC SPECIFIC CONSTANTS  P1V =0.018  P1D =0.0060   P5= 480.   G2 = 17.00  G3 = 1.38  G4 = 0.63

SOIL ALBEDO= 0.12  U=   6.0  SWCON=   0.50    RUNOFF CURVE NO.=   60.0   SOIL NO.= 3

 JULIAN DAY      IRRIGATION(MM)
    286             100.
    341             100.
     82             100.
     98             100.
    115             100.
    138             100.

 DEPTH-CM        LOW LIM    UP LIM    SAT SW    EXT SW    INIT SW     WR

   0.-   15.      0.180     0.323     0.383     0.143     0.260     1.000
  15.-   30.      0.220     0.357     0.383     0.137     0.280     0.700
  30.-   60.      0.215     0.329     0.362     0.114     0.230     0.300
  60.-   90.      0.170     0.288     0.335     0.118     0.170     0.100
  90.-  120.      0.170     0.261     0.311     0.091     0.190     0.050
 120.-  150.      0.170     0.260     0.290     0.090     0.200     0.025
 150.-  180.      0.170     0.260     0.290     0.090     0.220     0.012
 180.-  210.      0.170     0.260     0.290     0.090     0.240     0.005

        210.0      37.9      59.9      67.8      22.0      45.6    TOTAL FOR PROFILE

    THE PROGRAM STARTED ON JULIAN DAY   210
                                                                                       WATER BALANCE COMPONENTS
          JUL    CUM                                                                  CUMULATIVE AFTER GERMINATION
  DATE    DAY    DTT         PHENOLOGICAL STAGE
                                                    BIOMASS     LAI     CSD1    CSD2     ET      ES      EP     PREC    PESW
10/12/77 285      0.   SOWING                                                           45.3    45.3     0.0    29.7    16.1
10/13/77 286      6.   GERMINATION                                                      17.3    17.3     0.0   106.3    15.0
10/26/77 299    150.   EMERGENCE, PHINT =   95.                                        202.4    99.3   103.1   341.3    20.0
 3/31/78  90   1046.   TERM SPIKELET, VERN DAYS=50.   325.     3.26     0.00    0.01   304.2   111.9   192.4   452.3    17.7
 4/19/78 109   1343.   END VEG BEGIN EAR GROWTH       809.     5.93     0.00    0.00   368.8   118.6   250.3   552.3    19.5
 5/ 2/78 122   1535.   END EAR GROWTH,EARS=  728.    1176.     5.08     0.00    0.00   440.4   128.2   312.2   587.6    15.7
 5/16/78 136   1716.   BEGIN GRAIN FILL,GPSM=15534.  1484.     4.62     0.00    0.00   574.0   160.9   413.0   905.6    20.4
 6/11/78 162   2199.   MATURITY,GRAIN WT = 0.0342    1764.     0.62     0.00    0.00

          YIELD (KG/HA) =   5305.      (BU/ACRE)=   79.2       FINAL GPSM=   15534.

 MEASURED VALUES ARE:    YIELD=4798. KG/HA      GRAIN WEIGHT= 35.8 MG       GPSM= 13510.
                         EARS=  847.        MAX. LAI= 0.0      FINAL BIOMASS=1571. G/M**2
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Figure 1. An example of summary output from CERES-Wheat.

printed. The total user-specified period runoff, drainage and precipitation are printed at the end of the period. An example water balance output is shown in Figure 2.

For the plant growth output record, the date of input is listed along with the model estimates of above-ground biomass, tiller number, LAI, cumulative thermal time, maximum root water uptake, senescent leaf area, water deficit factors, root depth, fraction of assimilate partitioned to plant top, and root length density for each soil depth. Details of the weight of single plant roots, stems, leaf and grain are also output at the specified frequency. An example growth output is shown in Figure 3.

CROP MODEL PERFORMANCE

Data sets of wheat production from several places in the world have been assembled for use in testing and improving CERES-Wheat. Much of the data has come from published sources and the remainder was obtained through personal communication. In all instances, needed details of weather and soil information were usually not available in published reports and were obtained through personal communication. All data sets lacked some detail needed to validate all components of the model. We often used data with good detail in certain processes to calibrate and test those parts of the model.

Our data base was created to be able to test the model in all types of environments where wheat is grown. A data set of about 300 crop years was obtained for testing. These data were from about 25 different sites in the world with a range of latitudes from 36°S in Australia to 50°N in England. At many sites, there was multiple year or multiple treatment information available.

The value of our testing depends to a large degree on the quality of measured data. In practically all data sets used, information was collected for research purposes other than model testing. Thus many desired details are lacking. The minimum requirements for testing were that the needed soils, weather, and management data were available along with some important phase of development and yield.

A scattergram of the estimated yield vs. the measured yields for 168 data sets considered to meet the minimum standards for quality and where nitrogen and other nutrients were assumed non-limited is shown in Figure 4. The bias for the 168 data sets was -104 kg/ha with a standard error of 102 kg/ha. The mean of the absolute difference between estimated and measured yields was 1070 kg/ha with a standard error of 60 kg/ha. Although we wish the model estimates and yield agreed more closely with the field measurements, we believe the large range in yields present in the data set provide a good test of the overall value of the generality of the model for use in the intended applications mentioned earlier in this paper.

Comparison of measured and model estimates of crop growth details during the season has helped in model testing. Figures 5, 6 and 7 show comparisons of seasonal changes in LAI, biomass and tiller number, respectively, for selected tests. In each test it is apparent that considerable experimental variation existed in the measurements, but the general trends and absolute values in the model agreed reasonably well with the measured data.

WEATHER=BUSHLD77 BUSHLAND - TEXAS 1977 - 1978 PD-2 T-4

	JUL	AVERAGE							PERIOD			SOIL WATER CONTENT WITH DEPTH										TOTAL
DAY	DAY	ES	EP	ET	EO	SR	MAX	MIN	RUNOFF	DRAIN	PREC	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9	SW10	PESW
8/ 4/77	216	0.5	0.0	0.5	9.9	607.	33.9	16.7	0.00	0.00	0.00	0.23	0.28	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	7.3
8/11/77	223	0.4	0.0	0.4	8.8	496.	34.4	18.7	0.00	0.00	0.00	0.22	0.28	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	7.0
8/18/77	230	0.4	0.0	0.4	6.5	489.	28.3	17.6	0.00	0.00	0.00	0.20	0.28	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.7
8/25/77	237	0.3	0.0	0.3	7.2	529.	29.6	17.7	0.00	0.00	0.00	0.19	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.5
9/ 1/77	244	0.3	0.0	0.3	5.8	422.	29.4	18.0	0.00	0.00	0.00	0.17	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.3
9/ 8/77	251	1.9	0.0	1.9	6.2	487.	28.7	15.4	0.00	0.00	24.60	0.25	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	7.4
9/15/77	258	0.5	0.0	0.5	5.4	454.	27.3	13.1	0.00	0.00	0.80	0.23	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	7.2
9/22/77	265	0.4	0.0	0.4	6.7	468.	31.7	12.0	0.00	0.00	0.00	0.21	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.9
9/29/77	272	0.6	0.0	0.6	5.9	427.	31.1	12.0	0.00	0.00	4.30	0.21	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.9
10/ 6/77	279	0.3	0.0	0.3	3.9	350.	24.2	9.8	0.00	0.00	0.00	0.20	0.27	0.23	0.17	0.19	0.20	0.22	0.24	0.00	UUUU	6.6
10/13/77	286	0.8	0.0	0.8	3.5	395.	20.7	4.7	0.00	0.00	100.00	0.33	0.37	0.35	0.26	0.19	0.20	0.22	0.24	0.00	UUUU	16.1
10/20/77	293	1.6	0.0	1.6	4.0	412.	24.4	2.8	0.00	0.00	0.00	0.27	0.34	0.33	0.28	0.19	0.20	0.22	0.24	0.00	UUUU	15.0
10/27/77	300	1.0	0.0	1.0	2.7	285.	23.2	5.3	0.00	0.00	6.30	0.27	0.33	0.33	0.28	0.19	0.20	0.22	0.24	0.00	UUUU	14.9
11/ 3/77	307	0.5	0.2	0.7	2.7	307.	20.2	3.0	0.00	0.00	0.00	0.25	0.33	0.33	0.28	0.19	0.20	0.22	0.24	0.00	UUUU	14.4
11/10/77	314	0.6	0.3	0.9	2.1	274.	17.7	-0.0	0.00	0.00	4.30	0.25	0.32	0.33	0.28	0.20	0.20	0.22	0.24	0.00	UUUU	14.2
11/17/77	321	0.4	0.5	0.9	2.5	317.	19.9	-1.1	0.00	0.00	0.00	0.23	0.31	0.32	0.27	0.20	0.20	0.22	0.24	0.00	UUUU	13.6
11/24/77	328	0.4	0.5	0.9	1.9	260.	16.7	-3.2	0.00	0.00	0.00	0.21	0.29	0.32	0.27	0.20	0.20	0.22	0.24	0.00	UUUU	13.0
12/ 1/77	335	0.3	0.6	0.9	1.6	226.	13.7	-2.9	0.00	0.00	0.00	0.20	0.28	0.31	0.27	0.20	0.20	0.22	0.24	0.00	UUUU	12.4
12/ 8/77	342	0.7	0.6	1.3	1.8	268.	14.0	-5.4	0.00	0.00	100.80	0.32	0.36	0.34	0.30	0.28	0.25	0.22	0.24	0.00	UUUU	21.6
12/15/77	349	1.2	0.5	1.7	1.7	273.	13.0	-6.6	0.00	0.00	0.00	0.27	0.34	0.33	0.29	0.26	0.26	0.26	0.24	0.00	UUUU	20.4
12/22/77	356	0.8	0.5	1.3	1.4	220.	12.2	-4.4	0.00	0.00	1.50	0.24	0.32	0.33	0.29	0.26	0.26	0.26	0.24	0.00	UUUU	19.6
12/29/77	363	0.5	0.7	1.2	1.4	219.	10.9	-5.4	0.00	0.00	0.00	0.21	0.31	0.32	0.28	0.27	0.26	0.26	0.24	0.00	UUUU	18.7
1/ 5/78	5	0.3	0.4	0.7	0.9	188.	9.0	-6.7	0.00	0.00	0.00	0.20	0.30	0.32	0.28	0.27	0.26	0.26	0.24	0.00	UUUU	18.2
1/12/78	12	0.3	0.6	0.9	1.1	256.	7.4	-7.7	0.00	0.00	0.00	0.19	0.29	0.31	0.28	0.27	0.26	0.26	0.24	0.00	UUUU	17.6
1/19/78	19	0.3	0.5	0.8	1.3	306.	4.3	-11.4	0.00	0.00	0.50	0.18	0.28	0.30	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	17.1
1/26/78	26	0.3	0.2	0.5	0.8	255.	3.0	-10.6	0.00	0.00	3.00	0.18	0.28	0.30	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	17.0
2/ 2/78	33	0.2	0.1	0.4	0.6	315.	0.6	-7.8	0.00	0.00	1.30	0.17	0.28	0.30	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	16.7
2/ 9/78	40	0.6	0.3	0.9	1.2	351.	4.8	-5.9	0.00	0.00	10.60	0.15	0.27	0.30	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	16.2
2/16/78	47	0.3	0.0	0.3	0.3	342.	-0.2	-9.2	0.00	0.00	8.40	0.21	0.27	0.29	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	17.0
2/23/78	54	0.6	0.1	0.7	0.7	396.	0.4	-11.5	0.00	0.00	1.50	0.25	0.27	0.29	0.27	0.26	0.26	0.26	0.24	0.00	UUUU	17.6
3/ 2/78	61	0.5	0.6	1.2	2.2	326.	10.9	-2.4	0.00	0.00	0.80	0.22	0.27	0.29	0.26	0.26	0.26	0.26	0.24	0.00	UUUU	16.8
3/ 9/78	68	0.4	0.7	1.1	1.9	368.	7.2	-7.3	0.00	0.00	0.00	0.20	0.26	0.28	0.26	0.26	0.26	0.26	0.24	0.00	UUUU	16.1
3/16/78	75	0.4	1.6	2.0	3.3	446.	16.7	-1.5	0.00	0.00	0.00	0.18	0.25	0.26	0.25	0.26	0.26	0.26	0.24	0.00	UUUU	14.7
3/23/78	82	0.4	2.4	2.8	3.8	460.	21.8	1.8	0.00	0.00	100.00	0.34	0.37	0.35	0.30	0.26	0.26	0.26	0.24	0.00	UUUU	22.7
3/30/78	89	1.2	2.3	3.5	3.5	479.	17.8	1.8	0.00	0.00	2.30	0.27	0.32	0.32	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	20.5
4/ 6/78	96	1.0	4.5	5.5	5.5	560.	27.3	6.1	0.00	0.00	0.00	0.20	0.26	0.28	0.27	0.26	0.26	0.26	0.26	0.00	UUUU	16.6
4/13/78	103	0.6	4.5	5.1	5.1	575.	23.2	5.4	8.16	21.15	111.00	0.29	0.33	0.32	0.29	0.26	0.26	0.27	0.27	0.00	UUUU	21.2
4/20/78	110	0.5	4.8	5.3	5.3	617.	23.8	4.5	0.00	2.65	0.00	0.22	0.27	0.28	0.27	0.26	0.26	0.26	0.26	0.00	UUUU	17.3
4/27/78	117	0.5	4.5	5.0	5.0	618.	22.4	4.8	0.00	5.87	100.00	0.31	0.35	0.33	0.29	0.27	0.27	0.27	0.27	0.00	UUUU	23.1
5/ 4/78	124	0.4	3.4	3.9	3.9	418.	19.6	5.6	1.00	11.67	30.50	0.33	0.36	0.33	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	22.2
5/11/78	131	0.6	3.9	4.5	4.5	579.	19.9	6.3	0.80	0.00	4.80	0.26	0.32	0.31	0.27	0.26	0.26	0.26	0.26	0.00	UUUU	19.4
5/18/78	138	1.0	6.2	7.2	7.2	657.	28.7	10.6	0.00	0.76	100.50	0.34	0.36	0.34	0.31	0.28	0.27	0.26	0.26	0.00	UUUU	24.4
5/25/78	145	0.8	4.6	5.4	5.4	466.	29.0	13.2	1.71	14.92	11.20	0.27	0.32	0.31	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	20.1
6/ 1/78	152	1.0	4.3	5.3	5.3	548.	25.5	13.2	78.98	1.63	118.30	0.27	0.32	0.31	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	20.1
6/ 8/78	159	1.5	2.4	3.9	3.9	472.	22.6	12.5	37.40	1.17	88.00	0.32	0.36	0.33	0.29	0.26	0.26	0.26	0.26	0.00	UUUU	22.3
6/15/78	166	1.7	1.5	3.2	8.0	687.	29.0	15.9	0.00	0.67	0.00	0.23	0.33	0.32	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	20.0
6/22/78	173	0.6	0.0	0.6	9.9	646.	32.1	18.1	0.00	0.00	0.00	0.21	0.32	0.32	0.28	0.26	0.26	0.26	0.26	0.00	UUUU	19.6
6/29/78	180	0.4	0.0	0.4	11.3	630.	35.6	19.6	0.00	0.00	0.00	0.19	0.32	0.32	0.28	0.27	0.26	0.26	0.26	0.00	UUUU	19.3

Figure 2. An example of water balance output for CERES-Wheat.

WEATHER=BUSHLD77 BUSHLAND - TEXAS 1977 - 1978 PD-2 T-4

DATE	JUL DAY	BIO MASS	TILL /SM.	LAI	SUMDTT	TRWU	PSW	ROOT WT	STEM WT	GRAIN WT	LEAF WT	SEN LFA	SW DF1	SW DF2	ROOT DPTH	PTF	ROOT LENGTH VOLUME L1	L2	L3	L4	L5	L6	L7	L8
11/ 1/77	305	7.	230.	0.09	88.	0.04	7.0	0.007	0.000	0.000	0.028	0.	1.0	1.0	43.	0.79	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11/ 8/77	312	13.	230.	0.17	163.	0.10	7.5	0.013	0.000	0.000	0.057	0.	1.0	1.0	61.	0.82	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
11/15/77	319	21.	230.	0.23	218.	0.11	8.9	0.021	0.000	0.000	0.091	0.	1.0	1.0	69.	0.59	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
11/22/77	326	29.	357.	0.34	278.	0.20	8.5	0.033	0.000	0.000	0.126	0.	1.0	1.0	80.	0.63	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0
11/29/77	333	39.	474.	0.47	335.	0.22	8.2	0.042	0.000	0.000	0.170	0.	1.0	1.0	89.	0.65	0.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0
12/ 6/77	340	50.	544.	0.54	378.	0.25	8.5	0.053	0.000	0.000	0.217	2.	1.0	1.0	96.	0.61	0.4	0.4	0.2	0.0	0.0	0.0	0.0	0.0
12/13/77	347	57.	618.	0.51	413.	0.58	8.2	0.059	0.000	0.000	0.248	8.	1.0	1.0	98.	0.66	0.4	0.4	0.2	0.0	0.0	0.0	0.0	0.0
12/20/77	354	63.	694.	0.65	463.	0.58	7.6	0.060	0.000	0.000	0.276	8.	1.0	1.0	105.	0.76	0.5	0.4	0.2	0.0	0.0	0.0	0.0	0.0
12/27/77	361	71.	747.	0.73	497.	0.47	7.6	0.063	0.000	0.000	0.307	9.	1.0	1.0	109.	0.75	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0
1/ 3/78	3	71.	775.	0.74	517.	0.45	7.4	0.061	0.000	0.000	0.307	9.	1.0	1.0	109.	0.81	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0
1/10/78	10	85.	823.	0.68	557.	0.45	7.8	0.067	0.000	0.000	0.370	18.	1.0	1.0	116.	0.73	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
1/17/78	17	85.	832.	0.43	571.	0.36	7.8	0.064	0.000	0.000	0.371	29.	1.0	1.0	116.	0.75	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
1/24/78	24	85.	834.	0.36	582.	0.35	7.6	0.062	0.000	0.000	0.372	33.	1.0	1.0	116.	0.75	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
1/31/78	31	86.	835.	0.28	585.	0.34	7.6	0.060	0.000	0.000	0.373	37.	1.0	1.0	116.	0.77	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
2/ 7/78	38	86.	835.	0.33	604.	0.32	7.3	0.058	0.000	0.000	0.372	37.	1.0	1.0	116.	0.82	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
2/14/78	45	88.	840.	0.32	608.	0.35	7.4	0.057	0.000	0.000	0.382	37.	1.0	1.0	116.	0.80	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
2/21/78	52	88.	840.	0.31	608.	0.34	7.5	0.055	0.000	0.000	0.384	38.	1.0	1.0	116.	0.80	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
2/28/78	59	103.	900.	0.41	648.	0.39	7.8	0.063	0.000	0.000	0.449	39.	1.0	1.0	120.	0.77	0.6	0.5	0.2	0.1	0.0	0.0	0.0	0.0
3/ 7/78	66	114.	943.	0.48	673.	0.34	8.0	0.070	0.000	0.000	0.498	41.	1.0	1.0	126.	0.71	0.6	0.6	0.2	0.1	0.0	0.0	0.0	0.0
3/14/78	73	150.	1035.	0.77	728.	0.29	8.8	0.107	0.000	0.000	0.653	41.	1.0	1.0	137.	0.62	0.8	0.8	0.3	0.1	0.0	0.0	0.0	0.0
3/21/78	80	200.	1074.	1.44	794.	0.31	8.4	0.168	0.000	0.000	0.871	41.	1.0	0.9	149.	0.65	0.8	1.3	0.6	0.2	0.1	0.0	0.0	0.0
3/28/78	87	290.	1155.	2.65	868.	2.49	8.1	0.269	0.000	0.000	1.260	41.	1.0	0.9	165.	0.62	1.5	1.8	0.8	0.3	0.1	0.0	0.0	0.0
4/ 4/78	94	445.	788.	4.50	67.	2.32	0.7	0.353	0.071	0.000	1.863	41.	1.0	1.0	188.	0.80	2.2	2.3	1.0	0.3	0.2	0.1	0.0	0.0
4/11/78	101	615.	724.	5.53	178.	3.71	0.9	0.439	0.348	0.000	2.325	55.	1.0	1.0	210.	0.80	2.8	2.8	1.2	0.4	0.2	0.1	0.0	0.0
4/18/78	108	809.	728.	5.93	281.	3.58	1.0	0.536	0.870	0.000	2.647	80.	1.0	1.0	210.	0.80	3.5	3.2	1.4	0.5	0.2	0.1	0.0	0.0
4/25/78	115	1020.	728.	5.40	84.	4.58	1.4	0.604	1.833	0.000	2.602	104.	1.0	1.0	210.	0.85	4.0	3.6	1.6	0.5	0.2	0.1	0.0	0.0
5/ 2/78	122	1175.	728.	5.03	7.	4.80	1.4	0.651	2.560	0.000	2.551	119.	1.0	1.0	210.	0.90	4.4	3.8	1.7	0.5	0.2	0.1	0.0	0.0
5/ 9/78	129	1328.	728.	4.78	70.	4.75	1.4	0.669	3.248	0.000	2.524	130.	1.0	1.0	210.	0.90	4.3	3.7	1.6	0.5	0.2	0.1	0.0	0.0
5/16/78	136	1500.	728.	4.60	2.	2.75	1.4	0.698	3.747	0.303	2.471	138.	1.0	1.0	210.	0.89	4.5	3.8	1.7	0.5	0.2	0.1	0.0	0.0
5/23/78	143	1598.	728.	4.46	133.	4.82	1.4	0.712	3.701	0.829	2.419	144.	1.0	1.0	210.	0.89	4.5	3.8	1.7	0.5	0.2	0.1	0.0	0.0
5/30/78	150	1674.	728.	3.73	268.	4.74	1.4	0.715	3.509	1.401	2.369	176.	1.0	1.0	210.	0.90	4.4	3.7	1.6	0.5	0.2	0.1	0.0	0.0
6/ 6/78	157	1727.	728.	1.89	389.	4.62	1.4	0.708	3.191	1.978	2.341	256.	1.0	1.0	210.	0.93	4.3	3.6	1.6	0.5	0.2	0.1	0.0	0.0

Figure 3. An example of plant growth output for CERES-Wheat.

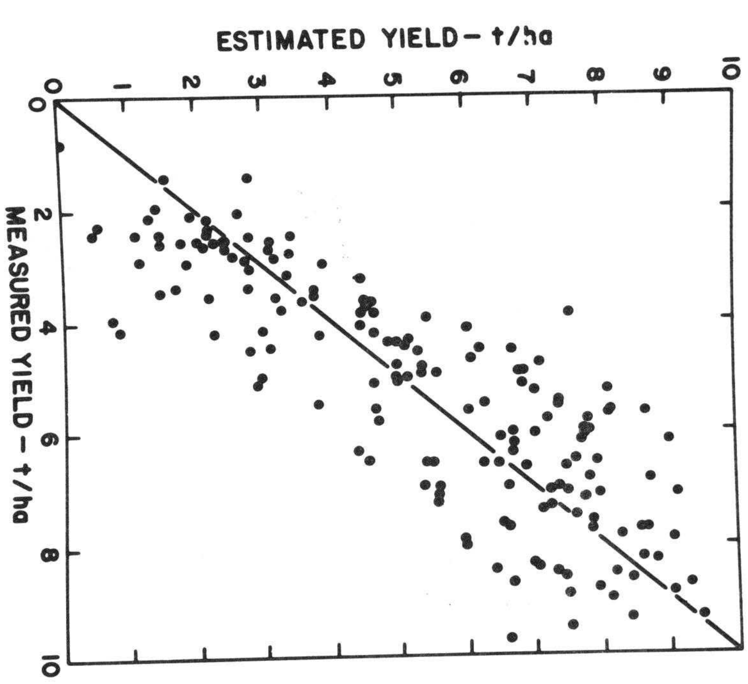

Figure 4. Estimated versus measured yields for individual crop-year data sets.

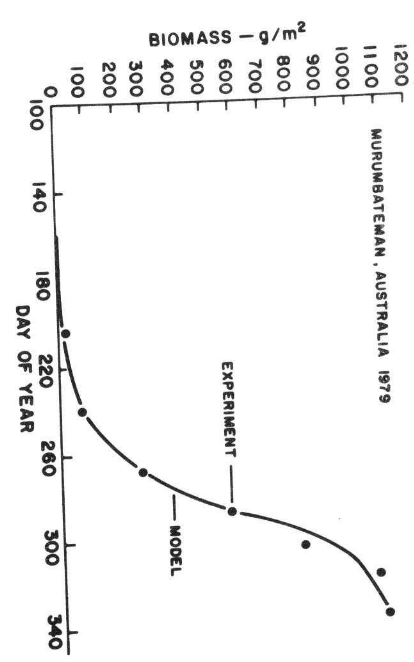

Figure 6. Seasonal changes in total wheat biomass for data from Murumbatem, Australia.

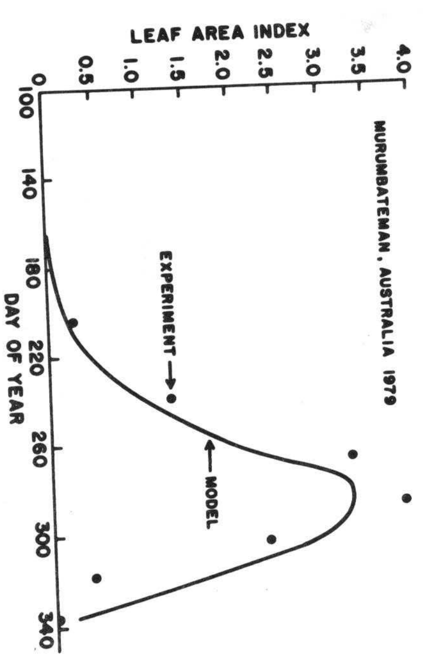

Figure 5. Seasonal changes in leaf area index for data from Murumbatem, Australia.

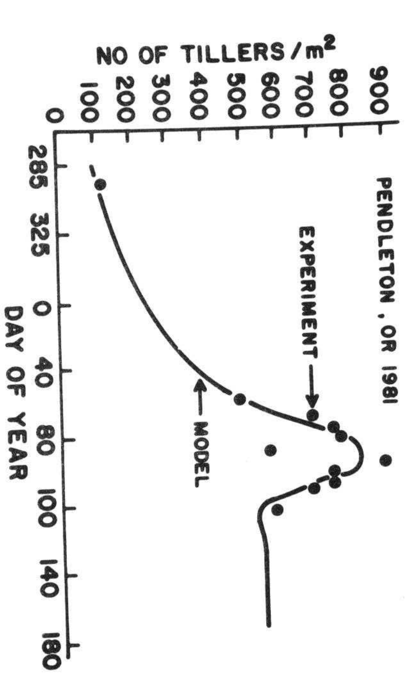

Figure 7. Seasonal changes in numbers of wheat tillers for data from Pendleton, Oregon.

Comparison of measured and model estimates of the average soil water content in the total profile for a wheat crop at Phoenix, Arizona, is presented in Figure 8. This comparison demonstrates the model capability to estimate water balance values reasonably well. There were no measurements of root length for this test, so errors in estimating root length could contribute to some of the error in estimating the soil water distribution.

Another valuable type of testing of CERES-Wheat was a sensitivity analysis performed by the Statistical Reporting Service (Larsen, 1981). That report, based on results from an analysis of an early version of CERES-Wheat, pointed out several critical functions in the model and made recommendations for improvement. Several of the weaknesses found in the study had already been recognized from other testing and improvements were made where possible.

The Foreign Agricultural Service has conducted operational tests of the model for large area yield estimation. That effort, primarily by Tom Hodges

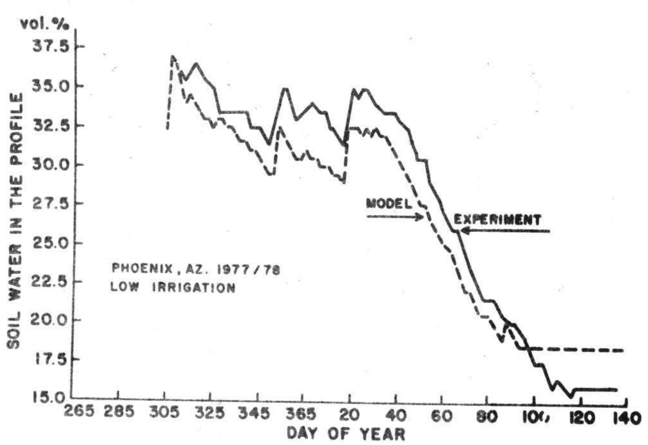

Figure 8. Measured and model estimates of seasonal total soil water (to 150 cm) with wheat at Phoenix, Arizona.

and Pat Ashburn, has helped us recognize a few programming errors that had gone unnoticed in other testing operations. Ashburn (personal communication) stated that the phasic development part of CERES-Wheat had estimated crop stages within a few days of reported dates for test regions in Europe and Asia. The yield estimates were also within reasonable agreement of reported yields for the region.

DISCUSSION AND CONCLUSIONS

The development of CERES-Wheat has been exciting and challenging. It is exciting because of the interest shown by the user community in models with a stronger scientific base. It is challenging because of the diversity of information from different scientific disciplines required to provide a general, balanced model sensitive to the major factors influencing yield. Although the model tests have demonstrated its usefulness for various purposes, several limitations still exist. A major limitation for large area yield estimation is the availability of good input information regarding spatial distribution of precipitation and soil properties. Errors in those inputs can cause large errors in yield, especially in areas where water deficits are common.

There are undoubtedly several parts of CERES-Wheat that need improvement as testing of the model has demonstrated. Improvement of some critical parts of the model is impaired by lack of available information. The formulation and testing of this model has generated several ideas about needed research and has created a demand for data not usually collected in experiments. An outstanding example of one future research need deals with shoot-root partitioning and the fate of assimilate partitioned to roots. While many studies have measured root-shoot weights through a season, the root weights may not reflect the amount of assimilate partitioned to them because of losses through exudation, sloughing and respiration. Several papers dealing with this problem have demonstrated that more than half the assimilate partitioned to roots is not recovered from the roots when observed a few days after C^{14} labeling, but rather is found in the soil. In CERES-Wheat, the partitioning principles had to be based on a few data sets where roots and shoots were measured, and this possible source of error could contribute to some of the error in yield estimation. Also, the dynamics of root growth into soils is poorly understood and needs more research, but the research needs to be done in the context of whole crop measurements to be useful in models.

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