Evapotranspiration Relationships and Crop Coefficient Curves of Irrigated Field Crops

by

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B.S., Agronomy, Kansas State University, 1980

A MASTER'S THESIS

Submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Agronomy

Kansas State University
Manhattan, Kansas

1982

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ACKNOWLEDGEMENTS

This thesis was made possible by the guidance and financial support of my major professor, Dr. Loyd R. Stone. I thank him for his time, patience, and willingness to assist whenever necessary. Many thanks are due Roy E. Gwin, director of the Tribune Branch Experiment Station, and his crew, for their generous and willing cooperation in project planning and field plot work. I also thank the Pat Gallaghers' and Roy Gwin for allowing me to stay in the house at the Tribune Branch Experiment Station.

Dedra Manes and Karla Hefty spent many hours collecting data from the Manhattan plots. I thank them both for their unstinting, conscientious labor. Dedra Manes also deserves thanks for keypunching computer cards, and especially for typing the rough and final drafts of my thesis.

I thank Matt Matulka for the hard hours he spent at Tribune and Manhattan helping with equipment installation and harvest. I also thank Karen Beam and Katherina Howie for their assistance in constructing tensiometers. Thanks also are due Rob Unruh for his assistance with harvest and equipment removal. Also deserving thanks is my sister, Alice R. Hattendorf, who performed innumerable calculations and helped harvest plots.

I thank Dr. E. T. Kanemasu and Dr. G. Posler for serving on my graduate committee.

Dorothy S. Harris, Susan C. Eadens, Maryann S. Redelfs, Jean L. Steiner, and my parents, Mr. and Mrs. Daryl G. Hattendorf, have my thanks for their friendship and support during my graduate program at Kansas State University.

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INTRODUCTION

Irrigation is essential for continuous row crop production in the western Great Plains. Irrigation in river valleys and from shallow water tables was practiced soon after settlement of the region, but not until the 1950's were the vast underground resources of the Ogallala aquifer tapped for use (Governor's Task Force, 1977). This aquifer is composed of gravels and shattered rock and is underlain by impermeable bedrock, thus trapping any water which percolates from the soil surface. Vast quantities of water are contained in the Ogallala, which underlies parts of South Dakota, Nebraska, Colorado, Kansas, Oklahoma, New Mexico, and Texas.

The immense size of the Ogallala aquifer led many farmers, water use planners, and politicians to believe that the Ogallala was inexhaustible. Actually, it is being depleted at rates that far exceed the rate of recharge. In some areas of heavy irrigation from the Ogallala, farmers are no longer able to meet the water requirements of their most popular row crop, corn (*Zea mays* L.). The alternatives to full irrigation of corn are to accept lower corn yields or grow other irrigated row crops that are less water-use intensive than corn. Grain sorghum (*Sorghum bicolor* (L.) Moench), sunflower (*Helianthus annus* L.), pinto bean (*Phaseolus vulgaris* L.), pearl millet (*Pennisetum americanum* L.), and soybean (*Glycine max* (L.) Merr.) are crop alternatives for corn, but little is known of the water use of alternative crops relative to that of corn. Increasing amounts of research are directed toward comparing water use of various crops. To be effective, a comparison must be conducted in one research plot area so differences in soil type and climate are minimized. In this manner, total seasonal water use and within season water use patterns of crops can be determined and compared.

Those data could be used in scheduling irrigations and in determining water requirements of various cropping systems.

In 1981, a study was conducted at Tribune and Manhattan with corn and five alternative crops comparing seasonal crop water use and water use patterns of the six crops. Specific goals of this project were to compare water use of six crops, examine evapotranspiration patterns among the crops, examine soil water depletion patterns among the crops, and to develop an empirical method of estimation of crop evapotranspiration rates based on potential evapotranspiration (Jensen and Haise, 1963) and growing degree units. The data obtained will assist in developing guidelines for irrigation scheduling and in designing irrigation systems.

LITERATURE REVIEW

Crop water use

In 1914, Briggs and Shantz published their now classical study of plant water requirements. They rated plants according to the amount of water a plant required to produce 0.45 kg of dry matter, or 0.45 kg of grain. Similar experiments were repeated by Shantz and Piemiesel (1927) and by Dillman (1931). Since then, the work has not been repeated with an extensive comparison of water requirements of modern crop cultivars.

In recent years, the emphasis changed to doing comprehensive research on the seasonal water use and soil water depletion of individual crops. Corn has been one of the most extensively researched crops.

Holt and Van Doren (1961) showed depth of water extraction and peak water use related to growth stage of corn. Their results indicated that corn extracted water from the upper 61 cm of soil until tasseling occurred. After tasseling, water extraction was also from the 91 to 152 cm layer of soil. Their second year of data showed that corn extracted water from the 122 to 152 cm layer by the time tasselling occurred. Their results indicated that depth of water extraction was dependent on soil moisture and climatic conditions. Highest rates of water use occurred from tasseling to kernel formation.

Doss et al. (1962) found that corn water use reached a maximum at dough stage and declined thereafter as the crop approached physiological maturity. They also found corn extracting water down to 91 cm at tasselling.

Other researchers have related soil moisture stress on corn to yield. Denmead and Shaw (1960) found that water stress at silking caused yield reduction of 50%, and yield reductions of only 25% with water stress before or after silking.

Denmead and Shaw (1959) also related evapotranspiration of corn to corn development and found that highest evapotranspiration rates occurred during silking. The two studies by Denmead and Shaw demonstrated a relationship between maximum water use and the most water stress-sensitive period of crop growth.

Grain sorghum was found to have its highest rate of water use from the booting to soft dough stage by Porter et al. (1960). They also found that rate of water use was not significantly affected by row width or planting rate.

The optimal time for irrigating grain sorghum is from boot stage to half bloom (Hay, 1980). He also showed how water use rates of grain sorghum peak during the reproductive stage.

Musick et al. (1976) researched how grain sorghum, winter wheat, and soybeans vary in their ability to extract water below -15 bars matric potential. Plant available water for soybeans, wheat, and grain sorghum were 17.0, 21.0, and 20.3 cm, respectively, showing that grain sorghum and wheat have a greater ability to extract water below -15 bars than does soybean. Stone et al. (1973) showed that 99.9% of sorghum roots were in the upper 130 cm of the soil profile.

Dry edible bean is a crop suited to the cool nights and dry climate of the Great Plains. Howe and Rhoads (1961) discussed Great Northern Field bean irrigation in Nebraska. Under limited water supplies, they advocated applying a single irrigation at pod fill. If two irrigations were applied, the first was early in the season and the second again at pod fill. Water use of the field bean increased to a maximum when the plant was runnering. A second, usually smaller, peak occurred at pod fill. Under a two-irrigation regime, Great Northern bean depleted 81% of water used from the top 46 cm of the profile. Twelve percent was depleted from the 46 to 72 cm depth, 2% from 72 to 107 cm, and 5% from 107 to 137 cm. A second year of data showed 1% of the depetion from the 137 to 168 cm zone, with the pattern otherwise remaining similar to that of the first year.

Stegman and Olson (1976) grew pinto bean under various irrigation regimes and found a positive linear response of yield to water use. Seasonal water use was 37.3 cm, measured from emergence to harvest. Peak water use rate occurred at 50 to 60 days after emergence, which approximately corresponded to time of full ground cover.

Greig et al. (1974) advocated light irrigation to dry edible beans. Excessive irrigation delayed maturity and caused excessive vine growth. The best times to irrigate were at bloom and pod set.

Timmons et al. (1967) found significant differences in soil water depletion under soybean by time periods, depths, and depth by time periods, but no significant effect of row spacing or plant population on water use. Soil water was not depleted from the profile at the 121.9 to 152.4 cm depth in the first year of the study. In the second year, soil water was depleted down to the 152.4 cm depth after 20 July. Cumulative evapotranspiration for Chippewa soybean ranged from 42.3 to 46.2 cm for different populations and row widths.

Eavis and Taylor (1979) studied the relationship of soybean transpiration to root length, leaf area, and soil water content. They concluded that transpiration is controlled primarily by leaf area when soil water content is not limiting. Root length was unimportant in modification of the plant transpiration rate, although soil water content had a profound effect on plant evapotranspiration rates.

Dusek et al. (1971) showed that soybean response to irrigation was greatest during pod set. They showed seasonal water uses ranging from 33.8 to 61.5 cm for Clark soybean, and 34.0 to 67.5 cm for Hill soybean under different irrigation treatments. Water use of both varieties was reduced when stress occurred at pod fill and at flowering plus pod fill. Dusek et al. (1971) also indicated that soybean was well able to use water down to 91 cm. Sorghum was a better water extractor at 122 cm than soybean. Grain sorghum was also grown at Bushland, Texas, as Dusek et al. (1971) described. Grain sorghum seasonal water use was compared with that of soybean grown at Bushland. Grain sorghum showed lower seasonal water use than soybean when both crops were adequately watered.

Peters and Johnson (1960) found that unirrigated and covered plots of irrigated soybean used more water when grown in 51 cm rows than 102 cm rows. Yield also was greater in the 51 cm rows. Water was extracted in significant quantities from depths below 76 cm in spite of its availability closer to the soil surface. The yield increase and greater water use of soybean in 51 cm rows was explained by understanding that soybean in 102 cm rows does not utilize soil moisture between the rows as fully as they ought.

Stanley and Shaw (1978) demonstrated a relationship between maximum ratio of evapotranspiration to pan evaporation and leaf area. The maximum ratios were reached during pod set and bean fill of soybean. Maximum ratio was approximately one.

Talha and Osman (1975) subjected sunflower to water stress during different growth stages. The most sensitive periods were during elongation of stems and flowering. Sunflower rooting depth was in the upper

40 cm during slow elongation and extended to the 80 cm depth during rapid elongation. Daily water use peaked during flowering. Lowest water use efficiency was obtained from plants stressed during the elongation or flowering stages.

Alessi et al. (1977) found that sunflower water use was greater for early plantings than late but was not affected by plant population or row spacing. Total average water use was 22.9 cm for 30 cm rows and 22.6 cm for 90 cm rows. Soil water depletion was confined to the top 150 cm of soil. Soil water content declined as the growing season progressed. Depletion was greatest before flowering, which left little water for seed development. Soil water extraction patterns were affected by planting date, but not by populations. The water content in the 120-150 cm zone at seeding was significantly different from the water content at harvest in the same layer.

Robinson (1971) found that irrigation and fertilizer, singly and in combination, increased sunflower yields.

Singh and Kanemasu (1980) grew several genotypes of pearl millet. Hybrids, early, and late maturing types were included. Water use of irrigated genotypes ranged from 50 to 64 cm, while non-irrigated millet water use ranged from 24 to 42 cm. Late genotypes tended to use more water because they had a longer growing season. Heights of the hybrids ranged from 77 to 105 cm. Total water use under irrigated conditions was 50.1 cm for the 77 cm tall hybrid, and 58.8 cm for the 105 cm tall hybrid. The tallest genotype at 219 cm also used the most water, 64.3 cm. Among the hybrids, however, the 95 cm tall hybrid used more water than the 105 cm tall hybrid. Genotypes that yielded well depleted soil water from the entire depth of the profile. The profile was more throughly depleted of water by higher yielding genotypes.

The International Crops Research Institute for the Semi-Arid Tropics (1976) indicated that pearl millet did not always respond significantly to irrigation, but one study showed a 770 kg of grain/ha increase in yield from a single 5 cm irrigation after a 30 day dry period.

Research in North Dakota by Bauder and Ennen (1981) compared the total seasonal water use of several crops. They found that at one location corn and sunflower water use did not differ significantly, but at another location, corn water use was significantly higher than that of sunflower. Also at the second location, water use of sunflower and corn were significantly higher than that of dry edible bean. At a third location, the water use of sunflower and soybean did not differ significantly. In a second year of data at a fourth location, water use of corn was significantly higher than that of soybean and sunflower, whose total water use did not differ significantly. Total water use values of the crops grown by Bauder and Ennen (1981) ranged from 259 mm for dry edible bean to 579 mm for sugarbeet. High correlation existed for the relationship of length of growing season and total water use, indicating that shorter season crops tended to use less water than longer season crops.

Heat Units

A brief discussion of heat units, or growing degree days, for crop development is in order. There is much literature that surveys the theory and development of the heat unit concept. For background information of theory see Arnold (1959), Katz (1952), Nuttonson (1955, 1956), Livingston (1916), and Robertson (1968). Heat units are often used to predict date of maturity of canning crop (Katz, 1952). Since this early use, heat unit concepts have been further developed and used for the prediction of phenological events in crops.

Wang (1960) discussed weaknesses of the heat unit concept. Several problems exist with the heat unit concept. The first is that plants really do not respond linearly to the same environmental factors throughout their life cycle. Secondly, the threshold, or base, temperature changes during the life cycle. Only where a coincidental linearity occurs between an environmental parameter and crop development rate are heat units an effective approach. Last, heat units certainly do not take into account vapor pressure deficit, soil moisture, solar radiation, wind, or daylength. The value of the heat unit system is that it does adequately satisfy practical needs, even though it is not necessarily accurate or theoretically sound in some respects.

Heat unit systems commonly used are described by Aspiazu and Shaw (1972). They discussed several types of developmental indices. One is an exponential of the form $U = 2^{(T - 40)/18}$ where U is the growth index, T is the temperature in °F, and 40 is the base temperature. A major criticism is that the exponential form does not differentiate between optimum growth temperatures and temperatures that are lethal to the plant.

A physiological index is based on the physiological response of plants to temperature. Brown (1969) developed the corn heat unit (CHU) system from field data for corn. The equation assumed a parabolic response to temperature where

$$CHU = \frac{1.85\ (Tmax - 10) - 0.026\ (Tmax - 10)^2 + Tmin - 4.4}{2}$$

and Tmax is the daily maximum temperature and Tmin is the minimum night temperature, both in °C. The equation showed corn responding differently to day temperature and night temperature.

The remainder system is another method of calculating heat units. The basic premise is that crop response to temperature is linear. Heat units are calculated above a base temperature.

The basic equation is:

$$\frac{Tmax + Tmin}{2} - 10°C$$

where Tmax and Tmin are daily maximum and minimum temperatures in °C, respectively. The base temperature is 10°C for corn and may vary with crop. This equation is referred to subsequently as the simple remainder or GDD system.

Gilmore and Rogers (1958) first introduced the modification of the remainder index system known as effective growing degree days (EGDD), or Weather Bureau 10-30. They tested 15 systems of heat units by comparing coefficients of variation. The system with the smallest C.V. was one in which 10°C was taken as base temperature, and 30°C as the upper limit (Tmax > 30 = 30). They called this the "effective degrees" system.

Crane et al. (1976) compared corn heat units (CHU) with days, growing degree days (GDD), and effective growing degree days (EGDD) where GDD, EGDD, and CHU have been defined previously. By comparing coefficients of variation (C.V.) of the different methods over a range of hybrids and environments, the CHU method exhibited the lowest C.V. in almost every case. Effective growing degree days were better as an indicator of developmental stage than GDD or days. Coefficients of variation for EGDD and CHU were often very close, and as it is impossible to statistically compare C.V. values, one does not know whether CHU are without doubt the best system to use.

Aspiazu and Shaw (1972) also found that Corn Heat Units (Brown, 1969) yielded the lowest standard deviation in calendar days. They evaluated different heat unit methods by using the criterion $F = sd_1^2 / sd_2^2$ where sd_1^2 is the larger variance. The method showing the least variation in heat units was considered the best heat unit expression. A CHU method using 10 as the base temperature ranked second, while the EGDD method ranked third. Mederski et al. (1973) had similar results.

Cross and Zuber (1972) countered with a criticism of the C.V. method of selection. Since a C.V. is nothing more than the ratio of the variance to the mean, they said the method was biased to heat unit systems that showed the largest mean accumulation. They advocated a "heat stress" method of calculating thermal units, i.e., if Tmax > 30 then T = 30 - (Tmax - 30) where T is the heat units. No base temperature was used.

Shaw (1975) calculated growing degree units by using the method introduced by Gilmore and Rogers (1958). It was used because of its simplicity and reasonable applicability.

Andrew et al. (1956) used a simple remainder index system with a base of 10°C as a measure of corn maturity at two widely separated locations. They found that cumulative thermal units were very closely negatively correlated with corn moisture content at both locations.

Neild and Seeley (1977) used the simple remainder index formula to calculate degree days for corn and sorghum in Nebraska. Numerical stages of corn development and of grain sorghum development were regressed against accumulated growing degree days for the various developmental stages of the crops. Their results showed that growing degree days had a closer relationship with stage of development (S.E. = 0.34) than days from planting (S.E. = 0.64) with r values of 0.99 and 0.95, respectively. Results also showed that sorghums of three maturity groups planted on the same date developed at almost the same rate until stage one. Thereafter, the later maturing hybrids developed at a slower rate than the earliest hybrid. A striking aspect of the research was that the same proportion of development units was allotted to a given phenological event among the maturity groups. Pauli et al. (1964) documented this relationship.

Smith et al. (1978) took into account that developmental rate of sunflower differed among developmental stages. They described equations of sunflower development for the vegetative, reproductive, and maturation stages of development. Model inputs included mean daily temperature in °C, relative available soil water depletion rates in percent, and daylength in hours. The developmental unit was the proportion of total development occurring per day. The proportions were summed and when the total reached one, the crop was switched to the next developmental stage.

Robinson et al. (1967) used the simple remainder index formula with a base temperature of 7.2°C. They agreed that 7.2°C seemed to be a reasonable base temperature to use, based on experience with sunflower and knowledge of bases for other crops. They stated that within a location, any base temperature sufficed for varietal comparison or descriptive data. But if locations of differing latitude were compared, results were unsatisfactory with the wrong base temperature. In a later paper, Robinson (1971) again used the simple remainder index formula with a base of 7.2°C.

Stegman (1976) used a simple remainder index formula for calculating growing degree days for pinto bean with a base temperature of 10°C. He found that the phenology relationship of pinto bean to growing degree units was quite consistent for three years of data.

Fryer et al. (1966) showed that day and night temperatures have various effects on sorghum development. Night temperatures had an especially strong influence on whether maturity was delayed or hastened.

Shaw (1975), Andrew et al. (1956), Neild and Seeley (1977), and Stegman (1976) used a base temperature of 10°C in EGDD and simple remainder formulas for corn, grain sorghum, and pinto bean.

Little literature is available on temperature response of millet. It is implicitly included in the discussion of sorghum since I treat them in the same manner in calculations.

Brown (1960) showed a curvilinear response of soybean developmental rate to temperature. He found that at a base temperature of 10°C, rate of development was essentially zero, while 30°C was the optimum temperature for soybean rate of development.

Major et al. (1975a) used thermal units to predict soybean development. After testing 11 methods of calculating heat units, they concluded that heat unit accumulation alone was not enough to adequately describe soybean development.

In a second paper, Major et al. (1975b) devised equations of soybean development using an iterative regression analysis (IRA) technique. This technique incorporated temperature and daylength data into the model. The model outperformed any other method considered, such as thermal units or calendar days. Different coefficients were developed for each variety tested. Varieties were from maturity groups I through V. The general equation was:

$$M = \sum_{s_1}^{s_2} [a_1 (L-a_o) + a_2 (L-a_o)^2] [b_1 (T-b_o) + b_2 (T-b_o)^2]$$

where a and b are regression coefficients for the daylength and temperature terms, respectively. L is daylength in hours and T is mean daily temperature. S_1 and S_2 signify two developmental stages of soybean. When the sum of the photothermal units equals one, soybean is at the S_2 growth stage. The equation then switches to the next set of coefficients.

Concepts of Potential Evapotranspiration

Potential evapotranspiration is defined as the rate at which water if available would be removed from the soil and plant surface expressed as the rate of latent heat transfer per square centimeter or depth of water (Jensen, 1974).

Jensen and Haise (1963) described how the problem of potential evapotranspiration was approached by researchers. Penman (1948) used a theoretical approach to estimate potential evapotranspiration. Combined in his equation were aerodynamic and energy balance terms, where evaporation was estimated from a free water surface. To adapt the equation to transpiring surfaces, empirical coefficients were added. Thus Penman's equation can be recalibrated for different climates. His equation is an example of the "combination" approach. Other researchers have used climatic parameters such as air temperature, humidity, and the relationship of evapotranspiration to open-pan evaporation. Refer to Thornthwaite (1948), Blaney and Morin (1942), and Blaney and Criddle (1950, 1962) for a more complete description of their techniques of relating evaporation to mean air temperature.

Pan evaporation can be used with a proportionality coefficient to estimate evapotranspiration. Stanhill (1961, 1962) developed an irrigation scheduling program in Israel using pan evaporation data. Other researchers who used this concept were Pruitt and Jensen (1955) and Chang et al. (1963). Stanley and Shaw (1978) also related evapotranspiration to open-pan evaporation for soybean. Maximum ratios were reached when pod development and bean fill occurred.

Estimation of potential evapotranspiration (ETP) units using solar radiation data has been developed by Jensen and Haise (1963). They discussed the energy balance approach to estimation of ETP by saying that evapotranspiration was dependent on the amount of heat energy available to an evaporating or transpiring surface. Their empirical equation was developed in arid and semi-arid climates, so a turbulent transport term for water vapor removal was unnecessary. Because many ETP equations required the assumption that the area in question be surrounded by an unlimited boundary of freely transpiring vegetation, those equations were inapplicable to the irrigated areas of arid or semi-arid regions. Jensen and Haise (1963) specified that the only assumptions made for their radiation approach were that the boundary area was large enough to prevent horizontal gradients of temperature or vapor pressure, and that the crop was well-watered.

Jensen and Haise (1963) developed the following equation:

$ETP = (0.014\ T - 0.37)\ RS$, where T is the mean daily air temperature in °F, and RS is solar radiation expressed in millimeters of water per day. Potential evapotranspiration will therefore be expressed in mm/day. The equation also accomodates °C by using a different slope and intercept in the term.

Jensen et al. (1970) developed an altitude correction for their solar radiation model of potential evapotranspiration. The modified equation is $ETP = C_T(T-T_x)RS$ for °F.

$C_T = \frac{1}{C_1+13C_H}$ where C_1 is modified for altitude by this equation:

$C_1 = 68-3.6E/1000$ where E is elevation in feet.

C_H is a humidity index term.

$C_H = \frac{50\ mb}{e_2 - e_1}$ where e_2 and e_1 are saturation vapor pressure in millibars at mean maximum and minimum temperatures in °F, respectively, during the warmest month. RS is solar radiation in equivalent millimeters of water.

T_x is a constant value for a given area. It can be calculated:

$T_x = 27.5°F - 0.25\ (e_2 - e_1) - E/1000$, where e_2 and e_1 are in millibars and E is elevation in feet.

Jensen and Haise (1963) also described how the actual ET/RS ratio changes during the growing season of grain sorghum at two locations. The ET/RS ratio increases to a maximum at heading in a curvilinear fashion and declines almost linearly after heading. Stage of plant growth is used as the X axis and is expressed as a percentage up to heading (expressed as 100%) and thereafter as days after heading.

Jensen et al. (1970) used percent of growing season as a basis for indicating crop development in relation to crop coefficients K_c by the daily potential evapotranspiration. The effects of wet soil and irrigation on crop coefficients were discussed. Estimated irrigation amounts to be applied and the technique of estimation were described.

Parmele and McGuinness (1974) tested several methods of estimating ETP in a humid region. Combination equations performed well, and the Jensen-Haise (1963) equation worked adequately if soil moisture was not limiting, although it was developed in arid and semi-arid climate.

Crop coefficient curves

Crop coefficient curves utilize a ratio of evapotranspiration to pan evaporation, as mentioned previously, or a ratio of evapotranspiration to potential evapotranspiration (ET/ETP). Stegman and Olson (1976) used the latter method for irrigation scheduling in North Dakota. They used the original Jensen-Haise equation (Jensen and Haise, 1963) as the denominator of the ratio and regressed the ratio against days after emergence. The crop was pinto bean. The crop coefficient curve was a fourth order polynomial, beginning with a ratio of 0.2 and increasing to 1.0 at about 70 days after emergence.

Stegman and Olson (1976) also related the ET/ETP ratio to growing degree days and found a strong relationship. Using this relationship would eliminate some of the problems of relying on a days after emergence (DAE) method of predicting crop developmental stage. Using the DAE method required constant monitoring of the crop in order to shift the curve appropriately in case of different development rates between years.

Stegman et al. (1977) further developed the crop curve concept using ratio of ET/ETP to days past emergence. Evapotranspiration was calculated with a water balance technique. Potential evapotranspiration was calculated using the Jensen and Haise (1963) equation. In each time interval, ET and ETP were averaged and the relationship

$$K_{c\phi} = \left(\frac{ET}{ETP}\right)$$

was calculated, providing a series of data points for which a regression equation was developed. The equations were fifth order polynomials developed for each of six crops. A fair amount of variability was associated with the curves. At least three years of data were used in developing the curves. Those curves were intended to convert estimated potential evapotranspiration values to estimates of crop evapotranspiration. In order to overcome the difficulty of shifting the curves from year to year to allow for differing crop growth rates, certain crop growth stages were associated with points on the curve.

Dylla et al. (1980) estimated crop water use using crop coefficients developed by Stegman et al. (1977). Results of the study by Dylla et al. (1980) indicated that using the Jensen-Haise (1963) equation adequately estimated crop evapotranspiration. An ET/ETP curve using the Jensen and Haise (1963) technique agreed fairly well with the curve developed by Stegman et al. (1977), although pan evaporation was found to estimate crop ET with greater precision than the ETP technique.

Instrumentation

Neutron probes are instruments used to measure the water content of the soil. According to Hillel (1971), a neutron probe has two major components. The first is a probing device which is lowered into an aluminum access tube in the soil. The probe contains a radioactive source, either radium--beryllium or americium--beryllium, which emits fast neutrons. The neutrons go out into the soil, where they can collide with many particles. If a neutron encounters a particle with a similar mass to its own, such as a hydrogen atom, it is slowed, or "thermalized", and goes off in a random direction after the collision. Some of the slowed neutrons return to the detector cell of the probe, which is filled with BF_3 gas. If a neutron collides with a ^{10}B nucleus, an alpha particle is emitted, which in turn triggers an electrical impulse on a charged wire. The impulse travels to the scalar, where it is then counted and displayed.

Cannell and Asbell (1974) discussed the use of neutron probe data in determining soil water content. They said that count ratios, that is, the ratio of the measured count to that of the standard count, should be used in calculations to reduce instrumental error. Regression analysis can be used to determine the relationship of count ratio and volumetric soil water content.

McGowan and Williams (1980) discussed the kind of errors that can be associated with the use of a neutron probe. They stated that probes are not suited to making measurements of absolute water content in the soil. They are, however, good for determining differences in soil water content between two points in time. McGowan and Williams (1980) claimed that more error was associated with installation problems than with the calibration of the instrument. Poor installation can allow cracks or cavities in the tube vicinity, compaction, or other such problems. Another source of error was drift in the readings. Standard counts were taken in a barrel of water to detect any drift in the counts. As a standard counter, the polythene shield was unsatisfactory because of thermal expansion or contraction of the shield during the day. Error can be associated with not locating the probe at exactly the same depth in the tube each time a measurement is made. McGowan and Williams (1980) especially emphasized knowing the "center" of a probe, that is, where its active source is located in the housing, particularly if two different probes must be used.

Bowman and King (1965) showed how number of counts made by a probe is influenced by distance in the soil from the source, with a uniform soil moisture distribution. At a few centimeters from the source, the influence of soil moisture is very great on the number of counts, but at a distance of 15 cm, the count diminishes from over 600 to little more than 100, about a sixth of the counts taken close to the source.

Hillel (1971) described the use of tensiometers to measure soil matric potential. Measurement of soil water potential establishes the energy status of soil water. Tensiometers are constructed of a porous cup attached at the bottom of a tube, which is filled with water to expel gasses, and connected to a manometer. A tensiometer equilibrates with the soil water through the porous cup. When water is drawn from the tensiometer tube, it creates a drop in the hydrostatic pressure inside the tensiometer. This change is indicated by the mercury manometer.

Solutes do not affect the operation of a tensiometer. The main limitation of tensiometers is the range of pressure potentials in which they are operational. At very low potentials, air can enter the porous cup, and cause the system to cavitate. Therefore, the actual range of tensiometers is saturation to -0.8 bars soil water potential.

Rose (1966) defined hydraulic potential as the sum of gravitational and pressure potentials. Hydraulic potential is commonly expressed as hydraulic head in centimeters. Knowledge of hydraulic head allows the soil water gradient to be calculated in order to determine direction of water flux between two points.

MATERIALS AND METHODS

This project was conducted on the Ashland Evapotranspiration research site near Manhattan, Kan., and at the Ross Irrigation Field near Tribune, Kan., in 1981. The soil at the Manhattan location is a Muir silt loam, a fine-silty, mixed, mesic Pachic Haplustoll. It is deep, nearly level, well-drained with high water retention capacity, and was formed in deep alluvium. The soil at the Tribune site is a Ulysses silt loam, a fine-silty, mixed, mesic Ardic Haplustoll with 0 to 1% slope. It is an upland soil which is formed in deep loess. The soil is fertile, calcareous, deep, friable, and well drained with high water-holding capacity.

The plots at Tribune were moldboard plowed in the fall, disked twice, level planed, disked again, and furrowed in the spring before planting. Crops were seeded into the top of the ridge. Row width was 76.2 cm at both locations. The Manhattan plots were disked to provide a smooth, clean seed bed and furrowed after planting. The crops planted at both locations are field crops that are grown or have good commercial potential in Kansas. Table 1 provides a list of crops, scientific names, and specific varieties planted. Table 2 gives the planting dates of each crop at both locations.

Prior to planting, fertilizer was applied at both locations. At Tribune, 182 kg/ha of actual nitrogen in the form of anhydrous ammonia were applied. Also, 9.8 kg N/ha and 20.4 kg P/ha in the form of 11-52-0 were broadcast applied. At Manhattan, 72.5 kg N/ha were broadcast applied as 34-0-0 ammonium nitrate. Also, 55 kg N/ha and 61 kg P/ha were bradcast applied as 18-46-0 fertilizer.

The project was organized in a randomized complete block design with six crops and three replications per crop. Figures 1 and 2 show the plot arrangement at each location. The plots at Manhattan were

Table 1. Scientific names and varieties of crops grown at Tribune and Manhattan.

Crop	Scientific name	Variety/hybrid
Corn	*Zea mays* L.	Prairie Valley 76S
Grain sorghum	*Sorghum bicolor* (L.)Moench	Prairie Valley 535 GR
Pearl millet	*Pennisetum americanum* L.	79-2094/78-7088 Fl Row 11458 1980 Field Custer B
Pinto bean	*Phaseolus vulgaris* L.	UI 114
Soybean	*Glycine max* (L.) Merr.	Cumberland
Sunflower	*Helianthus annuus* L.	Interstate 907

Table 2. Planting dates of crops at Tribune and Manhattan.

	Planting date	
Crop	Tribune	Manhattan
Corn	15 May	21 May
Grain sorghum	27 May	2 June
Pearl millet	5 June	2 June
Pinto bean	4 June	22 May
Soybean	4 June	22 May
Sunflower	4 June*	22 May

*Sunflower at Tribune was abandoned on 15 July due to crop damage.

↑ North

9 Pearl millet 3	10 Corn 3
8 Pinto bean 3	11 Sunflower 3
7 Grain sorghum 3	12 Soybean 3
6 Sunflower 2	13 Pinto bean 2
5 Corn 2	14 Soybean 2
4 Pearl millet 2	15 Grain sorghum 2
3 Soybean 1	16 Sunflower 1
2 Corn 1	17 Pearl millet 1
1 Pinto bean 1	18 Grain sorghum 1

Fig. 1. Plot arrangement at Tribune, showing plot number (top), crop, and block number (bottom).

↑ North

4 Corn 3	Extra (Soybean)	11 Grain sorghum 3	12 Pinto bean 3	Extra (Corn)
3 Sunflower 2	5 Soybean 3	10 Pearl millet 3	13 Sunflower 3	18 Corn 2
2 Pinto bean 2	6 Sunflower 1	9 Grain sorghum 2	14 Soybean 2	17 Pearl millet 2
1 Soybean 1	7 Pinto bean 1	8 Corn 1	15 Pearl millet 1	16 Grain sorghum 1

Fig. 2. Plot arrangement at Manhattan, showing plot number (top), crop, and block number (bottom).

approximately 16 m long and 12 m wide with 16 rows per plot. Tribune plots were 15 m long and 12 m wide, with 15 rows per plot. At Tribune, only 14 rows of pearl millet were planted, however, because of the planter type used.

Crops were not irrigated at Manhattan in 1981, due to plentiful summer rainfall. At Tribune, the plot area was pre-plant irrigated in the spring. The amount of water applied was approximately 152 mm. Berms were built around each plot after they were furrowed on the east and west edges of the Manhattan plots. In-season irrigations were applied on 1 July, 23 July, and 12 August at Tribune. The amount of water applied each time was approximately 114 mm.

A Lasso ™ (2-chloro-2',6'-diethyl-N[methoxymethyl]acetanilide) + Bladex ™(2-[[4-chloro-6-[ethylamino]-s-triazin-2-yl]-amino]-2-methyl-propionitrile) tank mix was applied just after planting to the corn plots at Manhattan. Milogard ™(2-chloro-4, 6 bis [isopropylamino]-s-triazine) was applied to the Manhattan grain sorghum and pearl millet plots immediately after planting. Treflan ™(a,a,a-trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine) was applied preplant and incorporated into the soil surface on the pinto bean, soybean and sunflower plots. Atrazine (2-chloro-4[ethylamino]-6-[isopropylamino]-s-triazine) was applied to the Tribune corn plots 2 days before emergence. Treflan™ was applied pre-plant and incorporated into the soil surface of the pinto bean, soybean, and sunflower plots.

Four mercury-manometer tensiometers were installed in the center row of each plot at Tribune. Two were at the 180 cm depth and two were at the 210 cm depth. All were positioned in the crop row and spaced so that crop damage was minimal. Tensiometers were constructed with a ceramic cup epoxyed into the lower end of the PVC pipe. A piece of clear, hard plastic tubing was inserted into the other end of the PVC pipe to serve as a sight tube. A small hole was drilled about 3.8 cm below the upper end of the PVC pipe. Spaghetti tubing was epoxyed into the hole. All four tensiometers were connected to one mercury manometer and primed with water. Tensiometers were read about three times a week and reprimed to replenish the water inside and to dispel air from the system. Tensiometers were primed on 22 June, 7 July, 16 July, and 12 August. Mercury manometer readings from each plot were averaged by depth on each reading date. Hydraulic head was then calculated for each depth on a date. No statistical analysis of tensiometer data was performed.

Two neutron access tubes of O.D. 4.13 cm and wall thickness of 0.09 cm were installed in each plot at each location, one in each row flanking the center row. Tubes were installed in the Tribune corn plots on 25 May and in the remaining Tribune plots on 13 June. Tubes were installed in the Manhattan plots on 4 June. Data were collected approximately every 10 days down to 3.14 m in 15 cm increments. Tubes were installed with minimal disturbance to the crop. When necessary the crop was replanted by the tube to ensure a proper stand.

Three neutron probes were used throughout the season. Two were identical Troxler 3221 series probes, and the third was a Troxler 2601 series probe. In order to adjust the data from the 3221 series probes to that of the 2601 series probe, we regressed the count ratio of the first 3221 series probe against the count ratios of the other probes, and then coordinated the count ratio (CR) of the second probe's data to the CR of the 2601 series probe. This was possible because we had taken data on the same day for the two 3221 series probes, and for the second 3221 series probe and 2601 series probe. Water content by volume was calculated for each 15 cm increment of the soil profile using the calibration equation of the 2601 series probe.

Two gravimetric samples were taken at 0 to 60 mm from each plot, weighed, dried for 48 hours at 105°C, and weighed again. Water content by volume was calculated from the wet and dry soil weights and the known bulk density of the surface soil. To obtain the water content in millimeters of each sampling increment, water content by volume from the gravimetric sample was multiplied by 60, the uppermost water content by volume reading obtained with the probe was multiplied by 192, and all other volumetric water content values were multiplied by 152 mm. The water contents in mm of each sampling increment in the entire profile were then summed to obtain the total water in the profile on each sampling date.

Evapotranspiration rate (ET rate) in mm/day was obtained by calculating the change in total profile water between water content reading dates, adding irrigation and rainfall values, and dividing by the number of days in the period. Regression analyses were performed on ET rate by Julian date, and on ET rate by fraction of growing season for each crop. Analysis of variance was performed on the total seasonal water use of each crop and Duncan's Multiple Range Test was applied to each analysis of variance test.

Depletion rates (DR) were calculated during four selected time periods at each location. The periods selected had no irrigations and little rainfall. Depletion rates are the change in water content in 30 cm increments in a period divided by the number of days in the period. The uppermost water content by volume value was multiplied by 152 mm instead of 192 mm as done for ET rate calculation to obtain the soil water in mm for that layer. The water contents in mm of 15 cm increments were added together in pairs to get the water content for a particular 30 cm layer. Midpoints of the 30 cm increments were 25.4, 55.4, 85.4, 115.4, 145.4, 175.4, 205.4, 235.4, 265.4, and 295.4 cm. Analysis of variance was performed on the depletion rates to test for significantly different depletion rates among crops by layer and by depth within a crop. Duncan's Multiple Range Test was used to compare means of each variable.

Leaf area and plant parts were sampled throughout the growing season at both locations. At first, 2 and 3 m of row sanples were taken from the plots at both locations. As the plant size increased, sampling was reduced to 1 m lengths, and to one plot of each crop at both locations. To avoid stripping any one plot, we rotated selections from one plot to another as the summer progressed. Leaf area in cm^2 was obtained by using a Type AAM5 Hayashi Denko leaf area meter. Leaf area index (LAI) was calculated from the data. Dry weights were recorded of leaves, stems, and reproductive parts. Reproductive parts were not sampled as such until they had emerged from the plant. Samples were dried in an 80°C oven for 1 week, weighed, and the weight recorded in grams. Kilograms of dry weight per hectare were calculated and converted to metric tons per hectare for regression analyses. Regression analysis was performed on each plant component and LAI by Julian date and fraction of growing season.

Fraction of growing season is an index of plant development based on use of growing degree units as an estimate of length of growing season of each crop. Growing degree units were calculated from climatic data to provide a measure of crop growth and development. For all crops except soybeans, the only inputs are maximum and minimum daily temperature in °C, where $T_{max} > 30°C = 30°C$ and $T_{min} < 10°C = 10°C$. For sunflower, if $T_{min} <$

7.2°C, then Tmin = 7.2°C. Soybean growth units are photothermal units with inputs of calculated daylengths in hours and maximum and minimum temperatures in °C (Major et al., 1975b). Values of growth units on specific dates are indexed against the total accumulated growth units from emergence to physiological maturity. This provides a common fraction of growing season, allowing comparison among crops. A review of literature indicated that using a plant development index would more reliably estimate crop development than days after emergence.

Potential evapotranspiration rates were calculated on a daily basis using solar radiation and maximum-minimum temperature data (Jensen and Haise, 1963). Average potential evapotranspiration rates were calculated for the same time periods as acutal evapotranspiration rates. Dividing average actual evapotranspiration rates (ET_A) by average potential evapotranspiration rates (ET_P) provides an index of ET_A to ET_P.

Descriptions of crop developmental stages were taken during the growing season. Planting, emergence, reproductive events, and physiological maturity were recorded for each crop. Tables of crop developmental stages are in the Appendix, Tables 9A and 10A.

Rainfall data were collected near the project sites at Manhattan and Tribune. Solar radiation and temperature data at Manhattan were obtained from the Kansas State University Climatological Records. Tribune solar radiation and temperature data were collected at the main experiment station one mile west of Tribune. Tables of climate data are in the Appendix, Tables 15A and 16A.

RESULTS AND DISCUSSION

Total seasonal crop water use is the difference in total soil profile water content between the beginning and end of the growing season, plus rainfall and irrigation, and minus runoff and drainage. Runoff and drainage were considered negligible at Manhattan and Tribune.

Pressure potential data taken at Tribune indicated that the soil was so dry at the 180 and 210 cm depths that drainage from the profile was negligible. Pressure potentials ranged from a high of -233 cm of water to a low of -619 cm of water. Hydraulic potentials are listed in the Appendix, Table 4A.

Table 3 shows the total seasonal water use at Tribune and Manhattan for the six crops. Soybean used the most water of the crops at Manhattan and pinto bean the least. Intermediate water users were sunflower, pearl millet, corn, and grain sorghum, respectively. The analysis of variance performed on the data showed significant differences in total seasonal crop water use at the 0.05 level. Duncan's Multiple Range Test (DMRT) at the 0.05 level was used to distinguish significantly different total seasonal water use among the crops. Total water use of soybean, sunflower, pearl millet, and corn were not significantly different. Pinto bean water use was significantly lower than that of the other crops, excepting grain sorghum.

At Tribune, corn used more water than the other crops and pinto bean the least. Water use of corn, pearl millet, and grain sorghum did not differ significantly according to DMRT at the 0.05 level. This agrees with results from Manhattan, where the water use of those three crops did not differ significantly. However, corn water use was significantly high than soybean and pinto bean water use at Tribune. Soybean water use at Tribune may be explained by the climate difference between Tribune and Manhattan. Night temperature at Tribune

Table 3. Total seasonal water use of crops at Tribune and Manhattan.

Crop	Total water use Manhattan	Tribune
	mm	
Corn	561ab[†]	542a
Grain sorghum	521bc	504abc
Pearl millet	562ab	530ab
Pinto bean	473c	444c
Soybean	586a	468bc
Sunflower	564ab	----

[†]Letters summarize Duncan's Multiple Range Test results at the 0.05 level. Means with the same letter are not significantly different. Analysis of variance tests were significant at the 0.05 level.

was low compared to Manhattan's, thus the growth rates of soybean and pinto bean were lower.

Soil water depletion rates were calculated for four time periods during the growing season at each location. Data were analyzed by analysis of variance in two ways. The depletion rates were compared within a specific layer among the crops to test for significant differences in depletion rate. Then each crop was examined separately to test for significant differences in depletion rate by layer within a crop. Table 4 shows F values from the analysis of variance test of depletion rates by crop within a layer at Tribune. Table 5 shows soil water depletion rate means by crop within a layer at Tribune with results of DMRT. General trends among the crops showed that corn strongly depleted the 100 to 404 mm and 404 to 708 mm layers throughout the growing season. Corn showed higher depletion rates in the 708 to 1012 mm layer than other crops. In the 1012 to 1316 mm layer, soybean and corn showed higher depletion rates than corn, with depletion rates totalled over all the selected depletion periods. The 16-25 June and 6-14 July period generally showed stronger soil water depletion under corn and pearl millet than under soybean in the top four soil layers. During the 3-10 Aug. and 20-27 Aug. periods, soybean soil water depletion rates in the 1620 to 1924 mm layer were higher than depletion rates of the other crops. Layers deeper than 1924 mm showed few trends in soil water depletion rates.

Significant differences at the 0.05 level of the analysis of variance test existed in the 100 to 404, 404 to 708, 708 to 1012, and 1316 to 1620 mm layers of the soil profile. During the 6-14 July period, grain sorghum depletion rates was significantly higher than depletion rates of the other crops in the 100 to 404 mm layer. In the 404 to 708 mm layer, the corn soil water depletion rate was significantly higher than

Table 4. F values from analysis of variance of depletion rates by crop within a layer at Tribune.

Period	F values for indicated soil layer									
	100 to 404mm	404 to 708mm	708 to 1012mm	1012 to 1316mm	1316 to 1620mm	1620 to 1924mm	1924 to 2228mm	2228 to 2532mm	2532 to 2836mm	2836 to 3140mm
16-25 June	0.61	0.58	0.19	1.88	0.71	0.65	1.85	3.18	3.68	3.84
6-14 July	15.33**	11.28**	4.61*	2.64	0.90	0.22	0.41	0.31	0.31	2.71
3-10 Aug.	0.60	0.94	2.00	0.42	1.73	0.74	0.24	0.26	1.78	1.57
20-27 Aug.	0.89	3.98*	1.76	3.08	5.95*	0.99	0.28	2.41	1.24	0.67

*Analysis of variance is significant at the 0.05 level.

**Analysis of variance is significant at the 0.01 level.

F values not followed by an asterisk are not significant at the 0.05 level.

Table 5. Soil water depletion rate means by crop within a soil layer at Tribune.

Crop	16-25 June	6-14 July	3-10 Aug.	20-27 Aug.
	100 to 404 mm layer			
	mm/day			
Corn	1.34	2.79b**	2.36	2.26
Grain sorghum	0.85	3.40a	1.84	1.99
Pearl millet	0.79	2.73b	2.13	2.19
Pinto bean	0.75	2.36b	1.95	1.74
Soybean	1.21	1.54c	1.85	1.94
	404 to 708 mm layer			
Corn	0.44	1.59a**	1.38	1.15a*
Grain sorghum	0.15	1.19ab	0.91	0.80ab
Pearl millet	0.24	0.78bc	1.10	0.95a
Pinto bean	-0.03	0.59c	1.10	0.49b
Soybean	0.21	0.64c	0.97	0.79ab

Table 5. Cont.

Crop	16-25 June	6-14 July	3-10 Aug.	20-27 Aug.
	708 to 1012 mm layer			
	mm/day			
Corn	-0.42	1.34a*	0.98	0.66
Grain sorghum	-0.13	0.36b	0.40	0.04
Pearl millet	0.07	0.36b	0.40	0.19
Pinto bean	-0.26	0.29b	1.13	0.52
Soybean	-0.06	0.50b	0.88	0.66
	1012 to 1316 mm layer			
Corn	-0.33	0.49	0.78	0.37
Grain sorghum	0.32	-0.01	0.42	0.18
Pearl millet	0.36	0.34	1.15	0.00
Pinto bean	-0.50	0.26	0.83	0.48
Soybean	-0.11	0.63	0.62	0.69

Table 5. Cont.

Crop	16-25 June	6-14 July	3-10 Aug.	20-27 Aug.
	1316 to 1620 mm layer			
	mm/day			
Corn	-0.19	0.21	0.43	0.30ab*
Grain sorghum	-0.30	-0.13	0.20	-0.01c
Pearl millet	0.50	-0.03	0.26	-0.04c
Pinto bean	-0.04	0.01	0.38	0.16bc
Soybean	-0.36	0.20	0.51	0.48a
	1620 to 1924 mm layer			
Corn	-0.08	0.03	0.33	0.046
Grain sorghum	-0.24	-0.15	0.03	-0.10
Pearl millet	0.09	-0.16	0.16	-0.06
Pinto bean	0.06	-0.09	0.18	-0.14
Soybean	-0.24	-0.16	0.25	0.05

Table 5. Cont.

Crop	16-25 June	6-14 July	3-10 Aug.	20-27 Aug.
	1924 to 2228 mm layer			
	mm/day			
Corn	0.03	-0.11	0.11	-0.04
Grain sorghum	-0.04	-0.07	-0.05	-0.17
Pearl millet	-0.15	-0.20	-0.01	-0.15
Pinto bean	0.64	-0.12	0.01	-0.17
Soybean	0.42	-0.06	-0.03	-0.12
	2228 to 2532 mm layer			
Corn	0.05	-0.10	-0.01	0.10
Grain sorghum	0.32	-0.19	-0.01	-0.19
Pearl millet	-0.09	-0.12	0.14	-0.27
Pinto bean	1.02	-0.03	-0.03	-0.33
Soybean	0.46	-0.13	-0.16	-0.19

Table 5. Cont.

Crop	16-25 June	6-14 July	3-10 Aug.	20-27 Aug.
	2532 to 2836 mm layer			
	mm/day			
Corn	0.32	-0.13	0.10	0.12
Grain sorghum	0.12	-0.09	-0.05	-0.20
Pearl millet	0.12	-0.03	0.26	-0.19
Pinto bean	0.88	-0.09	0.07	-0.22
Soybean	0.43	-0.21	-0.07	-0.18
	2836 to 3140 mm layer			
Corn	-0.40	-0.17	0.12	-0.19
Grain sorghum	0.17	-0.07	-0.004	-0.17
Pearl millet	0.21	0.00	-0.20	-0.40
Pinto bean	0.70	0.05	0.04	-0.24
Soybean	-0.29	-0.10	-0.05	-0.34

*Means with the same letter were not significantly different by Duncan's Multiple Range Test (DMRT) at the 0.05 level. Analysis of variance was significant at the 0.05 level.

**Means with the same letter were not significantly different by DMRT at the 0.05 level. Analysis of variance was significant at the 0.01 level.

Means with no letter were not significantly different by analysis of variance at the 0.05 level.

that of pearl millet, soybean, and pinto bean from 6 to 14 July. From 20 to 27 Aug., corn soil water depletion rate was significantly higher than that of pinto bean. The 708 to 1012 mm layer showed that the corn soil water depletion rate was significantly higher than depletion rates of the other crops from 6 to 14 July. During the 20 to 27 Aug. period, soybean soil water depletion rate was significantly higher than that of pinto bean, grain sorghum, and pearl millet in the 1316 to 1620 mm layer.

When data were analyzed by depth within a crop by analysis of variance, depletion rates were almost invariably highest in the 100 to 404 mm layer. Table 6 shows F values from the analysis of variance of depletion rate by layer within a crop at Tribune. Table 7 shows depletion rate means by layer within the crops at Tribune. Layers 404 to 708 and 708 to 1012 mm had successively declining depletion rates among the crops.

Depletion rates at Manhattan showed no clear patterns, probably due to the high amount of rainfall received (447 mm) over the growing season. Data and statistical analyses are listed in the Appendix, Tables 6A,8A.

Leaf area data were collected for all crops at each location throughout the growing season. Because of a 3 Sept. hail storm, data were not collected after 3 Sept. at Tribune. Table 8 lists leaf area index (LAI) for each crop on the sampling dates at Tribune and Manhattan.

Periodic evapotranspiration rates at each location were regressed against Julian date and fraction of growing season. The actual Julian date was divided by 100 in order to yield more manageable coefficients. Tables 9 and 10 and Fig. 3 and 4 show regression equations and curves with data points, respectively, of ET rate vs. Julian date/100 at each location.

Table 6. F values from analysis of variance of depletion rates by layer within a crop at Tribune.

	F values for indicated crop				
Period	Corn	Grain sorghum	Pearl millet	Pinto bean	Soybean
16-25 June	4.91**	4.62**	1.96	1.43	2.26
6-14 July	33.09**	104.97**	29.93**	48.74**	11.40**
3-10 Aug.	61.99**	24.85**	7.30**	18.21**	12.49**
20-27 Aug.	22.56**	101.30**	155.72**	56.23**	32.54**

F values with no asterisk were not significant at the 0.05 level.

** Analysis of variance was significant at the 0.01 level.

Table 7. Depletion rate means by layer within a crop at Tribune.

	Soil water depletion rate			
Soil layer	16-25 June	6-14 July	3-10 Aug.	20-27 Aug.
	Corn			
— mm —	mm/day			
100-404	1.34a*	2.79a*	2.36a*	2.26a*
404-708	0.44b	1.59b	1.38b	1.15b
708-1012	-0.42c	1.34b	0.98c	0.66c
1012-1316	-0.33bc	0.49c	0.78c	0.37cd
1316-1620	-0.19bc	0.21cd	0.43d	0.36cd
1620-1924	-0.08bc	0.03cd	0.33de	0.05de
1924-2228	0.03bc	-0.11d	0.11ef	-0.04de
2228-2532	0.05bc	-0.10d	-0.01f	0.10de
2532-2836	0.32bc	-0.13d	0.10ef	0.12de
2836-3140	-0.40c	-0.16d	0.12ef	-0.19e
	Grain sorghum			
100-404	0.85a*	3.46a*	1.84a*	1.99a*
404-708	0.15bc	1.19b	0.91b	0.80b
708-1012	-0.13bc	0.36c	0.40c	0.04cd
1012-1316	-0.32c	-0.01c	0.42	0.18c
1316-1620	0.30c	-0.13d	0.20cd	-0.01cde
1620-1924	-0.24c	-0.15d	0.03cd	-0.10de
1924-2228	-0.04bc	-0.67d	-0.05d	-0.17de
2228-2532	0.32b	-0.19d	-0.008d	-0.19de
2532-2836	0.12bc	-0.09d	-0.05d	-0.20e
2836-3140	0.17bc	-0.07d	-0.004d	-0.17de

Table 7. Cont.

Soil layer	Soil water depletion rate			
	16-25 June	6-14 July	3-10 Aug.	20-27 Aug.
	Pearl millet			
— mm —	mm/day			
100-404	0.79	2.73a*	2.13a*	2.19a*
404-708	0.24	0.78b	1.10b	0.95b
708-1012	0.07	0.366c	0.40bc	0.19c
1012-1316	0.36	0.34bcd	1.15b	0.00d
1316-1620	0.50	-0.03cd	0.26bc	-0.04d
1620-1924	0.09	-0.16cd	0.16c	-0.06d
1924-2228	-0.15	-0.20d	0.01c	-0.15de
2228-2532	-0.09	-0.12cd	-0.14c	-0.27ef
2532-2836	0.12	-0.03cd	-0.26c	-0.19de
2836-3140	0.21	0.00cd	-0.20c	-0.40f
	Pinto bean			
100-404	0.75	2.3ba*	1.95a*	1.74a*
404-708	-0.03	0.59b	1.10b	0.49b
708-1012	-0.26	0.29bc	1.13b	0.52b
1012-1316	-0.50	0.26cd	0.83bc	0.48b
1316-1620	-0.04	0.01cde	0.38cd	0.16c
1620-1924	0.06	-0.09de	0.18d	-0.14d
1924-2228	0.64	-0.11e	0.01d	-0.17d
2228-2532	1.02	-0.03cde	-0.03d	-0.33d
2532-2836	0.88	-0.09de	0.07d	-0.22d
2836-3140	0.70	0.05cde	0.04d	-0.24d

Table 7. Cont.

	Soil water depletion rate			
Soil layer	16-25 June	6-14 July	3-10 Aug.	20-27 Aug.
	Soybean			
— mm —	mm/day			
100-404	1.21	1.54a*	1.85a*	1.94a*
404-708	0.21	0.64b	0.97b	0.79b
708-1012	-0.06	0.50b	0.88b	0.48b
1012-1316	-0.11	0.63b	0.62bc	0.69b
1316-1620	-0.36	0.20bc	0.51bcd	0.66b
1620-1924	-0.24	-0.16c	0.25cde	0.05c
1924-2228	0.42	-0.06c	-0.03de	-0.12c
2228-2532	0.46	-0.13c	-0.16e	-0.19c
2532-2836	0.43	-0.21c	-0.07de	-0.18c
2836-3140	-0.29	-0.10c	-0.05de	-0.34c

*Means with the same letter were not significantly different by Duncan's Multiple Range Test at the 0.05 level. Analysis of variance was significant at the 0.05 level.

Means with no letter were not significantly different by analysis of variance at the 0.05 level.

Table 8. Leaf area index (LAI) of crops at Manhattan and Tribune.

Crop	8 June	16 June	23 June	30 June	10 July	15 July	22 July	29 July	6 Aug.	18 Aug.	28 Aug.	4 Sept.
						Manhattan						
Corn	0.09	1.54	1.94	3.93	4.52	3.67	4.36	4.16	3.83	4.12	3.97	2.09
Grain sorghum	---	0.05	0.38	1.27	2.99	4.64	4.95	4.35	4.29	3.84	3.88	3.28
Pearl millet	---	0.06	0.63	2.48	4.79	4.51	5.55	3.99	5.27	4.08	4.85	4.40
Pinto bean	0.10	0.65	1.53	2.87	4.48	3.52	4.17	5.48	3.54	4.47	3.60	1.11
Soybean	0.04	0.20	0.51	1.35	2.56	3.08	5.06	6.21	6.27	5.15	5.24	3.39
Sunflower	0.17	0.45	1.61	3.36	3.73	3.45	5.25	7.18	4.76	2.51	1.47	----

Crop	11 June	23 June	1 July	6 July	15 July	3 Aug.	11 Aug.	20 Aug.	30 Aug.
						Tribune			
Corn	0.20	0.79	1.46	2.64	4.57	3.79	4.76	4.52	3.55
Grain sorghum	----	0.31	0.96	2.15	4.16	4.49	4.03	3.44	3.24
Pearl millet	----	0.19	0.57	2.01	3.76	4.47	5.88	4.94	5.27
Pinto bean	----	0.15	0.24	0.54	1.23	4.99	5.30	5.04	3.19
Soybean	----	0.10	0.23	0.40	1.05	3.60	4.61	6.99	4.68

Table 9. Regression equations of evapotranspiration rate (Y) and Julian date/100 (X) at Manhattan.

Crop	Equation†	R^2	N	Range of X values	Model Significance
Corn	$Y = -117.9 + 124X - 30.5X^2$	0.72	9	1.58 - 2.53	0.02
Grain sorghum	$Y = -239.1 + 293.8X - 92.6X^2 + 0.888X^5$	0.91	8	1.58 - 2.53	0.02
Pearl millet	$Y = -45.9 + 54.5X^3 - 37.3X^4 + 6.71X^5$	0.88	9	1.58 - 2.53	0.01
Pinto bean	$Y = -117.3 + 123.9X - 30.8X^2$	0.92	9	1.58 - 2.49	0.001
Soybean	$Y = -90.8 + 96.6X - 23.7X^2$	0.73	9	1.58 - 2.54	0.02
Sunflower	$Y = -116.3 + 93.5X - 7.67X^3$	0.82	8	1.58 - 2.42	0.01

†All variables significant at the 0.10 level.

Table 10. Regression equations of evapotranspiration rate (Y) and Julian date/100 (X) at Tribune.

Crop	Equation†	R^2	N	Range of X values	Model significance
Corn	$Y = -47.6 + 38.4X - 2.84X^3$	0.71	10	1.50 - 2.69	2.01
Grain sorghum	$Y = -63.2 + 63.5X - 14.7X^2$	0.50	8	1.72 - 2.69	0.18
Pearl millet	$Y = -527.4 + 714.6X - 315.1X^2 + 45.4X^3$	0.79	7	1.72 - 2.69	0.15
Pinto bean	$Y = 21.2 + 6.84X^3 - 0.865X^5$	0.81	7	1.72 - 2.47	0.03
Soybean	$Y = -69.5 + 67.8 X - 15.3X^2$	0.97	7	1.72 - 2.69	0.001

† All variables significant at the 0.10 level.

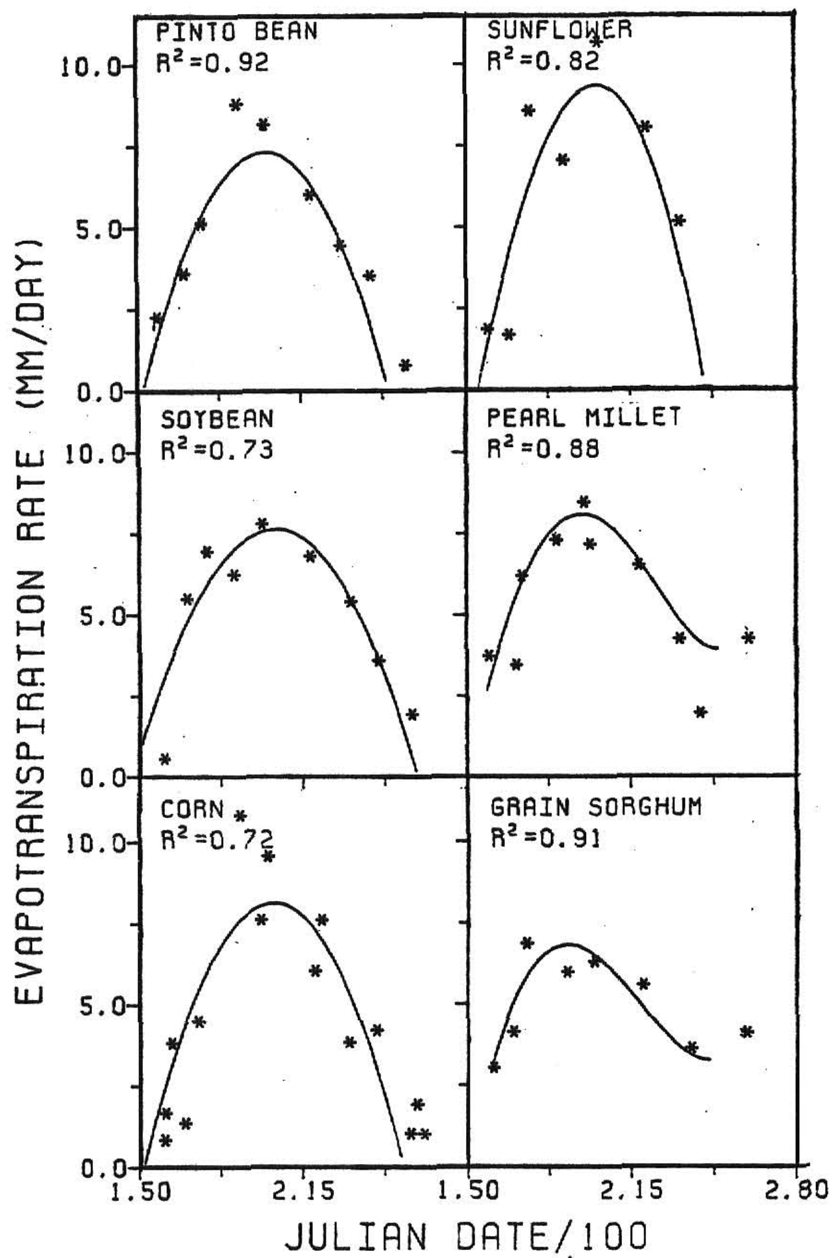

Fig. 3. Regression curves of evapotranspiration rate vs. Julian date/100 at Manhattan.

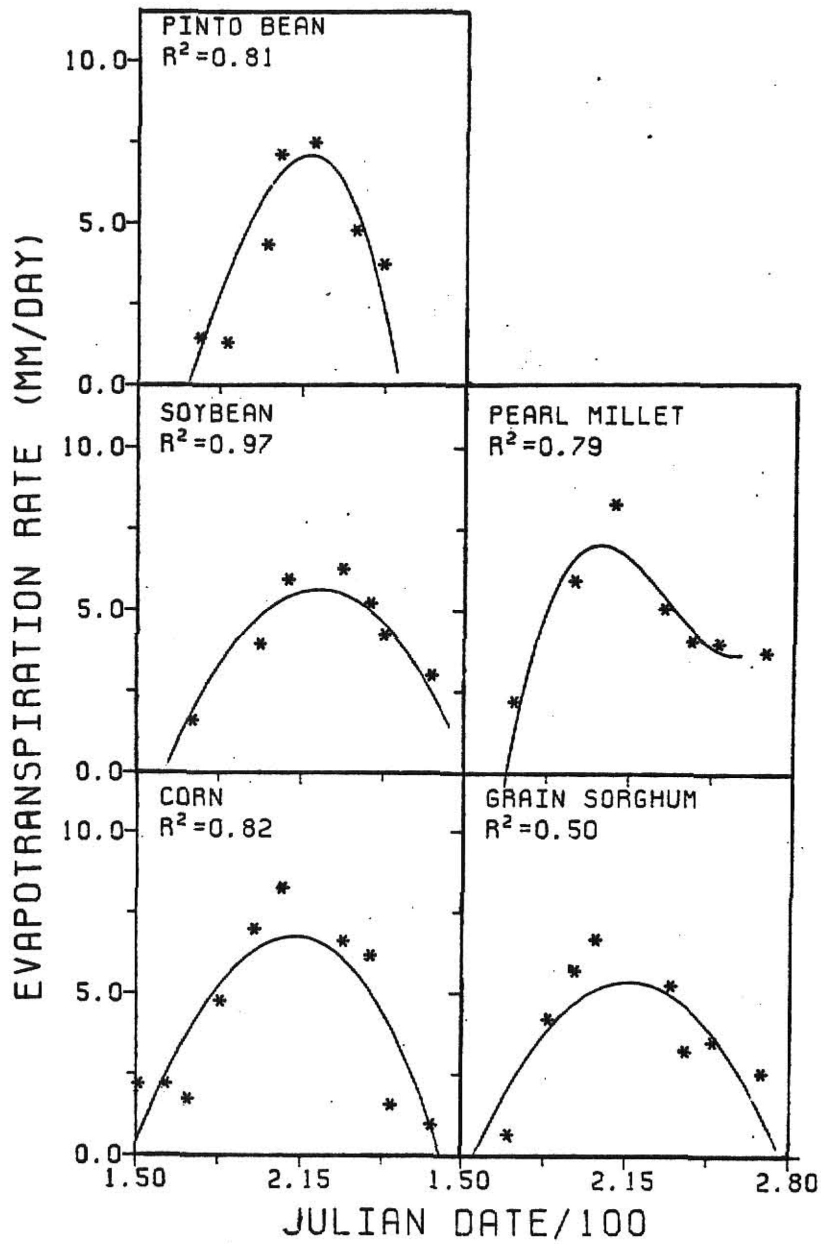

Fig. 4. Regression curves of evapotranspiration rate vs. Julian date/100 at Tribune.

Definite patterns of crop water use existed against an absolute time scale such as Julian date. At Tribune, corn reached peak water use earlier than grain sorghum, pinto bean, and soybean, respectively. Pearl millet achieved peak water use earlier than corn. Two main reasons exist for this well-defined spread in times of peak crop water use among crops. The first is the difference in normal planting dates of the crops in the cooler climate of Tribune. Corn is normally planted in early to mid-May, while the other crops are not planted until late May or early June, since the remaining four crops are rather sensitive to chilling and need warmer soil for germination than corn. The second reason for varied peak water use dates was the of crop growth rates. Soybean and pinto bean appeared to be particularly sensitive to the cool nighttime temperatures at Tribune. At 34 days after soybean emergence at Tribune (15 July), soybean LAI was 1.05, while at 30 days after soybean emergence at Manhattan (30 June), LAI was 1.35 (Table 8). Pinto bean showed a similar trend in comparison of LAI at each location.

Peak water use of crops at Manhattan fall within a small range, except for pearl millet and grain sorghum, which showed peak water use occurring considerably earlier than peak water use of corn.

The evapotranspiration rates of pearl millet and grain sorghum tended to level off at approximately 3 to 4 mm per day (Fig. 3 and 4) close to physiological maturity. At physiological maturity, pearl millet and grain sorghum still have green leaves and are actively transpiring, unlike other crops. Pinto bean, soybean, and sunflower have the criterion of percentage of dry leaves, stems, pods, etc., and basis of physiological maturity.

A black layer showing on the grain signified physiological maturity of corn, grain sorghum, and pearl millet, although corn leaves are usually well dried at physiological maturity. Tables 11 and 12 and Figs. 5 and 6 show regression equations and crop curves, respectively, of ET rate vs. fraction of growing season. The patterns exhibited by evapotranspiration rate regressed against fraction of growing season (emergence to physiological maturity) showed peak water use occurring just after 50% of the growing season for corn, soybean, and pinto bean at Tribune. Pearl millet and grain sorghum ET rates peaked sooner in the life cycle. Soybean, pinto bean, sunflower, and pearl millet ET rates peaked at or just after 50% of their respective growth cycles at Manhattan. Corn and grain sorghum reach peak evapotranspiration rates earlier than 50% of their growth cycles.

Evapotranspiration rate in mm per day was indexed against potential evapotranspiration rate for the same time periods at each location to provide a ratio. Data from both locations were pooled and regressed against Julian date/100 and fraction of growing season. Regression curves and data points are shown in Fig. 7 and 8. Tables 13 and 14 list regression equations. Most of the curves peaked close to a ratio of one except grain sorghum and sunflower. No sunflower data were available from Tribune because of crop damage.

The R^2 values were strengthened when ET rates and ratios were regressed against fraction of growing season, rather than Julian date/100. This was because evapotranspiration rates do not have a cause and effect relationship with Julian date. Julian date can be used within a locale to measure crop parameters because the climate within a locale is similar from year to year in a given time period. Crop ET rates do, however, vary in accordance with crop growth. Potential ET rates vary

Table 11. Regression equations of evapotranspiration rate (Y) and fraction of growing season (X) at Manhattan.

Crop	Equation†	R^2	N	Range of X values	Model significance
Corn	$Y = -4.30 + 63.6X - 76.6X^2 + 19.6X^5$	0.86	9	0.10 - 0.98	0.01
Grain sorghum	$Y = 2.72 + 23.4X - 33.2X^2 + 11.0X^5$	0.87	8	0.00 - 0.97	0.03
Pearl millet	$Y = 3.34 + 76.6X^2 - 124X^3 + 47.4X^5$	0.95	9	0.01 - 1.00	0.001
Pinto bean	$Y = -1.34 + 34.9X - 33.7X^2$	0.93	9	0.10 - 0.98	0.001
Soybean	$Y = -1.78 + 33.97X - 31.6X^2$	0.83	9	0.12 - 0.95	0.003
Sunflower	$Y = -2.76 + 46.5X - 43.4X^2$	0.83	8	0.10 - 0.97	0.01

†All variables significant at the 0.10 level.

Table 12. Regression equations of evapotranspiration rate (Y) and fraction of growing season (X) at Tribune.

Crop	Equation[†]	R^2	N	Range of X values	Model significance
Corn	$Y = 1.44 + 282.4X^3 - 624.7X^4 + 344.2X^5$	0.92	10	0.02 - 0.96	0.001
Grain sorghum	$Y = -8.74 + 87.9X - 156.1X^2 + 80.1X^3$	0.98	8	0.14 - 0.96	0.001
Pearl millet	$Y = 21.6 - 364.7X + 2154.3X^2 - 5115.6X^3 + 5290.5X^4 - 1988.6X^5$	0.99	7	0.10 - 0.94	0.10
Pinto bean	$Y = 0.426 + 244.9X^3$	0.93	7	0.12 - 0.03	0.01
Soybean	$Y = -0.670 + 14.8X - 13.3X^3$	0.93	7	0.11 - 0.92	0.004

[†]All variables significant at the 0.10 level.

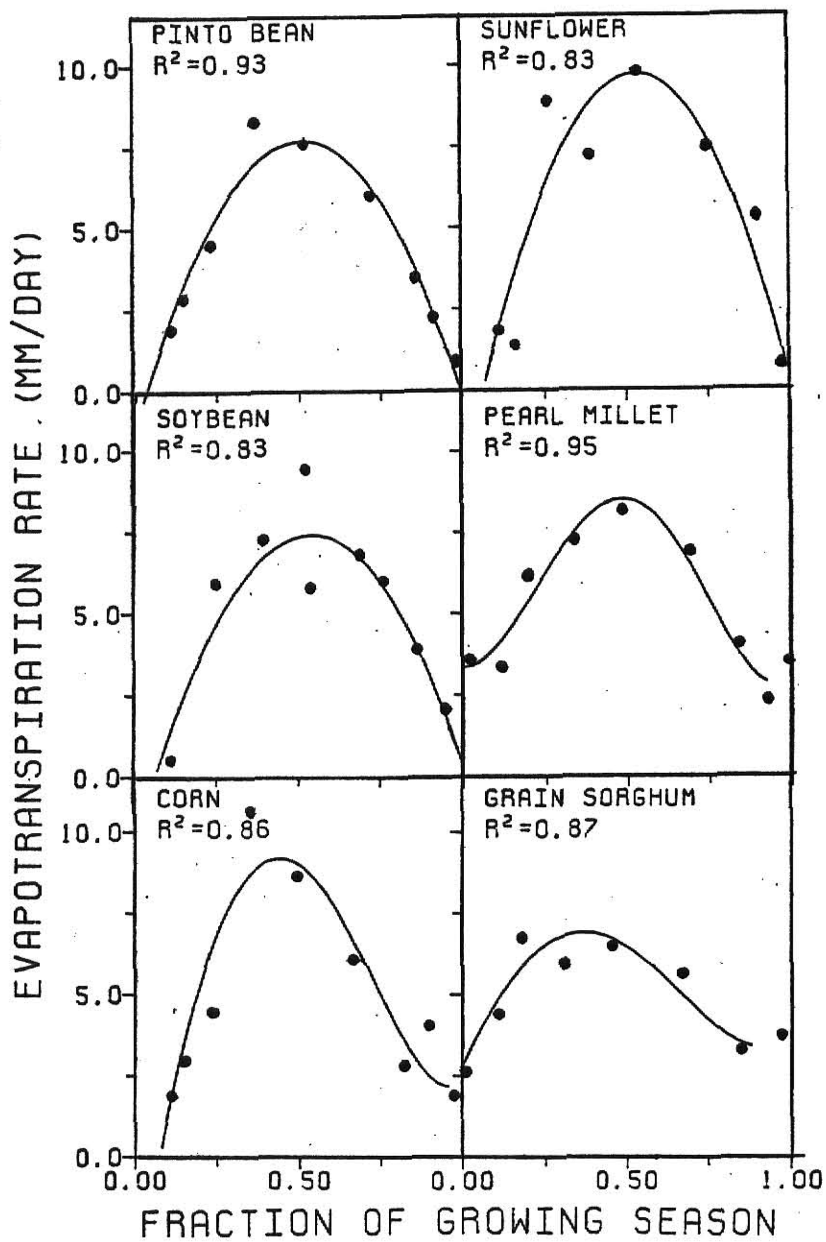

Fig. 5. Regression curves of evapotranspiration rate vs. fraction of growing season at Manhattan.

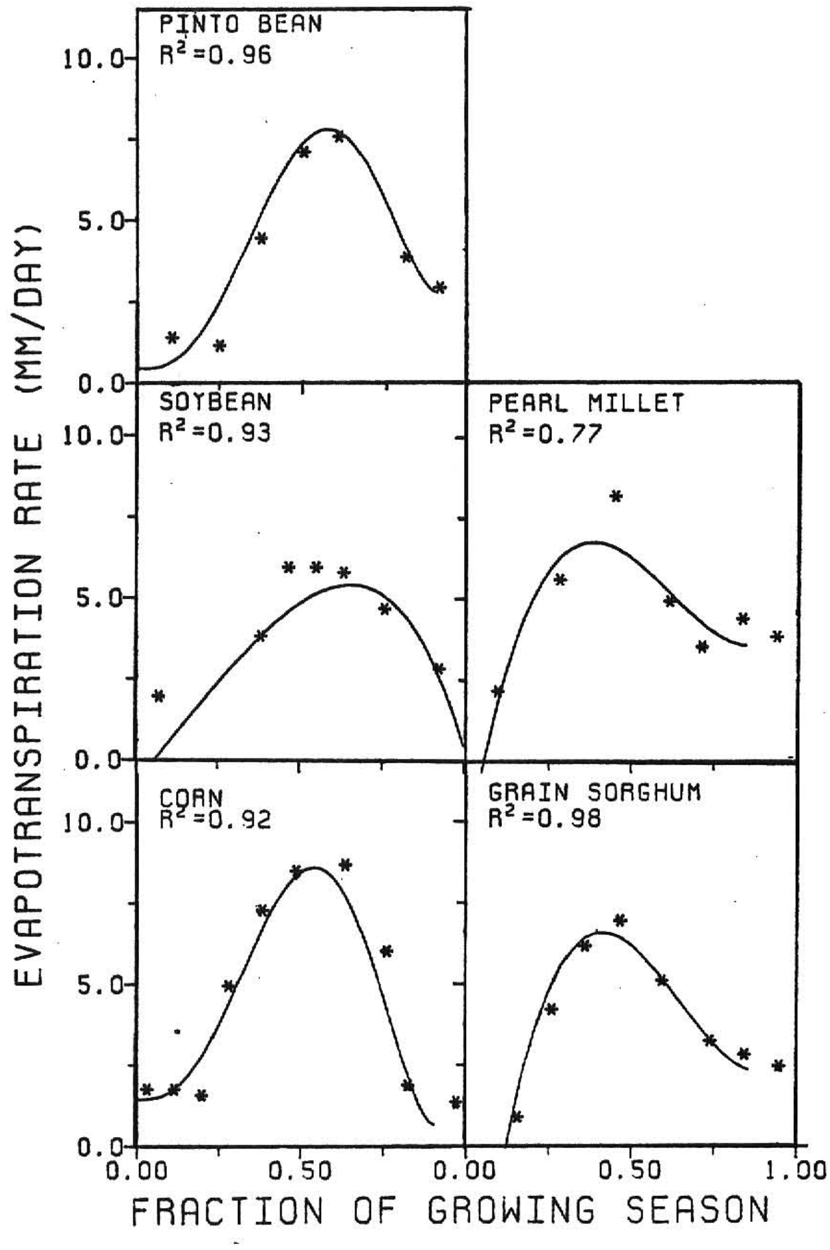

Fig. 6. Regression curves of evapotranspiration rate vs. fraction of growing season at Tribune.

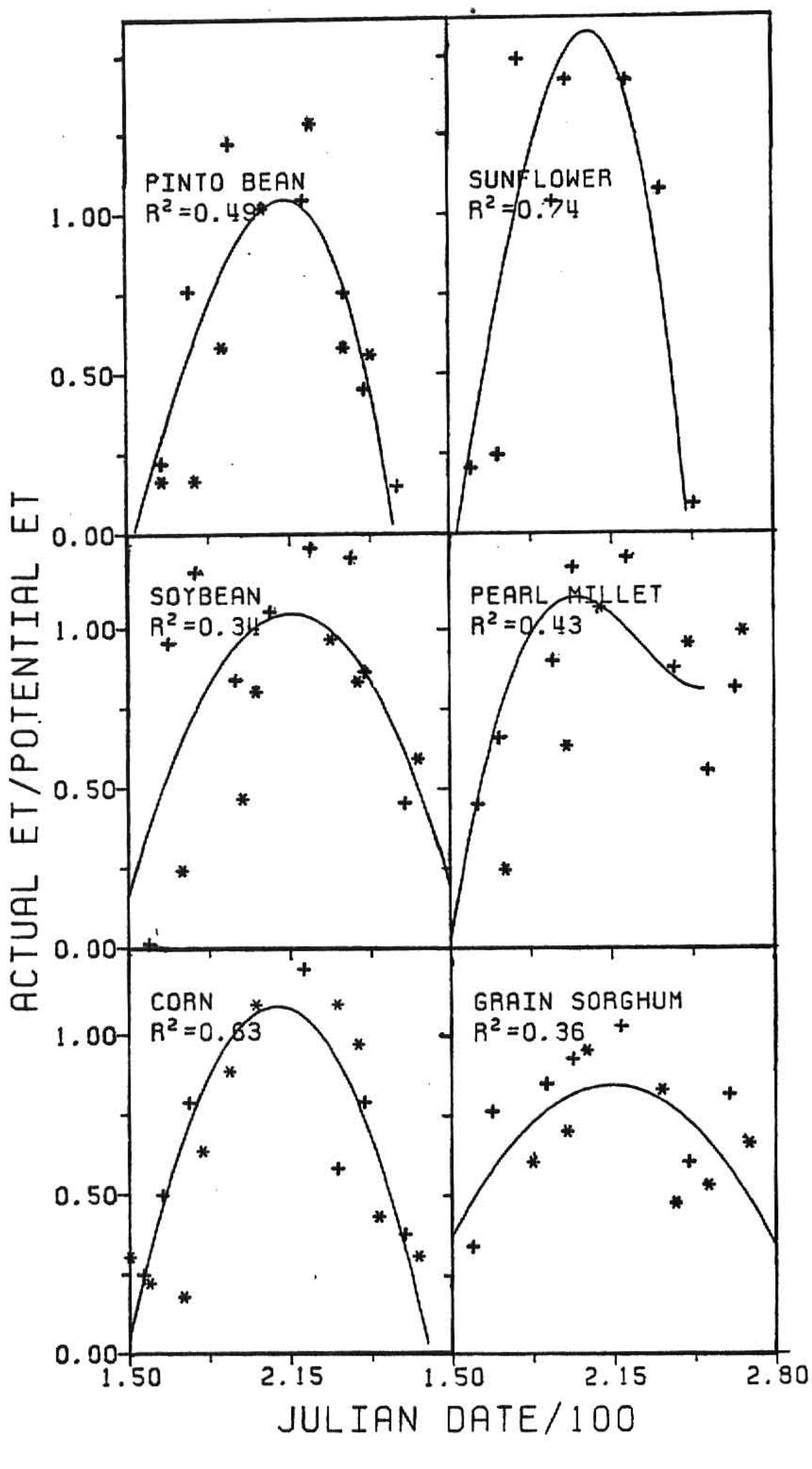

Fig. 7. Regression curves of actual evapotranspiration rate to potential evapotranspiration rate ratio vs. Julian date/100. Manhattan data points are '+'. Tribune data points are '*'.

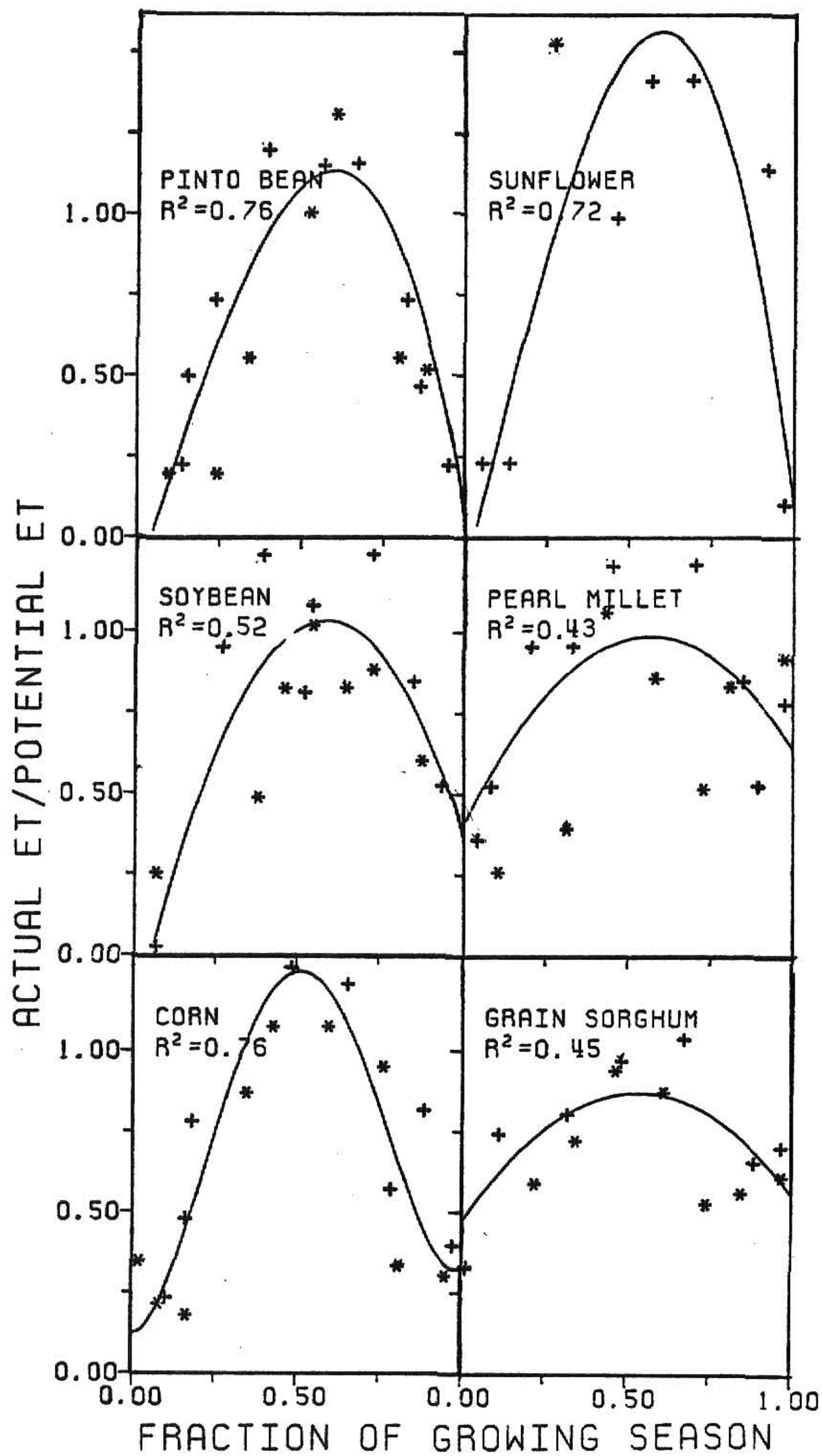

Fig. 8. Regression curves of actual evapotranspiration rate to potential evapotranspiration rate ratio vs. fraction of growing season. Manhattan data points are '+'. Tribune data points are '*'.

Table 13. Regression equations of the evapotranspiration rate/potential evapotranspiration rate ratio (Y) and Julian date/100(X) with pooled data.

Crop	Equation†	R^2	N	Range of X values	Model significance
Corn	$Y = -11.7 + 12.2X - 2.91X^2$	0.63	19	1.50 - 2.69	0.001
Grain sorghum	$Y = -4.46 + 4.96X - 1.16X^2$	0.36	14	1.58 - 2.69	0.09
Pearl millet	$Y = -11.3 + 15.4X^2 - 9.21X^3 + 1.53X^4$	0.45	16	1.58 - 2.69	0.06
Pinto bean	$Y = -2.18 + 1.32X^3 - 0.463$	0.49	16	1.58 - 2.49	0.01
Soybean	$Y = -8.58 + 8.95X - 2.08X^2$	0.34	16	1.72 - 2.69	0.06
Sunflower	$Y = -4.08 + 2.57X^3 - 0.934X^4$	0.74	8	1.58 - 2.42	0.03

† All variables significant at the 0.10 level.

Table 14. Regression equations of the evapotranspiration rate/potential evapotranspiration rate ratio (Y) and fraction of growing season (X) with pooled data.

Crop	Equation†	R^2	N	Range of X values	Model significance
Corn	$Y = 0.126 + 17.4X^2 - 34.5X^3 + 17.3X^4$	0.76	19	0.02 - 0.98	0.001
Grain sorghum	$Y = 0.440 + 1.52X - 1.40X^2$	0.45	13	0.00 - 0.97	0.09
Pearl millet	$Y = 0.350 + 2.31X - 2.04X^2$	0.43	14	0.01 - 1.00	0.05
Pinto bean	$Y - -0.137 + 3.18X - 2.96X^3$	0.76	16	0.10 - 0.98	0.001
Soybean	$Y = -0.237 + 4.26X - 3.60X^2$	0.52	16	0.11 - 0.95	0.004
Sunflower	$Y = -0.133 + 4.28X - 4.05X^3$	0.72	8	0.10 - 0.97	0.04

†All variables significant at the 0.10 level.

with climatic conditions.

It is possible to obtain an estimate of evapotranspiration by using curves developed from actual crop evapotranspiration data as related to potential evapotranspiration and estimates of potential evapotranspiration (Figs. 7 and 8). The potential evapotranspiration method used in this study was the Jensen and Haise (1963) equation utilizing solar radiation in equivalent millimeters of water and maximum and minimum temperatures in degrees Fahrenheit. Other equations of potential ET have been used successfully, such as Penman's combination approach, but the Jensen-Haise radiation equation was used because of the wide availability of the input data and its simplicity of use. Crop development in this study was measured as a fraction of the total length of the growing season, which has been expressed in growing degree units.

Stegman et al. (1977) stated a need to closely observe crop phenology and to shift the curves accordingly, since the curves they developed were based on days past emergence. Use of growing degree units as the crop related factor for estimating ET would eliminate the need to displace the crop curve to compensate for differences in crop development rates from year to year.

We used two locations with widely differing climates--Manhattan, a subhumid regions where precipitation averages 87 cm annually, and Tribune, a semiarid climate with annual precipitation of 41 cm and an altitude 783 m higher than that of Manhattan. Despite such striking climatic differences the accumulation of growing degree units from emergence to physiological maturity was very similar at both locations. Table 15 lists days to maturity and growing degree units to maturity for all crops at Tribune and Manhattan. Agreement of corn growing degree units was especially good--a total of 1500 at

Table 15. Days from crop emergence to physiological maturity, accumulation of growing degree units, and average daily growing degree units for crops at Tribune and Manhattan.

Crop	Days to maturity	Growing degree units to maturity	Average daily growing degree units
Corn			
Tribune	129	1500	11.6
Manhattan	107	1490	13.9
Grain sorghum			
Tribune	120	1417	11.8
Manhattan	96	1355	14.1
Pearl millet			
Tribune	115	1371	11.9
Manhattan	92	1311	14.3
Pinto bean			
Tribune	93	1176	12.6
Manhattan	100	1405	14.1
Soybean†			
Tribune	114	2.54	0.02
Manhattan	109	2.08	0.019
Sunflower			
Manhattan	94	1595	17.0

† See Majors et al. (1975b) for explanation of soybean developmental units.

Tribune and 1490 at Manhattan. Pinto bean, however, showed a strong disparity in accumulated growing degrees. It is possible that apparent maturity of pinto bean was hastened by severe damage caused by the 3 September hail storm. Noting the trend of more days necessary for crop maturation at Tribune, it is clear that only pinto bean violated the trend. Apparent days to maturity for pinto bean were 93 days at Tribune, but at 12.6 average daily growing degrees, pinto bean at Tribune should have reached maturity in 111.5 days, if maturity is taken to be an accumulation of 1,405 growing degrees, the accumulation calculated for Manhattan pinto bean.

Exact dates of physiological maturity were lacking because daily observation of crops at Tribune was not possible. But except pinto bean, the error was at the most 6 days and probably 5 days or less. All crops, except pinto bean, were physiologically mature on 3 October, and reached that state between 22 September and 3 October. Observed crop growth stages as related to fraction of growing season with accumulated growing degrees as the based measurement at both locations are in the Appendix, Tables 9A and 10A.

Neild and Seeley (1977) list growing degrees accumulated for each crop growth stage and the accumulated totals for varieties of three maturity groups of each corn and grain sorghum. Table 16 shows a comparison of Neild and Seeley's crop growth stage/fraction of growing season results and the results from my study. My observations are not as detailed as those of Neild and Seeley, but agreement is good for corn and grain sorghum.

The crop varieties grown in this study were medium maturity varieties, except sunflower, which was an early maturing variety. Accumulation of

Table 16. Comparison of corn and grain sorghum fractions of growing season at Tribune and Manhattan and values from Neild and Seeley (1977).

Observed developmental stage	Fraction of growing season		
	Neild and Seeley	Tribune	Manhattan
	Corn		
Emergence	----	0.007	0.007
Two leaves emerged	0.08	0.04	----
Six leaves emerged	0.18	0.15	----
Eight leaves emerged	0.22	----	----
Silk emergence and anthesis	0.51	0.52	0.49
Blister stage	0.61	0.66	0.60
Dough stage	0.71	0.69	0.68
Beginning dent	0.81	----	0.78
Full dent	0.90	0.87	----
Physiological maturity	1.00	1.00	1.00
	Grain sorghum		
Emergence	----	0.007	0.01
Growing point differentiation	0.34	0.30	----
Boot stage	0.56	0.43	0.45
Half bloom	0.67	0.49	0.53
Soft dough stage	0.78	0.67	0.74
Hard dough stage	0.89	----	0.77
Physiological maturity	1.00	1.00	1.00

growing degrees will be significantly greater or less than our total growing degrees with late or early maturing varieties. In order to avoid this difficulty, average accumulated growing degrees for crops in the various maturity groups could be calculated from climate data and variety test information. This would provide a reasonable estimate for crop curve users to base their fraction of growing season calculations on.

Crop coefficient curves will not accurately estimate crop evapotranspiration from potential evapotranspiration if the soil surface is wet, especially under limited crop canopy cover. Jensen et al. (1971) described how to estimate evapotranspiration under those conditions. Under full canopy cover, the inaccuracy of ET estimation is less severe.

Another limitation to using the crop coefficient curves is that the Jensen and Haise (1963) potential ET equation assumes well-watered conditions and an adequate fetch around the area in question. If crops are stressed, the relationships developed will possibly not hold.

SUMMARY AND CONCLUSIONS

This study was undertaken in response to the growing need for information about comparative crop water use in an area where continuous row crop production is possible only with irrigation from a limited subterranean water source.

Specific goals of this project were to compare water use of six crops, examine evapotranspiration patterns among the crops, examine soil water depletion patterns among the crops, and to develop an empirical method of estimating of crop evapotranspiration rates based on potential evapotranspiration (Jensen and Haise, 1963) and growing degree units.

Volumetric soil water content was determined periodically during the growing season. Crop ranking for total seasonal water use varied somewhat between locations, although there were no significant differences in total water use at either location among corn, pearl millet, and grain sorghum. The most notable variation in ranking of crop water use occurred with soybean, indicating a climate-specific response of soybean to the differences in location.

Definite patterns in crop evapotranspiration existed at Tribune and Manhattan. Julian dates of peak water use were well separated at Tribune, but tended to peak in a four day time span at Manhattan, with the exception of pearl millet and grain sorghum. This knowledge can be useful in scheduling irrigations at either location.

Patterns of soil water depletion at Tribune indicated that the highest depletion rates were in the 100-404 mm layer of soil with progressively declining rates deeper in the soil profile. Corn depleted the soil most strongly of the crops in the 100-404 and 404-708 mm layers. Soil water depletion data from Manhattan were inconclusive.

Results were masked by the high in-season rainfall received in 1981.

An empirical method of determining crop evapotranspiration was developed by calculating the ratio of actual average ET rate/average potential ET rate and regressing the ratio against fraction of growing season. The length of growing season was determined by a summation of growing degree units from crop emergence to physiological maturity. Data from both locations were pooled in the analysis and a random mixing of data points was obtained. Ratios rose to approximately one when crop water use was highest and declined as maturity approached.

LITERATURE CITED

1. Anon. 1982. Sunflower water needs researched three years. Ag Consultant and Fieldman 38(4); 44pp.

2. Alessi, J., J.F. Power, and D. C. Zimmerman. 1977. Sunflower yield and water use as influenced by planting date, population and row spacing. Agron. J. 69:465-469.

3. Andrew, R.H., F.P. Ferwerda, and A.M. Strommen. 1956. Maturation and yield of corn as influenced by climate and production technique. Agron. J. 48:231-236.

4. Arnold, C.Y. 1959. The determination and significance of the base temperature in a linear heat unit system. J. Am. Soc. Hort. Sci. 74:430-445.

5. Aspiazu, C., and R.H. Shaw. 1972. Comparison of several methods of growing degree-unit calculations for corn (Zea mays L.). Iowa State J. of Sci. 46:435-442.

6. Bauder, J.W., and M.J. Ennen. 1981. WAter use of field crops in Eastern North Dakota. North Dakota Farm Research 38(5):3-5.

7. Blaney, H.F., and W.D. Criddle. 1950. Determining water requirements in irrigated areas from climatological and irrigation data. U.S.D.A. Soil Conserv. Serv. SCS-TP 96. 44 pp.

8. Blaney, H.F., and W.D. Criddle. 1962. Determining consumptive use and irrigation water requirements. U.S.D.A. Tech. Bull. 1275, 59 pp.

9. Blaney, H.F., and Morin, K.V. 1942. Evaporation and consumptive use of water empirical formulas. Am. Geophys. Union Trans., Aug.; pg. 76-83.

10. Briggs, L.J., and N.L. Shantz. 1914. Relative water requirements Dept. of Agric. and Food, Canada, unnumbered information leaflet.

12. Cannell, G.H., and L.W. Asbell. 1974. The effects of soil-profile variations and related factors in neutron moderation measurements. Soil Sci. 117:124-127.

13. Chang, J.R.B. Campbell, and F.E. Robinson. 1963. On the relationship between water and sugar cane yield in Hawaii. Agron. J. 55:450-453.

14. Crane, P.L., P.R. Goldsworthy, R.L. Cuany, M.S. Zuber, and C.A. Francis. 1976. Climatological factors in maize adaptation. Agrometeorology of the Maize (corn) Crop. World Meteorological Organization. No. 481:49-66.

15. Cross, H.Z., and M.S. Zuber, 1972. Prediction of flowering dates of maize based on different methods of estimating thermal units. Agron. J. 641:351-355.

16. Denmead, O.T., and R.H. Shaw. 1959. Evapotranspiration in relation to the development of the corn crop. Agron. J. 51:725-726.

17. Denmead, O.T., and R.H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron J. 52:272-274.

18. Dillman, A.C. 1931. Water requirements of certain crops and weeds in the northern Great Plains. J. Agr. Res. 42:187-238.

19. Doss, B.D., O.L. Bennett, and D.A. Ashley. 1962. Evapotranspiration by irrigated corn. Agron. J. 54:497-498.

20. Dusek, D.A., J.T. Musick, and K.B. Porter. 1971. Irrigation of soybeans in the Texas High Plains. Tex. Agr. Exp. Sta. Misc. Pub. 973.

21. Dylla , H.S., D.R. Timmons, and H. Shull. 1980. Estimating water used by irrigated corn in west central Minnesota. Soil Sci. Soc. Am. J. 44:823-827.

22. Eavis, B.W., and H.M. Taylor. 1979. Transpiration of soybeans as related to leaf area, root length, and soil water content. Agron. J. 71:441-445.

23. Fehr, W.R., C.E. Caviness, D.T. Burmwood, and J.S. Pennington. 1971. Stage of development descriptions for soybeans, Glycine max (L.) Merrill. Crop Sci. 11:929-931.

24. Fryer, H.C., A.W. Pauli, and F.C. Stickler. 1966. Temperature influence of anthesis date in grain sorghum, Sorghum vulgare Pers. AGron. J. 58:9-12.

25. Gilmore, E.C., and J.S. Rogers. 1958. Heat units as a method of measuring m aturity in corn. Agron. J. 50:611-615.

26. Governor's Task Force. 1977. Interim Report of the Governor's Task Force on Water Resources. The State of Kansas.

27. Greig, J.K., Roy Gwin, Jr., and Charles Marr. 1974. Dry beans. Cooperative Extension SErvice, Kansas State University. MF-348.

28. Hanway J.J. 1971. How a corn plant develops. Iowa State Univ. of Sci. and Technol. Spec. Rep. No. 48.

29. Hanway, J.J., and H.E. Thompson. 1971. How a soybean plant develops. Iowa State Univ. of Sci. and Technol. Spec. Rep. No. 53 (Rev.).

30. Hay, Delynn. 1980. Irrigate properly. p. 13-15. In Grain Sorghum Handbook. Cooperative Extension Service. Kansas State University. C-494.

31. Holt, R.F., and C.A. Van Doren. 1961. Water utilization by field corn in western Minnesota. Agron. J. 53:43-45.

32. Howe, O.W., and H.F. Rhoades. 1961. Irrigation of Great Northern Field beans in western Nebraska. Univ. Nebraska Agr. Exp. Sta. Bull. 459. 28 pp.

33. International Crops Research Institute for the Semi-Arid Tropics. 1976. ICRISAT Annual Report 1975-1976.

34. Jensen, M.E. (ed.) 1973. Consumptive use of water and irrigation water requirements. Am. Soc. of Civ. Eng., New York.

35. Jensen, M.E., and H.R. Haise. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. and Drain. Div., Am. Soc. Div. Engr. 89:15-41.

36. Jensen, M.E. and D.C.N. Robb, and C.E. Franzoy. 1970. Scheduling irrigations using climatic-crop-soil data. Am. Soc. Civ. Eng. J. Irrig. and Drain. 96:25-38.

37. Jensen, M.E., J.L. Wright, and B.J. Pratt. 1971. Estimating soil moisture depletion from climate, crop and soil data. Trans. ASAE 14(5):954-959.

38. Katz, Y.H. 1952. The relationship between heat unit accumulation and the planting and harvesting of canning peas. Agron. J. 44:74-78.

39. Livingston, B.E. 1916. Physiological temperature indices for the study of plant growth in relation to climatic conditions. Physiol. Res. 1:399-420.

40. Major, D.J., D.R. Johnson, and V.D. Luedders. 1975a. Evaluation of eleven thermal units for predicting soybean development. Crop Sci. 15:172-174.

41. Major, D.J., D.R. Johnson, J.W. Tanner, and I.C. Anderson. 1975b. Effects of daylengths and temperature on soybean development. Crop. Sci. 15:174-179.

42. McGowan, M., and J.B. Williams. 1980. The water balance of an agricultural catchment. I. Estimation of evaporation from soil water records. J. of Soil Sci. 31:217-230.

43. Mederski, H.J., M.E. Miller, and C.R. Weaver. 1973. Accumulated heat units for classifying corn hybrid maturity. Agron. J. 65:743-747.

44. Musick, J.T., and D.A. Dusek. 1976. Soil water depletion relations of irrigated grain sorghum, wheat, soybeans. Trans ASAE. 19:489-493.

45. Neild, R.E., and M.W. Seeley. 1977. Growing degree day predictions for corn and sorghum development and some applications to crop production in Nebraska. Neb. Agric. Exp. Sta. Res. Bull. 280.

46. Nuttonson, M.Y. 1955. Wheat climate relationships and the use of phenology in ascertaining the thermal and photothermal requirements of wheat. Am. Inst. Crop Ecol., Washington, D.C. 388 pp.

47. Nuttonson, M.Y. 1956. A comparative study of lower and upper limits of temperature in measuring the variability of day-degree summations of wheat, barley, and rye. Am. Inst. Crop. Ecol., Washington, D.C. 42 pp.

48. Parmele, L.H., and J.L. McGuinness. 1974. Comparison of measured and estimated daily potential evapotranspiration in a humid region. J. Hydrol. 22:239-251.

49. Pauli, A.W., F.C. Stickler, and J.R. Lawless. 1964. Developmental phases of grain sorghum (Sorghum vulgare, Pres.) as influenced by variety, location, and planting date. Crop Sci. 4:10-13.

50. Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. Lond. A193:120-146.

51. Peters, Doybe B., and Leonard C. Johnson. 1960. Soil moisture use by soybeans. Agron. J. 52:687-689.

52. Porter, K.B., M.E. Jensen, and W.H. Sletten. 1960. The effect of row spacing, fertilizer and planting rate on the yield and water use of irrigated grain sorghum. Agron J. 52:431-434.

53. Pruitt, W.O., and M.C. Jensen. 1955. Determining when to irrigate. Agr. Engr. 36:389-393.

54. Robertson, G.W. 1968. A Biometeorological time scale for a cereal crop involving day and night temperatures and photoperiod. Int. J. Biometeorol. 12:191-223.

55. Robinson, R.G. 1971. Sunflower phenology, year, variety, and date of planting effects on day and growing degree-day summations. Crop Sci. 11:635-638.

56. Robinson, R.G. 1971. New crops for irrigated sand soils. Minnesota Sci. 27(3):10-11.

57. Robinson, R.G., and L.A. Bernat, H.A. Geise, F.K. Johnson, M.L. Kinman, E.L.Mader, R.M.Oswalt, E.D. Putt, C.M. Swallers, and J.H. Williams, 1967. Sunflower development at latitudes ranging from 31 to 49 degrees. Crop Sci. 7:134-136.

58. Schneiter, A.A., and J.F. Miller. 1981. Description of sunflower growth stages. Crop Sci. 21:901-903.

59. Shantz, H.L., and L.N. Piemiesel. 1927. The water requirements of plants at Akron, Colo. J. Agr. Res. 34:1093-1190.

60. Shaw, R.H. 1975. Growing degree units for corn in the north central region. Iowa Agric. and Home Econ. Exp. Sta. Res. Bull. 581. 13 pp.

61. Singh, Piara, and E.T. Kanemasu. 1980. Soil water plant water and temperature relations of millet and their relationship to crop yield. Third Annual report, Oct. 197-Sept. 1980. Improvement of Pearl Millet. p. 75-93.

62. Smith R.C.B., and W.K. Anderson, and Hazel C. Harris. 1978. A systems approach to the adaptation of sunflower to new environments. III. Yield predictions for continental Australia. Field Crops Research 1:215-228.

63. Stanhill, G. 1961. A comparison of methods of calculating potential evapotranspiration from climatic data. Israel J. Agr. Res. 11:159-171.

64. Stanhill, G. 1962. The control of field irrigation practice from measurements of evaporation. Israel J. Agr. Res. 12:51-62.

65. Stanley, C.D., and R.H. Shaw. 1978. The relationship of evapotranspiration to open-pan evaporation throughout the growth cycle of soybeans. Iowa State J. Res. 53(2):129-136

66. Stegman, E.C. 1980. On-farm irrigation scheduling evaluations in southeastern North Dakota. Agr. Exp. Sta. North Dakota Res. Rep. No. 76.

67. Stegman, E.C., A. Bauer, J.C. Zubriski, and J. Bauder. 1977. Crop Curves for water balance irrigation scheduling in S.E. North Dakota. Agr. Exp. Sta. North Dakota Res. Rep. No. 66.

68. Stegman, E.C., and N.M. Olson. 1976. Water management relationships for irrigated pinto beans. North Dakota Agr. Exp. Sta. Res. Rep. No. 61.

69. Stegman, E.C., and J.D. Valer. 1972. Irrigation scheduling by computational methods: Crop data and evaluations in North Dakota. Agr. Exp. Sta. Res. Rep. No. 41.

70. Stone, L.R., M.L. Horton, and T.C. Olson. 1973. Water loss from an irrigated sorghum field: II. Evapotranspiration and root extraction. Agron. J. 65:495-497.

71. Talha, M. and F. Osman. 1975. Effect of soil water stress on water economy and oil composition in sunflower. J. Agric. Sci. 84:49-36.

72. Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. Geogrph. Rev. 38:55.

73. Timmons, P.R., R.F. Nolt, and R.L. Thompson. 1967. Effect of plant population and row spacing on evapotranspiration and water use efficiency by soybeans. Agron. J. 59:262-265.

74. Treidl, R.A. 1976. Zonation for maize (corn) growing in Canada. Agrometeorology of the Maize (corn) Crop World Meteorological Organization. No. 481:27-39.

75. Vanderlip, R.L. 1972. How a sorghum plant develops. Kansas State Univ. Bull. C-447.

76. Wang, J.Y. 1960. A critique of the heat unit approach to plant response studies. Ecology 41:785-790.

APPENDIX

Calculations

Regression equations were used to transform the count ratio (CR) of one probe to that of another so that volumetric water content could be determined.

Equations

Stone' probe (SCR) to Jean's probe (JCR): (3220 series probes)

$JCR = 0.001 + 0.979\ (SCR)$. $PR > F = 0.0001$. $R^2 = 0.96$.

Enter Stone's count ratio as SCR. Value yielded is the equivalent count ratio of Jean's probe (JCR).

To use JCR to find the count ratio of probe 399 (399CR): (2601 series probe)

$399CR = 0.0978 + 1.381\ (JCR)$

To go directly from SCR to 399CR:

$399CR = 0.0992 + 1.352\ (SCR)$

Calibration equation of probe 399:

$\theta = 0.457152\ (399CR) - 0.034818$

θ is water content by volume (cm^3/cm^3).

Leaf Area Index (LAI)

The raw data were in square centimeters (cm^2). Instrument calibrations were averaged for each data set. Leaf area was calculated by this method:

$$\frac{\text{measured L.A. } (cm^2)}{\text{actual L.A. } (cm^2)} = \frac{\text{measured calibration area } (cm^2)}{\text{reference calibration area} = 100\ cm^2}$$

where actual leaf area was the unknown value.

$$LAI = \frac{\text{actual L.A. } (cm^2)}{7620\ cm^2 \text{ (ground sample area)}}$$

which yields leaf area index (LAI). If 2 or 3 m samples were taken, 7620 cm^2 was multipled by either 2 or 3, respectively, to obtain LAI.

Dry weight

At 0.762 m row spacing and 10,000 m^2/ha, there are 13,123 m of row/ha.

Kilograms of dry matter per hectare were calculated as follows:

(kg dry matter/m) * (13,123m of row/ha) = kg/ha, and metric tons of dry matter per hectare:

Kilograms/ha ÷ 1,000 = metric tons/ha.

Evapotranspiration rate (ET)

Volumetric water content using the neutron probe was calculated as follows:

$\theta = 0.457152\ (399CR) - 0.034818.$

The top layer measured by the neutron probe was multiplied by 192 mm. The volumetric water content by gravimetric was multiplied by 60 mm. All remaining layers measured by neutron probe were multiplied by 152 mm. The water content in equivalent mm depth was totaled.

The ET rate was calculated as follows:

$$\text{ET rate} = \frac{\text{rain + irrigation + (SW1 - SW2)}}{\text{No. of days in SW1 to SW2 time period}}$$

where SW1 and SW2 are total water in the profile in mm equivalents on the sampling dates. The date of SW1 precedes that of SW2.

Soil Water Depletion Rates (SWDR)

	Tribune	Manhattan
Selected time periods:	16-26 June	5-10 June
	6-15 July	12-24 July
	3-11 Aug.	18-26 Aug.
	20-28 Aug.	26 Aug.-4 Sept.

For these calculations, only neutron probe data were used. All neutron probe volumetric water content values were multiplied by 152 mm, then each of values added, 1 + 2, 3 + 4, etc., to yield total water in 30.4 cm layers.

SWDR (mm/day) = $(SW1_1 - SW2_1)$/No. days in the period.

Subscript 1 is the layer number (1 through 10), and SW1 and SW2 are dates of soil water content measurement. The date of SW1 precedes that of SW2.

Potential Evapotranspiration (ET_p)

The Jensen and Haise (1963) technique was used, with inputs of Tmax, Tmin, and solar radiation. Tmax and Tmin are maximum and minimum daily temperatures, respectively, and solar radiation is measured in equivalent water in millimeters. To calculate equivalent water from solar radiation (RS) in langleys/day:

RS = solar radiation (ly/day) * (1/580) * 1/.99568 * 10

ET_p = (0.014 * Tave - 0.37) *RS

where $Tave = \frac{Tmax + Tmin}{2}$ in °F on a daily basis.

To obtain average ET_p values for a particular period:

The ET_p values for that period were summed and divided by the number of days in that period.

Ratios of average ET rate to average ET_p rate were calculated by dividing observed average ET by average ET_p rate for the same period.

Growing Degree Units (GDU)

Corn, grain sorghum, pearl millet, and pinto bean:

If Tmax > 86°F, then Tmax = 86°F

If Tmin < 50° F, then Tmin = 50°F

Convert to °C:

CTmax = (Tmax - 32) * 0.5556 CTmin = (Tmin - 32) * 0.5556

GDU = (CTmax + Ctmin)/2 - 10°C

Sunflower:

If Tmax > 86°F, then Tmax = 86°F

If Tmin < 45°F, then Tmin = 45°F.

Convert to °C:

GDU = (CTmax + CTmin)/2 - 7.2°C.

Soybean:

See Major et al. (1975b) for references and listing of the equation and crop coefficients in relation to stage of development.

Table 1A. Average evapotranspiration rates in each evapotranspiration period at Manhattan and Tribune.

Crop	Average evapotranspiration rate										
	5-9 June	10-17 June	18-30 June	1-11 July	12-23 July	24-July-17 Aug.	18-25 Aug.	26 Aug.-3 Sept.	4-7 Sept.	4-14 Sept.	4-17 Sept.
					Manhattan						
					mm/day						
Corn	1.93	2.92	4.51	10.64	8.67	6.51	2.88	4.11	---	---	1.83
Grain sorghum	2.60	4.38	6.85	6.06	6.50	5.75	---	3.20†	---	3.76	---
Pearl millet	3.53	3.21	6.10	7.15	8.19	6.81	4.04	2.37	---	3.52	---
Pinto bean	1.87	2.88	4.44	8.39	7.50	5.92	3.63	2.30	0.83	---	---
Soybean	0.60	5.96	7.33	5.88	7.58	6.85	5.96	3.81	---	---	2.21
Sunflower	1.93	1.42	8.77	7.24	9.75	7.55	5.54	0.70	---	---	---
	27 May-2 June	3-15 June	16-25 June	26 June-5 July	6-14 July	15 July-2 Aug.	3-10 Aug.	11-19 Aug.††	20-27 Aug.	28 Aug.-11 Sept.	12 Sept.-9 Oct.
					Tribune						
					mm/day						
Corn	1.67	1.67	1.43	4.93	7.15	8.26	6.69	---	6.08	1.91	1.29
Grain sorghum	---	---	0.83	4.23	6.00	6.88	4.90	---	3.17	2.96	2.56
Pearl millet	---	---	2.03	0.13	5.52	8.09	4.90	---	3.46	4.64	3.76
Pinto bean	---	---	1.40	1.23	4.67	7.14	7.44	---	3.75	2.84	---
Soybean	---	---	1.90	-1.23	3.93	5.91	5.73	---	5.13	4.47	2.30

† Grain sorghum evapotranspiration rate was averaged over 18 Aug. to 3 Sept. because of data loss from 26 Aug. readings.

††No data used from this period because of difficulties with determining the irrigation amount applied on 12 Aug.

Table 2A. Average potential evapotranspiration rates in each time period as calculated by the Jensen and Haise (1963) technique at Tribune and Manhattan for all crops.

Average potential evapotranspiration rate										
27 May - 2 June	3-15 June	16-25 June	26 June- 5 July	6-14 July	15 July- 2 Aug.	3-10 Aug.	11-19 Aug.	20-27 Aug.	28 Aug.- 11 Sept.	12 Sept. 9 Oct.
					Tribune					
					mm/day					
5.55	7.60	8.13	7.45	8.35	7.20	5.80	4.43	6.37	5.41	4.03
5-9 June	10-17 June	18-30 June	1-11 July	12-23 July	24 July- 17 Aug.	18-25 Aug.	26 Aug.- 3 Sept.	4-7 Sept.	4-14 Sept.	4-17 Sept.
					Manhattan					
					mm/day					
8.21	5.78	5.88	7.29	6.88	5.44	4.83†	4.89	4.06	4.73	4.43

†Grain sorghum potential evapotranspiration rate was averaged over the period 18 Aug. - 3 Sept. because of data loss on 26 Aug. Value calculted was 4.86 mm/day.

Table 3A. Ratios of observed evapotranspiration rate to potential evapotranspiration rate by the Jensen-Haise (1963) technique and fractions of growing season at Tribune and Manhattan.

Ratio of observed ET rate to potential ET rate and fraction of growing season											
Corn		Grain sorghum		Pearl millet		Pinto bean		Soybean		Sunflower	
Ratio	Fraction	Ratio	Fraction	Ratio	Fraction	Ratio	Fraction	Ratio	Fraction	Ratio	Fraction
0.30	0.02†	0.32	0.00	0.43	0.01	0.23	0.10	0.23	0.11†	0.24	0.10
0.22	0.10†	0.76	0.10	0.25	0.10†	0.17	0.12†	0.07	0.12	0.25	0.15
0.24	0.10	0.10	0.14d†	0.56	0.10	0.50	0.15	1.00	0.24	1.50	0.25
0.51	0.14	1.20	0.17d	1.00	0.19	0.17	0.23†	0.47	0.38†	0.99	0.38
0.18	0.19†	0.17	0.24†	0.66	0.29†	0.76	0.24	1.25	0.38	1.40	0.53
0.77	0.23	0.83	0.30	0.98	0.32	0.56	0.34†	0.78	0.46†	1.40	0.73
0.66	0.28†	0.72	0.32†	1.10	0.43†	1.20	0.36	0.81	0.52	1.40	0.89
1.50	0.35	1.20	0.45†	1.20	0.48	0.99	0.50†	1.10	0.52	1.10	0.89
0.86	0.36†	0.96	0.45	0.84	0.57†	1.10	0.51	0.99	0.54†	0.14	0.97
1.15	0.48†	0.84	0.60†	1.25	0.68	1.30	0.67†	0.81	0.67†	----	----
1.30	0.49	1.10	0.65	0.54	0.71†	1.10	0.70	1.30	0.67	----	----
1.15	0.62†	0.50	0.72†	0.86	0.80†	0.59	0.82†	0.83	0.75†	----	----
1.20	0.66	0.55	0.81†	0.84	0.84†	0.75	0.85	1.20	0.76	----	----
0.95	0.74†	0.64	0.96†	0.48	0.92	0.47	0.92	0.78	0.86	----	----
0.60	0.81	0.79	0.97	0.93	0.95†	0.86	0.93†	0.57	0.92†	----	----
0.35	0.82†	----	----	0.74	1.00	0.20	0.98	0.50	0.95	----	----
0.84	0.88	----	----	----	----	----	----	----	----	----	----
0.32	0.96†	----	----	----	----	----	----	----	----	----	----
0.41	0.98	----	----	----	----	----	----	----	----	----	----

†Pairs followed by the symbol are Tribune data points. All others are Manhattan data points.

dPairs followed by "d" have been deleted from analysis.

Table 4A. Hydraulic potentials at the 180 and 210cm depths at Tribune, referenced from the soil surface.

	Soil water hydraulic potential					
	Plot 2		Plot 5		Plot 10	
	Depth		Depth		Depth	
Julian date	180cm	210cm	180cm	210cm	180cm	210cm
	Corn					
	cm of water					
174	-624	-565	-624	-585	-616	-641
180	-725	-715	-718	-710	-672	-647
189	-695	-722	-697	-736	-587	-702
190	-728	-755	-731	-758	-591	-706
194	-715	-748	-737	-743	-617	-690
197	-718	-750	-745	-749	-628	-694
198	-725	-738	-732	-728	-629	-669
201	-740	-753	-760	-759	-665	-700
203	-751	-755	-755	-754	-687	-689
209	-739	-752	-762	-750	-714	-728
212	-733	-747	-753	-750	-707	-748
215	-721	-645	-752	-749	-710	-709
216	-718	-653	-748	-747	-705	-699
218	-727	-574	-754	-754	-717	-709
222	-735	-628	-756	-760	-726	-713
229	-761	-750	-763	-763	-759	-739
231	-765	-746	-764	-764	-755	-730
233	-767	-751	-771	-766	-747	-742
241	-638	-615	--71	-762	-717	-744
246	-778	-688	-771	-763	-743	-754
250	-775	---	-783	-776	-768	-763
256	---	---	-799	-774	---	-764
265	---	---	-773	-774	---	-780

Table 4A . Cont.

Julian date	Plot 7 Depth 180cm	Plot 7 Depth 210cm	Plot 15 Depth 180cm	Plot 15 Depth 210cm	Plot 18 Depth 180cm	Plot 18 Depth 210cm
	Soil water hydraulic potential					
	Grain sorghum					
	cm of water					
174	-654	-664	-614	-626	-575	-632
180	---	---	-708	-728	-718	-725
189	-594	-667	-591	-644	-693	-729
190	-618	-707	-614	-663	-734	-757
194	-635	-674	-619	-664	-746	-752
197	-643	-669	-612	-671	-733	-755
198	-633	-681	-599	661	-723	-746
201	-658	-690	-605	-681	-747	-756
203	-677	-694	-623	-694	-745	-755
209	-679	-707	-634	-705	-760	-768
212	-672	-698	-641	-703	-756	-763
215	-688	-703	-653	-705	-757	-763
216	-686	-700	-651	-700	-756	-763
218	-694	-708	-666	-644	-763	-768
222	-705	-716	-679	-647	-770	-768
229	-711	-719	-691	-711	-740	-770
231	-634	-691	-677	-707	-742	-763
233	-645	-693	-680	-704	-716	-763
241	-713	-686	-664	-690	-757	-768
746	-691	-698	-699	-776	-756	-764
250	-761	-636	-693	-752	-771	-782
256	-719	-708	---	-757	-763	-775
265	-729	---	-765	-765	-747	-769

Table 4A . Cont.

Julian date	Soil water hydraulic potential					
	Plot 4		Plot 9		Plot 17	
	Depth		Depth		Depth	
	180cm	210cm	180cm	210cm	180cm	310cm
	Pearl millet					
	cm of water					
174	-557	-621	-506	-657	-584	-621
180	-606	-676	-694	-718	---	-734
189	-628	-699	-699	-745	-597	-738
190	-656	-710	-730	-766	-608	-707
194	-641	-678	-702	-744	-581	-710
197	-644	-673	-702	-749	-576	-722
198	-622	-661	-679	-741	-555	-707
201	-640	-661	-678	-754	-568	-710
203	-645	-666	-680	-752	-583	-714
209	-649	-653	-662	-758	-598	-706
212	-647	-651	-657	-742	-613	-695
215	-648	-648	-665	-744	-623	-700
216	-639	-638	-703	-737	-617	-695
218	-643	-648	-672	-736	-630	-705
222	-645	-649	-680	-737	-639	-707
229	-663	-669	-708	-761	-654	-717
231	-662	-671	-707	-747	-656	-709
233	-669	-680	-708	-744	-662	-710
241	-665	-669	-695	-725	-658	-707
246	-688	-690	-709	-735	-674	-717
250	-689	-679	-704	-744	-685	-691
256	-690	-677	-702	-742	-690	-693
265	-711	-695	-719	-744	-732	-727

Table 4A. Cont.

Julian date	Soil water hydraulic potential					
	Plot 1		Plot 8		Plot 13	
	Depth		Depth		Depth	
	180cm	210cm	180cm	210cm	180cm	210cm
	Pinto bean					
	cm of water					
174	-592	-614	-639	-633	-627	-626
180	-714	-704	-712	-704	-698	-713
189	-741	-738	-748	-742	-644	-740
190	-765	-766	-766	-761	-644	-757
194	-755	-760	-739	-745	-614	-733
197	-760	-763	-764	-433	-615	-738
198	-685	-622	-752	-734	-605	-741
201	-696	-711	-754	-757	-615	-733
203	-708	-722	-743	-707	-623	-727
209	-745	-752	-739	-700	-602	-728
212	-744	-753	-734	-722	-582	-730
215	-744	-754	-732	-723	-583	-702
216	-745	-757	-722	-722	-580	-689
218	-753	-763	-728	-728	-599	-694
222	-763	-772	-733	-733	-614	-692
229	-766	-776	-755	-754	-667	-678
231	-763	-773	-747	-748	-661	-677
233	-774	-770	-749	-744	-662	-681
241	-766	-773	---	-720	-686	-669
246	-750	-768	---	---	-711	-693
250	-785	-778	---	---	-723	-704
256	---	-773	---	---	-595	-734
265	---	-778	---	---	---	---

Table 4A . Cont.

	Soil water hydraulic potential					
	Plot 3		Plot 12		Plot 14	
	Depth		Depth		Depth	
Julian date	180cm	210cm	180cm	210cm	180cm	210cm
	Soybean					
	cm of water					
174	-627	-628	-504	-553	-636	-577
180	-685	-704	-539	-590	-717	-721
189	-600	-699	-385	-408	-753	-762
190	-615	-729	-377	-427	-770	-779
194	-563	-717	-392	-439	-723	-776
197	-557	-699	-415	-447	-716	-774
198	-549	-692	-413	-442	-626	-630
201	-551	-685	-431	-454	-658	-717
203	-557	-674	-427	-464	-666	-724
209	-474	-593	-360	-404	-662	-742
212	-455	-570	-378	-404	-639	-737
215	-455	-456	-387	-417	-626	-738
216	-448	-535	-403	-419	-617	-735
218	-459	-478	-419	-426	-619	-739
222	-486	-540	-450	-459	-624	-738
229	-434	-522	-406	-448	-698	-743
231	-413	-497	-419	-450	-696	-747
233	-435	-493	-433	-457	-708	-748
241	-484	-507	-514	-514	-715	-734
246	-537	-539	-576	-554	-735	-758
250	-571	-563	-600	-580	-743	-763
256	-595	-592	-626	-611	-767	-766
265	-623	-631	-667	-650	-773	-744

Table 5A. F values from analysis of variance of depletion rates by crop within a layer at Manhattan.

Period	F values for indicated soil layers 100 to 404 mm	404 to 708 mm	708 to 1012 mm	1012 to 1316 mm	1316 to 1620 mm	1620 to 1924 mm	1924 to 2228 mm	2228 to 2532 mm	2532 to 2836 mm	2836 to 3140 mm
5-9 June	1.14	0.37	0.38	0.31	1.61	0.62	2.45	0.24	2.06	1.24
12-23 July	0.35	3.80*	8.55**	1.06	1.67	3.25	0.34	0.54	0.70	0.97
18-25 Aug.	1.37	0.62	0.83	0.92	1.70	0.40	0.34	0.30	0.79	0.91
26 Aug.-3 Sept.	1.97	4.78*	54.44**	3.66*	0.63	1.69	1.04	0.14	1.90	1.67

*Analysis of variance was significant at the 0.05 level.

**Analysis of variance was significant at the 0.01 level.

F values not followed by an asterisk were not significant at the 0.05 level.

Table 6A. Soil water depletion rate means by crop within a layer at Manhattan.

Crop	Soil water depletion rate 5-9 June	12-23 July	18-25 Aug.	26 Aug.- 3 Sept.
	100-404 mm layer mm/day			
Corn	0.13	0.38	0.55	0.32
Grain sorghum	0.23	0.18	0.86	-0 12
Pearl millet	0.65	0.24	0.51	-0.11
Pinto bean	0.31	0.22	0.11	-0.02
Soybean	0.08	0.30	0.80	0.20
Sunflower	0.47	0.21	0.94	-0.04
	404-708 mm layer			
Corn	0.36	1.51a*	0.90	0.54ab*
Grain sorghum	0.35	0.87b	0.70	0.14bc
Pearl millet	0.61	0.69b	0.99	0.36bc
Pinto bean	0.17	1.10ab	0.58	0.34bc
Soybean	0.53	1.03ab	1.05	0.89a
Sunflower	0.31	1.59a	0.85	0.01c

Table 6A. Cont.

Crop	Soil water depletion rate			
	5-9 June	12-23 July	18-25 Aug.	26 Aug. - 4 Sept.
	708-1012 mm layer			
	mm/day			
Corn	0.19	1.05ab*	0.73	0.48b*
Grain sorghum	0.63	0.53c	0.85	0.53b
Pearl millet	0.21	1.18a	0.64	0.55b
Pinto bean	0.34	0.82b	0.95	0.15c
Soybean	0.21	0.97ab	1.08	0.71a
Sunflower	0.18	1.24a	0.52	-0.06d
	1012-1316 mm layer			
Corn	0.10	0.49	0.22	0.39a*
Grain sorghum	-0.24	0.34	0.50	-0.08b
Pearl millet	0.09	0.69	0.54	0.24ab
Pinto bean	0.03	0.55	0.56	0.37a
Soybean	-0.17	0.62	0.56	0.46a
Sunflower	0.12	0.86	0.75	-0.13b

Table 6A . Cont.

Crop	Soil water depletion rate 5-9 June	12-23 July	18-25 Aug.	26 Aug.- 3 Sept.
	1316-1620 mm layer			
	mm/day			
Corn	0.09	0.18	0.02	0.16
Grain sorghum	0.39	0.21	0.37	0.13
Pearl millet	0.17	0.47	0.26	0.02
Pinto bean	0.19	0.43	0.36	0.04
Soybean	-0.11	0.29	1.27	-0.51
Sunflower	0.07	0.59	0.45	-0.13
	1620-1924 mm layer			
Corn	0.03	0.04	-0.03	0.06
Grain sorghum	0.12	0.18	0.26	-0.24
Pearl millet	0.16	0.33	0.17	-0.15
Pinto bean	0.40	0.34	0.23	0.01
Soybean	-0.12	0.23	0.29	0.14
Sunflower	0.21	0.35	0.23	-0.12

Table 6A . Cont.

Crop	Soil water depletion rate			
	5-9 June	12-23 July	18-25 Aug.	26 Aug.-3 Sept.
	1924-2228 mm layer			
	mm/day			
Corn	-0.17	0.19	-0.02	-0.04
Grain sorghum	-0.23	0.23	0.18	-0.29
Pearl millet	0.99	0.19	0.15	-0.13
Pinto bean	-0.03	0.19	0.30	-0.03
Soybean	-0.13	0.23	0.10	-0.04
Sunflower	0.15	0.32	0.23	-0.11
	2228-2532 mm layer			
Corn	-0.05	0.33	-0.04	-0.03
Grain sorghum	-0.01	0.43	0.24	-0.10
Pearl millet	0.16	0.20	0.05	-0.08
Pinto bean	-0.09	0.15	0.08	-0.07
Soybean	-0.11	0.08	0.20	-0.09
Sunflower	-0.11	0.34	0.19	-0.16

Table 6A. Cont.

Crop	Soil water depletion rate			
	5-9 June	12-23 July	18-25 Aug.	26 Aug. - 3 Sept.
	2532-2836 mm layer			
	mm/day			
Corn	0.02	0.18	-0.10	0.10
Grain sorghum	0.43	-0.19	0.33	-0.37
Pearl millet	-0.04	0.12	0.15	-0.11
Pinto bean	-0.33	-0.01	-0.07	-0.13
Soybean	0.19	0.06	0.16	-0.08
Sunflower	-0.19	0.25	0.30	-0.27
	2836-3140 mm layer			
Corn	0.13	-0.44	-0.02	0.60
Grain sorghum	0.33	0.18	0.15	-0.89
Pearl millet	0.08	0.04	0.28	0.10
Pinto bean	0.05	-0.18	0.08	-0.56
Soybean	-0.10	0.09	-0.04	-0.41
Sunflower	-0.03	0.39	-0.004	0.51

*Means with the same letter were not significantly different by Duncan's Multiple Range Test at the 0.05 level. Analysis of variance was significant at the 0.05 level.

Means with no letters were not significantly different by analysis of variance at the 0.05 level.

Table 7A . F values from analysis of variance of depletion rate means by layer within a crop at Manhattan.

	F values for indicated crop					
Period	Corn	Grain sorghum	Pearl millet	Pinto bean	Soybean	Sunflower
5-9 June	1.79	1.20	1.35	0.90	1.07	2.00
12-23 July	6.58**	1.22	11.11**	9.93**	35.59**	6.01**
18-25 Aug.	14.96**	11.55**	4.45**	1.22	2.56*	7.14**
26 Aug.-3 Sept.	1.05	3.63**	5.32**	2.65	3.99**	1.14

* Analysis of variance was significant at the 0.05 level.

** Analysis of variance was significant at the 0.01 level.

F values with no asterisk were not significant at the 0.05 level.

Table 8A . Soil water depletion rate means by layer within a crop at Manhattan.

	Soil water depletion rate			
Soil layer	5-9 June	12-23 July	18-25 Aug.	26 Aug.-3 Sept.
	Corn			
— mm —	mm/day			
100-404	0.13	0.38c*	0.55b*	0.32
404-708	0.36	1.51a	0.90a	0.54
708-1012	0.19	1.05ab	0.73ab	0.48
1316-1620	0.09	0.18cd	0.02c	0.16
1620-1924	0.03	0.04cd	-0.03c	0.06
1924-2228	-0.17	0.19cd	-0.02c	-0.04
2228-2532	-0.05	0.33c	-0.04c	-0.03
2532-2836	0.02	0.08cd	-0.10c	0.10
2836-3140	0.13	-0.04d	-0.02c	0.60
	Grain sorghum			
100-404	0.23	0.18ab*	0.86a*	-0.12ab*
404-708	0.35	0.87a	0.70ab	0.14ab
708-1012	0.63	0.53ab	0.85ab	0.53a
1012-1316	-0.24	0.34ab	0.50c	-0.08ab
1620-1924	0.12	0.18ab	0.26cd	-0.24b
1924-2228	-0.23	0.23ab	0.18d	-0.29bc
2228-2532	-0.01	0.43ab	0.24cd	-0.10ab
2532-2836	0.43	-0.19b	0.33cd	-0.37bc
2836-3140	0.33	0.18ab	0.15d	-0.89c

Table 8A . Cont.

Soil layer	Soil water depletion rate 5-9 June	12-23 July	18-25 Aug.	26 Aug.-3 Sept.
	Pearl millet			
—— mm ——	mm/day			
100-404	0.65	0.24cd*	0.51bcd*	-0.11d*
404-708	0.61	0.69b	0.99a	0.36ab
708-1012	0.21	1.18a	0.64ab	0.55a
1012-1316	0.09	0.69b	0.54bc	0.24abc
1316-1620	0.17	0.47bc	0.26bcd	0.02cd
1620-1924	0.16	0.33cd	0.17cd	-0.15d
1924-2228	0.99	0.19cd	0.15cd	-0.13d
2228-2532	0.16	0.20cd	0.05d	-0.08cd
2532-2836	-0.04	0.12cd	0.15cd	-0.11d
2836-3140	0.08	0.04d	0.23bcd	0.10bcd
	Pinto bean			
100-404	0.31	0.22 cd*	0.11	-0.02a*
404-708	0.17	1.10a	0.58	0.34a
708-1012	0.34	0.82ab	0.95	0.15a
1012-1316	0.03	0.55bc	0.56	0.37a
1316-1620	0.19	0.43c	0.36	0.04a
1620-1924	0.40	0.34cd	0.23	0.01a
1924-2228	-0.03	0.19cde	0.30	-0.03a
2228-2532	-0.09	0.15cde	0.08	-0.07ab
2532-2836	-0.33	-0.01de	-0.07	-0.13ab
2836-3140	0.05	-0.18e	0.08	-0.56b

Table 8A . Cont.

Soil layer	Soil water depletion rate			
	5-9 June	12-23 July	18-25 Aug.	26 Aug.-3 Sept.
	Soybean			
—— mm ——	—— mm/day ——			
100-404	0.08	0.30c*	0.80abc*	0.20abcd*
404-708	0.53	1.03a	1.05ab	0.89a
708-1012	0.21	0.97a	1.08ab	0.71ab
1012-1316	-0.17	0.62b	0.56abc	0.46abc
1316-1620	-0.11	0.29c	1.27a	-0.51d
1620-1924	-0.12	0.23cd	0.29abc	0.14bcd
1924-2228	-0.13	0.23cd	0.10bc	-0.04cd
2228-2532	-0.11	0.08d	0.20bc	-0.09cd
2532-2836	0.19	0.06d	0.16bc	-0.08cd
2836-3140	-0.10	0.09d	-0.04c	-0.41d
	Sunflower			
100-404	0.47	0.21d*	0.94a*	-0.04
404-708	0.31	1.59a	0.85ab	0.01
708-1012	0.18	1.24ab	0.52bcd	-0.06
1012-1316	0.12	0.86bc	0.75abc	-0.13
1316-1620	0.07	0.59cd	0.45cd	-0.13
1620-1924	0.21	0.35cd	0.23de	-0.12
1924-2228	0.15	0.32cd	0.23de	-0.11
2228-2532	-0.11	0.34cd	0.19de	-0.16
2532-2836	-0.19	0.25cd	0.30de	-0.27
2836-3140	-0.03	0.39cd	-0.004e	0.51

*Means with the same letter were not significantly different by Duncan's Multiple Range Test at the 0.05 level. Analysis of variance was significant at the 0.05 level.

Means with no letter were not significantly different by analysis of variance at the 0.05 level.

Table 9A Crop developmental stages, dates of occurrence, and fraction of growing season at each observed stage at Manhattan.

Date	Julian date	Fraction of growing season	Crop development
			Corn
21 May	141	---	Planting
30 May	150	0.007	Emergence
12 July	193	0.42	Tassel emergence
18 July	199	0.49	Silk emergence
25 July	206	0.56	20% at blister stage
30 July	211	0.60	Late blister stage
5 Aug.	217	0.66	Milky ripe stage
7 Aug.	219	0.68	Roasting ear stage
14 Aug.	226	0.75	Hard dough stage
18 Aug.	230	0.78	Denting stage
24 Aug.	236	0.82	Denting progressing
14 Sept.	257	1.00	Physiological maturity
			Grain sorghum
2 June	153	---	Planting
8 June	159	0.01	Emergence
12 July	193	0.38	Not yet booting
18 July	199	0.45	Boot stage
20 July	201	0.48	Head emergence
25 July	206	0.53	30% bloom
30 July	211	0.58	75% bloom
5 Aug.	217	0.65	Beginning grain development
7 Aug.	219	0.67	Milk stage
14 Aug.	226	0.74	Soft dough stage
18 Aug.	230	0.77	Hard dough stage
24 Aug.	236	0.82	Hard dough stage
12 Sept.	255	1.00	Physiological maturity

Table 9A Cont.

Date	Julian date	Fraction of growing season	Crop development
			Pearl millet
2 June	153	---	Planting
7 June	158	0.01	Emergence
8 July	189	0.35	Flag leaf visible
10 July	191	0.37	Heads appearing
12 July	193	0.40	Some heads emerged
13 July	194	0.41	50% head emergence
18 July	199	0.48	Flowering
25 July	206	0.56	Milk stage
30 July	211	0.61	Late milk stage
5 Aug.	217	0.68	Milky to soft dough stage
14 Aug.	226	0.77	Variable--some at hard dough
18 Aug.	230	0.81	Hard dough stage
24 Aug.	236	0.86	Mature heads, much variability
7 Sept.	250	0.99	Physiological maturity
			Pinto bean
22 May 81	142	---	Planting
31 May 81	151	0.01	Emergence
24 July 81	175	0.24	Vining
4 July 81	185	0.34	Beginning bloom
12 July 81	193	0.43	Beginning pod set
15 July 81	196	0.47	Pods 10 cm long
18 July 81	199	0.51	Beans filling
25 July 81	206	0.58	Continued development
30 July 81	211	0.63	Large bean in the pods
5 Aug. 81	217	0.70	No change
14 Aug. 81	226	0.78	No change
18 Aug. 81	230	0.82	No change
24 Aug. 81	236	0.87	Mottling of beans
8 Sept. 81	251	1.00	Physiological maturity and harvest.

Table 9A Cont.

Date	Julian date	Fraction of growing season	Crop development
			Soybean
22 May 81	142	---	Planting
31 May 81	151	0.01	Emergence
4 July 81	185	0.50	Some blooms appearing
12 July 81	193	0.52	Numerous blooms
18 July 81	199	0.53	A few pods
25 July 81	206	0.57	Numerous pods
30 July 81	211	0.61	Continued pod development
5 Aug. 81	217	0.64	Beginning bean fill
7 Aug. 81	219	0.65	Beans filling
14 Aug. 81	226	0.71	Bean fill continues
18 Aug. 81	230	0.74	Bean fill continues
24 Aug. 81	236	0.79	Bean fill continues
17 Sept. 81	260	1.00	Physiological maturity
			Sunflower
22 May 81	142	---	Planting
31 May 81	151	0.007	Emergence
1 July 81	182	0.33	Many heads
4 July 81	185	0.36	Heads 2 cm in diameter
12 July 81	193	0.46	Heads 5 cm in diameter
13 July 81	194	0.47	Some ray flowers showing
15 July 81	196	0.50	10% bloom
18 July 81	199	0.53	75% bloom
20 July 81	201	0.56	100% bloom
25 July 81	206	0.61	Pollination 80% complete
30 July 81	211	0.66	Seed development continues
7 Aug. 81	219	0.75	Seed development continues
14 Aug. 81	226	0.82	Seeds are well developed
18 Aug. 81	230	0.86	Leaves are drying
24 Aug. 81	236	0.91	Considerable leaf drop
2 Sept. 81	245	1.00	Harvest

Table 10A. Crop developmental stages, dates of occurrence, and fraction of growing season at each observed stage at Tribune.

Date	Julian date	Fraction of growing season	Crop development
			Corn
15 May 81	135	---	Planting
27 May 81	147	0.007	Emergence
1 June 81	152	0.04	Two leaves emerged
16 June 81	167	0.15	Six leaves emerged
8 July 81	189	0.34	Nine leaves emerged Developing tassel is 10.2 cm long
21 July 81	202	0.46	Tassel above corn, but notunwrapped
23 July 81	204	0.47	Tassel emergence
28 July 81	209	0.52	Silking and flowering
11 Aug. 81	223	0.66	Blister stage
18 Aug. 81	230	0.69	Dough stage
12 Sept. 81	254	0.87	Dent progresses ½ down the ear
22 Sept. 81	265	0.93	Black layer 3/4 down the ear
2 Oct. 81	276	1.00	Harvest
			Grain sorghum
27 May 81	147	---	Planting
5 June 81	156	0.007	Emergence
16 June 81	167	0.10	Four leavesemerged
8 July 81	189	0.30	Six leaves emerged and panicle development beginning
21 July 81	202	0.43	Flag leaf visible
23 July 81	204	0.44	Head emergence
28 July 81	209	0.49	Two-thirds bloom
11 Aug. 81	223	0.62	Milk stage
18 Aug. 81	230	0.67	Soft dough
12 Sept. 81	254	0.86	Black layer at top of head
22 Sept. 81	265	0.93	Black layer appearing 3/4 down the head
2 Oct. 81	276	1.00	Harvest

Table 10A.Cont.

Date	Julian date	Fraction of growing season	Corn development
			Pearl millet
5 June	156	---	Planting
10 June	161	0.009	Emergence
16 June	167	0.06	Two leave emerged.
8 July	189	0.27	Five leaves emerged
21 July	202	0.40	Flag leaf visible.
23 July	204	0.42	Head emergence
28 July	209	0.46	Flowering
18 Aug.	230	0.65	Seed set
12 Sep.	254	0.85	Black layer at top of older heads.
22 Sept.	265	0.92	Much variability in black layer development.
3 Oct.	276	1.00	Physiological maturity and harvest.
			Pinto bean
4 June	155	---	Planting
10 June	161	0.01	Emergence
16 June	167	0.07	First trifoliates
8 July	189	0.32	14 sets of trifoliates, unifoliates still present.
16 July	197	0.41	First bloom
21 July	202	0.47	Vining, flowering continues
23 July	204	0.49	Tiny pods visible
28 July	209	0.54	Continued blooming and vining.
11 Aug.	223	0.70	Beans filling
18 Aug.	230	0.76	Pod striping
12 Sept.	254	1.00	Physiological maturity and harvest.

Table 10A. Cont.

Date	Julian date	Fraction of growing season	Crop development
			Soybean
4 June 81	155	---	Planting
11 June 81	162	0.05	Emergence
16 June 81	167	0.11	Unifoliates emerged
8 July 81	189	0.40	5 sets of trifoliates
16 July 81	197	0.46	Beginning bloom
21 July 81	202	0.49	Continued bloom with 11 sets of trifoliates.
23 July 81	204	0.49	Tiny pods visible--beginning pod set
11 Aug. 81	223	0.60	Beans filling
18 Aug. 81	230	0.65	Flowering and pod set at the upper 4 nodes
12 Sept. 81	254	0.83	Continued bean fill
22 Sept. 81	265	0.90	Continued bean fill
3 Oct. 81	276	1.00	Physiological maturity and harvest

Table 11A. Regression equations of leaf area index (LAI), leaf dry weight (DWLV), stem dry weight (DWST), reproductive part dry weight (DWRP), and total dry weight (DWTOT) against Julian date/100 (X) at Tribune.

Crop	Equation†	R^2	N	Range of X values	Model significance
Corn	$LAI = -69.2 + 69.6X - 16.4X^2$	0.87	12	1.59 - 2.47	0.001
	$DWLV = -33.9 + 32.8X - 7.27X^2$	0.90	12	1.59 - 2.47	0.001
	$DWST = -14.3 + 6.73X^3 - 2.17X^4$	0.93	12	1.59 - 2.47	0.001
	$DWRP = -9.13 + 0.618X^4$	0.91	8	1.59 - 2.47	0.001
	$DWTOT = -9.64 + 2.21X^3$	0.96	12	1.59 - 2.47	0.001
Grain sorghum	$LAI = -107.7 + 103.6X - 23.9X^2$	0.91	8	1.74 - 2.42	0.002
	$DWLV = -5.37 + 3.36X$	0.80	8	1.74 - 2.42	0.003
	$DWST = -11.7 + 4.74X^3 - 1.15X^4$	0.94	8	1.74 - 2.42	0.001
	$DWRP = -6.91 + 0.397X^4$	0.99	4	2.15 - 2.42	0.005
	$DWTOT = -13.1 + 4.23X^2$	0.99	8	1.74 - 2.42	0.001
Pearl millet	$LAI = -61.6 + 43.2X - 2.71X^3$	0.95	8	1.74 - 2.42	0.001
	$DWLV = -5.96 + 2.33X^3 - 0.70X^4$	0.98	8	1.74 - 2.42	0.001
	$DWST = -6.98 + 2.15X^2$	0.97	8	1.74 - 2.42	0.001
	$DWRP = -3.10 + 0.170X^4$	0.99	4	2.15 - 2.42	0.004
	$DWTOT = -7.59 + 1.35X^3$	0.99	8	1.74 - 2.42	0.001

Table 11A. Cont.

Crop	Equation†	R^2	N	Range of X values	Model significance
Pinto bean	$LAI = -19.9 + 8.53X^3 - 2.83X^4$	0.87	8	1.74 - 2.42	0.006
	$DWLV = 53.2 - 82.8X^2 + 55.3X^3 - 10.2X^4$	0.99	7	1.74 - 2.42	0.002
	$DWST = 62.8 - 96.2X^2 + 63.8X^3 - 11.7X^4$	0.98	8	1.74 - 2.42	0.001
	$DWRP = -29.4 + 13.6X$	0.96	4	2.15 - 2.42	0.02
	$DWTOT = -2.39 + 0.248X^4$	0.97	8	1.74 - 2.42	0.001
Soybean	$LAI = -11.7 + 5.96X^3 - 2.01X^4$	0.89	8	1.62 - 2.42	0.001
	$DWLV = -6.69 + 3.18X^3 - 1.03X^4$	0.92	8	1.62 - 2.42	0.001
	$DWST = 104.6 - 169.3X^2 + 114.1X^3 - 21.1X^4$	0.96	8	1.62 - 2.42	0.001
	$DWRP = -7.33 + 0.436X^4$	0.88	5	1.96 - 2.42	0.001
	$DWTOT = -5.99 + 0.724X^4$	0.94	8	1.62 - 2.42	0.001

†All variables significant at the 0.10 level.

Table 12A. Regression equations of leaf area index (LAI), leaf dry weight (DWLV), stem dry weight (DWST), reproductive part dry weight (DWRP), and total dry weight (DWTOT) against Julian date/100 (X) at Manhattan.

Crop	Equation†	R^2	N	Range of X values	Model significance
Corn	$LAI = -69.2 + 69.6X - 16.4X^2$	0.87	12	1.59 - 2.47	0.001
	$DWLV = -33.9 + 32.8X - 7.27X^2$	0.90	12	1.59 - 2.47	0.001
	$DWST = -14.3 + 6.73X^3 - 2.17X^4$	0.93	12	1.59 - 2.47	0.001
	$DWRP = -9.13 + 0.618X^4$	0.91	8	1.91 - 2.47	0.001
	$DWTOT = -9.64 + 2.21X^3$	0.96	12	1.59 - 2.47	0.001
Grain sorghum	$LAI = -87.6 + 84.6X - 19.4X^2$	0.91	11	1.67 - 2.47	0.001
	$DWLV = -11.7 + 7.65X^2 - 2.13X^3$	0.96	11	1.67 - 2.47	0.001
	$DWST = -11.8 + 4.71X^3 - 1.44X^4$	0.82	11	1.67 - 2.47	0.001
	$DWRP = -11.03 + 0.602X^4$	0.99	5	2.10 - 2.47	0.001
	$DWTOT = -6.52 + 0.716X^4$	0.98	11	1.67 - 2.47	0.001
Pearl millet	$LAI = -84.9 + 82.1X - 18.6X^2$	0.85	11	1.67 - 2.47	0.001
	$DWLV = -42.8 + 40.5X - 8.92X^2$	0.78	11	1.67 - 2.47	0.002
	$DWST = -10.4 + 4.51X^3 - 1.41X^4$	0.90	11	1.67 - 2.47	0.001
	$DWRP = -21.8 + 11.4X$	0.90	7	1.96 - 2.47	0.001
	$DWTOT = -31.6 + 18.9X$	0.90	11	1.67 - 2.47	0.001

Table 12A. Cont.

Crop	Equation[†]	R^2	N	Range of X values	Model significance
Pinto bean	$LAI = -13.2X^3 - 2.57X^4$	0.86	12	1.59 - 2.47	0.001
	$DWLV = -4.46 + 2.41X^3 - 0.823X^4$	0.77	12	1.59 - 2.47	0.001
	$DWST = -4.91 + 2.33X^3 - 0.744X^4$	0.93	12	1.59 - 2.47	0.001
	$DWRP = 0.670 - 4.93X^3 + 1.87X^4$	0.98	7	1.96 - 2.47	0.001
	$DWTOT = -6.26 + 2.45X^2$	0.96	12	1.59 - 2.47	0.001
Soybean	$LAI = 343.3 - 559X + 297.7X^2 - 51.4X^3$	0.96	12	1.59 - 2.47	0.001
	$DWLV = -4.13 + 1.97X^3 - 0.636X^4$	0.93	12	1.59 - 2.47	0.001
	$DWST = 57.9 - 95.6X^2 + 65.1X^3 - 12.1X^4$	0.97	12	1.59 - 2.47	0.001
	$DWRP = -5.50 + 0.275X^4$	0.99	5	2.10 - 2.47	0.001
	$DWTOT = -4.89 + 1.04X^3$	0.97	12	1.59 - 2.47	0.001
Sunflower	$LAI = -18.8 + 10.5X^3 - 3.79X^4$	0.83	11	1.59 - 2.40	0.001
	$DWLV = -9.37 + 5.04X^3 - 1.76X^4$	0.83	11	1.59 - 2.40	0.001
	$DWST = 412.4 - 675.8X = 362.9X^2 - 63.6X^3$	0.94	11	1.59 - 2.40	0.001
	$DWRP = -17.5 + 6.81X^3 - 2.2X^4$	0.85	8	1.81 - 2.40	0.01
	$DWTOT = -29.2 + 14.5X^3 - 4.87X^4$	0.84	11	1.59 - 2.40	0.001

[†] All variables significant at the 0.10 level.

Table 13A. Regression equations of leaf area index (LAI), leaf dry weight (DWLV), stem dry weight (DWST), reproductive part dry weight (DWRP), and total dry weight (DWTOT) against fraction of growing season (X) at Manhattan.

Crop	Equation†	R^2	N	Range of X values	Model significance
Corn	$LAI = -1.68 + 21.2X - 18.1X^2$	0.86	12	0.09 - 0.92	0.001
	$DWLV = -1.05 + 11.3X - 7.85X^2$	0.90	12	0.09 - 0.92	0.001
	$DWST = -0.518 + 26.9X^2 - 23.3X^4$	0.97	12	0.09 - 0.92	0.001
	$DWRP = -1.76 + 20.7X^3$	0.91	8	0.39 - 0.92	0.001
	$DWTOT - 0.624 + 27.9X^2$	0.95	12	0.09 - 0.92	0.001
Grain sorghum	$LAI = -2.24 + 21.9X - 17.4X^2$	0.93	11	0.09 - 0.93	0.001
	$DWLV = -0.762 + 6.51X - 2.92X^3$	0.97	11	0.09 - 0.93	0.001
	$DWST = -1.352 + 51.7X^3 - 48.9X^4$	0.92	11	0.09 - 0.93	0.001
	$DWRP = -2.46 + 17.6X^3$	0.98	5	0.57 - 0.93	0.001
	$DWTOT = -0.444 + 23.9X^2$	0.99	11	0.09 - 0.93	0.001
Pearl millet	$LAI = -2.02 + 21.4X - 15.6X^2$	0.87	11	0.11 - 0.97	0.001
	$DWLV = -1.18 + 11.1X - 7.31X^2$	0.79	11	0.11 - 0.97	0.002
	$DWST = -1.47 + 10.4X - 3.9X^3$	0.91	11	0.11 - 0.97	0.001
	$DWRP = -4.61 + 11.1X$	0.90	7	0.44 - 0.97	0.001
	$DWTOT = -2.06 + 17.2X$	0.92	11	0.11 - 0.97	0.001

Table 13A. Cont.

Crop	Equation†	R^2	N	Range of X values	Model significance
Pinto bean	$LAI = -0.87 + 11.5X - 10.1X^4$	0.86	12	0.08 - 0.96	0.001
	$DWLV = -0.292 + 4.28X - 2.96X^4$	0.77	12	0.08 - 0.96	0.002
	$DWST = -0.042 + 8.57X^2 - 6.52X^4$	0.95	12	0.08 - 0.96	0.001
	$DWRP = -0.419 + 6.11X^4$	0.97	7	0.47 - 0.96	0.001
	$DWTOT = -1.14 + 9.70X$	0.95	12	0.08 - 0.96	0.001
Soybean	$LAI = -1.00 + 68.7X^3 - 69.9X^4$	0.87	12	0.14 - 0.89	0.001
	$DWLV = -0.584 + 3.22X$	0.76	12	0.14 - 0.89	0.001
	$DWST = -0.274 + 6.49X^2$	0.78	12	0.14 - 0.89	0.001
	$DWRP = -3.77 + 25.9X^3 - 15.5X^4$	0.99	5	0.61 - 0.89	0.001
	$DWTOT = -1.28 + 15.5X^2$	0.93	12	0.14 - 0.89	0.001
Sunflower	$LAI = -1.62 + 14.4X - 13.3X^4$	0.85	11	0.09 - 0.95	0.001
	$DWLV = 0.952 + 7.82X - 5.80X^4$	0.85	11	0.09 - 0.95	0.001
	$DWST = -0.063 + 5.80X$	0.57	11	0.09 - 0.95	0.001
	$DWRP = 12.6 - 81.7X - 161X^2 - 90.0X^3$	0.94	8	0.32 - 0.95	0.006
	$DWTOT = -0.935 + 14.4X$	0.71	11	0.09 - 0.95	0.001

† All variables significant at the 0.10 level.

Table 14A. Regression equations of leaf area index (LAI), leaf dry weight (DWLV), stem dry weight (DWLV), stem dry weight (DWST), reproductive part dry weight (DWRP), and total dry weight (DWTOT) against fraction of growing season at Tribune.

Crop	Equation†	R^2	N	Range of X values	Model significance
Corn	$LAI = -1.52 + 13.4X - 14.2X^4$	0.90	9	0.11 - 0.78	0.001
	$DWLV = -0.339 + 5.01X$	0.86	9	0.11 - 0.78	0.001
	$DWST = -0.499 + 72.8X^3 - 72.7X^4$	0.95	9	0.11 - 0.78	0.001
	$DWRP = -1.08 + 24.6X^4$	0.90	5	0.41 - 0.78	0.01
	$DWTOT = -0.791 + 31.8X^2$	0.94	9	0.11 - 0.78	0.001
Grain sorghum	$LAI = -4.26 + 31.7X - 29.1X^2$	0.92	8	0.16 - 0.77	0.002
	$DWLV = -1.83 + 12.9X - 9.94X^2$	0.95	8	0.16 - 0.77	0.001
	$DWST = 0.352 + 55.9X^3 - 62.2X^4$	0.99	8	0.55 - 0.77	0.001
	$DWRP = -1.82 + 16.6X^3$	0.99	4	0.16 - 0.77	0.004
	$DWTOT = -3.73 + 19.3X$	0.99	8	0.10 - 0.77	0.001
Pearl millet	$LAI = -1.335 + 8.62X$	0.86	8	0.12 - 0.75	0.001
	$DWLV = -0.577 + 5.13X$	0.97	8	0.12 - 0.75	0.001
	$DWST = -0.245 + 44.6X^3 - 41.7X^4$	0.99	8	0.12 - 0.75	0.001
	$DWRP = -0.10 + 8.96X^4$	0.99	4	0.53 - 0.75	0.001
	$DWTOT = -0.291 + 21.1X^3$	0.99	8	0.12 - 0.75	0.001

Table 14A. Cont.

Crop	Equation†	R^2	N	Range of X Values	Model significance
Pinto bean	$LAI = -1.324 + 59.3X^3 - 61.5X^4$	0.98	8	0.14 - 0.88	0.001
	$DWLV = -1.0135 + 17.8X^3 - 18.1X^4$	0.98	8	0.14 - 0.88	0.001
	$DWST = -1.35 + 18.5X^3 - 18.6X^4$	0.96	8	0.14 - 0.88	0.02
	$DWRP = -8.83 + 14.2X$	0.96	4	0.62 - 0.88	0.001
	$DWTOT = -0.137 + 8.08X^2$	0.98	8	0.14 - 0.88	0.001
Soybean	$LAI = -0.811 + 73.5X^3 - 78.5X$	0.88	8	0.14 - 0.72	0.005
	$DWLV = -0.182 + 4.94X^2$	0.85	8	0.14 - 0.72	0.001
	$DWST = 0.185 - 9.53X^2 + 24.9X^3$	0.99	8	0.14 - 0.72	0.001
	$DWRP = -2.48 + 8.81X^2$	0.97	4	0.52 - 0.72	0.001
	$DWTOT = -0.0312 + 33.5X^4$	0.97	8	0.14 - 0.72	0.001

†All variables were significant at the 0.10 level.

Table 15A. CLIMATE DATA AT MANHATTAN, KAN. IN 1981

DATE IS SHOWN BY MONTH/DAY/YEAR
SOLAR RADIATION (SOLRAD) UNITS ARE LANGLEYS/DAY
TMAX AND TMIN ARE DAILY MAXIMUM AND MINIMUM TEMPERATURES IN DEGREES FAHRENHEIT
CTMAX AND CTMIN ARE DAILY MAXIMUM AND MINIMUM TEMPERATURES IN DEGREES CELSIUS
JDAY SIGNIFIES JULIAN DATE
PRECIPITATION (PPT) IS IN MILLIMETERS

OBS	DATE	SOLRAD	TMAX	TMIN	JDAY	PPT	CTMAX	CTMIN
1	51581	623.8	74	42	135	0.000	23.3352	5.5560
2	51681	141.5	68	55	136	6.350	20.0016	12.7788
3	51781	61.6	60	53	137	6.604	15.5568	11.6676
4	51881	33.4	60	49	138	22.098	15.5568	9.4452
5	51981	639.4	66	45	139	17.018	18.8904	7.2228
6	52081	665.4	73	38	140	0.000	22.7796	3.3336
7	52181	553.2	76	52	141	0.000	24.4464	11.1120
8	52281	604.2	86	64	142	0.000	30.0024	17.7792
9	52381	516.6	80	62	143	0.000	26.6688	16.6680
10	52481	668.4	76	49	144	0.000	24.4464	9.4452
11	52581	374.2	80	62	145	2.286	26.6688	16.6680
12	52681	625.4	81	54	146	31.750	27.2244	12.2232
13	52781	396.4	81	64	147	0.000	27.2244	17.7792
14	52881	166.2	76	65	148	0.762	24.4464	18.3348
15	52981	515.1	82	63	149	10.160	27.7800	17.2236
16	53081	587.0	78	62	150	0.000	25.5576	16.6680
17	53181	668.4	78	50	151	0.000	25.5576	10.0008
18	60181	665.6	84	50	152	0.000	28.8912	10.0008
19	60281	502.7	85	65	153	0.000	29.4468	18.3348
20	60381	568.2	82	65	154	0.000	27.7800	18.3348
21	60481	261.2	76	64	155	0.000	24.4464	17.7792
22	60581	609.8	86	64	156	0.000	30.0024	17.7792
23	60681	633.1	87	69	157	0.000	30.5580	20.5572
24	60781	616.9	92	68	158	0.000	33.3360	20.0016
25	60881	638.4	96	73	159	0.000	35.5584	22.7796
26	60981	625.6	97	74	160	0.000	36.1140	23.3352
27	61081	472.6	90	66	161	0.000	32.2248	18.8904
28	61181	252.4	76	58	162	26.416	24.4464	14.4456
29	61281	628.0	89	65	163	0.000	31.6692	18.3348
30	61381	506.4	88	73	164	0.000	31.1136	22.7796
31	61481	382.3	90	76	165	30.480	32.2248	24.4464
32	61581	338.2	84	58	166	0.000	28.8912	14.4456
33	61681	735.5	77	51	167	0.000	25.0020	10.5564
34	61781	713.3	85	59	168	0.000	29.4468	15.0012
35	61881	390.8	79	64	169	0.000	26.1132	17.7792
36	61981	560.4	85	57	170	0.000	29.4468	13.8900
37	62081	432.1	88	67	171	0.000	31.1136	19.4460
38	62181	427.5	86	63	172	21.844	30.0024	17.2236
39	62281	243.6	77	64	173	1.016	25.0020	17.7792
40	62381	609.5	91	66	174	0.000	32.7804	18.8904
41	62481	671.8	97	77	175	0.000	36.1140	25.0020
42	62581	682.1	90	70	176	0.000	32.2248	21.1128
43	62681	197.5	83	66	177	15.494	28.3356	18.8904
44	62781	440.0	89	65	178	51.562	31.6692	18.3348
45	62881	674.0	92	73	179	0.000	33.3360	22.7796
46	62981	436.7	90	69	180	4.572	32.2248	20.5572
47	63081	361.3	81	69	181	0.000	27.2244	20.5572
48	70181	536.4	85	67	182	0.000	29.4468	19.4460
49	70281	444.4	88	70	183	0.000	31.1136	21.1128

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JDAY SIGNIFIES JULIAN DATE
PRECIPITATION (PPT) IS IN MILLIMETERS

OBS	DATE	SOLRAD	TMAX	TMIN	JDAY	PPT	CTMAX	CTMIN
50	70381	277.0	83	70	184	14.478	28.3356	21.1128
51	70481	374.8	84	70	185	1.524	28.8912	21.1128
52	70581	630.2	88	68	186	0.000	31.1136	20.0016
53	70681	644.6	87	68	187	0.000	30.5580	20.0016
54	70781	584.8	88	70	188	0.000	31.1136	21.1128
55	70881	595.9	91	74	189	0.000	32.7804	23.3352
56	70981	665.3	93	70	190	52.070	33.8916	21.1128
57	71081	688.2	95	74	191	0.000	35.0028	23.3352
58	71181	672.6	98	79	192	0.000	36.6696	26.1132
59	71281	656.8	98	80	193	0.000	36.6696	26.6688
60	71381	659.0	97	78	194	0.000	36.1140	25.5576
61	71481	640.9	100	79	195	0.000	37.7808	26.1132
62	71581	556.2	95	77	196	0.000	35.0028	25.0020
63	71681	555.7	91	75	197	0.000	32.7804	23.8908
64	71781	362.8	88	71	198	0.508	31.1136	21.6684
65	71881	256.2	85	72	199	35.560	29.4468	22.2240
66	71981	444.4	89	73	200	2.286	31.6692	22.7796
67	72081	482.8	90	72	201	0.000	32.2248	22.2240
68	72181	392.2	86	65	202	0.000	30.0024	18.3348
69	72281	416.0	85	68	203	0.000	29.4468	20.0016
70	72381	580.5	88	72	204	0.000	31.1136	22.2240
71	72481	213.8	86	70	205	9.398	30.0024	21.1128
72	72581	510.6	84	69	206	0.000	28.8912	20.5572
73	72681	333.4	79	68	207	55.372	26.1132	20.0016
74	72781	323.8	81	66	208	0.000	27.2244	18.8904
75	72881	202.0	79	61	209	0.000	26.1132	16.1124
76	72981	275.0	80	59	210	0.000	26.6688	15.0012
77	73081	386.6	86	67	211	0.000	30.0024	19.4460
78	73181	440.0	88	70	212	0.000	31.1136	21.1128
79	80181	600.8	93	72	213	44.450	33.8916	22.2240
80	80281	477.0	89	69	214	0.000	31.6692	20.5572
81	80381	602.8	91	71	215	0.000	32.7804	21.6684
82	80481	609.2	95	72	216	0.000	35.0028	22.2240
83	80581	546.0	94	70	217	10.160	34.4472	21.1128
84	80681	217.2	86	70	218	0.000	30.0024	21.1128
85	80781	626.0	83	65	219	8.382	28.3356	18.3348
86	80881	594.3	86	60	220	0.000	30.0024	15.5568
87	80981	504.1	86	66	221	0.000	30.0024	18.8904
88	81081	563.8	80	60	222	26.670	26.6688	15.5568
89	81181	608.4	83	57	223	0.000	28.3356	13.8900
90	81281	581.6	85	59	224	0.000	29.4468	15.0012
91	81381	188.8	82	70	225	7.366	27.7800	21.1128
92	81481	568.0	94	75	226	0.000	34.4472	23.8908
93	81581	394.0	89	72	227	0.000	31.6692	22.2240
94	81681	490.2	82	69	228	0.000	27.7800	20.5572
95	81781	353.8	74	63	229	0.000	23.3352	17.2236
96	81881	558.1	76	55	230	0.000	24.4464	12.7788
97	81981	564.0	78	54	231	0.000	25.5576	12.2232
98	82081	588.3	80	52	232	0.000	26.6688	11.1120

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OBS	DATE	SOLRAD	TMAX	TMIN	JDAY	PPT	CTMAX	CTMIN
99	82181	588.1	84	54	233	0.000	28.8912	12.2232
100	82281	567.6	87	57	234	0.000	30.5580	13.8900
101	82381	169.2	79	68	235	0.000	26.1132	20.0016
102	82481	508.4	87	62	236	0.508	30.5580	16.6680
103	82581	171.0	84	71	237	0.000	28.8912	21.6684
104	82681	414.8	83	64	238	4.318	28.3356	17.7792
105	82781	296.6	78	64	239	0.000	25.5576	17.7792
106	82881	347.2	80	59	240	1.270	26.6688	15.0012
107	82981	545.4	90	61	241	0.000	32.2248	16.1124
108	83081	433.6	96	75	242	0.000	35.5584	23.8908
109	83181	423.1	88	70	243	15.240	31.1136	21.1128
110	90181	521.2	75	59	244	0.000	23.8908	15.0012
111	90281	527.2	80	51	246	0.000	26.6688	10.5564
112	90381	373.2	87	59	246	0.000	30.5580	15.0012
113	90481	373.4	81	63	247	0.000	27.2244	17.2236
114	90581	449.6	88	66	248	0.000	31.1136	18.8904
115	90681	109.6	80	69	249	0.000	26.6688	20.5572
116	90781	476.6	78	67	250	4.826	25.5576	19.4460
117	90881	533.4	82	52	251	0.000	27.7800	11.1120
118	90981	531.4	86	52	252	0.000	30.0024	11.1120
119	91081	517.8	88	57	253	0.000	31.1136	13.8900
120	91181	295.2	87	68	254	4.572	30.5580	20.0016
121	91281	475.4	86	58	255	0.000	30.0024	14.4456
122	91381	452.6	90	55	256	0.000	32.2248	12.7788
123	91481	464.0	83	65	257	0.000	28.3356	18.3348
124	91581	418.8	76	56	258	0.000	24.4464	13.3344
125	91681	415.6	64	51	259	0.000	17.7792	10.5564
126	91781.	462.8	64	40	260	0.000	17.7792	4.4448
127	91881	487.6	74	36	261	0.000	23.3352	2.2224
128	91981	484.0	84	51	262	0.000	28.8912	10.5564
129	92081	473.6	88	59	263	0.000	31.1136	15.0012
130	92181	411.6	83	57	264	0.000	28.3356	13.8900
131	92281	406.0	74	58	265	0.000	23.3352	14.4456
132	92381	355.2	90	58	266	0.000	32.2248	14.4456
133	92481	104.8	79	67	267	25.400	26.1132	19.4460
134	92581	299.0	84	66	268	12.446	28.8912	18.8904
135	92681	429.6	79	69	269	0.000	26.1132	20.5572
136	92781	451.6	78	46	270	0.000	25.5576	7.7784
137	92881	350.6	83	50	271	0.000	28.3356	10.0008
138	92981	433.0	92	69	272	0.000	33.3360	20.5572
139	93081	371.0	91	69	273	25.400	32.7804	20.5572

Table 16A. CLIMATE DATA AT TRIBUNE, KAN. IN 1981

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TMAX AND TMIN ARE DAILY MAXIMUM AND MINIMUM TEMPERATURES IN DEGREES FAHRENHEIT
CTMAX AND CTMIN ARE DAILY MAXIMUM AND MINIMUM TEMPERATURES IN DEGREES CELSIUS
JDAY SIGNIFIES JULIAN DATE
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OBS	DATE	SOLRAD	TMAX	TMIN	JDAY	PPT	CTMAX	CTMIN
1	51581	394	77	43	135	0.000	25.0020	6.1116
2	51681	173	58	50	136	10.160	14.4456	10.0008
3	51781	128	64	49	137	7.620	17.7792	9.4452
4	51881	153	59	46	138	1.778	15.0012	7.7784
5	51981	695	61	32	139	0.508	16.1124	0.0000
6	52081	553	69	40	140	0.000	20.5572	4.4448
7	52181	667	82	48	141	0.000	27.7800	8.8896
8	52281	724	81	38	142	0.000	27.2244	3.3336
9	52381	696	75	49	143	0.000	23.8908	9.4452
10	52481	623	76	40	144	0.000	24.4464	4.4448
11	52581	651	79	51	145	0.000	26.1132	10.5564
12	52681	577	83	52	146	0.000	28.3356	11.1120
13	52781	472	83	56	147	0.000	28.3356	13.3344
14	52881	593	80	57	148	9.652	26.6688	13.8900
15	52981	283	75	57	149	1.778	23.8908	13.8900
16	53081	486	72	52	150	7.366	22.2240	11.1120
17	53181	669	76	49	151	0.000	24.4464	9.4452
18	60181	707	83	55	152	0.000	28.3356	12.7788
19	60281	794	80	54	153	0.000	26.6688	12.2232
20	60381	401	80	55	154	0.000	26.6688	12.7788
21	60481	742	82	48	155	0.000	27.7800	8.8896
22	60581	609	88	52	156	0.000	31.1136	11.1120
23	60681	577	89	54	157	0.000	31.6692	12.2232
24	60781	724	98	57	158	0.000	36.6696	13.8900
25	60881	691	100	57	159	0.000	37.7808	13.8900
26	60981	741	100	57	160	0.000	37.7808	13.8900
27	61081	724	93	56	161	0.000	33.8916	13.3344
28	61181	387	86	63	162	0.000	30.0024	17.2236
29	61281	684	96	58	163	0.000	35.5584	14.4456
30	61381	762	102	66	164	0.000	38.8920	18.8904
31	61481	743	100	57	165	0.000	37.7808	13.8900
32	61581	702	85	46	166	1.778	29.4468	7.7784
33	61681	773	85	39	167	0.000	29.4468	3.8892
34	61781	777	98	57	168	0.000	36.6696	13.8900
35	61881	600	74	52	169	0.000	23.3352	11.1120
36	61981	735	93	45	170	0.000	33.8916	7.2228
37	62081	722	95	59	171	0.000	35.0028	15.0012
38	62181	670	94	61	172	0.000	34.4472	16.1124
39	62281	647	86	61	173	0.000	30.0024	16.1124
40	62381	743	98	64	174	0.000	36.6696	17.7792
41	62481	725	95	62	175	0.000	35.0028	16.6680
42	62581	694	95	60	176	0.000	35.0028	15.5568
43	62681	724	100	62	177	0.000	37.7808	16.6680
44	62781	744	102	71	178	0.000	38.8920	21.6684
45	62881	666	100	69	179	0.000	37.7808	20.5572
46	62981	397	93	63	180	0.000	33.8916	17.2236
47	63081	360	85	62	181	0.762	29.4468	16.6680
48	70181	430	89	65	182	0.000	31.6692	18.3348
49	70281	540	95	65	183	12.700	35.0028	18.3348

Table 16A. CLIMATE DATA AT TRIBUNE, KAN. IN 1981

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OBS	DATE	SOLRAD	TMAX	TMIN	JDAY	PPT	CTMAX	CTMIN
50	70381	682	85	65	184	3.302	29.4468	18.3348
51	70481	510	89	64	185	0.000	31.6692	17.7792
52	70581	722	91	66	186	4.064	32.7804	18.8904
53	70681	747	93	53	187	0.000	33.8916	11.6676
54	70781	627	92	59	188	0.000	33.3360	15.0012
55	70881	689	92	66	189	0.000	33.3360	18.8904
56	70981	684	90	53	190	0.000	32.2248	11.6676
57	71081	723	98	65	191	0.000	36.6696	18.3348
58	71181	725	101	67	192	0.000	38.3364	19.4460
59	71281	730	103	64	193	0.000	39.4476	17.7792
60	71381	621	103	68	194	0.000	39.4476	20.0016
61	71481	315	97	67	195	0.000	36.1140	19.4460
62	71581	426	94	63	196	0.000	34.4472	17.2236
63	71681	709	92	57	197	1.270	33.3360	13.8900
64	71781	459	91	66	198	0.000	32.7804	18.8904
65	71881	535	85	62	199	10.668	29.4468	16.6680
66	71981	697	97	62	200	0.000	36.1140	16.6680
67	72081	722	98	60	201	5.842	36.6696	15.5568
68	72181	709	103	65	202	0.000	39.4476	18.3348
69	72281	231	75	64	203	0.000	23.8908	17.7792
70	72381	554	97	62	204	0.000	36.1140	16.6680
71	72481	479	97	68	205	0.000	36.1140	20.0016
72	72581	414	87	60	206	2.286	30.5580	15.5568
73	72681	307	83	62	207	0.000	28.3356	16.6680
74	72781	386	80	61	208	9.144	26.6688	16.1124
75	72881	402	76	58	209	1.778	24.4464	14.4456
76	72981	685	90	62	210	0.000	32.2248	16.6680
77	73081	704	94	63	211	0.000	34.4472	17.2236
78	73081	704	94	63	211	4.064	34.4472	17.2236
79	73181	693	96	63	212	0.000	35.5584	17.2236
80	80181	753	97	65	213	0.000	36.1140	18.3348
81	80281	502	88	64	214	1.270	31.1136	17.7792
82	80381	591	93	64	215	0.000	33.8916	17.7792
83	80481	639	98	64	216	0.000	36.6696	17.7792
84	80581	658	96	64	217	0.000	35.5584	17.7792
85	80681	371	85	69	218	0.000	29.4468	20.5572
86	80781	562	84	57	219	0.000	28.8912	13.8900
87	80881	590	87	50	220	0.000	30.5580	10.0008
88	80981	369	75	58	221	0.000	23.8908	14.4456
89	81081	192	73	56	222	2.540	22.7796	13.3344
90	81181	317	80	57	223	0.000	26.6688	13.8900
91	81281	168	70	57	224	0.000	21.1128	13.8900
92	81381	597	90	62	225	2.540	32.2248	16.6680
93	81481	511	93	60	226	0.000	33.8916	15.5568
94	81581	332	83	63	227	0.000	28.3356	17.2236
95	81681	357	80	62	228	5.588	26.6688	16.6680
96	81781	406	79	56	229	0.000	26.1132	13.3344
97	81881	458	80	51	230	0.000	26.6688	10.5564
98	81981	568	85	51	231	0.000	29.4468	10.5564

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OBS	DATE	SOLRAD	TMAX	TMIN	JDAY	PPT	CTMAX	CTMIN
99	82081	629	90	56	232	0.000	32.2248	13.3344
100	82181	616	95	60	233	0.000	35.0028	15.5568
101	82281	471	91	59	234	0.000	32.7804	15.0012
102	82381	638	88	51	235	0.000	31.1136	10.5564
103	82481	578	95	59	236	0.000	35.0028	15.0012
104	82581	606	95	58	237	0.000	35.0028	14.4456
105	82681	463	90	58	238	0.000	32.2248	14.4456
106	82781	436	80	53	239	0.000	26.6688	11.6676
107	82881	533	89	51	240	0.000	31.6692	10.5564
108	82981	645	99	50	241	0.000	37.2252	10.0008
109	83081	545	97	63	242	0.000	36.1140	17.2236
110	83181	297	77	62	243	0.000	25.0020	16.6680
111	90181	554	81	97	244	0.000	27.2244	36.1140
112	90281	595	93	50	245	0.000	33.8916	10.0008
113	90381	107	69	57	246	0.000	20.5572	13.8900
114	90481	366	73	53	247	51.562	22.7796	11.6676
115	90581	470	82	59	248	0.000	27.7800	15.0012
116	90681	426	85	60	249	0.000	29.4468	15.5568
117	90781	568	77	55	250	0.000	25.0020	12.7788
118	90881	572	80	50	251	0.000	26.6688	10.0008
119	90981	580	85	50	252	0.000	29.4468	10.0008
120	91081	563	91	51	253	0.000	32.7804	10.5564
121	91181	550	90	57	254	0.000	32.2248	13.8900
122	91281	437	86	57	255	0.000	30.0024	13.8900
123	91381	495	87	50	256	0.000	30.5580	10.0008
124	91481	538	85	50	257	0.000	29.4468	10.0008
125	91581	492	83	53	258	0.000	28.3356	11.6676
126	91681	166	60	48	259	10.668	15.5568	8.8896
127	91781	518	69	35	260	0.000	20.5572	1.6668
128	91881	545	76	38	261	0.000	24.4464	3.3336
129	91981	541	88	41	262	0.000	31.1136	5.0004
130	92181	459	93	51	263	0.000	33.8916	10.5564
131	92181	477	91	50	264	0.000	32.7804	10.0008
132	92281	491	87	46	265	0.000	30.5580	7.7784
133	92381	409	81	65	266	0.000	27.2244	18.3348
134	92481	343	84	61	267	0.000	28.8912	16.1124
135	92581	468	86	50	268	0.000	30.0024	10.0008
136	92681	502	85	52	269	0.000	29.4468	11.1120
137	92781	498	80	41	270	0.000	26.6688	5.0004
138	92881	444	94	53	271	0.000	34.4472	11.6676
139	92981	477	95	55	272	0.000	35.0028	12.7788
140	93081	289	73	53	273	0.000	22.7796	11.6676
141	100181	436	74	47	274	0.000	23.3352	8.3340
142	100281	440	80	44	275	0.000	26.6688	6.6672
143	100381	440	83	57	276	0.000	28.3356	13.8900
144	100481	466	81	42	277	0.000	27.2244	5.5560
145	100581	343	79	47	278	0.000	26.1132	8.3340
146	100681	394	68	38	279	0.000	20.0016	3.3336
147	100781	399	69	45	280	0.000	20.5572	7.2228

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OBS	DATE	SOLRAD	TMAX	TMIN	JDAY	PPT	CTMAX	CTMIN
148	100881	342	70	36	281	0.000	21.1128	2.2224
149	100981	275	67	46	282	0.000	19.4460	7.7784
150	101081	210	66	40	283	0.000	18.8904	4.4448
151	101181	387	68	47	284	0.000	20.0016	8.3340
152	101281	429	85	46	285	0.000	29.4468	7.7784
153	101381	366	74	50	286	0.000	23.3352	10.0008
154	101481	188	55	40	287	0.000	12.7788	4.4448
155	101581	66	55	40	288	0.000	12.7788	4.4448
156	101681	80	57	42	289	6.096	13.8900	5.5560
157	101781	397	57	34	290	0.000	13.8900	1.1112

Table 17A. Yield summary at Tribune and Manhattan.

Crop	Plot	Yield Grain dry weight
		kg/ha
Corn		
Manhattan	4	9,461
	8	8,285
	18	10,062
Tribune	2	6,858
	5	6,635
	10	6,091
Grain sorghum		
Manhattan	9	7,106
	11	6,990
	16	8,046
Tribune	7	3,367
	15	3,771
	18	4,167
Pearl millet		
Manhattan	10	1,766
	15	2,760
	17	2,114
Tribune	4	1,540
	9	1,619
	17	1,308
Pinto bean		
Manhattan	2	2,592
	7	2,912
	12	3,224
Tribune	1	2,357
	8	1,577
	13	1,438

Table 17A. Cont.

Crop	Plot	Yield Grain dry weight
		kg/ha
Soybean		
Manhattan	1	3,729
	5	3,721
	14	3,671
Tribune	3	1,714
	12	1,837
	14	1,955
Sunflower		
Manhattan	3	2,809
	6	2,427
	13	2,830

Evapotranspiration Relationships and Crop
Coefficient Curves of Irrigated
Field Crops

by

Mary Jene Hattendorf

B.S., Agronomy, Kansas State University, 1980

AN ABSTRACT OF
A MASTER'S THESIS

Submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Agronomy

Kansas State University
Manhattan, Kansas

1982

ABSTRACT

An agronomic study comparing water use of six crops was initiated in 1981 at the Ross Irrigation Field, Tribune, Kan., and the Ashland Evapotranspiration Research Site, Manhattan, Kan. The six crops evaluated were corn, grain sorghum, pearl millet, pinto bean, soybean, and sunflower.

Volumetric soil water content was measured periodically at both locations to the 3,140 mm depth with a neutron probe. Tensiometers were installed at the 180 and 210 cm depths in each plot at Tribune.

Tensiometer data at Tribune indicated that drainage and water movement in the profile at those depths were negligible. Total seasonal water use was highest for corn at Tribune, and lowest for pinto bean. Total seasonal water use at Tribune was significantly higher for corn than for soybean and pinto bean. At Manhattan, soybean total seasonal water use was significantly higher than that of pinto bean, but was not significantly different from total seasonal water use of corn, sunflower, or pearl millet.

Soil water depletion rate data at Manhattan were inconclusive because of the high amount of in-season rainfall received in 1981. Depletion rate data at Tribune indicated that corn depleted the soil more than the other crops. Depletion rates were highest for all crops in the 100-404 mm soil layer and progressively declined with succeeding 304 mm soil layers.

Evapotranspiration rates varied among crops at both locations and the data strongly indicated that time of peak evapotranspiration rate was highly dependent upon rate of crop growth and therefore dependent upon climate.

Growing degree units were used to measure length of growing season for each crop from crop emergence to physiological maturity. The final

sum of growing degrees was used as the denominator in a ratio of accumulated growing degrees at a selected date to total growing degrees. Evapotranspiration rates for each time period were divided by the potential evapotranspiration rate for the same time period.

Data from Tribune and Manhattan were pooled and regression analyses of the evapotranspiration ratio (dependent variable) vs. fraction of growing season (independent variable) for each crop were performed. The resulting crop coefficient curves can be used to estimate crop evapotranspiration and assist in optimizing irrigation scheduling and system design.