5-1976

Modeling Spring Wheat Production as Influenced by Climate and Irrigation

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Recommended Citation

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MODELING SPRING WHEAT PRODUCTION AS INFLUENCED BY CLIMATE AND IRRIGATION

by

V. Philip Rasmussen, Jr.

A thesis submitted in partial fulfillment of the
requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science and Biometeorology

(Soil Physics)

Approved:

[redacted]

UTAH STATE UNIVERSITY
Logan, Utah

1976

ACKNOWLEDGMENTS

Many people deserve heartfelt thanks for their assistance given in many ways throughout the course of this project. Besides the appreciation due those committee members for their assistance in the final stages of this thesis, a special thanks is due each of them individually. Dr. Robert W. Hill gave much needed assistance in the early stages of the development of the model by tutoring this investigator in the rigors of the complex Burroughs B6700 computer system. Dr. Rulon Albrechtsen assisted in loaning the author the planting equipment and in tracking down the many varieties of wheat used in the field study. Dr. Gaylen Ashcroft gave constant advice, and more importantly, sincere encouragement throughout the course of the project. Dr. R. John Hanks, committee chairman, thesis director, employer, and friend deserves countless thanks for his help in this study and throughout the past five years of our association. His patience during the last stages of this thesis project is especially appreciated. Without his help and guidance these past years, this thesis would not have been a reality.

Sincere thanks are also due Gary Dennis Wilson, Terence L. Pearse, Shyrl Clawson, and Val Thompson for their assistance in the field portion of this study. Appreciation is extended to Mrs. Betty Smith for final typing of the manuscript.

Acknowledgment should be made of the contribution of Dr. R. John Hanks and Dr. Robert W. Hill for their development of the evapotranspiration/production and climatic subroutines (respectively) that were used as a basis of the beginning version of the model.

While not on the author's committee, Dr. Jay C. Andersen and Professor E. Arlo Richardson provided creative stimulus and suggestions as the author associated with them on the Utah Agricultural Experiment Station Project 411 Committee.

The author appreciates the financial support given by the Utah Agricultural Experiment Station at Utah State University, Logan, Utah through Projects 411 and 404. Without this assistance, the computer time and field studies could not have been possible.

Western Seeds, Inc. of Tremonton, Utah provided Bannock variety seed used in a portion of this study without cost to the author or the University. This support was gratefully appreciated.

The author acknowledges the lifetime support of his parents and is especially grateful for experience gained while being reared on a dryland wheat farm. It was here that he learned to appreciate the value of research applied to agriculture.

A final and most important thanks must go to my wife who has constantly supported me through many hours, and more importantly through many evening hours, of work on this project--even when very ill herself. Without this help and support, the author could not have undertaken--much less completed--this thesis project.

V. Philip Rasmussen

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ABSTRACT

Modeling Spring Wheat Production as Influenced
By Climate and Irrigation

by

V. Philip Rasmussen, Jr., Master of Science

Utah State University, 1976

Major Professor: Dr. R. John Hanks
Department: Soil Science and Biometeorology

A model has been developed that predicts spring wheat grain and dry matter yield. Preliminary tests show very favorable results when predicting grain yield in two different climatic regimes, one being a dryland and another being an irrigated area. The strengths of the model lie in its simplicity, relatively available input data, and low computer processing time cost. Weaknesses of the model stem from the assumptions that allow its simplicity. The basic assumption in the model is that grain and dry matter yield can be related to the ratio of actual to potential transpiration, computed for each of five phenological stages. Actual and potential evapotranspiration, transpiration, and soil evaporation are obtained in the model by numerical operations on a potential evapotranspiration/potential soil evaporation array obtained by empirical formulae or pan data, and a modified crop coefficient. Soil water status is monitored in the model by taking into account the balance of irrigation, drainage, precipitation, soil water storage and evapotranspiration. Phenological data is computed by a simple numerical formula utilizing maximum and minimum temperatures during the season. Good agreement was found in comparing predicted versus actual heading date for four varieties over four different years.

A field study was carried out to aid in model calibration and testing. A continuous variable plot design, with two replications of each of five spring wheat varieties (two soft white spring wheats and three hard red spring wheats). This allowed a large number of data points to be measured that related yield to many water levels within the soil. Although this design leads to difficulties in classical statistical analysis, it was shown to be especially useful in calibration of a model of the type shown herein.

(109 pages)

INTRODUCTION

Wheat plays a major role in the agricultural economies of many countries. As a food, wheat is preferred to any other grain by many societies, past and present. It has long been referred to as the "staff of life" by many authors. The average annual world production exceeds any other grain (Martin and Leonard, 1967). As a commodity, wheat is world-wide in its socio-political impact.

The current situation regarding world wheat production causes serious concern on the parts of those charged with keeping production in pace with demand. Wheat reserves reached an all-time 22-year low in the United States in 1974 even though U.S. (and world-wide) production reached all time highs in 1973 and 1974 (CIMMYT, 1974). Current estimates by the United Nations reveal that the current world grain reserves are at a dangerously low 26-day supply. A major crop loss in any of the world's major wheat producing areas would produce world-wide social, economic, and political crises. Few observers would disagree that wheat production must be kept at the highest possible levels in order to meet the needs of the world society (McCloud, 1975).

At the same time that food (wheat) producers are being called upon to increase production, the resources utilized in this production are being increasingly competed for by other users of these resources. Water is, perhaps, becoming the most critical resource in the food production cycle. With agriculture being the chief user of the world fresh water supplies, other users of water are calling upon the agricultural sector to limit their use of this precious resource. In the intermountain area, energy development and culinary use of water are putting increased demands upon water previously allocated to agriculture. It is certain that in the future the farmer will have to settle for less water than has been previously available. Water management practices that have previously developed from thoughts of abundant supplies of water will have to be changed; the wise use of this resource by the farmer will be a "forced" condition.

Previous crop production/water management studies for irrigated agriculture have focused upon maximum food production derived from maximum water application. This has placed water applied, in most irrigated agricultural situations, at the far end of the Mitscherlich yield response curve. As farmers in irrigated areas are forced to use less water due to cost and allocation factors, management schemes that will deliver the best possible yield from limited amounts of water will be desperately needed. In addition, dry land farming areas are becoming increasingly concerned with the value of additional rainfall as cloud seeding techniques become used more frequently. Thus, in both irrigated and dry land situations, it is of increasing value to be able to predict the results of climatic and management conditions.

With the advent of modern high-speed digital computers, coupled with systems analysis (modeling) techniques, it has become possible to simulate a season of soil-water-plant-atmospheric interactions in a few seconds. This modeling procedure can allow researchers to try out many different management schemes under given conditions and examine the changes in yield that occur. Thus, these modeling techniques can produce yield/management practice--climate relationships that can be used in linear programming models to find the optimum cost-effective water management practice for a given area. These models are only as good as our understanding of the processes involved.

Objectives

The objective of this research has been to develop, calibrate, and test a model that will predict spring wheat yield with given climatic and water management conditions. This model was envisioned to provide a data base for economic and management decision analyses of different management schemes and climatic effects. The specific objectives were:

1. To develop a predictive model for spring wheat development and yield as influenced by soil, water, and climatic factors.

2. To design and carry out a field experiment that would provide necessary phenological and yield information as related to varied levels of soil water, to calibrate the model.

3. To utilize other existing data in the testing of such a model in order to correlate the existing data into useful information.

LITERATURE REVIEW

Systems analysis and modeling

The terms "systems analysis" and "modeling" are becoming common in scientific and engineering disciplines. Although these words appear to describe a new and growing field of scientific endeavor, it can be shown that the so-called "systems approach" is as old as recorded history. Rivett (1972) documented that the ancient Greek and Babylonian societies used pure systems analysis techniques in their engineering and scientific affairs. Actually, today's systems techniques have their modern roots in Sir Isaac Newton's classic work on the solar system, Principia (White, 1974). Systems theory has as its basis the long-established scientific method: observation, generalization, experimentation, and validation. Systems theory merely extends the generalization portion of the scientific method into the formulation of a model. This model is then verified or discarded, and then subsequently used to evaluate many conditions imposed upon it. The analysis of the result of these imposed conditions upon the model then allows investigators to make logical decisions regarding possible conditions to be placed upon the real system.

White (1974, p. 198) gives the following steps in the systems approach:

1. Formulate the problem
2. Identify and describe the components of the system and their interrelationships
3. Develop mathematical or logical models
4. Analyze system performance and study alternative means for accomplishing objectives in terms of criteria such as cost, size, effectiveness, and risk

5. Select the best system on the basis of the specific criteria, and
6. Build or implement the physical or abstract system that has been selected.

Systems analysis can thus be explained as viewing of a system, constructing some type of model of that system, using the model to test alternative actions (that would be performed by some person, group, or entity), and then implementing the "best" course of action upon the real system. Modeling, in its true sense, is a part of the total systems analysis process. However, it can be seen that systems analysis and modeling are, in reality, synonymous terms as used presently. Most researchers are taking a systems approach to their science when they undertake a modeling project. In this paper, the two terms "modeling" and "systems analysis" will be used interchangeably to express the same meaning. All but the last step of the true systems approach will be implemented. This last step, in reality, must be left to the farmer.

Computer aided systems analysis

Perhaps the main reason for the broad scale use of systems theory in recent years has been the advent of the high speed electronic digital computer. Complex mathematical and logical models can be written in computer language and processed to produce results similar to the real system. Digital computer models have another very desirable quality--speed. For example, a year of crop-soil-water-climate interactions can be simulated, with interim and summary results printed in less than five seconds of central processing unit time on a medium size computer (Burroughs B6700) (Hanks et al., 1975). In a few minutes of time, numerous seasons of plant growth, all with different management schemes, can be simulated for later evaluation.

Systems analysis in agricultural crop production

The application of systems analysis (modeling) techniques to agriculture is now becoming widespread. Perhaps one of the most prevalent uses is in modeling crop production under various environmental patterns. Most models dealing with the estimation of crop production can be viewed as taking into account, to a greater or less degree, the crop material itself (with its inherent properties--genetic, etc.) and the environment that it resides in (Keller et al., 1973). These investigators stated that the crop production response vector $(\overline{Rc})$ can be expressed in terms of two multi-dimensional vectors--the crop material vector $(\overline{M})$, and the crop environment vector $(\overline{E})$.

There are probably as many models presently dealing with cereal crop production as there are investigators dealing with the same. Many investigators have developed models that predict production under certain conditions. Most of these are statistical approaches utilizing climatic data. Newell, Tanaka, and Misra (1976) report on a simple regression relationship between winter temperature and rainfall and the yield of winter wheat in the U.S.S.R. They also report on similar statistical relationships developed separately by Chirkov and Zabijaka in the Soviet Union and Lewis Thompson (1969) in the United States.

Increasingly, there has been effort to quantify the physical aspects of the crop production system more closely. It is felt that by modeling individual processes in the system, rather than merely quantifying statistical relationships, the results will be more transferable between locations and years (Hill et al., 1974).

There are numerous examples in recent literature of these "physical models." Splinter (1973) and Baker (1974) have developed models for corn. Hanks (1974) developed a simple model for corn that combines information on the soil-plant-water-atmosphere continuum mathematically in order to estimate the ratio of actual to potential transportation. Yield is then related to this relationship. This model has been extended by Hill et al. (1974) to include climatic computations to evaluate such factors as phenological stages and killing frosts. However, these two model approaches have only been evaluated on common hybrid field corn (*Zea mays indentata*).

Systems analysis in wheat production

Production models dealing with wheat production are not as numerous as the world-wide importance of wheat would seem to demand. As mentioned previously, there are statistical evaluations of precipitation patterns and other environmental factors as they relate to crop production (NOAA, 1973; Pochup et al., 1975; Bauer, 1972; Thompson, 1969; and Asfour, 1950). Others seem to combine some physical analysis with statistical methods such as those developed by Yaron et al. (1973), Haun (1973a, 1973b, and 1974), and Baier (1973).

Haun's approach (1973a, 1973b, and 1974) is in modeling daily growth and phenologic development with a number of factors. His approach, however, only crudely accounted for the effects of soil moisture on yield.

Neghassi (1974) attempted to formulate a winter wheat model using actual/potential evapotranspiration relationships to estimate yield.

His technique was similar to the approach taken by Hill et al. (1974) with corn. However, he noted problems in estimating phenological periods and problems in estimating evapotranspiration without resorting to sophisticated empirical techniques. He reported success in estimating dry matter production, while having some difficulty in estimating grain yield.

Modeling wheat yield system using transpiration relationships

Previous mention has been made of various methods of estimating yield in the wheat production system. Each method has advantages attendant to it. Most are adaptions of generalized approaches developed for use with many crops. One of these approaches was first published by de Wit (1958) wherein he relates dry matter yield, Y, to transpiration, T, as such:

$$Y = mT/E_o \qquad [1]$$

in which Y = yield

T = transpiration (actual)

E_o = average free water evaporation rate

m = a crop factor

For a given crop and year, the relation of relative transpiration to relative yield can be obtained from equation [2] as

$$Y/Y_p = T/T_p \qquad [2]$$

in which T_p = potential transpiration which occurred when soil water is not limiting

Y_p = potential yield when transpiration is equal to potential transpiration.

In the development of equation [1], de Wit (1958) analysed a vast amount of earlier data under conditions of maximum soil water. Most of the experimental work was done under semi-field conditions where plants were grown in containers, although some straight field data were also analyzed. He concluded that the influence of soil water had a similar effect on both transpiration and yield; therefore if transpiration could be measured, then yield could be measured.

The validity of equations [1] and [2] is not firmly established. Richards and Wadleigh (1952) cite research indicating that yield and transpiration are highly correlated. They also present conflicting data where yield is reduced before transpiration as soil water decreases as well as the reverse. Rawitz (1970) showed that transpiration is decreased much less than yield at high water levels in a laboratory study.

Experimental work under field conditions by Hanks et al. (1969) indicated that the model of de Wit (1958) seemed to hold for conditions of differential water status. However, under field conditions, water is returned to the atmosphere by evaporation directly from the soil as well as by transpiration by plants, so estimates of soil evaporation need to be made.

The model previously mentioned of Hanks (1974) and extended by Hill et al. (1974) for corn utilizes directly the relationship of equation [2] to estimate dry matter yield. For grain production, these models used a method of Jensen (1968) that accounts for some stages of growth being more critical to grain production than others.

For corn, the season was divided into five stages and relative grain production computed as

$$\frac{Y\ (\text{grain})}{Y_p} = \left(\frac{T_1}{T_{p1}}\right)^{\lambda_1} \cdot \left(\frac{T_2}{T_{p2}}\right)^{\lambda_2} \cdot \left(\frac{T_3}{T_{p3}}\right)^{\lambda_3} \cdot \left(\frac{T_4}{T_{p4}}\right)^{\lambda_4} \cdot \left(\frac{T_5}{T_{p5}}\right)^{\lambda_5} \qquad [3]$$

in which λ_i = an exponent to allow for weighting the "ith" stage

Y (grain) = actual grain yield realized

Y_p = the potential production for the situation where T_i always equals T_{pi}.

Modeling of wheat phenology

If the previously mentioned equation for grain production (equation [3]) is to be successfully used for grain yield prediction, the phenological progress of the plant must be accurately modeled.

Many investigators have developed means to predict phenological development in plants (Robertson, 1973). Nuttonson (1953, 1955, 1956, 1966) presented numerous approaches for wheat using temperature and other climatic data. Gilmore and Rogers (1958) reported a very simple method, now commonly called the "Weather Bureau 50-86" growing degree method. This has been applied successfully to corn by several investigators (Hill et al., 1974; Mederski, Miller, and Weaver, 1973). Spring wheat has been modeled successfully using a similar approach (Fitzpatrick, 1973). However, winter wheat has added problems of vernalization and photoperiodism that must be taken into account as it approaches and discontinues its winter rest period (Martinić, 1973).

FIELD PLOT EXPERIMENT

In order to provide data to calibrate and evaluate the model, a field experiment was devised that was hoped to provide necessary information not available from previous research records.

Experimental design

In order to provide yield values for a large number of irrigation rates and thus, hopefully, provide data for both dry and very wet soil water conditions, the line source continuous variable plot design similar to that described by Hanks, Keller, and Bauder (1974) and Hanks et al. (1976) was used. This design uses standard impulse sprinkler heads spaced twice as dense along the line as is usually prescribed. This produces a continuously decreasing irrigation application pattern outward at right angles from the line source. By making the plot approximately 30.5 meters in width, with the line source running through the middle, application rates at the edge are usually zero--with rate increasing toward a maximum at the center (see Figure 1).

To obtain a plot where water and a line source system was readily available, the wheat test plots were laid out in conjunction with two other line source studies at the Utah State University Greenville Experiment Farm near Logan, Utah. The wheat plots in relation to the other plots (some of which were treated with salty water from another line source) are shown in Figure 2.

Five varieties of spring wheat (Triticum aestivum L.) were chosen as the experimental material. All were standard tall or semi-dwarf

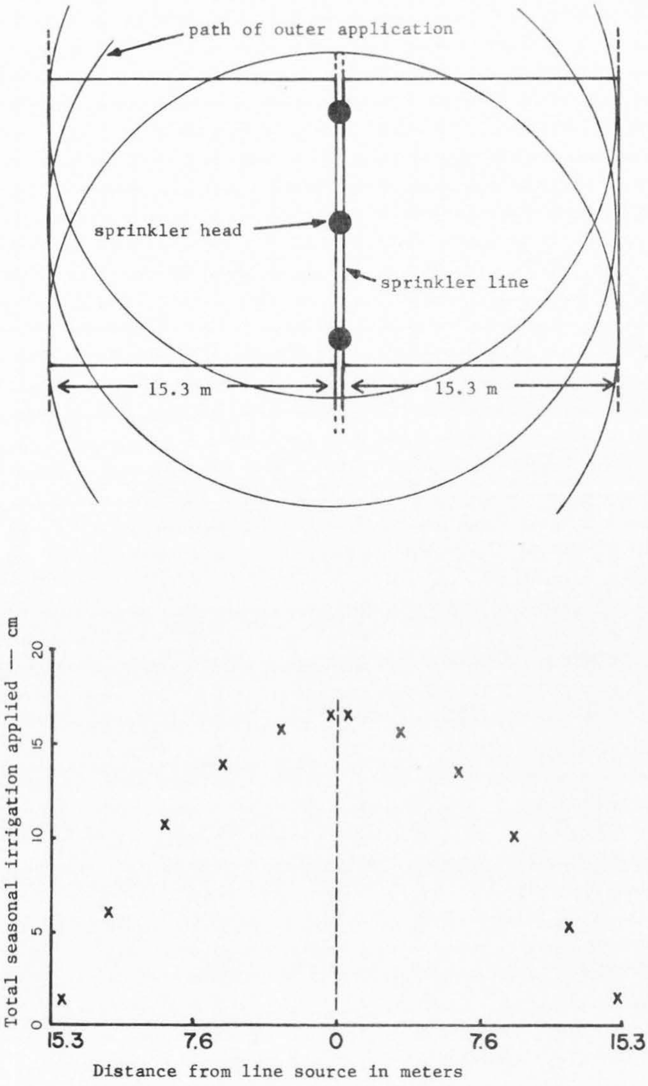
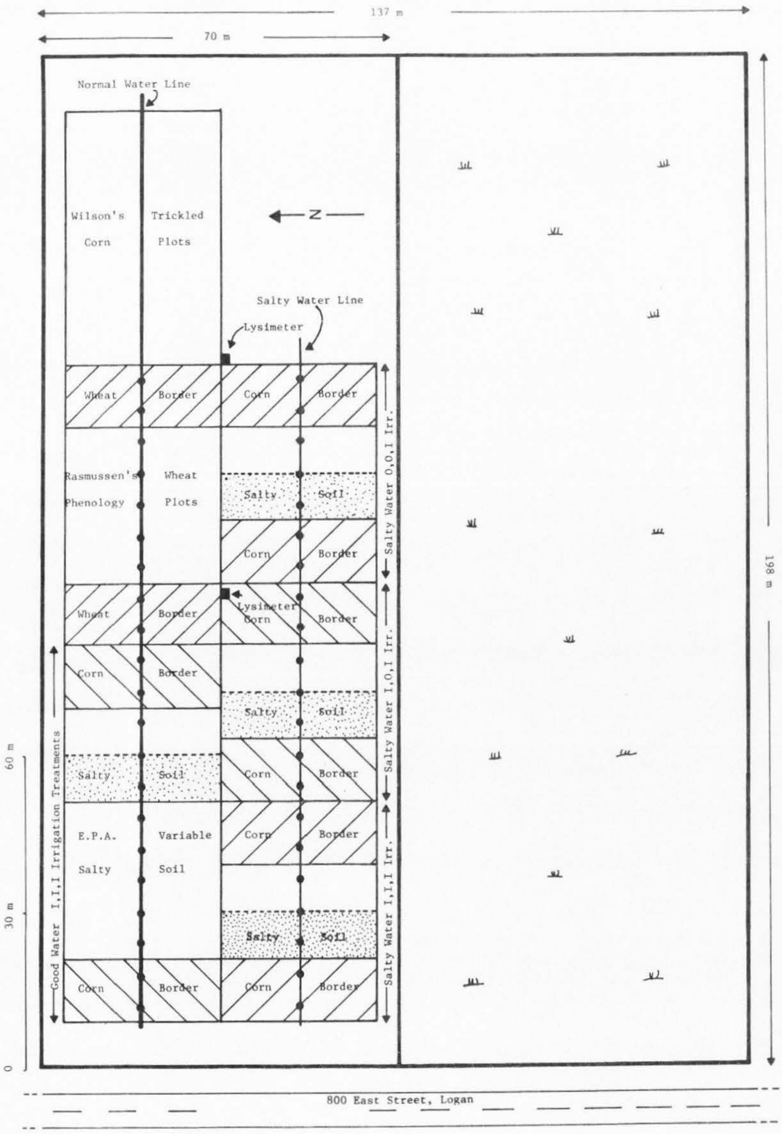


Figure 1. View of line source plot showing overlapping effect of sprinklers (upper portion); and resulting application pattern for the 1975 season (lower portion).

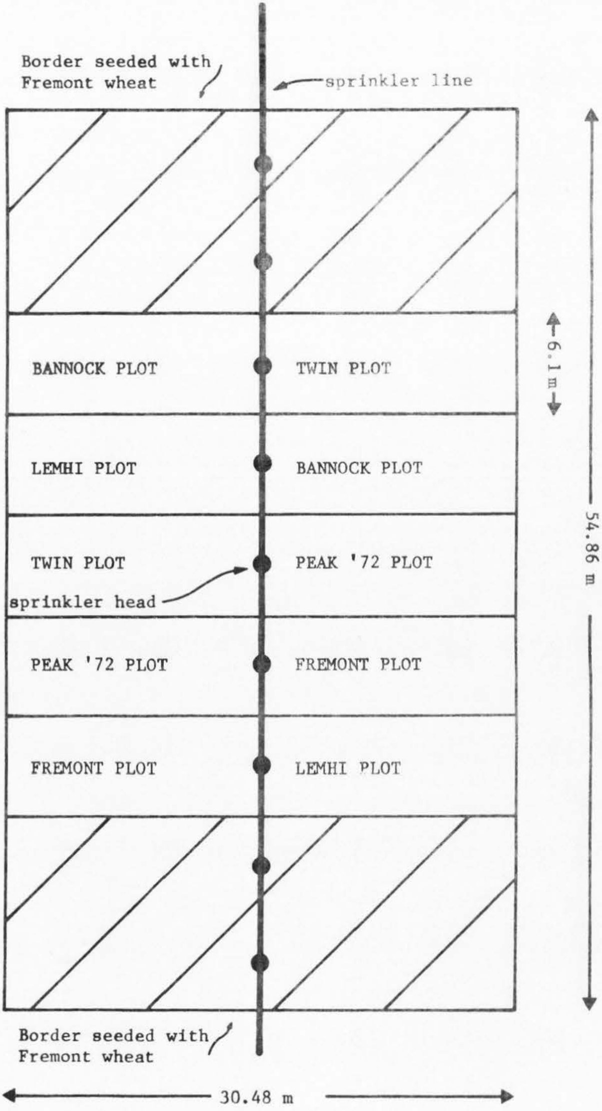
Figure 2. A view of relationship of wheat plots to other experimental plots using "line source" irrigators. Experimental plots are denoted as: Rasmussen's Phenology Wheat Plots.


137 m
70 m
Normal Water Line
Wilson's Corn
Trickled Plots
N
Salty Water Line
Lysimeter
Wheat
Border
Corn
Border
Rasmussen's Phenology
Wheat Plots
Salty Soil
Corn
Border
Wheat
Border
Lysimeter
Corn
Border
Corn
Border
Salty Soil
Salty Soil
Corn
Border
E.P.A. Salty
Variable Soil
Corn
Border
Salty Soil
Corn
Border
Corn
Border
Salty Water O,O,I Irr.
Salty Water I,O,I Irr.
Salty Water I,I,I Irr.
Good Water I,I,I Irrigation Treatments
198 m
60 m
30 m
0
800 East Street, Logan

varieties. This was done to provide data on two relatively different genetic types of spring wheat, soft white and hard red. Spring wheat was chosen because of possible problems in phenological modeling of winter wheat due to winter induced vernalization and photoperiodism as reported by Martinić (1973). The varieties used were all ones for which test data were available from other sites and/or years. All varieties used were currently being grown as test varieties in breeding trials at Utah State University.

The five varieties chosen were: (1) Bannock, a hard red semi-dwarf wheat, early maturing, usually produced on dry land; (2) Fremont, a large headed hard red semi-dwarf spring wheat of medium seasonal maturing, adapted to both irrigated and dryland production; (3) Peak '72, a hard red semi-dwarf spring wheat, medium in maturity, produced primarily under irrigated conditions; (4) Lemhi, a standard tall soft white spring wheat, later in maturity than the first varieties, produced under irrigation; (5) Twin, a soft white semi-dwarf spring wheat, comparable to Lemhi in maturity, produced under irrigation. All of these seeds were certified or of certified quality in purity.

The experimental plot was set up as shown in Figure 3. Each variety was randomly set in plots 15.2 m (50 ft) north to south and 6.1 m (20 ft) east to west on each side of the line source which was east to west. Thus, each variety was replicated twice, once on each side of the line. A border equivalent to four plots (30.4 m north to south by 12.2 m east to west) was set aside at the east and west edges of the plots to prevent line source applications from other experiments on each side from reaching experimental plots. These dimensions allowed 50 rows of planted wheat (30.5 cm row spacing) in


Border seeded with Fremont wheat
sprinkler line
BANNOCK PLOT
TWIN PLOT
6.1 m
LEMHI PLOT
BANNOCK PLOT
TWIN PLOT
PEAK '72 PLOT
sprinkler head
54.86 m
PEAK '72 PLOT
FREMONT PLOT
FREMONT PLOT
LEMHI PLOT
Border seeded with Fremont wheat
30.48 m

each plot. Thus, 100 rows of each variety were planted in the total experimental width of 30.4 m with the line source running between rows 50 and 51. A border of 61.0 cm was cut at right angles to the rows (north to south) between each plot after planting. This removed any contamination of varieties running into the edges of each plot due to planter error. This reduced the plot size to 5.5 m by 15.2 m. The randomized placement of variety plantings within the design is shown in Figure 3. Border areas were seeded with Fremont seed to avoid excessive edge effects from soil water storage within the borders.

The experimental area was located on Millville silt loam. The area had about a 2 percent slope. The soil was well drained but has frequent coarse gravel lenses throughout the profile in an undefined placement that was at about 150 cm in the plot area.

Field procedure

The experimental area had been fall plowed. Preplanting preparation included cultivation with a spring-tooth cultivator followed by spike-tooth harrowing two weeks prior to planting to prepare a semi-smooth surface and granulate subsurface soil. One week prior to planting, ammonium phosphate fertilizer (29-14-0) was applied with a hand spreader (Gandy) at a rate of approximately 112 kg/ha (100 lb/acre) N. The south replications received less fertilizer (5 percent) than the north replications due to an unnoticed change in the spreader setting.

Planting of all varieties was done on May 1, 1975. Seeding was at an approximate depth of 8 cm. Seeding rate was 95.2 kg/ha (85 lb/acre). Seeds for each 6.1 m row in each plot were weighed out and placed in small coin envelopes. Seeding was accomplished with a small belt planter mounted behind a small garden tractor. The planter was calibrated to plant each 6.1 m row without stopping. Four rows could be planted at a time with the planter. A very good stand of wheat was obtained on all plots, as evidenced upon inspection at the time of emergence. A seasonally abnormal snow storm and freezing temperatures occurred one week after emergence. The wheat was frozen on leaf blade edges and some blades killed completely. However, this seemed to encourage tillering and there was a very good stand at harvest.

Phenology was monitored throughout the study at weekly intervals. Color photographs of the plots and individual plants at each edge of the plots were taken at bi-weekly intervals. This allowed visual checking of phenology observations later.

Five weeks after planting, neutron probe access tubes were installed in rows 2, 10, 20, 30, 40, 49, 52, 61, 71, 81, 91, and 99 (numbering from north) in the middle (Twin and Peak) plots. This allowed a symmetrical observation pattern of soil moisture on each side of the line source with two varieties. Aluminum irrigation pipe that was 3.05 m in length and 5.08 cm in diameter was used for access tubing. Because of the rock lenses previously described in this experimental site, a pneumatic rock drill with a 7.62 cm carbide bit was used to drill holes within the soil profile for the access tubes. Even with this very laborious process, some tubes could not be installed to the desired 2.9 m depth.

Neutron probe measurements were made using a Troxler Scaler/ Ratemeter Model 2651, and a Troxler Model 104A Americium-Berylium Neutron Moisture Probe. Soil moisture status was measured during the season on June 10, June 26, July 3, July 17, July 28, July 31, August 12, and August 28. Measurements were taken at the following depths (cm): 15.2, 30.4, 45.7, 61.0, 91.4, 121.9, 152.4, 182.9, 213.4, 243.8, and 274.3.

Weeding was accomplished by hand with a Planet Jr. blade cultivator set at a 27 cm spacing for passing between rows. Other weeding was done by "hand-picking" weeds within the rows.

Irrigation of the plots took place on July 1-2, July 9, July 16, July 22 and July 28-29. The line source was allowed to apply a calculated amount of 3 to 4 cm in the center (2 hour application time). Catch-can rain gauges were placed across the line source plots to monitor the irrigation amounts at 5 points in each plot. The "rain gauges" were later attached to an aluminum pipe that could be raised so that gauges were at the same height as the crop. This eliminated errors due to deflection of irrigation by the crop.

Plots were harvested as they were fully ripe in the middle of the plots. Some lodging occurred due to rain and irrigation at the edges of the plots subject to high irrigation; so even at harvesting they were not fully ripe. This was due to lodging, however, and not due to higher moisture levels retarding development. Those rows of the same variety and the same position relative to the line source that did not lodge were mature at the time of harvesting.

Harvesting was accomplished by hand cutting each row of wheat including the straw and putting it in bundles. These bundles were marked with paper tags according to variety and row number and hauled into the storage area where they were kept until threshing due to possible rains at this period. Hand cutting was tedious and time consuming. Several methods other than using a standard hand sickle were tried (electric hedge trimmers and cordless grass shears) but none proved satisfactory.

At the time of threshing, each bundle was weighed on a Mettler P10 laboratory balance for wet total dry matter weight. Every fifth row of total dry matter was saved and dried in a large, steam heated, drying oven at 50°C to determine water content in the dry matter across the plot. The samples not dried were then threshed and the grain collected and weighed on the same balance. Every fifth row grain sample adjacent to the rows used for dry matter moisture determination was saved for moisture content analysis of the grain across the plot. Samples dried for dry matter in the ovens were weighed after 3 days of drying and then threshed. Grain from these samples was saved for moisture content analysis because weights of this grain would be less at threshing due to their being dried first.

Threshing was accomplished with a head thresher designed expressly for scientific purposes. It allowed thorough clean-out between each sample. Moisture analysis of the grain was accomplished with a Steinlite Electronic Moisture Meter on a scale calibrated for hard spring wheat and western soft white wheat.

Field plot results and discussion

Raw field plot data contained a wet grain weight and a wet dry matter weight for each plot. Also obtained were dry matter water content for every fifth row, and grain water contents for these same rows; and grain water contents for every fifth row adjacent to these.

To obtain dry weight values for each row, the water content values were paired with proper row numbers and fed into a standard multiple regression statistical package on the Burroughs B6700 computer (STATPAC/MREGR; Hurst, 1972). This regression was set to fit a least squares second order polynomial line through these data points, for each individual plot. The R^2 value (mean) for these manipulations was .41. This approach allowed a unique water content estimate to be utilized for each row in reducing field wet-weight values to dry weight. It was hoped that this approach would correct for water content differences across the plot caused by the line source treatments.

A similar procedure was used for the grain field (wet) weight values. STATPAC/MREGR was run upon the data points collected from the moisture meter and then an equation was developed that could give a unique water content value given the number of each row. The R^2 (mean) value for these manipulations was 0.62. An exception to this procedure was that generated water content values were not used on those grain samples that were dried for dry matter water content values. The actual water content measured by the Steinlite tester was used for these because their water contents did not correlate, obviously, with those sampled in the field. A summary table of the dry weight values for grain and dry matter for each row is given in Appendix A (Table 9). Those grain yield values that did not use the multiple regression generated water content values are marked with an asterisk.

Because of the variation apparent in the data due to many factors, values to be used for model testing were reduced to those taken at the neutron access tube rows. These values were obtained by averaging the data points at the neutron tube rows with the two rows on each side. Values obtained by this practice were then averaged over the two replicates to help eliminate field plot variation. These summary values are given in Table 1. These show grain and dry matter yields (respectively) for each of the five varieties. It can be seen that in all but the Bannock variety, there is a general upward trend in yield with increases in water application. The possible depression in Bannock yield with high water levels is due to factors not isolated in this study but possibly due to genetic breeding of this dryland variety for low water levels. Mean yields for grain (Figure 4) and for dry matter (Figure 5) are shown as a comparison between varieties.

Irrigation applied was computed for each row. This was done by taking the can catch data for each irrigation individually and running a second order multiple regression (as was done with grain and dry matter water contents). Several orders of polynomials were tested by a STATPAC computer routine. However, the second order was highly significant over all others. The mean R^2 values for these runs was over 0.96. When these runs were completed, an equation had been developed that predicted irrigation amounts for each row. By approaching irrigation delivery patterns in this manner, such problems as wind shift and sprinkler variation is automatically accounted for in each run. Table 2 gives the seasonal summary of irrigation for the rows containing the neutron tubes. These sums fit a second order (parabolic) regression equation with an R^2 of 0.998.

Evapotranspiration values were obtained for the twelve sites where neutron access tubes were installed. These values were computed by taking evapotranspiration to be equal to the sum of soil depletion (as measured through the season by neutron probe), precipitation, and irrigation. This assumes drainage and runoff are negligible. Values obtained for each neutron site are given in Table 3.

Table 1. Table of mean yields of symmetric replicates at neutron tubes smoothed by two points on each side. Values are in mt/ha for grain (G) and dry matter (DM). Bu/acre estimated at a constant bushel volume and 10 percent moisture are given for grain yields in parentheses

Means of Reps	Bannock		Peak '72		Fremont		Lemhi		Twin	
	G	DM	G	DM	G	DM	G	DM	G	DM
2 & 99	1.98 (32.4)	4.28	2.26 (36.9)	4.84	2.04 (33.3)	4.15	1.97 (32.2)	4.69	2.16 (35.3)	4.84
10 & 91	2.27 (37.1)	4.95	2.40 (39.2)	5.29	2.67 (43.6)	5.38	2.73 (44.6)	4.00	3.01 (49.2)	6.12
20 & 81	2.44 (39.9)	5.38	2.78 (45.4)	5.97	3.34 (54.6)	6.40	2.96 (48.4)	6.39	3.62 (59.2)	6.92
30 & 71	2.78 (45.4)	5.92	3.19 (52.1)	6.58	3.77 (61.6)	7.00	3.07 (50.2)	6.51	3.96 (64.7)	7.55
40 & 61	2.67 (43.6)	5.49	3.30 (53.9)	6.51	4.23 (69.1)	7.44	3.30 (53.9)	6.91	3.97 (64.9)	7.65
49 & 61	2.62 (42.8)	5.36	3.48 (56.9)	6.75	4.01 (65.5)	7.42	3.50 (57.2)	7.21	4.11 (67.2)	8.60

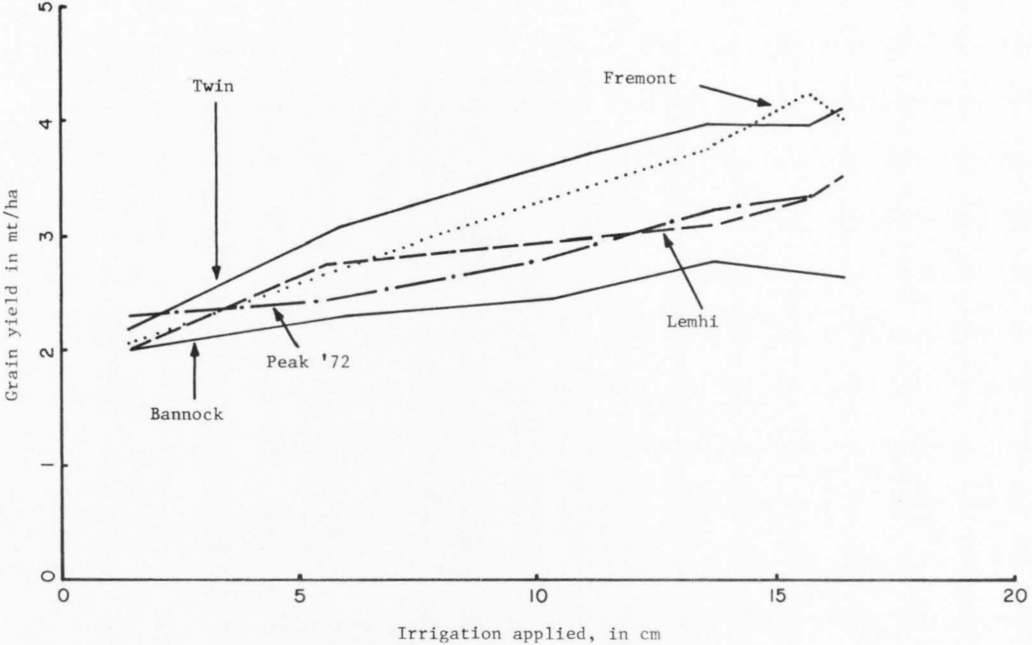


Figure 4. Grain mean yields vs. irrigation applied for all varieties grown in test plots, 1975.

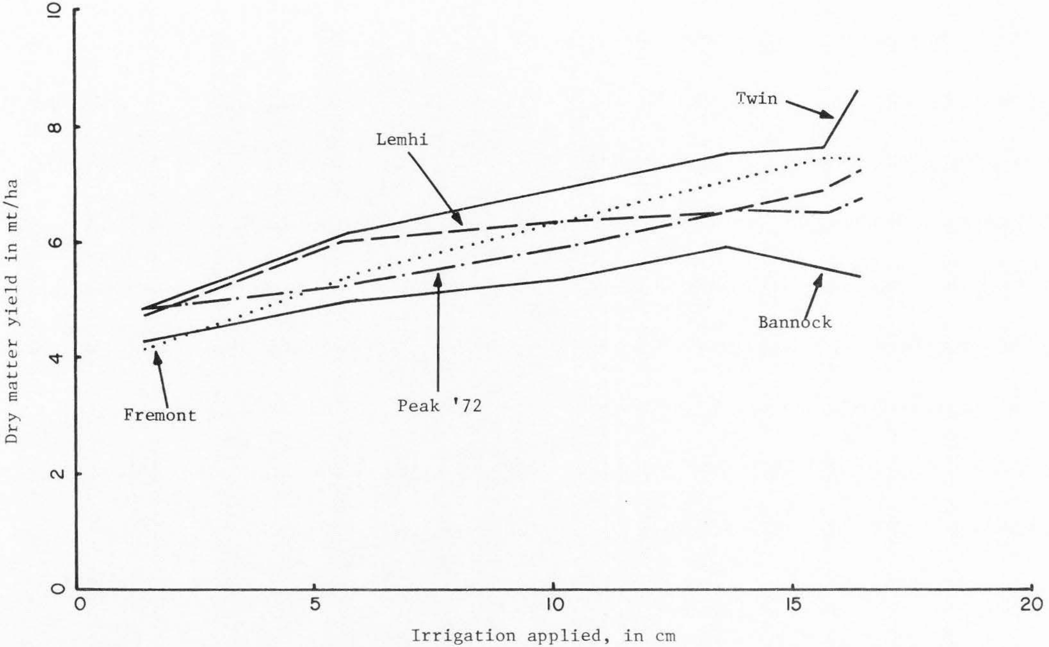


Figure 5. Dry matter mean yields vs. irrigation applied for all varieties grown in test plots, 1975.

Table 2. Irrigation amounts (in cm) at neutron tubes

Date of irrigation	Row 2	Row 10	Row 20	Row 30	Row 40	Row 49	Row 52	Row 61	Row 71	Row 81	Row 91	Row 99
July 1-2	.105	.991	1.885	2.542	2.962	3.137	3.153	3.072	2.757	2.206	1.417	.615
July 9	.161	1.020	1.890	2.535	2.953	3.137	3.158	3.098	2.817	2.310	1.577	.828
July 16	.666	1.750	2.809	3.539	3.939	4.017	3.984	3.707	3.707	2.136	.856	0.0
July 22	.438	1.149	1.847	2.333	2.607	2.673	2.656	2.493	2.493	1.514	.707	0.0
July 28	0.0	1.047	2.134	2.901	3.348	3.476	3.461	3.242	3.242	1.829	.641	0.0
Seasonal total	1.3	5.957	10.565	13.850	15.809	16.440	16.412	15.612	13.465	9.995	5.198	1.443

Mean values of symmetric rows in each replicate:

Row 1 & 12	Row 2 & 11	Row 3 & 10	Row 4 & 9	Row 5 & 8	Row 6 & 7
1.407	5.578	10.280	13.658	15.711	16.426

Table 3. Evapotranspiration (in cm) measured at neutron tubes

Row 2	Row 10	Row 20	Row 30	Row 40	Row 99	Row 52	Row 61	Row 71	Row 81	Row 91	Row 99
31.1	39.4	44.0	44.9	44.8	40.1	31.6	35.0	39.2	43.0	39.0	38.5

Mean values of symmetric rows in each replicate

Row 1 & 12	Row 2 & 11	Row 3 & 10	Row 4 & 9	Row 5 & 8	Row 6 & 7
31.4	37.2	41.6	44.0	41.9	39.3

Examining Figure 6 reveals that evapotranspiration (ET) for the varieties shown dropped off at the higher levels of water applied. This could be due to many factors. I believe, although proof is non-existent, that this is an effect of water being delivered to this area of the plot by the leakage from the line source pipe and the dripping of sprinklers for long periods after water is shut off. This would allow more water than that measured as applied to be in the profile, and, thus, would result in lower ET as calculated from soil depletion. Yields of other varieties tended to increase instead of decrease at these points. Figures 7 and 8 show a stronger linear trend if those points with high yields and lower ET at the portions of the plot near the line source were ignored. A linear trend has been substantiated by Hanks, Gardner, and Florian (1969) and others.

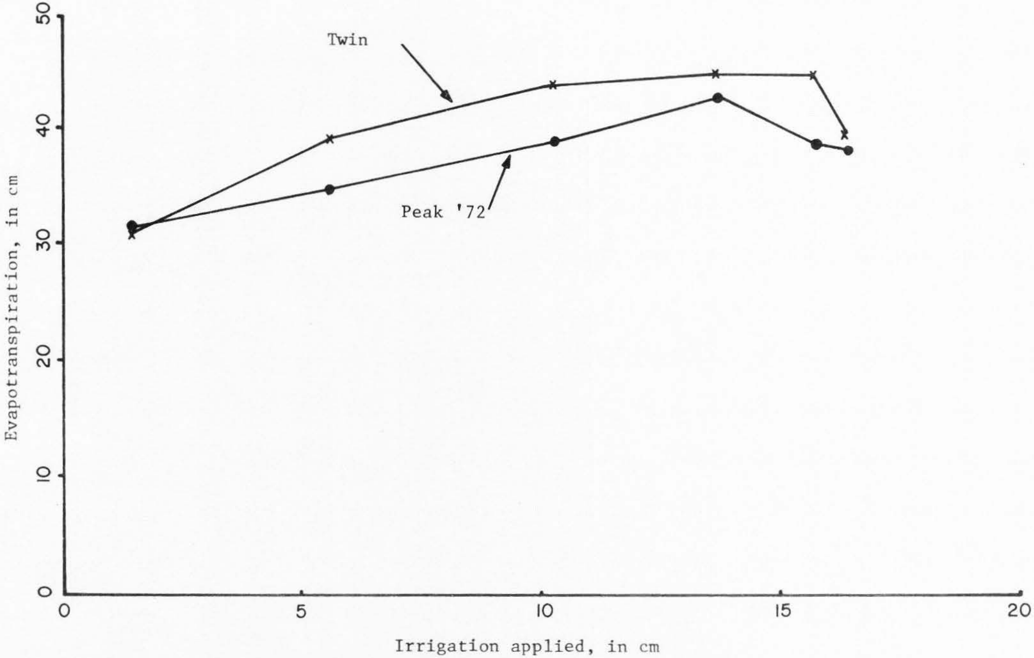


Figure 6. Evapotranspiration vs. water applied for neutron tube sites.

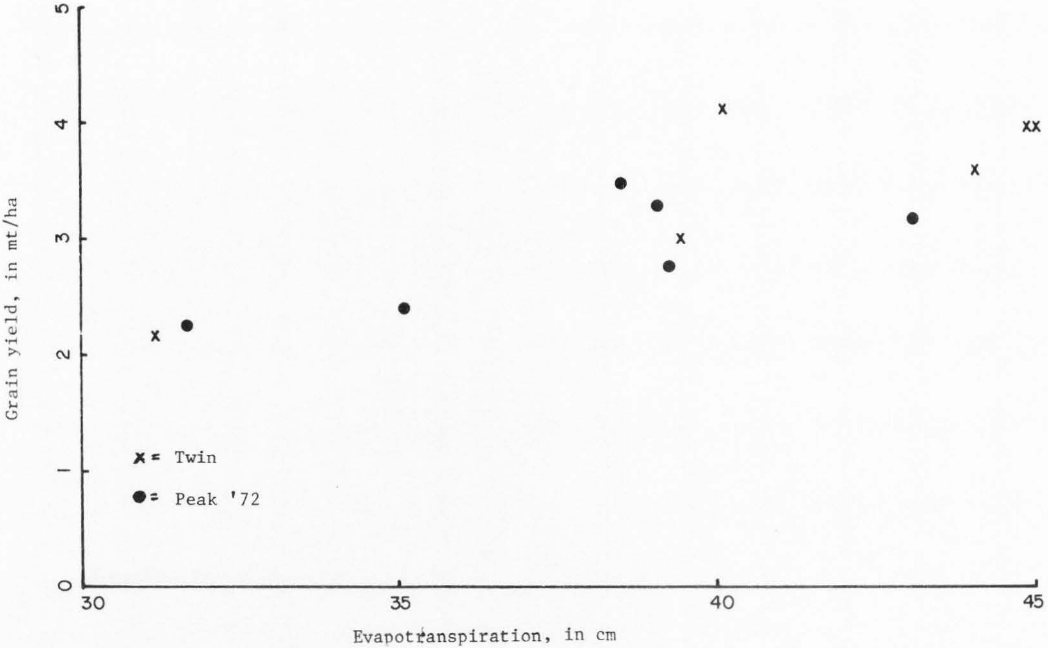


Figure 7. Grain yield vs. evapotranspiration for the two varieties monitored for soil moisture.

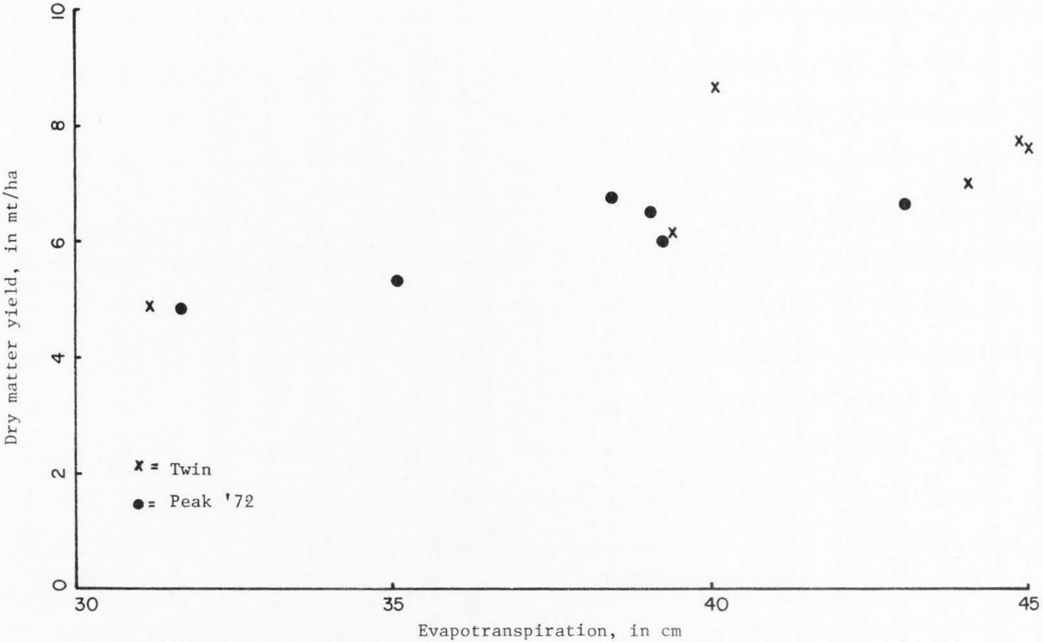


Figure 8. Dry matter yield vs. evapotranspiration for the two varieties monitored for soil moisture.

THE COMPUTER MODEL

Model theory

The model was constructed from the basic statements and theory of the model presented by Hill et al. (1974) for corn. Numerous changes were made within the original corn model to allow modeling of a dissimilar crop: spring wheat. Several improvements were also made in the soils ET section. The main program was completely rewritten.

The model's basic assumption is that dry matter yield can be related to the relationship of actual to potential transpiration expressed in equation [2]. Grain yield is computed as in equation [3], where the stages of growth are (a) plant to emerge, (b) emerge to booting, (c) booting to heading, (d) heading to soft milk, and (e) soft milk to maturity.

Transpiration is a complex process, with many factors affecting its rate. The model assumes a potential transpiration value determined by climatological parameters. This value is then adjusted to actual transpiration by relating it to the soil water status (soil water storage/available water storage), the soil water status is assumed to be the only factor limiting actual transpiration from reaching the climatologically determined potential transpiration for a given crop. Hanks (1974) showed that the model predictions were not very sensitive to the type of relationship between the existing soil water storage, SWS, and the maximum amount of available water storage, AW. The relationship used herein is

$$T = T_p / 0.5 \cdot SWS/AW, \text{ if } SWS/AW < 0.5 \quad [4a]$$

or

$$T = T_p, \text{ if } SWS/AW > 0.5 \quad [4b]$$

and

$$T_p = a\ E_o \quad [5]$$

in which SWS = existing soil water storage

AW = maximum amount of available water storage

a = a factor which depends on the crop and growth stage.

These equations assume there is a unique AW for a given soil which may be questionable for some situations. This computation is adapted to allow for five different layers of soil. A root growth estimation is used which allows root extraction to occur at increasingly deeper depths with time.

Soil evaporation is assumed to be related to potential soil evaporation and the time since the last wetting by

$$E = E_p / t^{1/2} \quad [6]$$

and (this computation is performed external to the model)

$$E_p = b(E_o - T_p) \quad [7]$$

in which E = evaporation from the soil

E_p = potential soil evaporation

b = a factor which depends on the crop and growth stage

t = the time in days since the last wetting

Equation [6] is the same type of relation used by Ritchie (1972) and Hanks (1974). It is subject to the constraint that the soil water storage in the surface 20 cm (8 in) of soil must be above the air dry soil water storage. The top 20 cm (8 in) of soil are dried by evaporation and transpiration to the wilting point and then by evaporation only to air dry. The value of T_p and, consequently, E_p (see equation [7]) are influenced by the kind of crop and stage of growth. E_o and E_p are read into the model and computed externally from pan data or empirical methods.

Drainage is assumed to occur if the sum of SWS and the water applied by irrigation or rain is greater than AW for all root depth increments. The model does not account for water flow upward into the root zone or runoff during high application-rate periods.

The progress of the plant through the individual growth stages is computed by a method employed by Hill et al. (1974). This method has been commonly referred to as the "Weather Bureau 50-86 Growing Degree Day" method and is attributed to Gilmore and Rogers (1958). This approach assumes that there are certain limits to the temperature range in which plant phenological development occurs; and that within this range, the rate of progression is proportional to the value of the average temperature. In equation form, this is expressed as

$$\text{GDD } ^\circ\text{F} = (\text{TH}/2 + \text{TL}/2) - 50 \qquad [8a]$$

in which GDD °F = growing degree days for the given day, °F

TH = maximum daily air temperature (TMX), if $\text{TMX} \leq 86$ °F, if $\text{TMX} > 86$ °F then $\text{TH} = 86$ °F.

TL = minimum daily air temperature (TMN), if TMN $\geq$ 50° F,
if TMN $<$ 50° F, then TL = 50° F.

This equation is express in terms of degrees Fahrenheit because all weather records presently collected are in this form. For reference, it is also given as follows in the SI system (degrees Celsius),

$$\text{GDD °C} = (TH/2 + TL/2) - 10 \qquad [8b]$$

in which GDD °C = growing degree days for the given day, °C
TH = maximum daily air temperature (TMX), if TMX $\leq$ 30° C,
if TMX $>$ 30° C, then TH = 30° C
TL = minimum daily air temperature (TMN), if TMN $\geq$ 10° C,
if TMN $<$ 10° C, then TL = 10° C.

In this thesis, the Fahrenheit form of growing degree days (GDD °F) will be presented because of the current convention of the U.S. Weather Service. However, Celsius equivalents will be given where practical (GDD °C). Fahrenheit growing degree days, rather than Celsius growing degree days, were used within the model because all data were collected from official U.S. Weather Service sources or their equivalents.

Within the computer model, the daily growing degree days are accumulated from a specified planting date and matched against required accumulated GDD °F's for the given spring wheat variety to reach growth stage end points, such as boot or head. The accumulated GDD °F's then serve as a timing mechanism for plant growth stage progress.

Thus, the model proceeds on a day-to-day basis by using a simple accounting procedure to keep a running account of SWS, cumulative T_p, T, E, drainage, irrigation and rain. The phenologic stage is determined by accumulating daily computed GDD °F, equation [1], and matching against the required sum for completion of each growth stage. At the end of the season, the cumulative T, E, irrigation, rain, drainage, total water use, T/T_p for each growth stage, and relative grain and dry matter yield are printed out. The program allows for a reinitialization of the input data with a different amount of water added at the same or different frequency and, if desired, a new planting date. The computations are then repeated for the same set of daily weather data and soils.

Model structure

The FORTRAN IV (Burroughs B6700 version) program, as used in this study, is given in Appendix B. A sample input deck for the Burroughs system is printed in Appendix C, with the resulting printout controlled by this deck given in Appendix D.

The model is divided into a main program and two subroutines. The main program reads all input data selectively and controls the execution of the two subroutines. The first subroutine (DATAR) computes GDD °F for all days, resulting phenological stages, and arranges other climate related information into the format used by the second subroutine. The second subroutine (PRDFNC) computes ET relationships, daily soil water status, and the yield components produced by these relationships.

The main subroutine is set up so as to be able to reinitialize any data set and then re-execute either or both subroutines. This format was especially valuable when evaluating large numbers of crop dependent factors or many irrigation treatments. All necessary computations can be executed, and the results printed, in one "pass" through the computer's processing unit. This arrangement provides much greater economy in multiple runs such as this. A variable designed ITYPE is used as a control input to guide the program through or around desired steps.

When ITYPE equals one, the program will read in site-specific information and control data. This includes five variables that control extensive interim printout of results for debugging purposes only (TSTCLM, TSTGDD, TSTSUM, TSTPHN, and DEBUG). An alpha-numeric array (SITE(N)) allows printing of a desired site identification character string. THK(N) is the thickness of each of five soil layers defined in the model. The summation of THK(N) should equal the maximum rooting depth of the plant in that soil. WHC(N) is the water holding capacity in each of the five layers of soil in dimensionless units. This is defined as the difference in the volumetric water content observed at field capacity and permanent wilting point for the given soil. AIRDRY is a variable used to set a limit on the amount of water that can be extracted beyond the water content of permanent wilting point, by evaporation from the surface layer of soil. The model assumes no other layer can be dried by evaporation, thus only the top layer can be dried below permanent wilting point water content. A value of -2.0 was used throughout this study. AWFAC is the available water factor used in equation [4a] and [4b] as 0.5. This value of 0.5 was used throughout this study. BGSM(N) is the beginning soil moisture in each of the five layers of soil expressed in units of depth such as cm. The model is arranged so that any system of length units may be used to express BGSM, THK, etc., as long as consistency is maintained. Thus, if soil water information is in centimeters, then rain and irrigation must be given in centimeters and the resulting ET and transpiration relationships will be computed in centimeters.

When ITYPE equals two, the main program reads in crop-specific information. CRPNM and VARNM are alphanumeric variables used to allow printing of the crop name and variety name, respectively. GDDMAT is a real variable used to allow printing of the required growing degree days for the crop to mature (GDD °F in this study). STAGE(N) is an alphanumeric array used to allow printing of the average desired growth stages for a given crop. GDDPH(N) is an array used to store the values of growing degree days (in GDD °F) required in each growth stage. RTDAMX, FROOTA, FROOTB, and DEPSEW are variables used in root growth computations; RTDAMX is the day since planting that the root reaches maximum depth (the sum of the five soil depths used). DEPSEW is the depth of planting. E(N) is the array of constants (λ_i) used in the grain yield equation (equation [3]).

When ITYPE equals three, the main program reads in year-specific (climatic) information for a given place and year. IYR and NDST are variables that refer to the year and number of days in the year (366 if a leap year). STRTEV is a value used to adjust the beginning value of ET_p and E_p according to the time since the last rain, because the model assumes in its computations that rain occurred on the day of planting. TMX(N), TMN(N), and PPT(N) refer to arrays of maximum temperatures, minimum temperatures, and precipitation for the entire year. A routine in DATAR changes precipitation values from inches to centimeters, if desired.

When ITYPE equals four, the main program reads the Julian day of planting (IPLT) and the Julian day of harvest (HRVST). The HRVST variable is only needed it the crop is to be harvested before calculated maturity, otherwise it is set to a value greater than 365.

When ITYPE equals five, the program reads-in sufficient climatic information so that DATAR need not be executed if these calculations have already been completed outside the program. SKIP2 is a variable that causes only a portion of DATAR to be executed if desired. DAYS is the number of days in the growing season. NR is the number of elements in the rain array. DDST is the fraction of the growth season in each of the five chosen growth stages. R(N) is the day of rain (day number since planting) and the amount, recorded sequentially in an array.

When ITYPE equals six, the main program reads the irrigation data, if desired. IR is the number of elements in the rain array. GIRR(N) is an array with elements of day number followed by irrigation amount configured as in the rain array.

When ITYPE equals seven, the ET_p and E_p information is read. IET is the number of elements in the ET array. ET(N) is the ET array containing sets of three elements: day number, then two numbers following, one being the potential evapotranspiration obtained by empirical methods or pan data, and the following number being the potential evaporation as calculated from equation [7]. Upon PRDFNC execution, the first array element is day 1 and associated values of E_p and ET_p are used by the model until the model reaches the day number expressed in the third trial of numbers. The procedure repeats until the day of crop maturity.

When ITYPE is greater than 10 and less than 20, subroutine DATAR is called. When ITYPE is greater than 20, subroutine FRDFNC is called.

If TYPE is equal or less than zero, the program stops. Thus a blank card is always needed at the end of a data deck.

Additional information regarding the program structure can be obtained by examining Appendixes B, C, and D. Comment statements have been provided to guide the would-be user.

Model calibration

Because the beginning form of the model was developed for hybrid field corn (Zea mays indentata L.) by Hill et al. (1974), considerable effort had to take place to alter numerical constants within the model and to change numerical procedures commonly utilized in input data preparation. A summary of model calibration is given in Appendix E.

The model as developed by Hill et al. (1974) contained a growing root function that was developed for corn by Childs (1975). This function, that described the maximum root depth at any time during the season was assumed to be a sigmoid curve with no roots at the time of planting and no change in root depth after the time of root profile maturity. Childs stated his equation thus:

$$\mathrm{Droot} = \mathrm{DD(kk)}/(1.0 + \exp\,(6.0-12.0 \cdot \mathrm{Time/Rdfday})) \qquad [9]$$

in which Droot = depth of rooting in cm

Time = time in days

DD(kk) = depth of root zone at maturity

Rdfday = number of days to root profile maturity

It can be seen that, when Time equals 0, droot equals $\mathrm{DD(kk)}/-(1.+e^{+6})$, essentially zero. At Time equals Rdfday, the time to root profile maturity, Droot equals $\mathrm{DD(kk)}/1.+e^{-6})$, essentially DD(kk). The distribution of roots for any value of droot is an algebraic scaling of the mature root density profile to fit a smaller depth.

This equation, when operated on data from the field plots of this study, gave results that were substantially in error when compared to actual rooting depth as estimated from neutron probe water depletion measurements. The method of Childs also causes the root to start at the surface and grow downward with no allowance for planting depth. This could lead to substantial errors with wheat planted at different depths. Therefore, Child's equation was modified to allow a depth-of-sowing constant to be added (DEPSEW) and allow the constants within the exponential argument to be altered at will (FROOTA and FROOTB). Thus the modified equation is expressed as follows:

$$\mathrm{DEPROT} = \mathrm{DEPSEW} + \frac{\mathrm{DEPMAX\text{-}DEPSEW}}{1.0 + \mathrm{EXP(FROOTA} - \mathrm{(FROOTB(DA/RTDAMX)))}} \qquad [10]$$

in which DEPROT = depth of root in cm at a given day since planting

DEPSEW = depth of planting (sowing)

DEPMAX = depth of maximum rooting, equal to sum of five depths of five layers used in the model

FROOTA, FROOTB = constants that vary according to crop (5 and 8 used in this study)

DA = sequential day since planting

RTDAMX = sequential day (since planting) when root reaches DEPMAX.

A simple FORTRAN IV (CANDE) program was written to test values of FROOTA and FROOTB in equation [10] from a remote computer terminal. Numerous tests were made of all possible combinations of integers between 1 and 20. Values of FROOTA and FROOTB that best fit actual rooting patterns for both types of wheat (white and red) with their individual RTDAMX, were determined to be 5 and 8, respectively. A representation of actual rooting depths observed, the values obtained with equation [9] of Childs, and the values obtained with equation [10] using FROOTA = 510 and FROOTB = 8.0, is given in Figure 9. The error of Child's equation (equation [9]) can be seen when applied to data from spring wheat.

The ET array that is read into the model is composed of triads of numbers, the first being a day number, the second being an ET_p value, and the third being an E_p value. The ET_p value for this study was obtained by taking the E_o value as estimated by a class-A U.S. Weather Service evaporation pan, and adjusting it for the shading effects of the late crop in the season when no transpiration was taking place. ET_p was considered equal to the pan value until the time of culm drying (estimated at 98 days after planting). At this time the ET_p value was dropped in a gradual sloping pattern to a low of 0.20 E_o at harvest. It was assumed that E_p is nearly the entire component of ET_p after the wheat culm starts to dry and transpiration slows. At this time, shading by the wheat plant would limit E_p and thus limit ET_p from its climatologically determined value that is registered by the pan.

After obtaining these basic values of ET_p, the crop factor, b, as shown in equation [7], was applied to ET_p to obtain a value for E_p. This crop factor is a result of transpiration of water by the plant competing for water normally available for E_p, and is also a result of crop shading during the active growing period. This crop factor allows T_p,

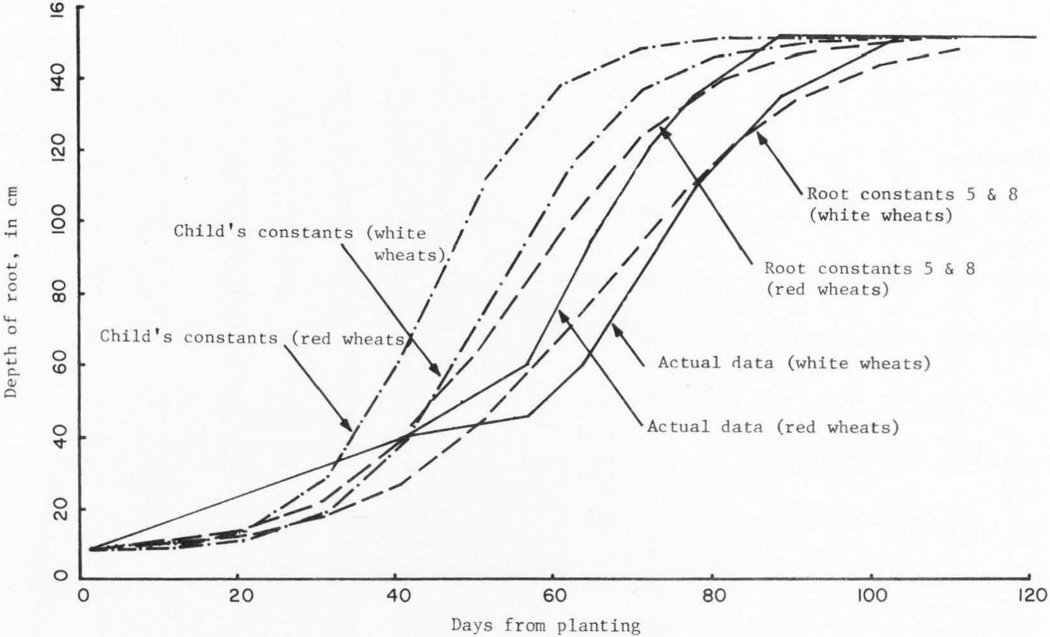


Figure 9. Graph of predicted vs. actual rooting depths for red and white wheats with Deprot Equation.

which is defined as $ET_p - E_p$, to start out at a zero value at planting and gradually approach ET_p at full-cover of plant growth. This is where T_p stays until the time of culm drying, when it drops to near zero. It should be noted that the program will not execute properly if E_p or T_p equals zero. Therefore, the ET array is adjusted so that E_p is never zero and ET_p is always (if only slightly) larger than E_p.

These values of the ET array were then multiplied by several weighting factors near 1.0 (0.8, 0.9, 1.1, 1.2, etc.) in order to calibrate the pan-obtained values for location effects in relation to wind, etc. that might be different from effects at the site. Selection of this scaling factor was done by comparing calculated evapotranspiration values with those observed at the neutron tubes sites in the field plots.

Evapotranspiration values obtained from the field plots had a range of approximately 31.0 to 44.0 cm. It was decided that the model should be adjusted to give these values at each extreme of the irrigation levels on the CVD plot. Adjusting the BGSM array (and thus the WHC array, since a full profile was assumed at the start) had a large effect on the calculated ET value for the dry end of the CVD plot, but a small effect on the wet end. Conversely, adjusting the ET array weighting factor had a large effect on calculated ET values at the wet end of the CVD plot, but a small effect on the dry end. Thus, these array values were adjusted up and down while holding some of them constant, until optimum values were obtained. It was found that a BGSM total of 16.6 cm gave the best fit, which was slightly less than the 18.8 cm calculated from neutron probe data. An ET array weighting factor of 1.0 was found to give best results on the overall data.

At the conclusion of model calibration, yield values of the wet plots were not at maximum values (e.g., $Y/Y_p < 1.0$). For the values of the ET array and the BGSM and WHC arrays used, even at the highest level of water application in the CVD plots, relative grain and dry matter production levels were all less than 0.90. Upon close examination of the model printout, it could be seen that a calculated ET deficit occurred in the second phenological period just prior to the first irrigation. Upon re-examining the neutron probe soil moisture data, this indeed seemed to be plausible.

For purposes of this study, it was then assumed that the values of the BGSM, WHC, and ET arrays were a reasonable approximation of the real environment that the wheat plants were being subjected to. Relying upon this assumption (which may not be entirely correct) an estimation could be made of the dimensional yield values associated with the Y/Y_p values calculated and printed by the computer model. The highest yield value (mt/ha) of each varietal trial was taken as the best representation of yield values for that variety. This yield was then multiplied by the reciprocal of the calculated relative yield fraction (Y/Y_p) for that particular row. This gave a quantitative value for the yield (in metric tons/hectare) associated with the Y/Y_p relationship of 1.00. Thus, any computed relative yield value could be multiplied by this value associated with Y/Y_p of 1.00, and the approximate yield value scaled to metric tons/hectare for that computed Y/Y_p would result. It should be re-emphasized that this particular method is only valid if it is assumed that the BGSM, WHC, and ET arrays are very close to correct values.

Calibration of E array values was done by testing a number of values until the data for grain yield matched that of the Peak '72 variety as close as thought practical. Values of 0.25 for all λ's constants in equation [3] gave a good fit. AIRDRY was set at 2.0 and AWFAC was set at 0.5.

Growing degree days (°F) were calculated and then calibrated against measured phenological stages so as to give proper results. Arrays were set up for each variety in the calibration (field) plots. The results are given in Table 4.

Table 4. Growing degree days (GDD °F) for stages of growth for five varieties grown for calibration in 1975

Phenological stage	Bannock	Fremont	Peak '72	Lemhi	Twin
Plant to emergence	61.5	61.5	61.5	61.5	61.5
Emergence to boot	427.5	436.0	436.0	488.0	471.0
Boot to heading	99.5	141.5	141.5	171.0	188.0
Heading to milk	348.5	345.5	345.5	307.0	307.0
Milk maturity	608.5	652.5	633.0	674.5	659.5
Total	1545.5	1637.0	1617.5	1702.0	1687.0

Model testing and results

All model calibration with respect to ET values was completed with neutron probe data from averages of the Twin and Peak '72 sites. All

The site of the Greenville Farm variety trials was essentially the same as the site where field plot studies for calibration were conducted. Therefore, no adjustments to site-specific data were made. The soil at the Bluecreek Experiment Farm also was similar enough in water holding capacity that no change in site-specific soil variables was made here either, even though the climate data is much different.

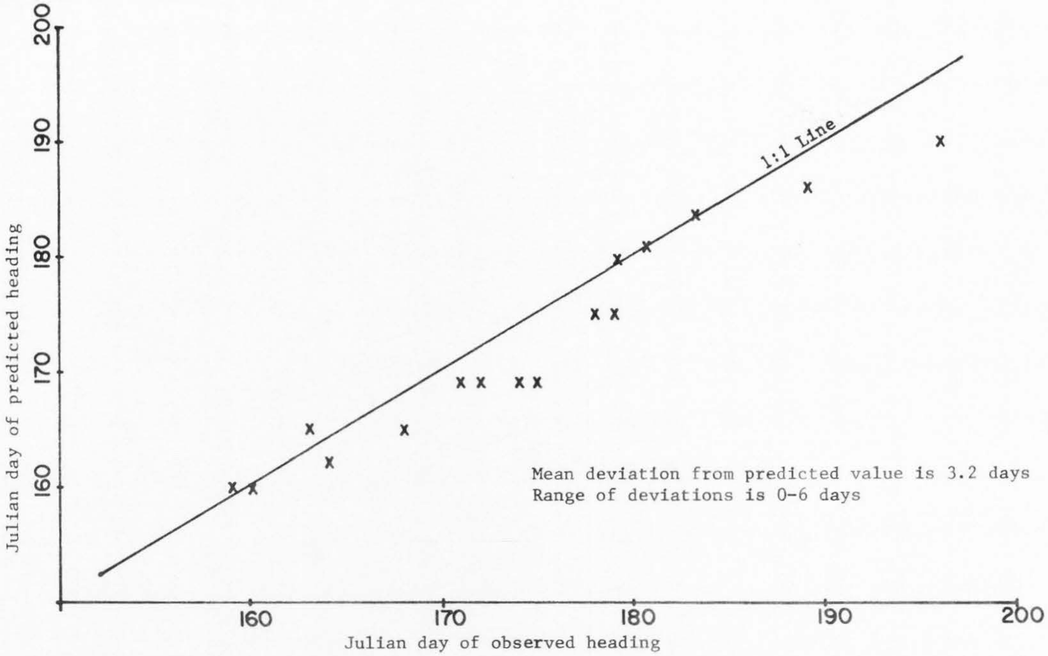
A preliminary test was made with the phenological portion of the model before any yield modeling took place. The model was calibrated for each variety with the climatic data for 1975, observed phenology of the calibration plots, and GDD °F computed for each day of the growth season. This data is summarized in Table 4. Climatic data was read into the model for each of the four years where heading dates were observed. Results of how observed and predicted values compare are shown in Table 5 and Figure 10. Mean deviation for all test years was 3.2 days. Maximum deviation of predicted from observed values was 6 days. Standard deviation of predicted from observed values was 3.22 days. When it is considered that the observation of the heading dates was possibly by different persons over the four years and that observations were taken every 2-7 days, then the prediction of the common "50-86 method" is seen as very adequate.

It should be noted that Neghassi (1974) reported that elapsed time in days was as significant as GDD for predicting phenology of winter wheat. It can be seen when examining Table 5 that the range of days from planting to heading in this test data is 50-75 days. Thus, in this study of spring wheat, GDD °F is more significant than elapsed days.

Table 5. Actual vs model predicted heading dates. USU Greenville Farm variety trials 1972-1975 (Month-day notation)

Variety	1975			1974			1973			1972		
	Obs.	Pred.	Deviation in days	Obs.	Pred.	Deviation in days	Obs.	Pred.	Deviation in days	Obs.	Pred.	Deviation in days
Fremont	7-8	7-5	3	6-17	6-14	3	6-24	6-18	6	6-8	6-8	0
Peak '72	7-8	7-5	3	6-12	6-14	2	6-23	6-18	5	6-7	6-8	1
Lemhi	7-15	7-9	6	6-20	6-18	2	6-27	6-24	3	6-14	6-12	2
Twin	7-15	7-9	6	6-21	6-18	3	6-28	6-24	4	6-14	6-12	2
			Mean deviation 4.5			Mean deviation 2.5			Mean deviation 4.5			Mean deviation 1.25

Mean deviation for all test years = 3.2 days.
Standard deviation for all test years = 3.22 days.
Maximum deviation for all test years = 6 days.



Mean deviation from predicted value is 3.2 days
Range of deviations is 0-6 days

Figure 10. Observed vs. predicted heading date for four test varieties during four years.

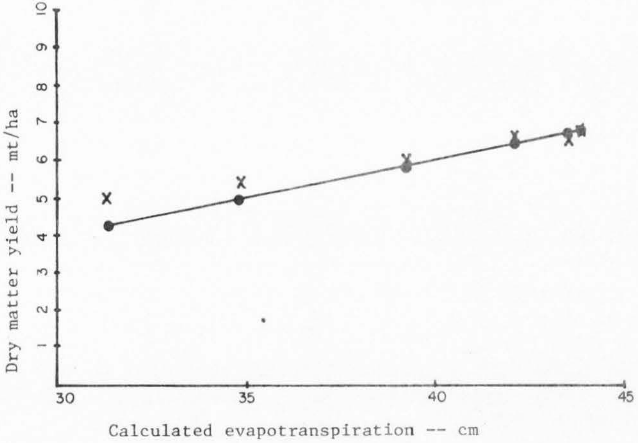
The next group of model validation runs were done with the data collected on the field plots conducted for this study in 1975. Data is given for both observed and predicted grain and dry matter in Table 6. Figures 11 and 12 show the model generated curve of predicted values vs actual values for both grain and dry matter for the Peak '72 calibration variety and for the Fremont variety (the only variety common to all validation tests), respectively. Prediction of dry matter leads prediction of grain in fitting measured values. However, if exponents in equation [3] were further optimized individually for each variety, this might not be the case. The deviation of predicted from observed grain yields seems to follow a general trend in both varieties, though not the same type of trend.

A model validation run was conducted for the Bluecreek site (Table 7). Only two of five test varieties were grown there, Fremont and Bannock. Prediction vs observed deviations were 0.04 mt/ha (0.6 bu/acre) and 0.4 mt/ha (6.5 bu/acre), respectively. Considering a maximum yield of approximately 5.0 mt/ha (82 bu/acre), these are errors of only 0.7 and 8.0 percent. Since this dryland area has very different climatic conditions from the calibration area at Logan, Utah, these results were very encouraging.

Additional validation was desired for the model. Data from variety trials at the USU Greenville Experiment Farm were very complete except that dates and amounts of irrigation had not been recorded, only the number of irrigations. It was decided to estimate these dates of irrigation at 7 days before predicted booting of the Bannock variety, and every 10 days thereafter for 3 irrigations, except in 1975 where

Table 6. Observed vs model predicted grain and dry matter yields in metric tons/hectare (estimated bushel/acre values in parentheses)

Variety	Irrigation Row #	Grain		Dry matter	
		Obs.	Pred.	Obs.	Pred.
Peak '72 (variety used to calibrate)	2 & 99	2.26 (36.9)	2.37 (38.7)	4.84	4.23
	10 & 91	2.41 (39.4)	2.74 (44.8)	5.29	4.94
	20 & 81	2.78 (45.4)	3.13 (51.1)	5.97	5.81
	30 & 71	3.19 (52.1)	3.35 (54.7)	6.58	6.40
	40 & 61	3.30 (53.9)	3.45 (56.4	6.51	6.67
	49 & 52	3.48 (56.9)	3.48 (56.9)	6.75	6.75
Fremont	2 & 99	2.05 (33.5)	2.88 (47.1)	4.15	4.71
	10 & 91	2.67 (43.6)	3.34 (54.6)	5.38	5.49
	20 & 81	3.34 (54.6)	3.82 (62.4)	6.40	6.47
	30 & 71	3.77 (61.6)	4.10 (67.0)	7.00	7.11
	40 & 61	4.23 (69.1)	4.23 (69.1)	7.44	7.44
	49 & 52	4.01 (65.5)	4.26 (69.6)	7.42	7.53
Bannock	2 & 99	1.98 (32.4)	2.01 (32.8)	4.28	3.94
	10 & 91	2.27 (37.1)	2.30 (37.6)	4.95	4.59
	20 & 81	2.24 (36.6)	2.61 (42.6)	5.38	5.40
	30 & 71	2.78 (45.4)	2.78 (45.4)	5.92	5.92
	40 & 61	2.68 (43.8)	2.84 (46.4)	5.49	6.12
	49 & 52	2.62 (42.8)	2.86 (46.7)	5.36	6.18
Lemhi	2 & 99	1.97 (32.2)	2.14 (35.0)	4.69	4.44
	10 & 91	2.73 (44.6)	2.61 (42.7)	6.00	5.18
	20 & 81	2.96 (48.4)	3.10 (50.7)	6.39	6.14
	30 & 71	3.07 (50.2)	3.34 (54.6)	6.51	6.76
	40 & 61	3.30 (53.9)	3.46 (56.5)	6.91	7.09
	49 & 51	3.50 (57.2)	3.50 (57.2)	7.21	7.21
Twin	2 & 99	2.16 (35.3)	2.52 (41.2)	4.84	5.30
	10 & 91	3.01 (49.2)	3.07 (50.2)	6.12	6.18
	20 & 81	3.62 (59.2)	3.66 (59.8)	6.92	7.33
	30 & 71	3.96 (64.7)	3.94 (64.4)	7.56	8.06
	40 & 61	3.97 (64.9)	4.08 (66.7)	7.65	8.46
	49 & 51	4.11 (67.2)	4.11 (67.2)	8.60	8.60



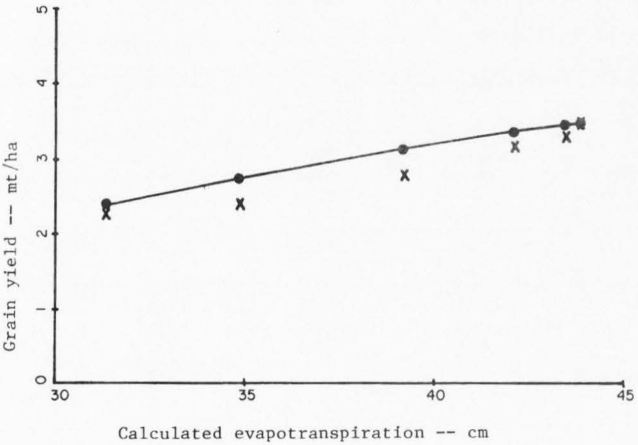
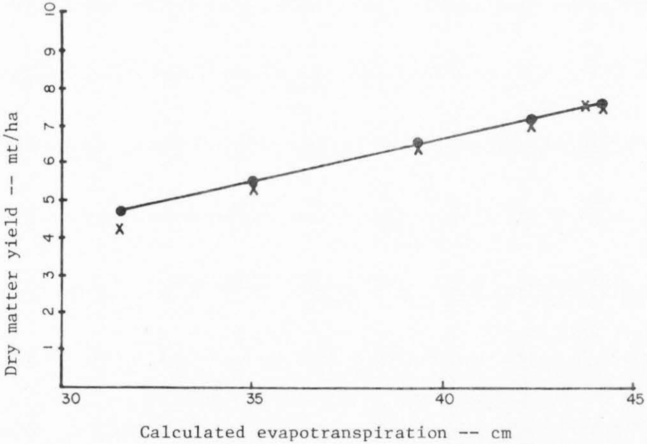


Figure 11. Model generated curve (dotted line) vs. observed data for Peak '72 variety on calibration plots.



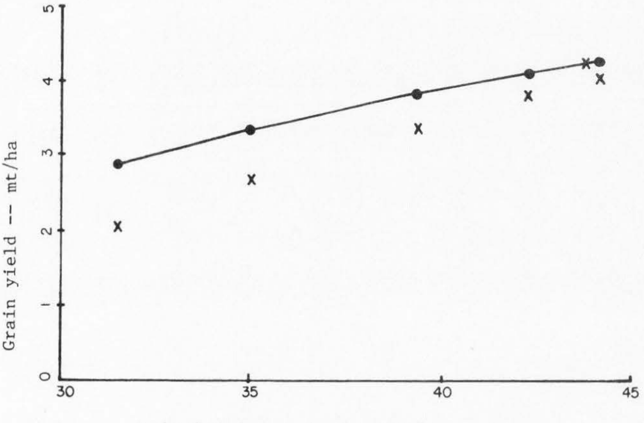


Figure 12. Model generated curve (dotted line) vs. observed data for Fremont variety on calibration plots.

Table 7. 1975 Bluecreek variety trials--actual vs model predicted grain yields (Dryland; WADD = PPT only)

Variety	Grain-Observed		Grain-Predicted	
	(mt/ha)	(bu/acre)	(mt/ha)	(bu/acre)
Fremont	1.55	(25.4)	1.59	(26.0)
Bannock	1.51	(24.7)	1.11	(18.2)

the first irrigation was skipped due to an extremely wet spring. This method would seem to follow the schedule that the author observed in 1975. Although this data would not provide as good a test as at Bluecreek, where no irrigation took place, it would give some idea as to the value of the model over several years of data and changing climatic patterns at a single site. The results of this test are given in Table 8.

Observed versus predicted yield diagrams for all data are given for each variety in Table 8 and Figures 13, 14, 15, 16, and 17. It can be seen that a very good fit to the 1:1 is found for the 1973, 1974, and 1975 data. The fit to the 1:1 line for the 1972 data is not as significant as the other years. The reason for this can be traced to the fact that observed production exceeded the models 100 percent value by as much as 30 percent. 1972 was a year that allowed planting to be done as much as 45 days earlier than normal and thus had a long, cool growing season. Thus more photosynthesis could take place in the longer phenological periods. The model has no means to compensate for these years when extended photosynthetic periods become

Table 8. 1972-1975 Greenville Farm Variety Trials--actual vs model predicted grain yields (Irrigation estimated, WADD = PPT + IRR (est.))

Variety	Grain-Observed		Grain-Predicted	
	(mt/ha)	(bu/acre)	(mt/ha)	(bu/acre)
1975 trials				
Fremont	4.61	(75.3)	4.52	(73.8)
Peak '72	3.93	(64.2)	3.68	(60.1)
Lemhi	3.55	(58.0)	3.78	(61.8)
Twin	3.35	(54.8)	4.41	(72.0)
1974 trials				
Fremont	4.46	(72.8)	4.33	(70.7)
Peak '72	3.79	(62.0)	3.51	(57.4)
Lemhi	2.96	(48.4)	3.56	(58.2)
Twin	4.15	(67.8)	4.17	(68.1)
1973 trials				
Fremont	3.97	(64.8)	4.71	(77.0)
Peak '72	3.33	(54.4)	3.83	(62.6)
Lemhi	3.54	(57.8)	3.86	(63.0)
Twin	3.56	(58.2)	4.55	(74.3)
1972 trials				
Fremont	5.39	(88.0)	4.97	(81.2)
Peak '72	5.58	(91.1)	4.04	(66.0)
Lemhi	5.48	(89.6)	4.17	(68.2)
Twin	6.56	(107.2)	4.90	(80.0)

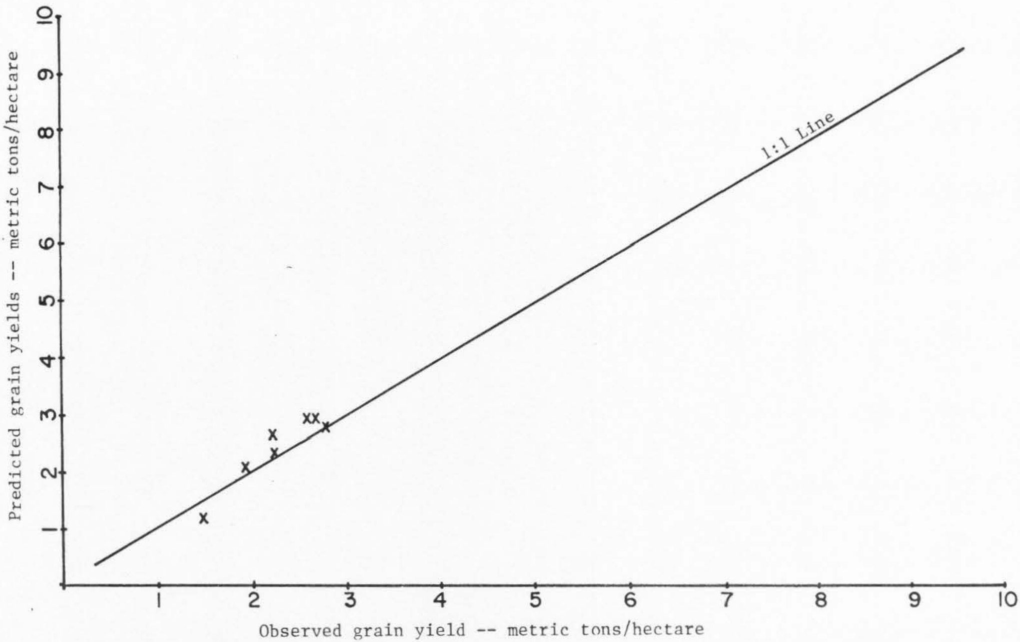


Figure 13. Observed vs. predicted grain yields for all data -- Bannock variety.

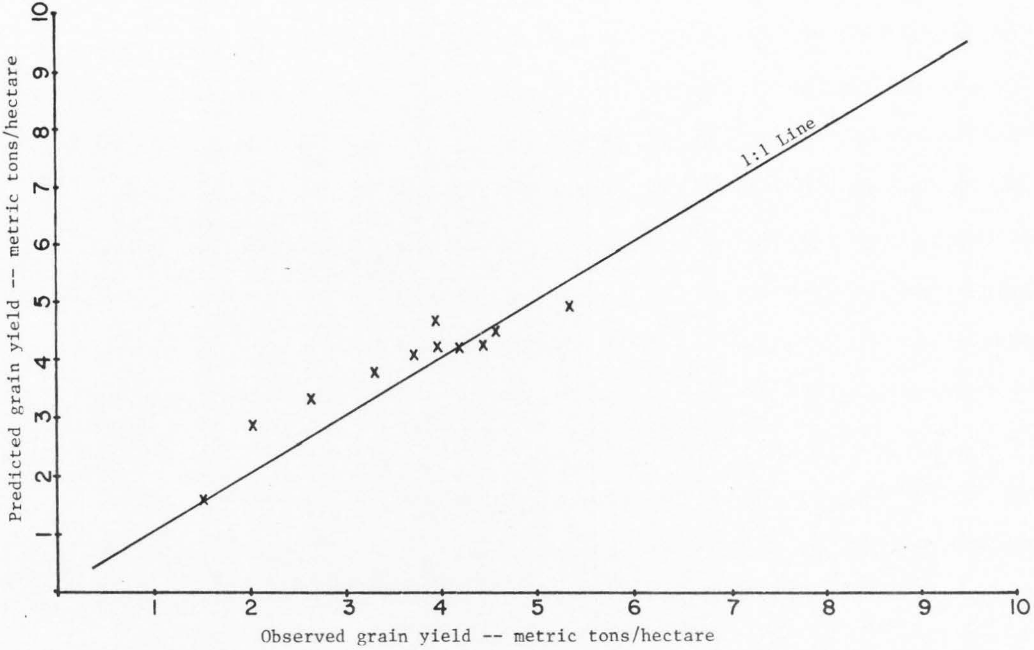


Figure 14. Observed vs. predicted grain yields for all data -- Fremont variety

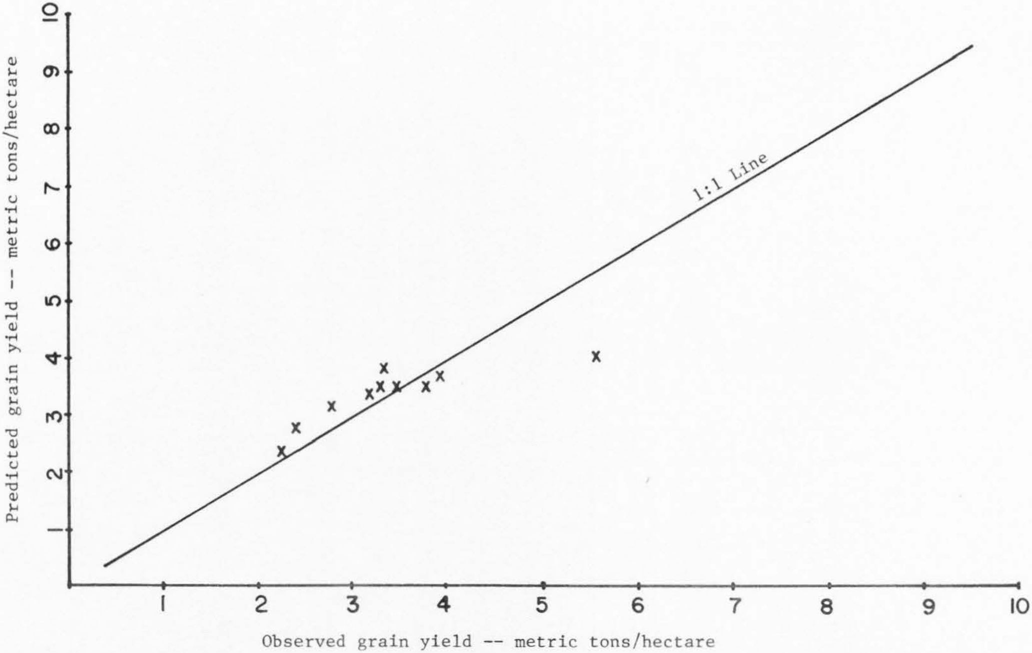


Figure 15. Observed vs. predicted grain yields for all data -- Peak '72 variety.

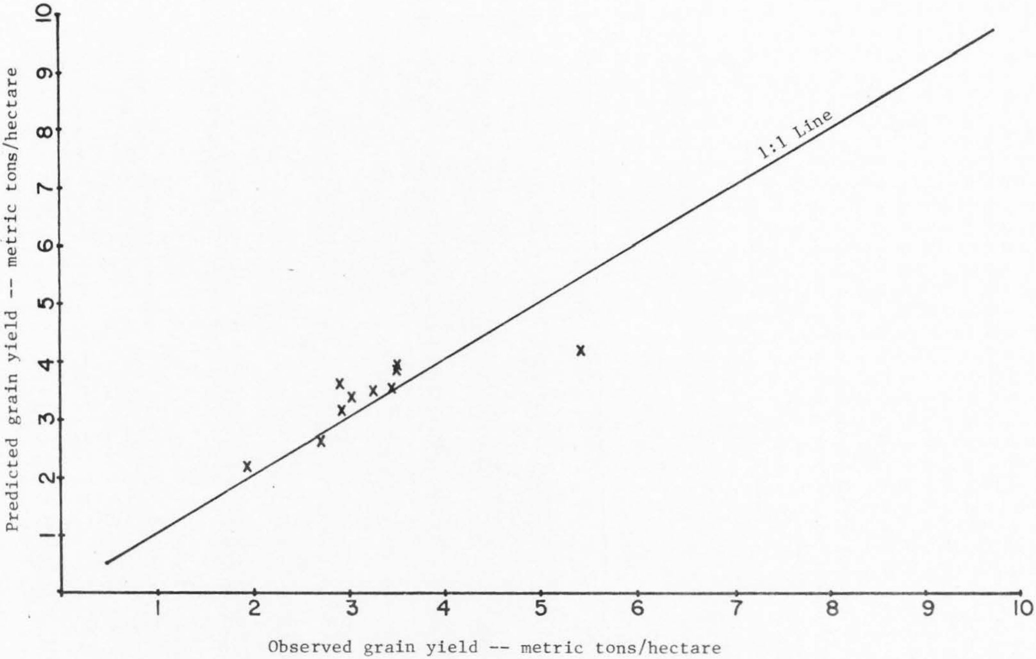


Figure 16. Observed vs. predicted grain yields for all data -- Lemhi variety.

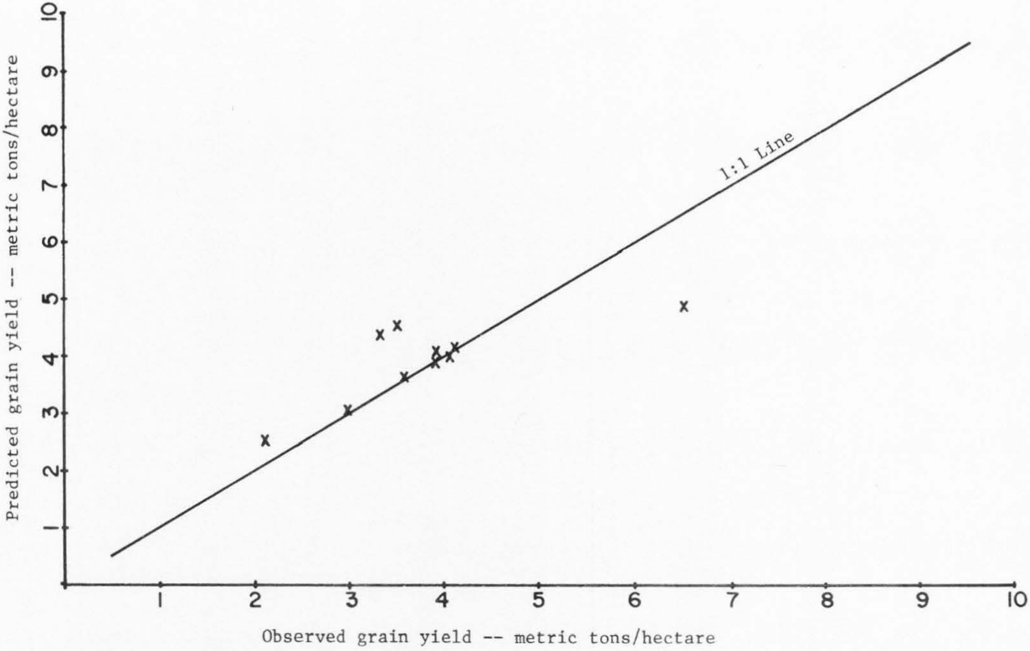


Figure 17. Observed vs. predicted grain yields for all data -- Twin variety.

a factor as important as transpiration relationships. If we neglect these points, the agreement between observed and predicted yields is more satisfactory. However, even when considering these outlying points, the model is giving results that are highly significant. If Y_p values for each year were determined by another process, the model would not be hampered by such an anomolous year.

If the results of all model tests are combined for all varieties and plotted for dry matter (Figure 18) and grain (Figure 19), a significant fit to the 1:1 line can be seen. A crude statistical analysis was performed on the predicted versus observed data. STATPAC/MREGT (Hurst, 1974), a terminal version of a versatile multiple regression computer program, was used to evaluate the data. This particular program has the capability of specifying that a least squares "best fit" line traverse through the origin. This allowed this "best fit" line to approximate the 1:1 line shown in Figures 13 through 19. For the combined dry matter data (calibration points included) as shown in Figure 18, and R^2 value of 0.996 was obtained, with the approximating line having a slope of 1.01 (instead of the desired 1.00). For the combined grain yield data (calibration points included) as shown in Figure 19, an R^2 value of 0.978 was obtained, with the approximating line having a slope of 0.997. For the grain yields from <u>test</u> data only (no calibration points included) an R^2 value of 0.965 was obtained, with the approximating line having a slope of 0.945.

Considering the error level in the calibration data, the fact that soils and ET calibration values were used from only one variety and applied to many, and the assumptions made when using test data,

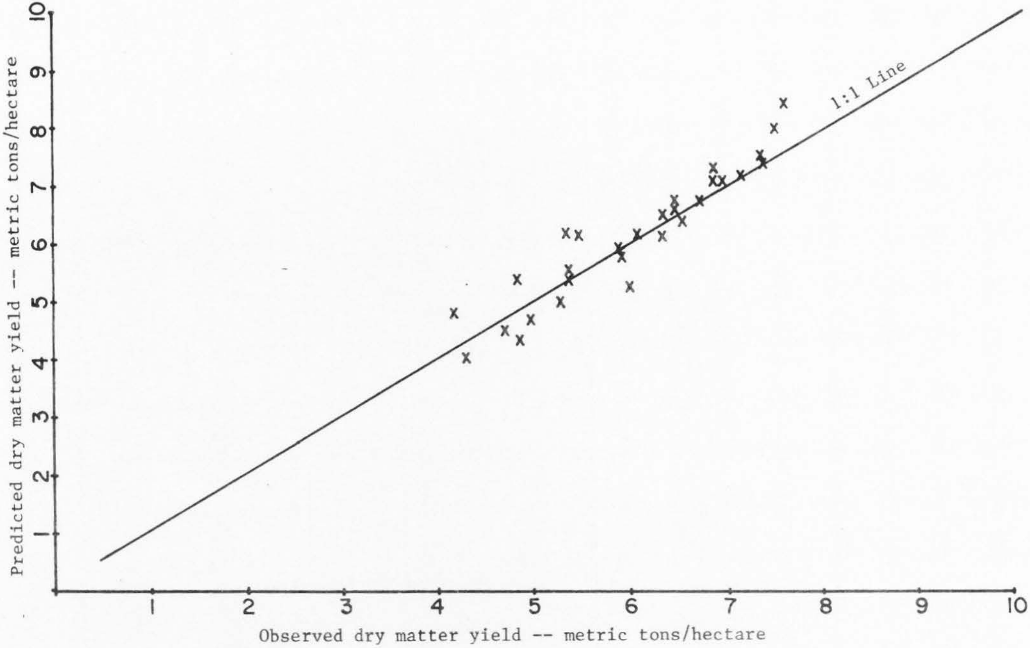


Figure 18. Observed vs. predicted dry matter yields for all data from all varieties.

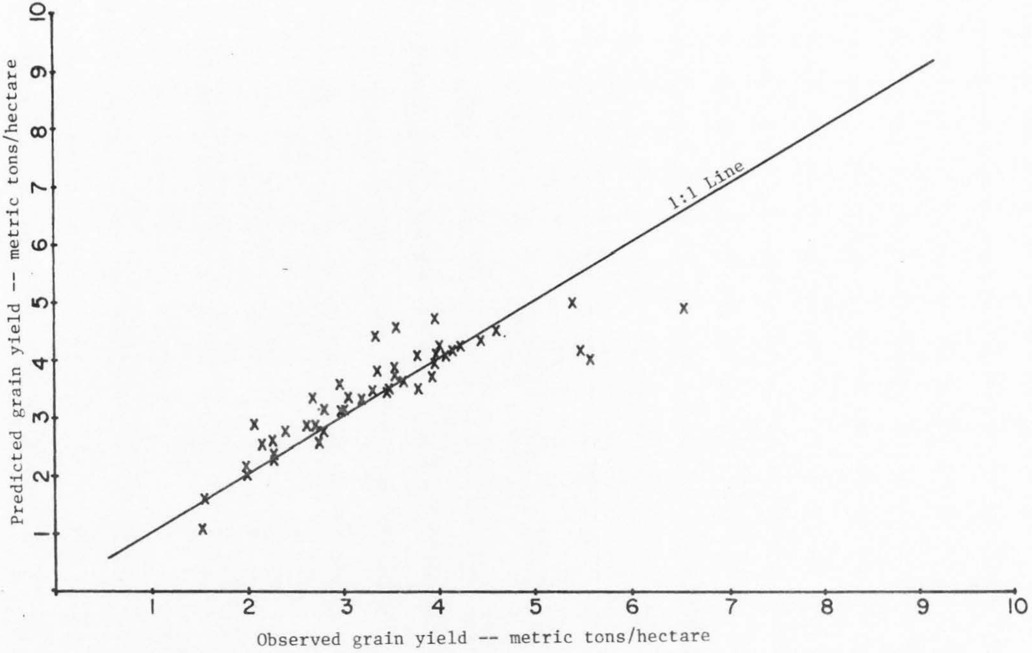


Figure 19. Observed vs. predicted grain yields for all data from all varieties.

the agreement of predicted and observed values is very good. It is apparent that the data points indicate that something in the model accounts for most of the important factors that influence yield.

SUMMARY AND CONCLUSIONS

One of the objectives of this study was to design and carry out a field experiment that would provide necessary phenological and yield information as related to varied levels of soil water, to calibrate the model. The continuous variable design was chosen for this study and did give information and a large number of irrigation applied levels. However, due to abnormally heavy spring rains, soil water storage was at a very high level and thus severe water stress was never achieved at the lowest water levels. Also, measured values of ET dropped at the wet ends of both plots monitored. The field study did provide abundant data to calibrate the model so as to get reasonable results when testing at other locations. The field study also provided invaluable phenological data for model calibration. A major contribution of this study was the realization of the tremendous usefulness of the continuous variable design in providing data for calibration of a model of this type. The numerous water levels available and easily obtained ET/water applied relationships aid in quickly finding the input variables required in the model. It is even more important when viewed in terms of economy of design and the numerous varieties that can be studied on one line source plot.

Another objective was to develop a predictive model for wheat development and yield as influenced by soil, water, and climatic factors. The model did fulfill this objective as far as could be determined with limited test data. Development was modeled sufficiently accurate to predict heading dates within the error of observation. Yield, both dry matter and grain, were modeled so as to fit an approximated 1:1 line with R^2 values of 0.95 or greater. This level of significance, when compared to purely statistical approaches used nationally to predict the United States wheat yield, seems very encouraging.

Another objective was to utilize existing data in the testing of the model. Some broad assumptions had to be made regarding irrigation data and soil properties. The model, when tested, came within 1.67 mt/ha in its worst case and had an average deviation of 0.59 mt/ha (for grain prediction). Thus, existing data can be matched relatively well by using climatological and soils inputs into the model. Therefore, much of existing yield data, on varieties where known phenology-growing degree days information exists, could be utilized in making management analysis studies with data generated by this model.

In summary, it should be noted that the model constructed during this study has limitations. It cannot account for variables other than climate and irrigation, except what is accounted for in the Y_p term in the dry matter and grain yield equations. However, this model does seem to have the capability, in this geographical area, to give reasonable yield predictions that can be utilized effectively if the user will keep in mind the assumpitons being made by the model.

SUGGESTIONS FOR FUTURE RESEARCH

It is apparent that the model is applicable and accurate for yield modeling under most climatic conditions in the Intermountain area. However, several limitations of the model could be improved upon with further research and subsequent model alterations.

The ability of the model to predict yield from year to year under long or short season conditions could be improved by adding a routine to compute a seasonal Y_p that is adjusted for a cool, long season or warm, short seasons. Investigation into this area would have to include examination of photoperiodism and possible phytochrome controlled photosynthetic reactions and other possible reasons that cause cooler seasons to produce larger yield.

The phenologic timeclock within the model could be improved by selectively choosing temperature limits other than 50 and 86 (°F) that are more optimum for wheat.

The exponents in the grain prediction equation could be optimized for each variety, provided enough information was available to calibrate the model properly.

Other desired variables, that are not now accounted for, such as soil fertility, could be added as an adjustment to Y_p, or directly into the prediction equation if needed.

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APPENDIXES

Appendix A

Adjusted Raw Data from Field Plot Experiments, by Rows

Table 9. Adjusted raw data from field plot experiments by rows

Row	Bannock		Peak '72		Fremont		Lemhi		Twin	
No.	G	DM	G	DM	G	DM	G	DM	G	DM
1	1.1	2.4	1.5	3.1	0.7	1.5	0.5	2.0	1.3	4.0
2	2.5	5.8	2.2	4.8	1.6	3.3	2.1	5.0	2.0	4.7
3	2.3	5.4	2.3	4.8	2.8	5.6	2.3	4.9	2.9	5.5
4	2.7*	7.2*	2.8*	6.2*	2.7*	5.6*	2.2*	5.0*	2.5*	2.4*
5	1.6	3.8	1.9	4.0	2.4	5.3	1.8	4.1	2.2	4.7
6	2.2	5.1	1.8	3.9	2.4	5.0	2.2	4.8	2.5	5.2
7	2.3	5.0	2.2	4.7	2.4	4.9	2.0	4.5	2.4	4.9
8	2.4	5.3	2.4	5.0	2.5	4.9	2.8	6.0	3.1	6.6
9	2.6*	5.7*	2.4*	5.3*	2.3*	4.9*	2.7*	6.0*	2.5*	6.1*
10	2.1	4.4	2.4	5.2	2.7	5.5	2.5	5.5	3.2	6.6
11	2.5	5.4	2.4	5.4	2.4	5.0	2.2	4.9	2.6	5.8
12	2.2	5.0	2.6	5.7	2.5	5.0	3.0	6.6	3.5	7.0
13	1.8	3.8	2.3	4.8	2.8	5.4	2.0	4.3	3.2	6.1
14	2.1*	4.7*	2.1*	4.5*	2.6*	5.1*	2.5*	5.5*	2.4*	5.1*
15	2.1	4.4	2.4	5.3	2.2	4.5	3.1	6.7	3.2	6.2
16	2.3	4.8	2.4	5.2	2.8	5.2	2.5	5.5	3.0	6.1
17	2.3	5.1	2.9	6.3	3.3	6.5	2.3	5.3	3.2	6.3
18	2.7	5.9	2.7	5.7	3.3	6.3	3.1	6.6	3.9	7.8
19	1.3*	4.0*	2.8*	5.9*	3.0*	5.9*	2.6*	6.0*	3.2*	6.6*
20	3.0	6.3	2.0	4.1	2.3	4.3	2.1	4.6	2.7	5.3
21	2.0	4.2	3.5	7.3	3.7	6.9	3.0	6.5	3.9	8.1
22	2.5	5.3	2.6	5.3	3.2	5.9	2.7	6.0	3.6	7.0
23	2.3	2.4	3.4	7.0	3.9	7.4	3.1	6.7	4.0	7.7
24	2.5*	5.7*	2.8*	4.7*	4.3*	8.4*	2.7*	5.8*	3.0*	6.5*
25	2.7	5.7	3.2	6.4	3.5	6.3	3.2	7.3	4.4	8.9
26	2.3	5.2	3.3	6.5	3.6	6.6	2.7	5.8	4.0	8.0
27	2.5	5.2	2.9	5.7	3.6	6.4	2.5	5.5	3.5	9.6
28	1.9	4.3	3.0	6.2	3.3	6.0	2.8	5.9	3.6	6.9
29	3.0*	6.9*	2.1*	5.9*	4.3*	8.0*	3.1*	7.1*	3.9*	N/R
30	2.2	4.6	4.3	8.4	3.8	6.9	2.4	5.1	4.0	7.9
31	2.6	5.4	3.0	5.8	4.1	7.3	3.2	6.6	4.0	7.6
32	2.5	4.7	2.7	5.2	3.2	5.9	2.2	4.7	4.7	10.1
33	3.5	7.1	4.1	8.1	3.0	5.7	3.9	8.2	4.9	9.0
34	2.2*	4.4*	3.0*	6.4*	4.1*	9.6*	2.7*	5.9*	3.3*	6.9*
35	2.4	4.9	3.7	7.2	3.4	6.2	2.7	5.7	3.6	6.9

Table 9. Continued

Row	Bannock		Peak '72		Fremont		Lemhi		Twin	
No.	G	DM	G	DM	G	DM	G	DM	G	DM
36	3.4	6.7	3.3	6.2	4.7	8.5	3.9	8.1	4.5	8.5
37	2.3	4.6	3.2	6.2	3.5	6.7	2.6	5.2	3.8	7.4
38	2.5	5.1	3.1	6.1	4.1	7.1	3.0	6.4	4.1	7.9
39	2.3*	4.8*	3.0*	6.4*	4.1*	7.5*	2.9*	6.0*	3.7*	7.2*
40	3.1	6.2	3.6	7.1	4.6	7.4	3.5	7.1	4.3	10.1
41	2.0	4.1	3.3	6.2	3.8	6.8	2.5	5.2	3.9	7.3
42	2.2	4.8	2.9	5.8	3.2	6.5	2.8	5.7	3.7	7.0
43	2.0	4.3	3.3	6.3	4.0	6.6	3.3	6.5	4.1	7.6
44	2.5*	5.2*	3.1*	6.2*	3.4*	6.5*	2.7*	5.6*	3.7*	6.9*
45	2.0	4.2	2.8	5.3	3.5	6.4	3.1	6.4	3.1	5.6
46	2.0	4.1	4.3	6.4	4.7	8.8	3.4	7.0	5.3	9.6
47	2.7	5.5	3.0	5.6	3.5	6.6	3.5	7.1	3.9	9.9
48	2.5	5.0	3.2	6.0	3.5	6.6	2.9	6.3	3.4	9.1
49	2.1*	4.4*	3.4*	7.0*	4.2*	8.1*	2.9*	6.3*	3.6*	7.1*
50	2.1	4.1	3.5	6.4	3.7	7.1	3.3	6.4	3.9	10.0
51	3.5	6.9	3.6	7.3	4.5	8.3	4.0	8.5	4.8	8.6
52	2.3	4.6	3.2	6.1	3.9	7.1	3.3	7.1	3.3*	6.6*
53	1.7	3.7	2.9	5.9	4.2	7.4	3.9	7.8	3.2	5.9
54	3.7*	7.8*	4.4*	8.7*	3.9*	7.5*	3.4*	7.1*	5.7	9.9
55	3.1	6.4	4.4	8.4	4.8	8.9	4.1	8.8	3.7	6.6
56	2.1	4.5	2.1	4.2	2.8	5.2	2.5	5.0	3.9	6.9
57	2.1	4.3	2.1	4.2	3.5	6.5	3.2	6.4	3.0*	5.7*
58	3.5	7.1	4.4	9.4	5.0	9.2	4.4	9.3	4.9	8.8
59	2.8*	5.9*	4.0*	7.9*	4.8*	9.1*	4.1*	8.6*	3.9	7.0
60	2.8	5.7	3.0	5.7	3.7	7.1	3.5	7.1	4.5	7.8
61	2.4	4.8	2.7	5.5	4.9	6.2	3.1	6.2	3.1	6.7
62	2.5	5.1	2.7	5.8	4.2	7.8	3.1	N/R	3.0*	5.9*
63	3.8	7.9	4.2	8.1	4.5	8.4	4.1	8.5	5.0	9.1
64	2.7*	5.7*	3.4*	7.2*	3.4*	6.4*	3.6*	7.4*	3.9	6.9
65	3.1	6.2	3.0	6.1	3.5	6.4	3.7	7.6	3.9	6.9
66	2.7	5.7	2.7	5.6	3.5	6.6	3.3	6.9	3.8	6.7
67	3.3	7.0	4.5	9.8	4.7	9.0	4.1	8.2	4.2*	8.3*
68	2.7	5.6	3.2	6.2	3.0	5.7	3.1	6.4	5.1	6.4
69	3.3*	7.1*	2.7*	5.6*	3.1*	6.1*	3.0*	6.9*	4.4	7.6
70	2.9	6.2	3.6	7.2	4.2	8.0	3.8	7.9	3.7	6.8

Table 9. Continued

Row	Bannock		Peak '72		Fremont		Lemhi		Twin	
No.	G	DM	G	DM	G	DM	G	DM	G	DM
71	2.6	5.5	2.7	N/R	3.4	6.3	3.1	6.7	3.6	6.3
72	2.8	5.9	2.9	6.3	3.6	6.9	3.6	7.6	3.2*	6.1*
73	3.5	7.7	4.4	N/R	4.1	8.1	3.0	6.3	4.1	7.5
74	2.5*	5.7*	2.3*	4.8*	2.6*	4.9*	2.5*	6.1*	4.0	7.3
75	2.5	5.6	3.4	N/R	3.6	7.2	3.4	7.1	3.6	6.6
76	2.8	6.3	2.6	N/R	3.1	6.1	3.2	7.2	3.6	6.6
77	2.2	4.7	3.5	7.2	4.2	8.6	3.2	6.9	2.2	4.3
78	2.9	6.3	2.5	5.1	2.8	5.5	3.3	7.0	4.9	9.2
79	2.9*	6.5*	2.4*	7.3*	3.9*	7.7*	3.1*	6.8*	3.4	6.2
80	2.1	4.4	2.5	N/R	3.3	6.4	3.2	6.7	3.0	5.8
81	2.4	5.1	2.0	4.3	2.9	5.5	2.9	6.2	3.9	7.1
82	2.4	5.2	3.4	7.7	4.2	8.3	3.3	7.4	3.9*	N/R
83	2.8	6.4	2.5	5.5	3.2	6.2	3.0	6.6	4.1	7.8
84	2.2*	4.8*	2.4*	5.3*	2.9*	6.0*	2.8*	6.0*	2.4	4.6
85	2.5	5.4	2.6	5.6	2.6	N/R	2.8	6.0	2.6	5.0
86	2.2	4.8	2.5	5.9	4.0	8.2	3.5	8.0	2.9	5.6
87	2.9	6.5	2.4	5.3	2.4	4.9	2.1	4.8	3.7*	N/R
88	2.2	4.8	2.2	5.2	2.9	5.7	2.9	6.6	2.8	5.7
89	1.7*	3.9*	2.3*	4.9*	2.7*	5.3*	2.5*	5.7*	2.7	5.0
90	2.2	5.0	2.5	5.6	2.9	5.9	3.1	6.8	3.3	6.5
91	2.8	6.3	2.6	6.1	3.1	6.5	3.0	6.7	3.1	6.1
92	2.0	4.4	2.1	4.8	2.7	5.6	2.7	6.1	2.4*	5.2*
93	1.7	3.7	2.0	4.4	2.3	4.7	2.3	5.4	3.0	5.7
94	2.1*	4.8*	2.3*	5.2*	2.5*	5.0*	2.7*	6.3*	2.9	5.7
95	2.6	5.7	3.1	7.4	3.0	6.5	2.9	6.8	3.0	6.6
96	2.1	3.9	2.0	4.5	2.3	4.7	2.3	5.2	2.2	4.5
97	2.0	4.3	2.2	5.1	2.5	5.1	2.4	5.6	2.7*	6.1*
98	1.8	4.6	2.0	4.6	2.4	5.0	2.3	5.3	2.2	4.7
99	2.0*	4.8*	2.8*	6.0*	2.7*	5.7*	2.5*	6.1*	2.4	4.7
100	1.9	3.9	2.4	5.1	2.0	3.9	2.1	5.3	1.9	4.4

Note: Items with * indicate rows in which total dry matter was dried for moisture content determination. Grain yields on these rows were not computed from moisture content-regression data but were computed separately.

Appendix B

Wheat Model Expressed in FORTRAN IV

```
C***********************************************************************
C     PROGRAM "WHEAT-ET-PRODUCTION"-KNOWN AS BIGWHEAT/BIGWHEATO ON DISK
C***********************************************************************
C***********************************************************************
C     MASTER CONTROL SECTION FOR "WHTPRD" CONTOLLED BY ITYPE CARD
C     ***ANY PORTION(S) CAN BE REREAD & THUS CHANGED...THEN SUBROUTINE
C     (S) CAN BE RUN OR SKIPPED...ALL UNDER CONTROL OF ITYPE CARD
C***********************************************************************
C     AN ITYPF=0 IS NEEDED TO STOP PROGRAM AT END ****NOTE****
C***********************************************************************
C***********************************************************************
C     -----LAST UPDATE: 11 MAY 1976; VERSION: "FINAL V"-----
      INTEGER DAYS,DAMAT,DEBUG,SMWGDD
      LOGICAL TSTCLM,TSTGDD,TSTSUM,TSTPHN
      COMMON/LOGIC/TSTCLM,TSTGDD,TSTSUM,TSTPHN
      COMMON/INPUT/SITE(13),THK(5),WHC(5),AIRDRY,AWFAC,BGSM(5),CRPNM
     &(3),VARNM(5),GDDMAT,STAGE(12),GDDPH(5),RTDAMX,FROOTA,FROOTB,DEPSEW
     &,IYR,NDST,STRTEV,FMT(10),TMX(366),TMN(366),PPT(366),IPLT,HRVST,
     &SKIP2,DAYS,DDST(5),NR,R(200),IR,GIRR(200),IET,ET(100),E(5),DEBUG
      COMMON/MISC/XMNTH(12),ITYPE,IFLAGR
      COMMON/DATAR/GDD(366),DAPH(5),IPH(6),SMGDPH(6),ISDAPH(6),NDAS(12),
     &JK(6),IDAY(6)
      COMMON/PRDFCN/BGSAV(5),WC(5),C(10)
      DATA NDAS/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA XMNTH/3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,3HJUN,3HJUL,3HAUG,3HSEP,
     &3HOCT,3HNOV,3HDEC/
      NDAS(2)=28
      WRITE(6,22)
      WRITE (6,23)
 23   FORMAT (/,'  READING-IN DATA BY CONTROL OF ITYPE:  ',)
C***********************************************************************
C   ---MAIN LOOP IS TO HERE WHERE ITYPE IS READ IN ORDER TO FIND OUT
C  WHERE TO PROCEED TO IN PROGRAM........
C***********************************************************************
 1000 READ(5,20) ITYPE
 20   FORMAT(14I5)
      IF (ITYPE.LE.0) STOP
      IF (ITYPE.NE.1) GO TO 1010
C***********************************************************************
C IF "ITYPE"=1, PROGRAM READS SITE SPECIFIC INFORMATION & DEBUG INFOR.
C***********************************************************************
      READ(5,30)TSTCLM,TSTGDD,TSTSUM,TSTPHN,DEBUG
 30   FORMAT(4L10,I10)
      WRITE (6,40) TSTCLM,TSTGDD,TSTSUM,TSTPHN,DEBUG
 40   FORMAT (/,'  LOGICAL TESTS FOR WRITING INTERMEDIATES:',4L5,I10)
      READ(5,50)(SITE(N),N=1,13)
 50   FORMAT(13A6)
      WRITE (6,60) (SITE(N),N=1,13)
 60   FORMAT (1X,13A6)
      READ (5,70)THK
 70   FORMAT(7F10.3)
      WRITE (6,80)THK
 80   FORMAT (1X,'THK  ARRAY',7F10.3)
      READ (5,70)WHC
      WRITE (6,90)WHC
 90   FORMAT (1X,'WHC  ARRAY',7F10.3)
      READ (5,70) AIRDRY,AWFAC
      WRITE (6,100) AIRDRY,AWFAC
 100  FORMAT ('  AIRDRY & AWFAC:  ',2F10.3)
      READ(5,70)BGSM
      WRITE (6,110)BGSM
```

```
 110  FORMAT (1X,'BGSM ARRAY',7F10.3)
 1010 IF (ITYPE.NE.2) GC TO 1020
C***********************************************************************
C IF "ITYPE"=2, PROGRAM READS CROP SPECIFIC INFORMATION
C***********************************************************************
      READ(5,120) CRPNM,VARNM,GODMAT
 120  FORMAT(3A4,5A4,F7.1)
      WRITE (6,130)CRPNM,VARNM,GCDMAT
 130  FORMAT (1X,3A4,5A4,F7.1)
      READ(5,140)(STAGE(L),L=1,12)
 140  FORMAT(12A4)
      WRITE (6,150)(STAGE(L),L=1,12)
 150  FORMAT (1X,12A4)
      READ(5,160) (GDDPH(K),K=1,5)
 160  FORMAT(5F16.2)
      WRITE (6,165)(GDDPH(K),K=1,5)
  165 FORMAT(1X,5F8.2)
      READ (5,70) RTDAMX,FROOTA,FROOTB,DEPSEW
      WRITE (6,170) PTDAMX,FROOTA,FROOTB,DEPSEW
 170  FORMAT ('  RTDAMX,FROCTA,FROOTB,DEPSEW:',4F10.3)
      READ (5,70) E
      WRITE (6,330) E
 330  FORMAT(1H ,'E ARRAY',7F10.3)
 1020 IF (ITYPE.NE.3) GO TO 1070
C***********************************************************************
C IF "ITYPE"=3, PROGRAM READS YEAR SPECIFIC AND CLIMATIC INFORMATION
C***********************************************************************
      IFLAGR=1
      READ(5,180) IYR,NDST,STRTEV
 180  FORMAT(2I10,E10.3)
      WRITE (6,190) IYR,NDST,STRTEV
 190  FORMAT ('  IYR,NDST,STRTEV:',2I10,2X,E10.3)
      IF(NDST.GT.365) NDAS(2)=29
C
      DO 1040 N=1,3
C    READ IN CLIMATE DATA
      IBG = 1
      READ(5,200) FMT
 200  FORMAT(10A4)
      CO 1040 J=1,12
      INC = IBG + NDAS(J)-1
      GO TO (2,4,6)N
 2    READ(5,FMT)(TMX(L),L=IBG,IND)
      GO TO 12
 4    READ(5,FMT)(TMN(L),L=IBG,IND)
      GO TO 12
 6    REAC(5,FMT) (PPT(L),L=IBG,IND)
 12   IB6=IND+1
 1040 CONTINUF
 1050 IF(.NOT.TSTCLM) GO TO 1070
      DO 1060 N=1,3
      GO TO(3,5,7) N
 3    WRITE(6,210) TMN
 210  FORMAT(15X,16F7.2)
      GO TO 1060
 5    WRITE(6,210) TMX
      GO TO 1060
 7    WRITE(6,210) PPT
 1060 CONTINUE
 1070 IF (ITYPE.NE.4) GO TO 1080
C***********************************************************************
```

```
C IF "ITYPE"=4, PROGRAM READS PLANTING DATE AND HARVEST DATE(ONLY NEEDED
C IF HARVESTED BEFORE MATURITY,OTHERWISE (HRVST.GT.DAYS)........
C***********************************************************************
      READ (5,180) IPLT
      WRITE (6,220) IPLT
  220 FORMAT (1X,'IPLT:',I6)
C     IF HARVESTING AT MATURITY; HRVST=500; OR VALUE > SEASON LENGTH
      READ (5,70) HRVST
      WRITE (6,340) HRVST
 340  FORMAT (1X,'HARVEST ON DAY   ',F5.1)
 1080 IF (ITYPE.NE.5) GO TO 1090
C***********************************************************************
C IF "ITYPE"=5, OPTIONALLY READS DAYS(#DAYS TO MATURITY),SKIP2(TO SKIP
C GDD & DDST CALC. FROM WEATHER DATA),NR(A COUNTER FOR RAIN ARRAY),DDST
C (BREAKDOWN OF GROWTH STAGES), & RAIN ARRAY; SO CAN SKIP DATAR IF WANT
C***********************************************************************
      READ (5,225) SKIP2,DAYS,NR
  225 FORMAT(3I10)
      WRITE (6,230) SKIP2,DAYS,NR
 230  FORMAT(1X,'SKIP2:',I5,'   DAYS:',I5,'   NR:',I5,/)
      READ (5,70)DDST
      WRITE (6,240)DDST
 240  FORMAT (1X,'DDST ARRAY',7F10.3)
      READ (5,250)(R(J),J=1,NR)
 250  FORMAT(9(I3,F5.2))
      WRITE (6,260)(R(J),J=1,NR)
 260  FORMAT ('  DAY RAIN', 14(I4,F5.2)/2X 15(I4,F5.2))
 1090 IF (ITYPE.NE.6) GO TO 1100
C***********************************************************************
C IF "ITYPE"=6, PROGRAM READS IN IR(IRRIGATION ARRAY COUNTER) & GIRR ARR
C***********************************************************************
      READ(5,270)IR
 270  FORMAT (24I3)
      WRITE (6,280) IR
 280  FORMAT (1X,'IR:',I3)
      READ(5,250) (GIRR(J),J=1,IR)
      WRITE (6,290) (GIRR(J),J=1,IR)
 290  FORMAT(' DAY IRRIGATION', 13(I4,F5.2)/2X 14(I4,F5.2)/2X 14(I4,F5.2
     $)/2X 14(I4,F5.2)/2X 14(I4,F5.2))
 1100 IF (ITYPE.NE.7) GO TO 1120
C***********************************************************************
C IF "ITYPE"=7, PROGRAM READS-IN ET ARRAY
C***********************************************************************
      READ (5,270) IET
      WRITE (6,300) IET
 300  FORMAT (1X,'IET:',I3)
      READ(5,310)(ET(J),J=1,IET)
 310  FORMAT (7(I3,F4.2,F4.2))
      WRITE (6,320)(ET(J),J=1,IET)
  320 FORMAT(' DAY,ETPOT,EPOT:',8(I3,1X,F4.2,1X,F4.2,1X)/2X9(I3,1X,F4.2,
     &1X,F4.2,1X)/2X9(I3,1X,F4.2,1X,F4.2,1X))
 1120 IF (ITYPE.GE.10.AND.ITYPE.LT.20) GO TO 1200
C***********************************************************************
C IF(10.LT.ITYPE.LT.20) THEN SUBROUTINE DATAR IS CALLED
C***********************************************************************
      IF (ITYPE.GE.20) GO TO 1300
C***********************************************************************
C IF(ITYPE.GE.20) THEN SUBROUTINE PROFNC IS CALLED
C***********************************************************************
      GO TO 1000
 1200 CALL DATAR
```

```
      GO TO 1000
 1300 CALL PRDFNC
      GO TO 1000
 22   FORMAT(1X,'*******************************************************
     &******************************************************************
     &**********')
      STOP
      END
```

```
C***********************************************************************
C***********************************************************************
      SUBROUTINE DATAR
C***********************************************************************
C     THIS IS THE CLIMATALOGICAL/PHENOLOGICAL SECTION KNOWN AS "DATAR"
C***********************************************************************
      INTEGER DAYS,DAMAT,DEBUG,SMWGDD
      LOGICAL TSTCLM,TSTGDD,TSTSUM,TSTPHN
      COMMON/LOGIC/TSTCLM,TSTGDD,TSTSUM,TSTPHN
      COMMON/INPUT/SITE(13),THK(5),WHC(5),AIRDRY,AWFAC,BGSM(5),CRPNM
     &(3),VARNM(5),GDDMAT,STAGE(12),GDDPH(5),RTDAMX,FROCTA,FROOTB,DEPSEW
     &,IYR,NDST,STRTEV,FMT(10),TMX(366),TMN(366),PPT(366),IPLT,HRVST,
     &SKIP2,DAYS,DDST(5),NR,R(200),IR,GIRR(200),IET,ET(100),E(5),DEBUG
      COMMON/MISC/XMNTH(12),ITYPE,IFLAGR
      COMMON/DATAR/GDD(366),DAPH(5),IPH(6),SMGDPH(6),ISDAPH(6),NDAS(12),
     &JK(6),IDAY(6)
      COMMON/PRDFCN/BGSAV(5),WC(5),C(10)
      DATA NDAS/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA XMNTH/3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,3HJUN,3HJUL,3HAUG,3HSEP,
     &3HOCT,3HNOV,3HDEC/
C     COMPUTE GROWING DEGREE DAYS FOR EACH DAY
 1000 DO 1005 I=1,NDST
      TN=TMN(I)
      TX=TMX(I)
      IF(TN.LT.50.0)TN=50.0
      IF(TX.GT.86.0)TX=86.0
      DD=((TX+TN)*0.5)-50.0
      IF(DD.LE.0.0) DD=0.0
      GDD(I)=DD
 1005 CONTINUE
      IF(.NOT.TSTGDD) GO TO 1010
      WRITE(6,310) GDD
 310  FORMAT(15X,16F7.2)
C     COMPUTE SUM OF GDD'S FROM DAY OF PLANTING TO END OF YEAR
 1010 SMGDD=0.0
      NPK=0
      DO 1012 I=IPLT,NDST
      NPK=NPK+1
      SMGDD=SMGDD+GDD(I)
      IF(.NOT.TSTSUM) GO TO 1014
      WRITE(6,315) SMGDD,I,NPK
  315 FORMAT (15X,F7.2,5X,I5,5X,I5)
 1014 CONTINUE
 1012 CONTINUE
C     COMPUTE DAYS ON WHICH PRECIPITATION OCCURED DURING GROWING SEASON
      IF (SKIP2.GT.0) GO TO 1200
      IF(IFLAGR.NE.1)GO TO 1025
      IFLAGR=0
```

```
C     (CONVERT INCHES PPT. TO CM. PPT.)
      DO 1020 IP=1,NDST
      PPT(IP)=PPT(IP)*2.54
 1020 CONTINUE
      IF (TSTCLM) WRITE (6,316) PPT
  316 FORMAT(15X,16F7.2)
 1025 NNH=0
      DO 1030 L=IPLT,NDST
      IF(PPT(L).LE.0.001) GO TO 1030
      NNH=NNH+2
      NL=NNH-1
      R(NL)=L-IPLT+1
      R(NNH)=PPT(L)
 1030 CONTINUE
      R(NNH+1)=NDST+2-IPLT
      R(NNH+2)=0.0
      NNH=NNH+2
C     COMPUTE MONTH AND DAY OF IPLT ****************************************
      IBG4=IPLT
      DO 1032 JJJ=1,6
      IPLDAY=IBG4-NDAS(JJJ)
      IF(IPLDAY.LE.0)GO TO 1034
      IBG4=IPLDAY
 1032 CONTINUE
 1034 IPDAY=NDAS(JJJ)+IPLDAY
C
C ----DATAR PHENOLOGY----------------
C     COMPUTE NUMBER OF DAYS IN EACH PERTINENT PHENOLOGICAL STAGE
      IBG4=IPLT
      DTGDD=0.0
      K=1
 1040 DTGDD=GDDPH(K) +DTGDD
      DO 1050 L=IBG4,NDST
      DTGDD=DTGDD-GDD(L)
      IF(DTGDD.LE.0) GO TO 1060
 1050 CONTINUE
 1060 DAPH(K)=L-IBG4+1
      K=K+1
      IBG4=L+1
      IF(K.LE.5) GO TO 1040
      DAYS=0
      DO 1070 K=1,5
 1070 DAYS=DAYS+DAPH(K)
      DO 1080 K=1,5
 1080 DDST(K)=DAPH(K)/DAYS
      IPH(1)=0
      SMGDPH(1)=0.0
      ISDAPH(1)=0
      DO 1090 L=2,6
      K=L-1
      IPH(L)=K
      SMGDPH(L)=SMGDPH(K)+GDDPH(K)
 1090 ISDAPH(L)=ISDAPH(K)+DAPH(K)
      IEMG=IPLT+DAPH(1)
      IBGT=IEMG+DAPH(2)
      IHED=IBGT+DAPH(3)
      IMLK=IHED+DAPH(4)
      IMTR=IMLK+DAPH(5)
      DO 1100 M=1,12
      IDTEMG=IEMG-NDAS(M)
      IF(IDTEMG.LE.0) GO TO 1110
```

```
      IEMG=IDTEMG
 1100 CONTINUF
 1110 IEMDAY=NDAS(M)+IDTEMG
      CO 1120 MA=1,12
      IDTBOT=IBOT-NDAS(MA)
      IF(IDTBOT.LE.0) GO TO 1130
      IBOT=IDTBOT
 1120 CONTINUF
 1130 IBTCAY=NDAS(MA)+IDTBOT
      DO 1140 MB=1,12
      IDTHED=IHED-NDAS(MB)
      IF(IDTHFD.LE.0) GO TO 1150
      IHED=IDTHED
 1140 CONTINUF
 1150 IHCDAY=NDAS(MB)+IDTHED
      DO 1160 MC=1,12
      IDTMLK=IMLK-NDAS(MC)
      IF(IDTMLK.LE.0) GO TO 1170
      IMLK=IDTMLK
 1160 CONTINUF
 1170 IMLDAY=NDAS(MC)+IDTMLK
      DO 1180 MD=1,12
      IDTMTR=IMTR-NDAS(MD)
      IF(IDTMTR.LE.0) GO TO 1190
      IMTR=IDTMTR
 1180 CONTINUF
 1190 IMTDAY=NDAS(MD)+IDTMTR
      JK(1)=JJJ
      JK(2)=M
      JK(3)=MA
      JK(4)=MR
      JK(5)=MC
      JK(6)=MD
      IDAY(1)=IPDAY
      IDAY(2)=IEMDAY
      IDAY(3)=IBTDAY
      IDAY(4)=IHDDAY
      IDAY(5)=IMLDAY
      IDAY(6)=IMTDAY
      IF(.NOT.TSTPHN) GO TO 1200
      WRITE(6,400) XMNTH(M),IEMDAY
      WRITE(6,410) XMNTH(MA),IBTDAY
      WRITE(6,420) XMNTH(MB),IHDDAY
      WRITE(6,430) XMNTH(MC),IMLCAY
      WRITE(6,440) XMNTH(MD),IMTDAY
      WRITE(6,450) GDOPH
      WRITE(6,460) DAPH
      WRITE(6,470) DOST
 400  FORMAT(/10X,'DATE EMERGES - ',A3,I4)
 410  FORMAT(/10X,'DATE BOOTS - ',A3,I4)
 420  FORMAT(/10X,'DATE HEADS - ',A3,I4)
 430  FORMAT(/10X,'DATE MILKS - ',A3,I4)
 440  FORMAT(/10X,'DATE MATURES - ',A3,I4)
 450  FORMAT(/5X,'GDCPH ARRAY',16F7.2)
 460  FORMAT(/5X,'DAPH ARRAY',16F7.2)
 470  FORMAT(/5X,'DDST ARRAY',16F7.2)
 1200 CONTINUE
C     SUMMARIZE RESULTS AND PRINT PHENOLOGICAL DATA, ET.
      WRITE(6,500)
      WRITE(6,500)
 1210 WRITE(6,100)
```

```
  100 FORMAT (//,42X,'BGWHT GROWTH AND PRODUCTION TEST RESULTS',/)       00365000
      WRITE(6,110)                                                        00366000
  110 FORMAT(9X,'THE SITE:')                                              00367000
      WRITE(6,120)(SITE(N),N=1,13)                                        00368000
  120 FORMAT(20X,13A6)                                                    00369000
      WRITE(6,130)CRPNM,VARNM,GDDMAT                                      00370000
  130 FORMAT (/9X,'THE CROP: ',/20X,3A4,5A4,/25X,'REQUIRES ',F7.1,' GROW00371000
     &ING DEGREE DAYS TO MATURE')                                         00372000
      WRITE(6,140)                                                        00373000
  140 FORMAT(//9X,'PHENOLOGICAL DATA:',//20X,'GDDPH=GROWING DEGREE DAYS 00374000
     &PER PHASE, DAPH=DAYS PER PHASE, DDST=DAYS PER PHASE/TOTAL DAYS PER00375000
     & SEASON')                                                           00376000
      WRITE(6,150) GDDPH                                                  00377000
  150 FORMAT(/20X,'GDDPH ARRAY',16F9.2)                                   00378000
      WRITE(6,160) DAPH                                                   00379000
  160 FORMAT(/20X,'DAPH ARRAY ',16F9.2)                                   00380000
      WRITE(6,170) DDST                                                   00381000
  170 FORMAT(/20X,'DDST ARRAY ',16F9.2)                                   00382000
      WRITE(6,180)                                                        00383000
  180 FORMAT('H'//9X,'PHENOLOGICAL SUMMARY:',///58X,'SEQUENTIAL DAY',9X,00384000
     &'GROWING DEGREE DAYS'/25X,'STAGE',12X,'DATE',12X,'NUMBER(DA)',10X,00385000
     &'FROM DAY OF PLANTING',10X,'PHASE')                                 00386000
      DO 190 K=1,6                                                        00387000
      KJ=JK(K)                                                            00388000
      IK=2*K-1                                                            00389000
      IIK=2*K                                                             00390000
  190 WRITE(6,200)STAGE(IK),STAGE(IIK)  ,XMNTH(KJ),IDAY(K),ISDAPH(K),SMG00391000
     &DPH(K),TPH(K)                                                       00392000
  200 FORMAT(/25X,A4,A4,12X,A3,I4,14X,I3,21X,F7.1,20X,I1)                 00393000
      WRITE(6,500)                                                        00394000
  500 FORMAT(1X,'*******************************************************00395000
     &******************************************************************00396000
     &**********')                                                        00397000
 2000 RETURN                                                              00398000
      END                                                                 00399000
```

```
C***********************************************************************00400000
C***********************************************************************00401000
      SUBROUTINE PRDFNC                                                   00402000
C***********************************************************************00403000
C***********************************************************************00404000
C     PRODUCTION ESTIMATION, EVAPOTRANSPIRATION, SOIL STATUS SECTION      00405000
C***********************************************************************00406000
C***********************************************************************00407000
C THE FOLLOWING IS A SHORT DESCRIPTION OF INPUT VARIABLE NAMES:           00408000
C     DAYS IS NUMBER OF DAYS IN SEASON                                    00409000
C     AIRDRY IS DIFF BETWEEN PERM WILT PT & AIRDRY H2O CONTENT (NEG.)     00410000
C     AWFAC IS AVAIL WATER FACTOR-- THE FRACTION BELOW WHICH ACTUAL TRAN00411000
C     IS LESS THAN POTENTIAL                                              00412000
C     RTDMAX IS DAY WHEN ROOT REACHES "DEPMAX" (BOTTOM OF 5 SOIL LAYERS)00413000
C     DEPMAX IS SET WITHIN THE PROGRAM TO THE SUM OF THK ARRAY            00414000
C     DEPSEW IS DEPTH THAT GRAIN SEEDS WERE SEWN (PLANTED)                00415000
C     FROOTA & FROOTB ARE VALUES IN THE ROOT GROWTH EQUATION              00416000
C     N,IR,IET ARE COUNTERS FOR READING IN ARRAYS                         00417000
C     DEBUG -- IF DEBUG =0, DAILY COMPUTATIONS ARE NOT WRITTEN OUT        00418000
C     E IS GRAIN EXPONENT BY STAGE OF GROWTH                              00419000
C     BGSM IS THE BEGINNING SOIL WATER BY LAYERS                          00420000
```

```
C       THK IS THICKNESS OF LAYERS
C       WHC IS WATER HOLDING CAPACITY BY LAYERS
C       DDST IS THE FRACTION OF SEASON IN EACH GROWTH STAGE
C       R IS THE DAY RAIN OCCURS, FOLLOWED BY THE AMOUNT
C       ET IS DAY AT BEGINNING PERIOD FOLLOWED BY ETPOT AND EPOT
C       GIRR IS DAY IRRIGATION OCCURRES FOLLOWED BY AMOUNT
C       *************************************************************
C THE FOLLOWING IS A SHORT DESCRIPTION OF PROGRAM VARIABLES:
C       SEVN IS SOIL EVAPORATED IN RATE PER DAY
C       EVAP IS EVAPOTRANSPIRATION RATE PER DAY -- POTENTIAL
C*********************************************************************
C*********************************************************************
      INTEGER DAYS,DAMAT,DEBUG,SMWGDD
      LOGICAL TSTCLM,TSTGDD,TSTSUM,TSTPHN
      COMMON/LOGIC/TSTCLM,TSTGDD,TSTSUM,TSTPHN
      COMMON/INPUT/SITE(13),THK(5),WHC(5),AIRDRY,AWFAC,BGSM(5),CRPNM
     &(3),VARNM(5),GDDMAT,STAGE(12),GDDPH(5),RTDAMX,FROOTA,FROOTB,DEPSEW
     &,IYR,NDST,STRTEV,FMT(10),TMX(366),TMN(366),PPT(366),IPLT,HRVST,
     &SKIP2,DAYS,DDST(5),NR,R(200),IR,GIRR(200),IET,ET(100),E(5),DEBUG
      COMMON/MISC/XMNTH(12),ITYPE,IFLAGR
      COMMON/DATAR/GDD(366),DAPH(5),IPH(6),SMGDPH(6),ISCAPH(6),NDAS(12),
     &JK(6),IDAY(6)
      COMMON/PRDFCN/BGSAV(5),WC(5),C(10)
      DATA NDAS/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA XMNTH/3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,3HJUN,3HJUL,3HAUG,3HSEP,
     &3HOCT,3HNOV,3HDEC/
      WRITE(6,500)
      WRITE (6,100)
100   FORMAT (//,9X,'WHEAT-ET PRODUCTION MODEL SUMMARY:',//)
      IF(DEBUG.NE.0)WRITE(6,101)
      IF(DEBUG.EQ.0)WRITE(6,103)
 101 FORMAT(/1X,'DAYS EVAP TRANS SOLEV IRRIG  RAIN DRAIN  WADD   CPROD
     &BGSM1  BGSM2  BGSM3  BGSM4  BGSM5    CET     SEV      C2      C3
     & C4  DEPROOT')
 103 FORMAT(/1X,'DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD       WC1
     & WC2     WC3     WC4     WC5   ETMAX ETDEF  DEPL  ETACT  WATADD
     &DERROT')
      DO 1100 I=1,5
1100  BGSAV(I)=BGSM(I)
      DEPMAX=THK(1)+THK(2)+THK(3)+THK(4)+THK(5)
      KE=1
      CFD=0.0
      KG=1
      SEVN=STRTEV
      I=1
      K=1
      J=1
      DD=DDST(J)
      C1=0.
      C2=0.
      C3=0.
      C4=0.
      CEV=0.
      CSE=0.
      CET=0.0
      SEV=STRTEV
      EVAP=STRTEV+.01
      CEVAP=0.0
      CSEVP=0.0
      CWADD=0.0
      RAIN=0.0
```

```
      ET(IET+1)=DAYS+2.
      IF(SKIP2.LE.0.9)GO TO 1110
      R(NR+1)=DAYS+2
 1110 GIRR(IR+1)=DAYS+2
      DA=1.
      FRQI=DA
      CDRAIN=0.0
      CPROD=1.0
      CIRR=0.0
      CPB=0.0
 1000 IF(DA.LT.R(K).AND.DA.LT.GIRR(KG)) GO TO 1120
      WADD=0.
      IF(DA.LT.R(K)) GO TO 1130
      K=K+2
      RAIN=RAIN+R(K-1)
      WACD=R(K-1)
      GO TO 1140
 1130 WACD=GIRR(KG+1)+WADD
      CIRR=CIPR+GIRR(KG+1)
      KG=KG+2
      GO TO 1150
 1140 IF(DA.EQ.GIRR(KG))GO TO 1130
 1150 SEV=SEVN
      CWADD=CWADD+WADD
      IF(WADD.LE.SEV)GO TO 1155
      FRQI=DA
      GO TO 1157
 1155 SEV=WADD
 1157 CO 1160 I=1,5
      BGSM(I)=BGSM(I)+WACO
      IF(BGSM(I).LT.THK(I)*WHC(I)) GO TO 1120
      WADD=BGSM(I)-THK(I)*WHC(I)
      BGSM(I)=THK(I)*WHC(I)
      IF(I.LT.5) GO TO 1160
      CDRAIN=CDRAIN+WADD
 1160 CONTINUF
 1120 IF(BGSM(1)-SEV.LT.AIRDRY) GO TO 1170
      BGSM(1)=BGSM(1)-SEV
      GO TO 1180
 1170 SEV=BGSM(1)-AIRDRY
      BGSM(1)=AIRDRY
 1180 DO 1190 I=1,5
 1190 WC(I)=BGSM(I)/(THK(I)*WHC(I))
      KI=1
      TRAN=EVAP-SEVN
      DEPROT=DEPSEW+((DEPMAX-DEPSEW)/(1.+EXP(FROOTA-(FRCCTB*DA/RTDAMX)))
     &)
 1260 THIK=0.
      IK=1
      DO 1200 I=1,5
      IF(I.EQ.1) GO TO 1210
      IF(WC(I).GT.WC(I-1)) IK=I
 1210 THIK=THIK+THK(I)
      IF(THIK.GE.DEPROT)GO TO 1220
 1200 CONTINUF
 1220 IF(BGSM(IK).LE.0.) GO TO 1230
      IF(WC(IK).GT.AWFAC) GO TO 1240
      TRN=TRAN*WC(IK)/AWFAC
      IF(BGSM(IK)-TRN.LT.0.0) GO TO 1250
      BGSM(IK)=BGSM(IK)-TRN
 1270 CEVAP=CFVAP+TRN
```

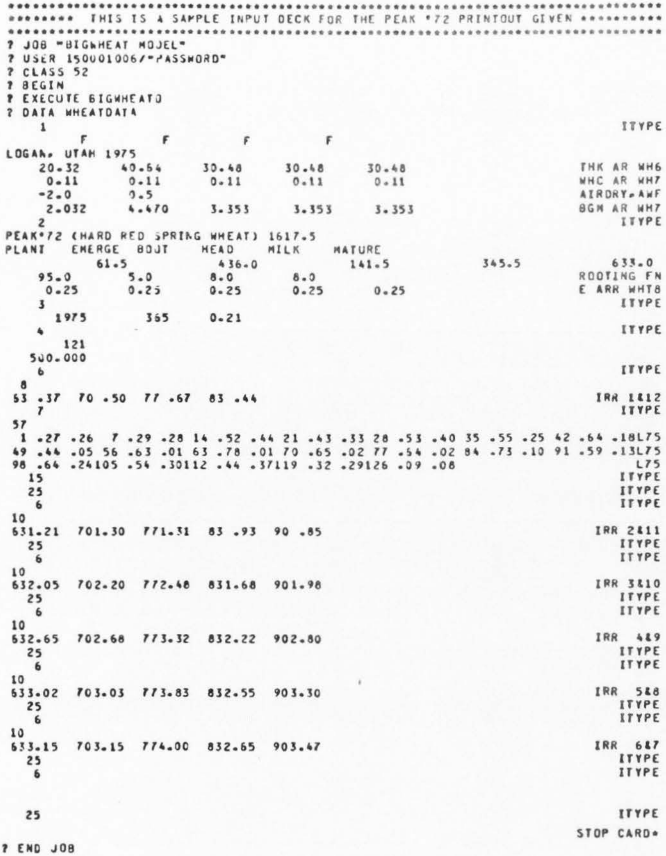
```
      IF (KI.GT.1) GO TO 1230
      KI=KI+1
      TRAN=TRAN-TRN
      WC(IK)=BGSM(IK)/(THK(IK)*WHC(IK))
      GO TO 1260
 1240 BGSM(IK)=BGSM(IK)-TRAN
      CEVAP=CEVAP+TRAN
      GO TO 1230
 1250 TRN=BGSM(IK)
      BGSM(IK)=0.0
      GO TO 1270
 1230 CET=CET+EVAP-SEVN
      CSEVP=CSEVP+SEV
      PI=DA/DAYS
      IF (DA.GE.HRVST) GO TO 1280
      IF(PI.LT.DD) GO TO 1290
 1280 CPROD=CPROD*((CEVAP-C1)/CET)**E(J)
      C(J+5)=((CEVAP-C1)/CET)
      CPD=CPD+CEVAP-C1
      CFD=CFD+CET
      C(J)=CPROD
      IF(DEBUG.NE.0)WRITE(6,111)
  111 FORMAT(/1X,'DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD     WC1
     & WC2    WC3    WC4    WC5   ETMAX  ETDEF  DEPL  ETACT  WATADD
     &DEPROT')
      DEPL=0.
      ETMAX=CET+CSEVP-C2
      ETDEF=CET-CEVAP+C1
      ETACT=CSEVP+CEVAP-C1-C2
      WATADD=CWADD-C4
      C4=CWADD
      C2=CSEVP
      DO 105 I=1,5
  105 DEPL=BGSAV(I)-BGSM(I)+DEPL
      DEP=DEPL-C3
      C3=DEPL
      WRITE(6,113)DA,EVAP,CEVAP,CSEVP,CIRR,RAIN,CDRAIN,CWADD,WC(1),WC(2)
     &,WC(3),WC(4),WC(5),ETMAX,ETDEF,DEP,ETACT,WATADD,DEPROT
  113 FORMAT (I4,7F6.2,10F7.3,2X,F7.2)
      C1=CEVAP
      IF (DA.GE.HRVST) GO TO 1290
      IF(DA.GE.DAYS) GO TO 1290
      J=J+1
      DD=DD+DDST(J)
      CET=0.0
 1290 SEV=SEVN/(SQRT(DA-FRQI+2.))
      IF(DEBUG.NE.0)WRITE(6,115)DA,EVAP,CEVAP,CSEVP,CIRR,RAIN,CDRAIN,CWA
     &DD,CPROD,BGSM(1),BGSM(2),BGSM(3),BGSM(4),BGSM(5),CET,SEV,C2,C3,C4,
     &DEPROT
  115 FORMAT (I4,7F5.2,11F7.4,F7.1)
      DA=DA+1.
      IF (DA.LT.ET(KE)) GO TO 1300
      SEVN=ET(KE+2)
      EVAP=ET(KE+1)
      KE=KE+3
      IF(SEV.GT.SEVN)SEV=SEVN
 1300 IF (DA.GT.HRVST) GO TO 1310
      IF(DA.LE.DAYS) GO TO 1000
C     MAIN LOOP TO #1000 FOR EACH DAY
 1310 CPD=CPD/CFD
      IF (DA.GE.HRVST) WRITE (6,119) J,HRVST
```

```
 119  FORMAT (1X'CROP HARVESTED BEFORE MATURITY IN STAGE: ',I3,'    ON
     $DAY: ',I4)
      DA=CA-1.0
      CWADD=CSEVP+CEVAP+CDRAIN
      WRITE(6,120)
 120  FORMAT(1H ,'DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN TOT USE GRAIN
     1   C1      C2      C3      C4      C5  DRY MAT   C6      C7      C8
     2C9      C10')
      WRITE (6,129)DA,EVAP,CEVAP,CSEVP,CIRR,RAIN,CDRAIN,CWADD,CPROD,C(1
     &),C(2),C(3),C(4),C(5),CPD,C(6),C(7),C(8),C(9),C(1C)
  129 FORMAT (I4,7F6.2,12F7.3)
      CO 1320 I=1,5
1320  BGSM(I)=BGSAV(I)
      WRITE(6,500)
 500  FORMAT(1X,'*******************************************************
     &******************************************************************
     &**********')
 2000 RETURN
      ENC
```

Appendix C

Sample Input Deck to Model

1975 Peak '72 experimental plots with
normal irrigations and a zero irrigation
test at the end.



```
*********************************************************************************
********  THIS IS A SAMPLE INPUT DECK FOR THE PEAK '72 PRINTOUT GIVEN **********
*********************************************************************************
? JOB "BIGWHEAT MODEL"
? USER 150001006/"PASSWORD"
? CLASS 52
? BEGIN
? EXECUTE BIGWHEATD
? DATA WHEATDATA
    1                                                                        ITYPE
         F            F             F            F
LOGAN, UTAH 1975
    20.32       40.64       30.48       30.48       30.48                THK AR WH6
     0.11        0.11        0.11        0.11        0.11                WHC AR WH7
    -2.0         0.5                                                     AIRDRY,AWF
     2.032       4.470       3.353       3.353       3.353               BGM AR WH7
    2                                                                        ITYPE
PEAK'72 (HARD RED SPRING WHEAT) 1617.5
PLANT   EMERGE  BOOT    HEAD    MILK    MATURE
            61.5            436.0           141.5           345.5           633.0
    95.0        5.0         8.0         8.0                              ROOTING FN
     0.25        0.25        0.25        0.25        0.25                E ARR WHT8
    3                                                                        ITYPE
      1975        365       0.21
    4                                                                        ITYPE
       121
   500.000
    6                                                                        ITYPE
  8
 53 .37  70 .50  77 .67  83 .44                                          IRR 1&12
    7                                                                        ITYPE
 57
  1 .27 .26  7 .29 .28 14 .52 .44 21 .43 .33 28 .53 .40 35 .55 .25 42 .64 .18L75
 49 .44 .05 56 .63 .01 63 .78 .01 70 .65 .02 77 .54 .02 84 .73 .10 91 .59 .13L75
 98 .64 .24105 .54 .30112 .44 .37119 .32 .29126 .09 .08                      L75
   15                                                                        ITYPE
   25                                                                        ITYPE
    6                                                                        ITYPE
 10
 631.21  701.30  771.31  83 .93  90 .85                                  IRR 2&11
   25                                                                        ITYPE
    6                                                                        ITYPE
 10
 632.05  702.20  772.48  831.68  901.98                                  IRR 3&10
   25                                                                        ITYPE
    6                                                                        ITYPE
 10
 632.65  702.68  773.32  832.22  902.80                                  IRR  4&9
   25                                                                        ITYPE
    6                                                                        ITYPE
 10
 633.02  703.03  773.83  832.55  903.30                                  IRR  5&8
   25                                                                        ITYPE
    6                                                                        ITYPE
 10
 633.15  703.15  774.00  832.65  903.47                                  IRR  6&7
   25                                                                        ITYPE
    6                                                                        ITYPE


   25                                                                        ITYPE
                                                                       STOP CARD.
? END JOB
```

Appendix D

Sample Printout From Model

1975 Peak '72 experimental plots with
normal irrigations and a zero irrigation
test at the end.

```
*******************************************************************************************************************

 REACING-IN CATA BY CONTROL OF ITYPE:

 LCGICAL TESTS FCR WRITING INTERMEDIATES:    F    F    F    F          0
LOGAN, UTAH 1975
THK  ARRAY    20.320     40.640     30.480     30.480     3C.480
WHC  ARRAY     0.110      0.110      0.110      0.110     C.110
 AIRDRY & ANFAC:        -2.000      0.500
BGSM ARRAY     2.032      4.470      3.353      3.353     3.353
PEAK'72 (HARD REC SPRING WHEAT)  1617.5
PLANT   EMERGE  BCOT     HEAD     MILK    MATURE
   61.50  436.00  141.50  345.50  633.00
 RTDAMX,FRCCT4,FROCTP,DEPSEW:     95.00C      5.000      8.C00      8.00C
E ARRAY      C.250      0.250      C.250      0.250     C.250
 IYR,NCST,STRTEV:        1975        365    .210E+00
IPLT:   121
HARVEST CN DAY   500.0
IR:  8
CAY IRRIGATION  63 0.37  70 0.50  77 0.67  83 C.44
IET: 57
DAY,ETPCT,EPCT:  1 0.27 0.26   7 0.29 0.28  14 0.52 0.44  21 0.43 0.33  28 0.53 0.40  35 0.55 0.25  42 0.64 0.18  49 0.44 C.C5
  56 0.63 0.C1  63 0.78 C.01  70 0.65 0.02  77 0.64 0.02  84 0.73 0.10  91 0.59 C.13  98 0.64 C.24 105 0.54 C.30 112 0.44 C.37
 119 0.32 0.29 126 0.09 C.08
*******************************************************************************************************************
*******************************************************************************************************************


                                  BGWHT GROWTH AAC PRCDUCTION TEST RESULTS

      THE SITE:
              LOGAN, UTAH 1975

      THE CROP:
              PEAK'72 (HARD RED SPRING WHEAT)
                   REQUIRES  1617.5 GRCWING DEGREE DAYS TC MATURE


      PHENCLOGICAL DATA:

              GODPH=GROWING DEGREE DAYS PER PHASE, CAPH=DAYS PER PHASE, DCST=DAYS PER PHASE/TOTAL DAYS PER SEASCN

              GCDPH ARRAY     61.50    436.00    141.50    345.50    633.00

              DAPH ARRAY      11.00     40.00     10.C0     15.00     32.00

              DDST ARRAY       0.10      0.37      0.C9      0.14      0.30


      PHENCLOGICAL SUMMARY:


                                                  SEQUENTIAL CAY        GROWING CEGREE DAYS
                  STAGE            DATE            NUMBER(DA)         FRCM DAY CF PLANTING          PHASE

                  PLANT            MAY  1                0                      0.0                   0

                  EMERGE           MAY 12               11                     61.5                   1

                  BCOT             JUN 21               51                    497.5                   2
```

```
                  HEAD            JUL  1           61                  639.0            3

                  MILK            JUL 16           76                  984.5            4

                  MATURE          AUG 17           108                 1617.5           5
*********************************************************************************************************
*********************************************************************************************************


          WHEAT-ET PRODUCTION MODEL SUMMARY*


DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD     WC1    WC2    WC3    WC4    WC5   ETMAX  ETDEF  DEPL  ETACT  WATADD     DEFRCT
 11  0.29  0.11  2.09  0.00  2.03  0.45  2.03  0.638  1.000  1.000  1.000  1.000  2.198  0.000  0.617  2.198  2.032     10.42
 51  0.44  6.37  7.80  0.00  8.41  0.45  8.41  0.077  0.036  1.000  1.000  1.000 14.392  2.419  5.598 11.973  6.375     55.75
 61  0.63 10.57  7.98  0.00  9.78  0.45  9.78  0.186  0.036  0.031  1.000  1.000  5.456  1.084  3.000  4.371  1.372     85.13
 76  0.65 15.83  8.10  0.87  9.78  0.45 10.65 -0.001  0.009  0.008  0.011  1.000 10.544  5.153  4.521  5.391  0.870    123.64
108  0.54 21.04 10.29  1.98 12.52  0.45 14.50 -0.328  0.001  0.001  0.001  0.001 17.920 10.521  3.545  7.399  3.853    150.03
DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN TOT USE GRAIN     C1     C2     C3     C4     C5  DRY MAT  C6     C7     C8     C9    C10
108  0.54 21.04 10.29  1.98 12.52  0.45 31.78  0.557  1.000  0.922  0.870  0.734  0.557  0.523  1.000  0.721  0.795  0.505  0.331
*********************************************************************************************************
IR: 10
DAY IRRIGATION  63 1.21  70 1.30  77 1.31  83 0.93  90 0.85
*********************************************************************************************************


          WHEAT-ET PRODUCTION MODEL SUMMARY*


DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD     WC1    WC2    WC3    WC4    WC5   ETMAX  ETDEF  DEPL  ETACT  WATADD     DEFRCT
 11  0.29  0.11  2.09  0.00  2.03  0.45  2.03  0.638  1.000  1.000  1.000  1.000  2.198  0.000  0.617  2.198  2.032     10.42
 51  0.44  6.37  7.80  0.00  8.41  0.45  8.41  0.077  0.036  1.000  1.000  1.000 14.392  2.419  5.598 11.973  6.375     55.75
 61  0.63 10.57  7.98  0.00  9.78  0.45  9.78  0.186  0.036  0.031  1.000  1.000  5.456  1.084  3.000  4.371  1.372     85.13
 76  0.65 17.37  8.10  2.51  9.78  0.45 12.29  0.018  0.019  0.012  0.011  1.000 10.544  3.615  4.420  6.930  2.510    123.64
108  0.54 24.56 10.29  5.60 12.52  0.45 18.12 -0.286  0.002  0.002  0.002  0.001 17.920  8.545  3.542  9.375  5.833    150.03
DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN TOT USE GRAIN     C1     C2     C3     C4     C5  DRY MAT  C6     C7     C8     C9    C10
108  0.54 24.56 10.29  5.60 12.52  0.45 35.30  0.643  1.000  0.922  0.870  0.782  0.643  0.611  1.000  0.721  0.795  0.653  0.457
*********************************************************************************************************
IR: 10
DAY IRRIGATION  63 2.05  70 2.20  77 2.48  83 1.68  90 1.98
*********************************************************************************************************


          WHEAT-ET PRODUCTION MODEL SUMMARY*


DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD     WC1    WC2    WC3    WC4    WC5   ETMAX  ETDEF  DEPL  ETACT  WATADD     DEFRCT
 11  0.29  0.11  2.09  0.00  2.03  0.45  2.03  0.638  1.000  1.000  1.000  1.000  2.198  0.000  0.617  2.198  2.032     10.42
 51  0.44  6.37  7.80  0.00  8.41  0.45  8.41  0.077  0.036  1.000  1.000  1.000 14.392  2.419  5.598 11.973  6.375     55.75
 61  0.63 10.57  7.98  0.00  9.78  0.45  9.78  0.186  0.036  0.031  1.000  1.000  5.456  1.084  3.000  4.371  1.372     85.13
 76  0.65 18.79  8.10  4.25  9.78  0.45 14.03  0.049  0.050  0.031  0.027  1.000 10.544  2.195  4.099  8.349  4.250    123.64
108  0.54 28.91 10.29 10.39 12.52  0.45 22.91 -0.168  0.015  0.013  0.014  0.013 17.920  5.610  3.427 12.311  8.883    150.03
DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN TOT USE GRAIN     C1     C2     C3     C4     C5  DRY MAT  C6     C7     C8     C9    C10
108  0.54 28.91 10.29 10.39 12.52  0.45 39.65  0.735  1.000  0.922  0.870  0.820  0.735  0.719  1.000  0.721  0.795  0.789  0.643
*********************************************************************************************************
IR: 10
DAY IRRIGATION  63 2.65  70 2.68  77 3.32  83 2.22  90 2.80
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        WHEAT-ET PRODUCTION MODEL SUMMARY:


DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD     WC1     WC2     WC3     WC4     WC5   ETMAX  ETDEF  DEPL  ETACT  WATADD    CEPRCT
 11  0.29  0.11  2.09  0.00  2.03  0.45  2.03  0.638   1.000   1.000   1.000   1.000  2.198  0.000  0.617  2.198  2.032     10.42
 51  0.44  6.37  7.80  0.00  8.41  0.45  8.41  0.077   0.036   1.000   1.000   1.000 14.392  2.419  5.598 11.973  6.375     55.75
 61  0.63 10.57  7.98  0.00  9.78  0.45  9.78  0.186   0.036   0.031   1.000   1.000  5.456  1.084  3.000  4.371  1.372     85.13
 76  0.65 19.44  8.10  5.33  9.78  0.45 15.11  0.070   0.136   0.031   0.027   1.000 10.544  1.549  3.665  8.995  5.330    123.64
108  0.54 31.80 10.29 13.67 12.52  0.45 26.19 -0.051   0.026   0.026   0.023   0.017 17.920  3.370  3.467 14.550 11.083    150.03
DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN TOT USE GRAIN      C1      C2      C3      C4      C5 DRY MAT   C6     C7     C8      C9     C10
108  0.54 31.80 10.29 13.67 12.52  0.45 42.54  0.787   1.000   0.922   0.870   0.836   0.787  0.791  1.000  0.721  0.795  0.851  0.788
*****************************************************************************************************************************
IR: 10
DAY IRRIGATION  63 3.02  70 3.03  77 3.83  83 2.55  90 3.30
*****************************************************************************************************************************

        WHEAT-ET PRODUCTION MODEL SUMMARY:


DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD     WC1     WC2     WC3     WC4     WC5   ETMAX  ETDEF  DEPL  ETACT  WATADD    CEPRCT
 11  0.29  0.11  2.09  0.00  2.03  0.45  2.03  0.638   1.000   1.000   1.000   1.000  2.198  0.000  0.617  2.198  2.032     10.42
 51  0.44  6.37  7.80  0.00  8.41  0.45  8.41  0.077   0.036   1.000   1.000   1.000 14.392  2.419  5.598 11.973  6.375     55.75
 61  0.63 10.57  7.98  0.00  9.78  0.45  9.78  0.186   0.036   0.031   1.000   1.000  5.456  1.084  3.000  4.371  1.372     85.13
 76  0.65 19.74  8.10  6.05  9.78  0.45 15.83  0.158   0.185   0.031   0.027   1.000 10.544  1.242  3.252  9.302  6.050    123.64
108  0.54 33.17 10.29 15.73 12.52  0.45 28.25  0.007   0.104   0.094   0.027   0.017 17.920  2.307  3.190 15.614 12.423    150.03
DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN TOT USE GRAIN      C1      C2      C3      C4      C5 DRY MAT   C6     C7     C8      C9     C10
108  0.54 33.17 10.29 15.73 12.52  0.45 43.91  0.810   1.000   0.922   0.870   0.843   0.810  0.825  1.000  0.721  0.795  0.881  0.853
*****************************************************************************************************************************
IR: 10
DAY IRRIGATION  63 3.15  70 3.15  77 4.00  83 2.65  90 3.47
*****************************************************************************************************************************

        WHEAT-ET PRODUCTION MODEL SUMMARY:


DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD     WC1     WC2     WC3     WC4     WC5   ETMAX  ETDEF  DEPL  ETACT  WATADD    CEPRCT
 11  0.29  0.11  2.09  0.00  2.03  0.45  2.03  0.638   1.000   1.000   1.000   1.000  2.198  0.000  0.617  2.198  2.032     10.42
 51  0.44  6.37  7.80  0.00  8.41  0.45  8.41  0.077   0.036   1.000   1.000   1.000 14.392  2.419  5.598 11.973  6.375     55.75
 61  0.61 10.57  7.98  0.00  9.78  0.45  9.78  0.186   0.036   0.031   1.000   1.000  5.456  1.084  3.000  4.371  1.372     85.13
 76  0.65 19.82  8.10  6.30  9.78  0.45 16.08  0.169   0.217   0.031   0.027   1.000 10.544  1.164  3.081  9.381  6.300    123.64
108  0.54 33.57 10.29 16.42 12.52  0.45 28.94  0.047   0.121   0.132   0.027   0.017 17.920  1.980  3.077 15.940 12.863    150.03
DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN TOT USE GRAIN      C1      C2      C3      C4      C5 DRY MAT   C6     C7     C8      C9     C10
108  0.54 33.57 10.29 16.42 12.52  0.45 44.31  0.817   1.000   0.922   0.870   0.845   0.817  0.835  1.000  0.721  0.795  0.888  0.874
*****************************************************************************************************************************
IR:  0
DAY IRRIGATION   0
*****************************************************************************************************************************

        WHEAT-ET PRODUCTION MODEL SUMMARY:
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DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN CWADD     WC1    WC2    WC3    WC4    WC5  ETMAX  ETDEF   DEPL  ETACT  WATADD    DEFFCT
 11  0.29  0.11  2.09  0.00  2.03  0.45  2.03  0.638  1.000  1.000  1.000  1.000  2.198  0.000  0.617  2.198  2.032     10.42
 51  0.44  6.37  7.80  0.00  8.41  0.45  8.41  0.077  0.036  1.000  1.000  1.000 14.392  2.419  5.598 11.973  6.375     55.75
 61  0.63 10.57  7.98  0.00  9.78  0.45  9.78  0.186  0.036  0.031  1.000  1.000  5.456  1.084  3.000  4.371  1.372     85.13
 76  0.65 15.10  8.03  0.00  9.78  0.45  9.78 -0.008  0.005  0.005  0.004  1.000 10.476  5.886  4.590  4.590  0.000    123.84
108  0.54 19.36 10.00  0.00 12.52  0.45 12.52 -0.330  0.000  0.000  0.000  0.000 17.702 11.470  3.489  6.233  2.743    150.03
DAYS EVAP TRANS SOLEV IRRIG RAIN DRAIN TOT USE GRAIN     C1     C2     C3     C4     C5 DRY MAT    C6     C7     C8     C9    C10
108  0.54 19.36 10.00  0.00 12.52  0.45 29.82  0.510  1.000  0.922  0.870  0.707  0.510  0.481  1.000  0.721  0.795  0.435  0.271
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Appendix E

A Summary of Model Calibration

Table 10. Summary of what data was used as calibration data for given variables in the model

Model variable	Data used to calibrate	Application of calibrated variables
Crop factors "a" and "b" used in equations 5 and 7	Peak '72 1975 calibration plots	All runs with all varieties (all years)
λ's used in equation [3]	Peak '72 1975 calibration plots	All runs with all varieties (all years)
and		
WHC(i), BGSM(i), ET(i)	Peak '72 1975 calibration plot neutron soil moisture data	All runs with all varieties (all years)
FROOTA and FROOTB from equation [10]	Peak '72 and Twin 1975 calibration plots neutron soil moisture data	All runs with all varieties (all years)
GDD(i) array	Individual phenologic observations for each variety in 1975 calibration plots	Variety specific array used with appropriate variety in all runs (all years)
Y_p	Maximum observed yield ($\hat{Y}$ obs) on each variety on 1975 calibration plots was used to estimate Y_p by the following relationship $Y_p = \frac{1}{\hat{Y}/\hat{Y}_p} \cdot Y_{obs}$ where $\hat{Y}/\hat{Y}_p$ is computed value for an associated $\hat{Y}_{obs}$.	Variety value array used with appropriate variety in all runs (all years)

VITA

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Education: Attended elementary school in Clarkston, Utah; graduated from Sky View High School, Smithfield, Utah, in 1968; received Bachelor of Science (Honors) degree from Utah State University, with a major in soil science and a minor in physics, in 1974; completed requirements for a Master of Science degree in Soil Science and Biometeorology, specializing in Soil Physics, at Utah State University, Logan, Utah in 1976.

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Professional Skills: Electronic technician; competence with FORTRAN IV, CANDE, and WFL computer languages and Burroughs B6700 operations; farm equipment operator.

Professional Recognition: 1973 Soil Conservation Society of America: Ray Y. Gildea Scholarship recipient; 1972 First Security Bank Corporation Agricultural Scholarship recipient; Sterling Taylor Memorial (soil physics) Scholarship recipient.

Professional Publications:

Hill, R.W., R.J. Hanks, J. Keller, and V.P. Rasmussen. 1974. Predicting corn growth as affected by water management: and example. Utah State University CUSUSWASH Publication 211(d)-6.

Hanks, R.J. and V.P. Rasmussen. 1976. Simulating soil temperatures. Journal of Agronomic Education. (In press).

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