Educational Software for Illustration of Drainage, Evapotranspiration, and Crop Yield

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ABSTRACT

Simulation models are useful in observing and understanding the interrelationships among soil water supply, drainage, evapotranspiration (ET), and crop yield. The objective of this study was to develop a water balance model and then a microcomputer software package for illustration of drainage, ET, and crop yield as influenced by water conditions. A model was developed that estimates drainage by using a Wilcox-type drainage equation, crop ET by using the Jensen-Haise reference ET equation, and crop yield from yield–ET functions. Weather records and field research results from Tribune, KS, were used for adaptation of the model to western Kansas. Based on this model, a Windows compatible microcomputer software package (KS Water Budget v. T1) was developed for corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], sunflower (*Helianthus annuus* L.), and winter wheat (*Triticum aestivum* L.). The software allows users to study the effects of irrigation system efficiency, water application timing and amount, and water conservation under dryland conditions. Daily crop ET, drainage, and available soil water are illustrated in graph form. Estimated drainage, ET, and seed yield are presented in a summary table. The software is to be used as an educational tool for illustration of water's influence on crop production in the region of western Kansas–eastern Colorado with a deep silt loam soil developed from loess.

IRRIGATED AREAS of corn, grain sorghum, and winter wheat in western Kansas totaled about 0.5 million acres[1] in 1960 and 2.0 million acres by 1982 (Buller, 1991). Water supply in western Kansas is dependent on groundwater (U.S. Geological Survey, 1987), for which the Ogallala Aquifer is the main source. Withdrawal from the Ogallala Aquifer exceeds recharge in most areas where extensive irrigation development has occurred and, as a result, water table elevations are declining. Since 1980, declines in water table elevation of more than 20 ft and of 10 to 20 ft have been widespread in southwestern Kansas and in northwestern Kansas, respectively (McGrath and Dugan, 1993).

Increased competition for water among users, declining groundwater supplies, and possible contamination of groundwater by drainage of water and dissolved chemicals dictate a need for proper management of water in crop production. An understanding of interrelationships among irrigation system efficiency, irrigation timing and amount, drainage, crop water use, and crop yield is essential for efficient water management. Simulation models of plant–water–soil systems are useful means to observe and understand these interrelationships.

The objective of this work was to develop a water balance model and then a microcomputer software package for illustration of drainage, evapotranspiration (ET), and crop yield as influenced by water conditions. This paper presents a description of the model, model adaptation to western Kansas, software operation, and software application. This software project was the subject of Ph.D. program work by Khan (1996). Detailed descriptions and instructions for the model and software are presented by Stone et al. (1995).

MODEL DESCRIPTION

A field water balance model (KS Water Budget, hereafter referred to as the *KSWB model*) was developed to illustrate patterns of drainage of water from the soil profile, ET, and crop yield by using empirical equations. Total water (SW) in the soil profile on each day of year (DOY) is calculated by using a water balance equation:

$$SW_i = SW_{i-1} - AET_{i-1} - DR_{i-1} + EPR_{i-1} + EIR_{i-1}$$

where i represents DOY1, DOY2, . . . , DOY365; AET is actual ET; DR is drainage; EPR is effective precipitation; and EIR is effective irrigation. In the KSWB model, the SW value at 40% available soil water is assigned as the initial SW value for the calculation process. The model calculates the field water balance through a 4-yr sequence, with all inputs held constant during the 4 yr. Four yearly cycles are used, with profile water content stabilizing during three yearly cycles and results from the 4th cycle (year) used as output.

The amount of ET on any day depends on weather, the size and age of the crop, and the amount of soil water available to plants. Crop ET can be estimated by using reference ET techniques. *Reference ET* was defined by Jensen et al. (1970) as the maximum ET that occurs under given climatic conditions for a field having a well-watered, 12- to 18-inch-tall alfalfa (*Medicago sativa* L.) crop. In the KSWB model, reference ET is estimated daily for 365 d of the year by using meteorological data (maximum and minimum air temperatures and solar radiation) and the Jensen and Haise (1963) equation.

[1] Due to the nature of this article, SI units are not used. The KSWB software that is referred to uses English units; their conversions are as follows: 1 acre = 0.4 ha; 1 foot = 0.3 m; 1 inch = 2.54 cm; 1 pound = 0.45 kg.

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Published in J. Nat. Resour. Life Sci. Educ. 25:170–174 (1996).

Abbreviations: ET, evapotranspiration; KSWB, Kansas Water Budget; SW, total water; DOY, day of year; EPR, effective precipitation; EIR, effective irrigation; ASW, available soil water.

The ratio of maximum evaporation from the soil surface without crops to reference ET is termed the *bare soil ET coefficient*. In the KSWB model, the FAO technique (Doorenbos and Pruitt, 1977) is used to determine bare soil coefficients for the entire year. The ratio of maximum ET of a cropped surface to reference ET is termed the *crop ET coefficient*. The distribution of crop coefficients for a particular crop as a function of time constitutes a crop curve.

The calculation of maximum ET assumes that soil water is not a limiting factor. In the KSWB model, maximum ET during the noncrop season is estimated by multiplying reference ET by the bare soil ET coefficients, and maximum ET during the crop season is estimated by multiplying reference ET by the crop ET coefficients. The actual ET component of the water balance equation depends on weather conditions (reference ET), crop characteristics (crop coefficient curve), and water status of soil. In the KSWB model, the logarithmic relationship proposed by Jensen et al. (1971) is used in describing the influence of water status on ET.

The drainage component of the water balance equation is calculated by using a Wilcox-type drainage equation (Miller and Aarstad, 1972). The effective precipitation (EPR) component of the water balance equation is calculated for each day by using daily precipitation and runoff fractions. The effective irrigation (EIR) amount in the water balance equation is calculated for each irrigation as depth of irrigation water pumped multiplied by the application efficiency as a fraction. Irrigation application efficiency is the percentage of irrigation water applied to an area that is stored in the soil for crop use (SCSA, 1976).

The effect of water stress on growth and yield depends on the crop species and variety, as well as on the magnitude and time of occurrence of water deficit (Doorenbos and Kassam, 1979). To estimate crop yield under water stress conditions, weighting factors are developed for different growth periods of the crops. Weighting factors are different for various growth periods of a crop depending on the sensitivity of the growth period to water stress. Weighting factors relate yield with actual ET relative to maximum ET. In the KSWB model, the crop growing season is divided into four growth periods: vegetative, flowering, seed formation, and ripening. For each growth period, the model calculates a weighted ET by using actual ET, maximum ET, and the weighting factor for that growth period. An *effective ET* then is calculated as the sum of weighted ET values for the four growth periods. This effective ET is used in estimating crop yield from yield–ET relationships.

MODEL ADAPTATION TO WESTERN KANSAS

Weather and field research data collected near Tribune, KS (38.5°N, 101.7°W, 3563 ft above sea level), were used for adaptation of the KSWB model to western Kansas. The weather data file consists of long-term, daily, mean, maximum and minimum air temperatures, precipitation, and solar radiation for 365 d of the year. Temperature and precipitation data are means of 76 yr (1915–1990), and solar radiation data are means of 22 yr (1952–1973). Temperature and precipitation were collected at the Tribune unit of the Southwest Kansas Research-Extension Center. Solar radiation was measured at Goodland, KS (39.4°N, 101.7°W, 3655 ft above sea level). Maximum and minimum air temperatures were recorded each day with mercury-in-glass MAX-MIN thermometers. Daily precipitation was recorded with a standard rain gauge. Snow precipitation was recorded as liquid equivalent. Solar radiation was measured with an Eppley pyranometer (Model PSP; Eppley Laboratory, Newport, RI).

Reference ET for western Kansas was calculated by using MAX and MIN air temperatures, solar radiation, and the equation of Jensen and Haise (1963). Bare soil coefficients were calculated by using the FAO technique (Dorrenbos and Pruitt, 1977) and reference ET for western Kansas. Crop coefficient curves were developed for the growing seasons of the four crops (Stone et al., 1995). Coefficient curves for the entire year were developed from coefficients for bare soil and crops. Cropping dates and growth stage dates used in the model for the four crops are consistent with conditions of full-season cropping in the Tribune area of western Kansas.

The KSWB model uses the upper (25.6 inches) and lower (11.4 inches) limits of available soil water for a 6-ft profile of Ulysses silt loam (fine-silty, mixed, mesic Aridic Haplustoll) with slope <1% located near Tribune, KS. The drainage component of the water balance equation is calculated by using a Wilcox-type drainage equation developed for the same 6-ft soil profile. The Ulysses is a deep, well-drained soil that formed in loess and similar soils occupy about 5.78 million acres of the central High Plains (Aandahl, 1982). Runoff fractions of 0.12, 0.13, 0.15, and 0.02 are used for corn, grain sorghum, sunflower, and winter wheat, respectively. These runoff values are similar to values reported for the central and southern High Plains (Stone et al., 1995).

In the KSWB model, growth periods were weighted so the date of silking, head emergence, head beginning to open, and head emergence for corn, grain sorghum, sunflower, and winter wheat, respectively, were the most critical dates for water stress and also the most benefited by irrigation. Yield–ET functions were developed for corn, grain sorghum, sunflower, and winter wheat at Tribune and used in the KSWB model.

SOFTWARE OPERATION

The KS Water Budget v. T1 software package (hereafter referred to as the KSWB software) was based on the KSWB model, adapted to western Kansas. When the program starts, the first screen (Fig. 1) displays the list of authors, programmers, and funding agencies. The *Help* menu (Fig. 1) contains brief descriptions of the needed inputs. Detailed descriptions (including graphs and tables) of the inputs are presented by Stone et al. (1995). Other screens of the software are for user inputs and presentation of output.

The first requirement for the user is to select a crop (Fig. 2). The four crop choices are corn, winter wheat, grain sorghum, and sunflower. The default crop is corn, i.e., the cursor is at the *Corn* box when a new run starts. A crop can be selected with a mouse or by using the *Tab* key. The default annual rainfall (precipitation) is 16.4 in. (long-term mean for Tribune). Annual rainfall can be varied (Fig. 2) from 0 to 24 inches. To calculate daily precipitation, the program divides the user-input annual rainfall by 16.4 and then multiplies by the daily long-term mean rainfall from the data file built into the software package. However, all of the precipitation does not go into the soil profile because of surface runoff. An effective rainfall is calculated by considering the surface runoff fractions.

The next item in the software that needs to be specified is the number of irrigations (Fig. 2). The number of irrigations desired should be entered in the irrigation box. Zero (no irrigation) is the default value, and the number can be chosen between 0 and 18. The user also can account for rainfall events by entering them as irrigation events. Once

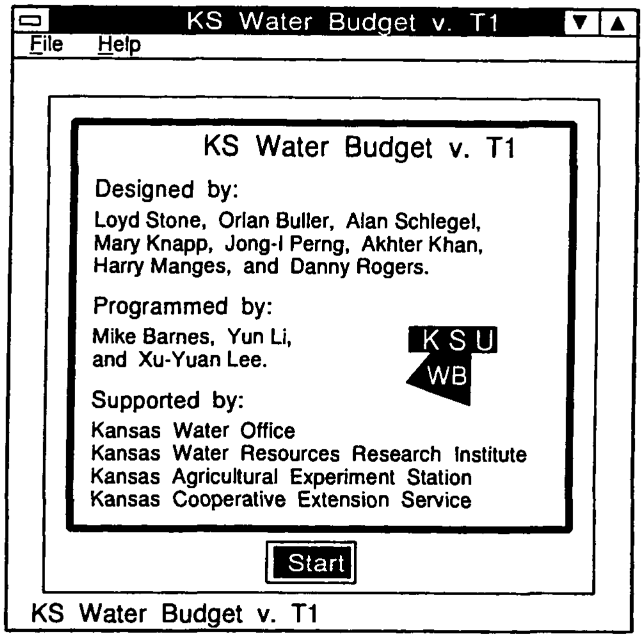

Fig. 1. Beginning screen of the KS Water Budget v. T1 software.

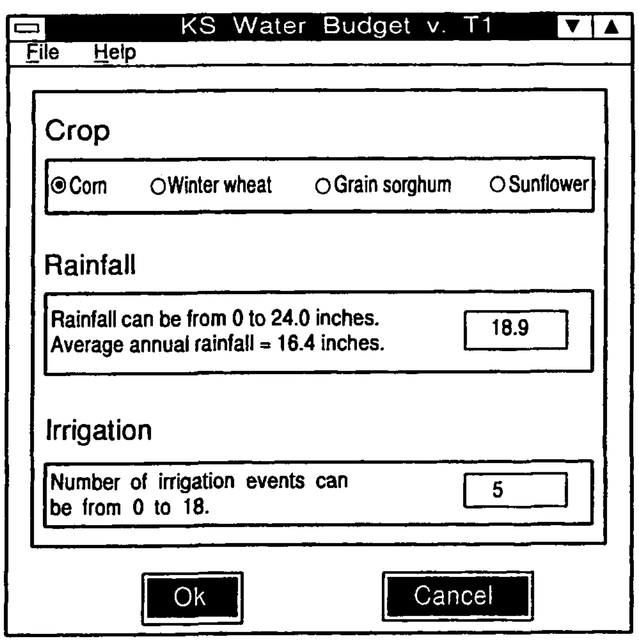

Fig. 2. Crop, annual rainfall, and number of irrigation events need to be selected in this screen of the KS water budget v. T1 software.

the crop, annual rainfall, and number of irrigation and/or rainfall events have been selected, the user can click the *OK* button or press *Enter*.

If the selected number in the irrigation event box is zero, the program will start calculating, and the results will be for dryland continuous cropping with conventional tillage. If the number typed is other than zero, the program will ask for additional information on the next screen of the software (Fig. 3). On this screen, the first box shows the number of the current irrigation event. The user needs to type the day of irrigation (a number) in the second box, the month (first three letters) in the third box, and the depth of irrigation water pumped (inches) in the fourth box. The irrigation or rainfall depth can be from 0 to 12 inches. The mouse or *Tab* key can be used to go from one box to another.

The application efficiency as a percent needs to be typed in the fifth box. A user can specify any application efficiency from 0 to 100, depending on the irrigation system. With rainfall events, efficiency is the percent of rainfall that goes into the soil profile, i.e., 100 minus the runoff percentage. After providing information for an irrigation or rainfall event, the user can click *OK* or press *Enter*. Information for additional events then should be provided. Once information for all irrigation and/or rainfall events is provided, the program will start calculating.

The program calculates ET, drainage, available soil water, and crop yield. Software results can be viewed by using the view option. The software presents the results in two pages. On page 1 (Fig. 4), ET vs. date and drainage vs. date are presented. On page 2 (Fig. 5), ASW (available soil water) vs. date and a summary table are presented. The three plots and summary table can be printed on one page by using the print option.

The rate of ET depends on the evaporative demand of the atmosphere, water status of the soil, and stage of crop growth. Crop ET is calculated by using the Jensen and Haise

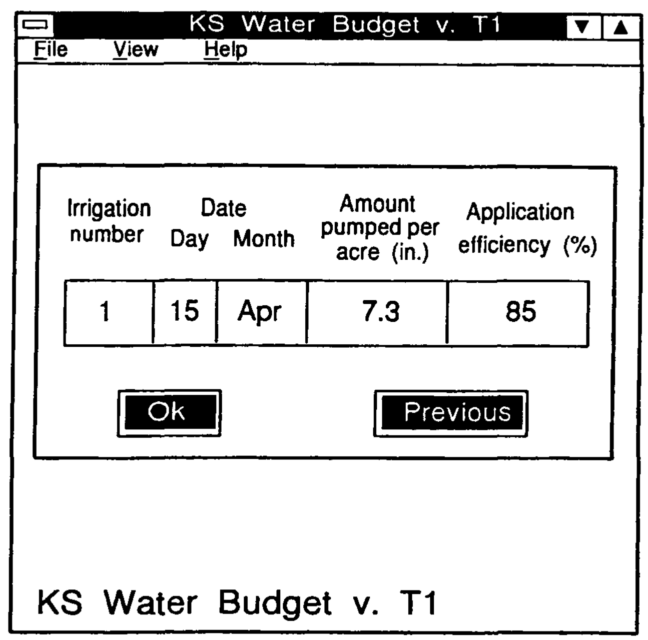

Fig. 3. Information about an irrigation event needs to be provided in this screen of the KS water budget v. T1 software.

(1963) equation, crop coefficient curves, and the available soil water coefficient. The KSWB software calculates daily ET and illustrates the values graphically for 365 d of the year (Fig. 4). A considerable portion of rain or irrigation water added to the soil profile can be lost from the root zone through drainage. The KSWB software calculates drainage rate by using the Wilcox-type drainage equation for a Ulysses silt loam soil near Tribune and plots the calculated drainage rate vs. date (Fig. 4). Water content at the lower limit of available soil water for the 6-ft profile of Ulysses silt loam is 11.4 inches (Stone et al., 1987). Available soil water on each day is calculated by subtracting 11.4 inches from the total profile water content of that day and presented vs. day of year (Fig. 5).

A summary table presents total ET and drainage for the crop and noncrop seasons (Fig. 5). All daily ET and drainage values from crop emergence until physiological maturity are added to obtain the ET and drainage amounts for the crop season. The amounts are subtracted from the yearly total ET or drainage to estimate values for the noncrop season. For winter wheat, crop-season ET and drainage include values for the dormant period.

The program calculates crop-season effective ET and then uses it with the yield–ET equations to estimate crop yield. The software presents estimated yields in the summary table (Fig. 5). Seed yields are at 0.155, 0.125, 0.125, and 0.100 lb/lb water contents (wet mass basis) for corn, grain sorghum, winter wheat, and sunflower, respectively.

The software does not allow total water content of the 6-ft profile to exceed 31.0 inches. Water content in excess of 31.0 inches is considered waste and does not enter into water balance calculations. Water content in excess of 31.0 inches on any date is summed for the year and presented in the summary table. The user-input annual rainfall is printed in the summary table. The table also contains a summary of irrigation schedules showing date, amount, and efficiency of each irrigation event.

SOFTWARE APPLICATION

The KSWB software can be used to examine the effect of water application amount and timing on crop yield. Insufficient water application reduces crop yield, and excessive water application causes loss of water from the soil profile through drainage. These effects can be observed in the results obtained by running the KSWB software. Water applied at critical times will result in more crop yield than water applied at other times. In the KSWB software, the most benefit from water application occurs with application at silking in corn (24 July), head emergence in grain sorghum (3 August), head beginning to open in sunflower (28 July), and head emergence in winter wheat (19 May). The effects of timing and amount of irrigation on crop yield are more pronounced for relatively dry conditions than wet conditions.

The effects of different runoffs from rainfall on results obtained from the software can be observed by changing runoff fractions. The procedure for changing runoff fractions is given by Stone et al. (1995). The user can vary the irrigation application efficiency in the software (Fig. 3) and observe the effects of different irrigation system efficiencies on software results.

Results for different dryland farming practices can be illustrated with the software. To simulate continuous dryland, the user should specify "0" irrigation events. For other dryland practices, such as fallow and/or reduced tillage, the user needs to know how much additional water the 6-ft soil profile would have at crop emergence because of that practice relative to continuous cropping with conventional tillage. Then, in the software, the user would add that amount of water as a single irrigation at crop emergence.

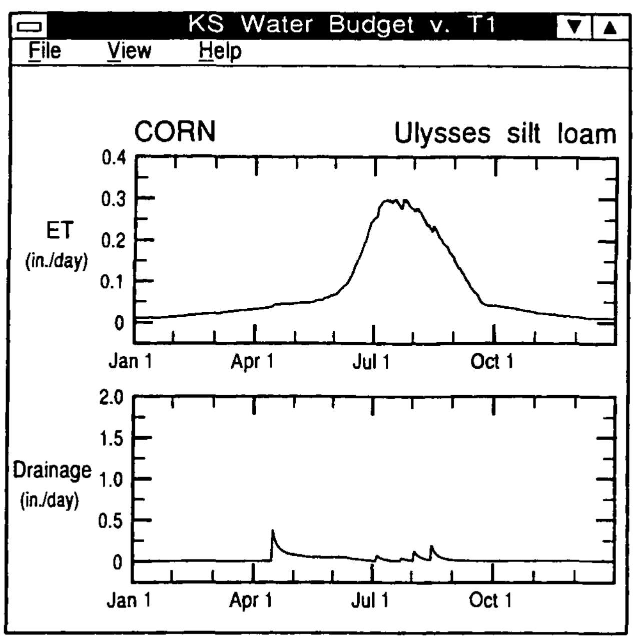

Fig. 4. The KS water budget v. T1 software screen presenting plots of ET (evapotranspiration) and drainage vs. date.

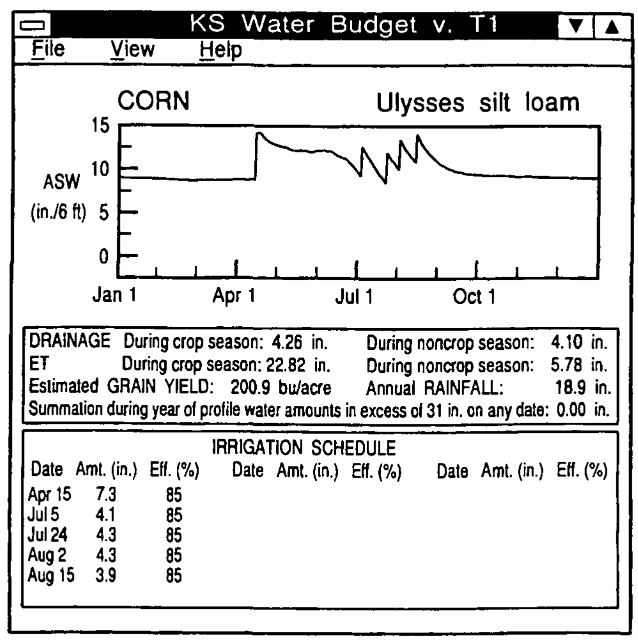

Fig. 5. The KS water budget v. T1 software screen presenting the plot of ASW (available soil water) vs. date and a summary table.

With the single irrigation, the user should specify 100% application efficiency so the desired amount will be added to the soil profile. The dates of crop emergence used in the KSWB software are 16 May for corn, 9 June for grain sorghum and sunflower, and 17 September for winter wheat.

SUMMARY

The KS Water Budget v. T1 software was designed and built to project the influence that varying water conditions in a silt loam soil of western Kansas–eastern Colorado would have on ET, drainage, and crop yield. Within the software, conditions of air temperature, solar radiation, growing season dates, and soil properties are fixed, based on field data, primarily from Tribune. These conditions are considered appropriate for the High Plains region of western Kansas–eastern Colorado, provided the soil is a deep silt loam developed from loess. Water conditions can be varied by the software user through changing rainfall amount and timing, irrigation amount and timing, surface runoff from rainfall, and irrigation system efficiency.

With favorable water conditions for crops, yields projected by the software will be greater than long-term maximum yields for western Kansas–eastern Colorado, because the model does not factor in calamitous events such as freezes, hail storms, insects, or diseases, which would skew the long-term maximum yields downward. The software projects yields for the user-specified water conditions by assuming that those same water conditions would exist for multiple consecutive years.

The KS Water Budget v. T1 software is not intended for use in, and is not capable of, providing results for multiple-site situations. This software illustrates patterns and amounts that are typical for the region of western Kansas–eastern Colorado, provided the soil is a deep silt loam developed from loess. This software is intended for use as an educational tool to illustrate the influence of water conditions on drainage, ET, and crop yield.

SOFTWARE SPECIFICATIONS

The program for the KSWB software was written in Turbo Pascal for Windows (Version 1.5; Borland International, Scotts Valley, CA). The computer system needed to run KSWB software is an IBM or compatible personal computer with 386 processor (or higher), 640K of conventional memory plus 256K of extended memory, at least 0.5Mb of free hard disk space, Microsoft MS-DOS Version 3.1 (or later), MS-Windows Version 3.1 (or later), and a printer with capability of printing 300 dpi (dots per inch).

The KS Water Budget v. T1 software package is available from Dr. Loyd R. Stone, Department of Agronomy, Throckmorton Hall, Kansas State University, Manhattan, KS 66506- 5501; phone (913) 532-5732; fax (913) 532-6094. A floppy disk (3.5- or 5.25-inch) containing KS Water Budget v. T1 software (executable file and data files) and a resource manual (Stone et al., 1995) will be shipped upon receipt of $10. There are no restrictions on copying this software and users are encouraged to make the KS Water Budget v. T1 software available to interested persons.

ACKNOWLEDGMENTS

Support was received from the Kansas Water Office, Topeka, KS, and the Kansas Water Resources Research Institute, Manhattan, KS. We thank student programmers Mike Barnes, Yun Li, and Xu-Yuan Lee for their assistance. A special acknowledgment is made of the significant work of the late Roy E. Gwin, Jr., during his tenure as head of the Tribune Branch Experiment Station.

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