EVAPOTRANSPIRATION ESTIMATES AND INFRARED THERMOMETRY USE FOR IRRIGATION SCHEDULING IN THE OKLAHOMA PANHANDLE REGION

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PREFACE

This study focused upon the measurement and estimation of evapotranspiration (ET) for alfalfa, corn, grain sorghum, and soybeans in the Oklahoma Panhandle. In addition infrared thermometry was utilized to monitor canopy temperatures and canopy-air temperature differences for the four crops. These data were used to predict non water-stressed baselines and available soil moisture.

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CHAPTER I

INTRODUCTION

A large sector of the agricultural economy in Oklahoma is dependent upon the availability of voluminous quantities of fresh groundwater. In 1983 about 84 percent of the state's 302,000 hectares (747,000 acres) of irrigated land received supplemental water from underground sources (Schwab, 1983). The use of subterranean waters from the Ogallala aquifer and the expansion of agriculture in western Oklahoma are inseparable. In the Panhandle of Oklahoma alone virtually all irrigated land received water from the Ogallala formation in 1983 (Schwab, 1983). With the introduction of high volume, vertical turbine pumps into the Panhandle region, thousands of hectares have come under cultivation. This expansion has led to the development of a number of commercial and industrial support enterprises. Inexpensive natural gas and oil have fueled these rural economies and thus promoted a stable socioeconomic environment.

Unfortunately, the day of boundless resources and inexhaustible supplies, as envisioned by the first settlers to Oklahoma, has come to an end. Conservation of nonrenewable natural resources and terms such as "energy efficient" and "scarcity" have replaced the vocabulary of "infinite" and "inexhaustible" in minds of developers and regional planners.

Depletion of groundwater reserves and rising production costs have forced many Panhandle farmers to return to dryland farming. Production cost increases include those attributed to the continuing escalation of fuel prices and concurrent increases in pumping lifts. Fluctuating fuel prices may be partially regulated by governmental control, however pumping lifts may not be reduced unless some form of groundwater recharge is employed. Due to the confined nature of the Ogallala aquifer, and the distance to the nearest recharge source, artificial replenishment is currently an economic impossibility. As more and more farmers revert back to dryland farming, yields decrease and the risks of crop failure climb. This can shake the agricultural foundations of many rural communities and adversely affect supporting industries.

In the light of diminishing groundwater reserves and serious economic problems in agriculture, this project was conceived. Conserving existing water reserves by efficiently meeting crop needs is a logical step towards extending the economic life of the aquifer.

Background of the Study

The Great Plains territory extends west of the ninety-eighth meridian to the Pacific ranges in California and stretches northward from Mexico to Canada (Webb, 1931). The region's climate is characterized by chronic, often prolonged, periods of drought. While the Homestead Act was in force, and prior to 1880, the westward push of settlers nearly stopped at the ninety-eighth meridian due to the low annual levels of precipitation (Kraenziel, 1955). Settlers passed through the area but few remained in the Great Plains. The combined assault of high temperatures and dry winds frequently spelled economic disaster for those who chose to stay (Webb, 1931). To mitigate the withering effects of the environment, settlers in the Plains drilled shallow wells and employed windmills to meet domestic water needs. The location and size of these early, rural settlements were heavily dependent upon the volume and depth of groundwater reserves.

As agrarian societies continued to expand and commodity markets enlarged, settlers considered the idea of irrigated crop production. The feasibility of irrigated commercial farming in Oklahoma was first investigated in 1895 by the Optima Irrigation and Improvement Company (Green, 1979). The company's proposal was to divert water from the North Canadian River and convey water to local farms by constructing a canal. The canal was never built, but the concept of irrigated agriculture continued. The idea revived again when drought swept through the southwest region of the Great Plains in 1910. During this period a few 65 L/s (1,000 gpm) wells were drilled in Kansas, New Mexico, and Texas. Groundwater was then discovered in the

Oklahoma Panhandle at a depth of about 90 meters (300 feet). When the drought ended in 1913, interest in pumping water from such a depth waned due to the expense involved.

In the late 1930's groundwater development in the Southern High Plains progressively increased. Prior to World War II, the area was utilized almost exclusively for cattle grazing and dryland wheat (Triticum aestivum L.). It was during this period that Panhandle A & M College (now Panhandle State University) drilled the first well in the region. In 1947 the first privately owned well was drilled in the Oklahoma Panhandle. This event ushered in a new era of irrigated commercial farming. Within a few decades the entire region would switch from windmill pumping to high speed, vertical turbine pumps and extraction rates would soar from a few thousand liters per day to between 35 and 65 L/s (600 and 1000 gpm) (Green, 1979).

Withdrawals from the Ogallala aquifer accelerated after World War II as low-cost natural gas and other petroleum energy sources were developed in the region. According to Green (1979) and Schwab (1983), between 1950 and 1983 the irrigated area in the Oklahoma Panhandle grew from 4700 to 137,000 hectares (11,600 to 339,000 acres). Irrigated agriculture in the High Plains from Texas to Nebraska likewise jumped from 1.4 million hectares (3.5 million acres) in 1950 (High Plains Associates, 1982) to over 6.5 million hectares (16 million acres) in 1981 (U.S. Army Corps of Engineers, 1982). Annual withdrawal from the Ogallala climbed from 8.6 to 26 billion cubic meters (7 to 21 million acre-feet) during this period (High Plains Associates, 1982). Significant improvements in irrigation efficiency also were realized during this time. From 1950 to 1980 the depth of water applied to produce the same crop dropped from 0.61 to 0.43 meters (2 to 1.4 feet), (High Plains Study Council, 1982).

The deep fertile soils, flat terrain, extensive groundwater reserves, and cheap energy sources of the High Plains opened the door for a massive expansion of irrigated farms, feedlots, and their supporting industries. Dealerships specializing in farm and irrigation equipment, fertilizers, pesticides, milling, storage, etc., flourished. Between 1950 and 1980 feed grain production jumped from 4.1 to more than 34 million metric tons (150 to 1250 million bushels). The increase in grain production was needed to support the burgeoning feedlot industry. By 1977 the region was supporting over nine million head, or approximately 38 percent of the national total of grain-fed cattle (High Plains Study Council, 1982).

Statement of the Problem

In 1984 one third of the global harvest came from only 17 percent of the world's cultivated land area (Postel, 1985). This exceptional rate of productivity may be largely attributed to the supplemental use of irrigation water in meeting crop water requirements. As the world population continues to expand, the dependence and draft upon freshwater streams, lakes, and groundwater reserves for irrigation purposes accelerate.

Today, twenty percent of all irrigated cropland within the United States is threatened by the specter of diminishing groundwater reserves. Portions of the vast Ogallala aquifer of the High Plains are rapidly approaching a point of economic exhaustion (High Plains Associates, 1982). Since 1954 annual withdrawal rates have exceeded recharge (Bekure, 1971), and in many areas economic exhaustion of the aquifer has already occurred (Chowning, 1973). It is estimated (Postel, 1985) that during the past forty years 500 billion cubic meters (132 trillion gallons) have been withdrawn from the extensive aquifer that stretches from South Dakota to the western Panhandle of Texas (Fig. 1). Recent estimates by hydrologists indicate that the southern portion of the aquifer, which underlies 8,000 hectares (2.2 million acres) of Kansas, Oklahoma, New Mexico, and Texas, has already been reduced by half (Postel, 1985). Unless corrective countermeasures are expedited, it is estimated that the Ogallala's economic life will expire early in the next century (High Plains Study Council, 1982).

The water crisis facing High Plains farmers has been accentuated by recent rises in energy costs. For example, between 1974 and 1980 Oklahoma farmers saw the price of natural gas rise 500 percent (Hulsman, 1984). In conjunction with spiraling energy costs, diminishing natural

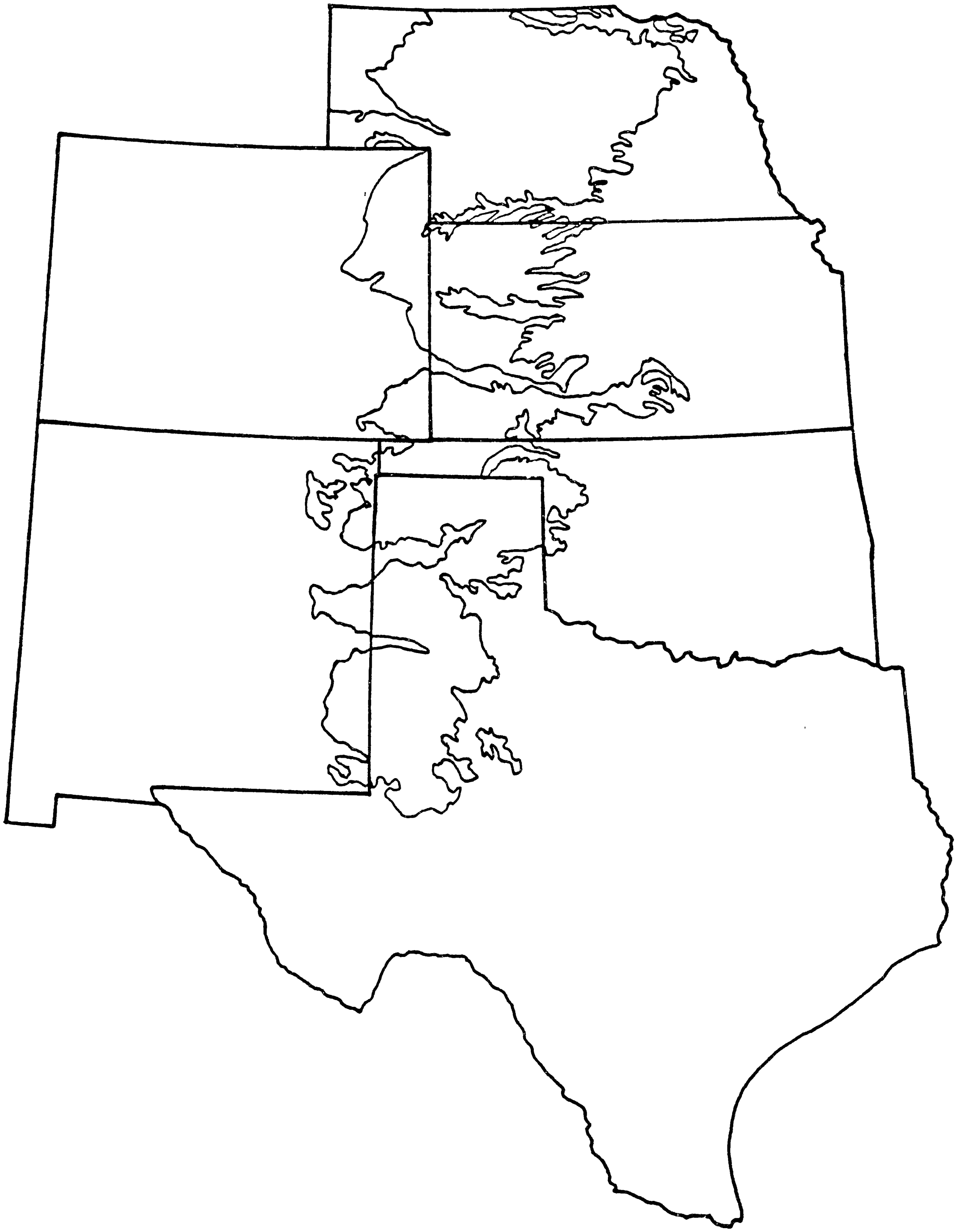

Figure 1. Approximate delineation of the Ogallala Aquifer (After High Plains Study Council, 1982).

gas and oil reserves, sluggish grain markets and depressed commodity prices have all contributed to the demise of irrigation farming.

Adverse water, energy, and marketing conditions have forced many farmers to return to dryland farming. It is estimated that between 1978 and 1982 the irrigated land in New Mexico, Oklahoma, and Texas dropped by 9, 18, and 20 percent, respectively (Postel, 1985). The ensuing socioeconomic consequences are summarized by the following statement:

> The simultaneous decline of the ground water and energy resource base of the High Plains Region threatens long-term impacts on the area's socioeconomic structure. Impacts will be felt in reduced levels of income by the labor force directly involved with irrigation enterprises and associated agribusinesses, and in reduced revenues to local, state and federal governments from property, income, and other taxes. Integrity of long-term investments may be jeopardized. Experience elsewhere indicates that the viability of small towns and communities dependent almost exclusively on the irrigated economy of the Region may be adversely affected. Public costs will increase to provide increased support for job training, income support, and certain health costs for the unemployed or underemployed. There may be significant environmental impacts. The impacts will be felt at the state and national levels as well as locally and regionally. (High Plains Associates, 1984, p. 1-4).

Rapidly declining groundwater levels of the Ogallala aquifer have accentuated the necessity of controlling the wastage that can be associated with traditional irrigation scheduling practices. Current scheduling techniques are based primarily upon the moisture stressed appearance of the crop, or upon a fixed, "by the calendar" interval. These methods have inherent flaws which can translate into inefficient water use at the farm level. Regardless of the scheduling technique used, water applied at the wrong time or in excess amounts is wasted water.

Ideally an irrigation should be metered in quantities sufficient to just meet crop water needs. An accurate assessment of crop water requirements based upon meteorological data and the stage of plant development is an essential element in the development of such a strategy.

Presently the Oklahoma Panhandle region is devoid of any locally calibrated equation for predicting the evaporative flux of field crops. A number of studies involving the economics of irrigation, crop growth modeling, and cropping strategies have been presented by other researchers with promising results. However, all have incorporated data extrapolated from areas outside of the immediate region. The need for an accurate accounting of evapotranspiration (ET) has been stated by these same researchers (Elliott, 1984; Mapp, 1975). Information on crop water requirements would be invaluable since the validity of past and future investigations involving water and energy conservation are dependent upon an accurate accounting of ET.

Objectives

The development of efficient quantitative techniques for scheduling irrigations is dependent upon the acquisition and analysis of local weather, soil, and crop data. Once pertinent field data are collected in the Oklahoma Panhandle region, the following objectives will be pursued:

1. To evaluate existing techniques for estimating ET.

2. To determine the feasibility of using infrared thermometry to estimate crop water stress.

To accomplish these objectives the following procedures will be implemented:

1. Various factors known to influence the hydrologic balance of the rhizosphere will be monitored and used in a water balance formula to calibrate ET rates for alfalfa (Medicago sativa L.), corn (Zea mays L.), soybeans [Glycine max (L.) Merr.] and grain sorghum [Sorghum bicolor (L.) Moench].

2. Non-stressed alfalfa ET rates will then be used to calibrate modified-Penman, Priestly-Taylor,and pan evaporation equations. The Jensen-Haise formula will be calibrated using local long term temperature data.

3. Coefficients will then be calculated which relate the ET flux rate of a row crop at a particular growth stage to that of non-stressed alfalfa.

4. Air temperature (T_a) and crop canopy temperature (T_c) measured with an infrared thermometer will be used to predict the percent of available soil moisture and to investigate a possible relationship between T_c-T_a and the vapor pressure deficit.

The development of ET estimating equations in conjunction with infrared estimates of crop water stress will facilitate the development of quantitative irrigation scheduling techniques. The adaptation of these methods at the local level could extend the economic life of the aquifer for years to come.

Scope

Crop ET is dynamic and responsive to an array of variables. Plant species, rooting depth, and stage of growth play an important role in determining the water requirements of a cultivar. Environmental factors such as solar radiation, temperature, rainfall, wind, soil moisture, and soil type play an important interactive role as well. By monitoring both crop ET and environmental factors it is assumed that a meaningful correlation may be established between the two. Once verified, the relationship may be employed to predict crop water requirements from daily summaries of meteorological events.

The applicability of the study is primarily confined to the three Panhandle counties of Beaver, Cimarron, and Texas, with the research site located at Goodwell in Texas County, Oklahoma. The information may be extrapolated beyond the Panhandle region, but only if discretion is exercised.

CHAPTER II

REVIEW OF LITERATURE

Irrigation Scheduling: An Emerging Science

Various methods of timing irrigation events to meet crop water needs have been developed. Scheduling techniques range in sophistication from a simple "feel" of the soil or a "water stressed" appearance of the crop (USDA Soil Conservation Service, 1964), to computer programs involving numerous physical inputs (Jensen, 1969). Qualitative methods of scheduling irrigation events require little or no capital investment to evaluate apparent moisture needs, but tend to either waste water via deep percolation and runoff, or reduce yields and net returns by inadequately replenishing soil moisture reserves. Quantitative approaches generally schedule irrigations more efficiently, but incur a data acquisition and analysis expense in proportion to the degree of efficiency desired.

As profit margins narrow and the viability of commercial farming is threatened, irrigators look to technology for answers to irrigation management questions. Given the proper input information, low-cost modern computers can aid in answering these questions, but often lack the necessary calibrated software for such tasks.

Although sophisticated programs for answering scheduling questions have been developed and refined by researchers (e.g. Day and Brase, 1985; Stegman and Coe, 1984), those which employ calibrated ET estimating equations lose their utility outside of the environment in which they were calibrated. The toll of imprecise scheduling information may be measured in one way by the reduction of program acceptance among irrigators (Shearer and Vomocil, 1981).

Measuring Evapotranspiration

To transform the qualitative art of irrigation scheduling into a quantitative science, field research at the local level is needed. Many ET measurement alternatives are available to the researcher but it is normally expedient to sacrifice accuracy in exchange for economic feasibility.

The most accurate, and most expensive, means of measuring crop ET employs a weighing lysimeter. Lysimeters are normally classified as either potential, weighing, or floating. Precision weighing lysimeters however are preferred over others for measuring reference crop ET rates (Rosenburg, 1974). A weighing lysimeter permits the measurement of water content fluctuations within a mass of soil over time. Measured changes reflect either the amount of moisture added to the soil via rainfall or irrigation or lost through deep percolation or ET. Unfortunately weighing lysimeters are quite expensive, thus limiting their usage in research (Rosenburg, 1974). This is one of the reasons that a weighing lysimeter could not be employed in this study.

Evapotranspiration rates may be estimated less precisely but more economically with an evaporation pan. Pans such as the U.S. Weather Bureau Class A are located at weather stations around the country. They are fairly inexpensive, and integrate many of the same climatic factors that influence crop ET. An evaporation pan was located on the Goodwell station and evaporative measurements were included as a part of this study.

One method of measuring crop ET accounts for variables that affect the hydrologic moisture balance in the rhizosphere. Figure 2 illustrates each of the components involved in the hydrologic balance and the following formula describes the interrelationships mathematically (Stegman, 1983):

$$S_t - S_{t-1}$$

$$ET = I + P - RO - DP - dS \qquad (2.1)$$

$$S_t = S_{t-1} - ET + I + P - RO - DP$$

where

ET = Actual evapotranspiration (mm)

I = Depth of irrigation (mm)

P = Depth of effective rainfall (mm)

RO = Depth of runoff (mm)

DP = Depth of deep percolation (mm) (Negative if capillary rise is present)

dS = Change in total soil moisture (mm)

The equation was selected for calculating crop water use in this study because of its widespread use in irrigation scheduling research, and its rational appeal. The equation is based on the law of conservation of matter, i.e. matter

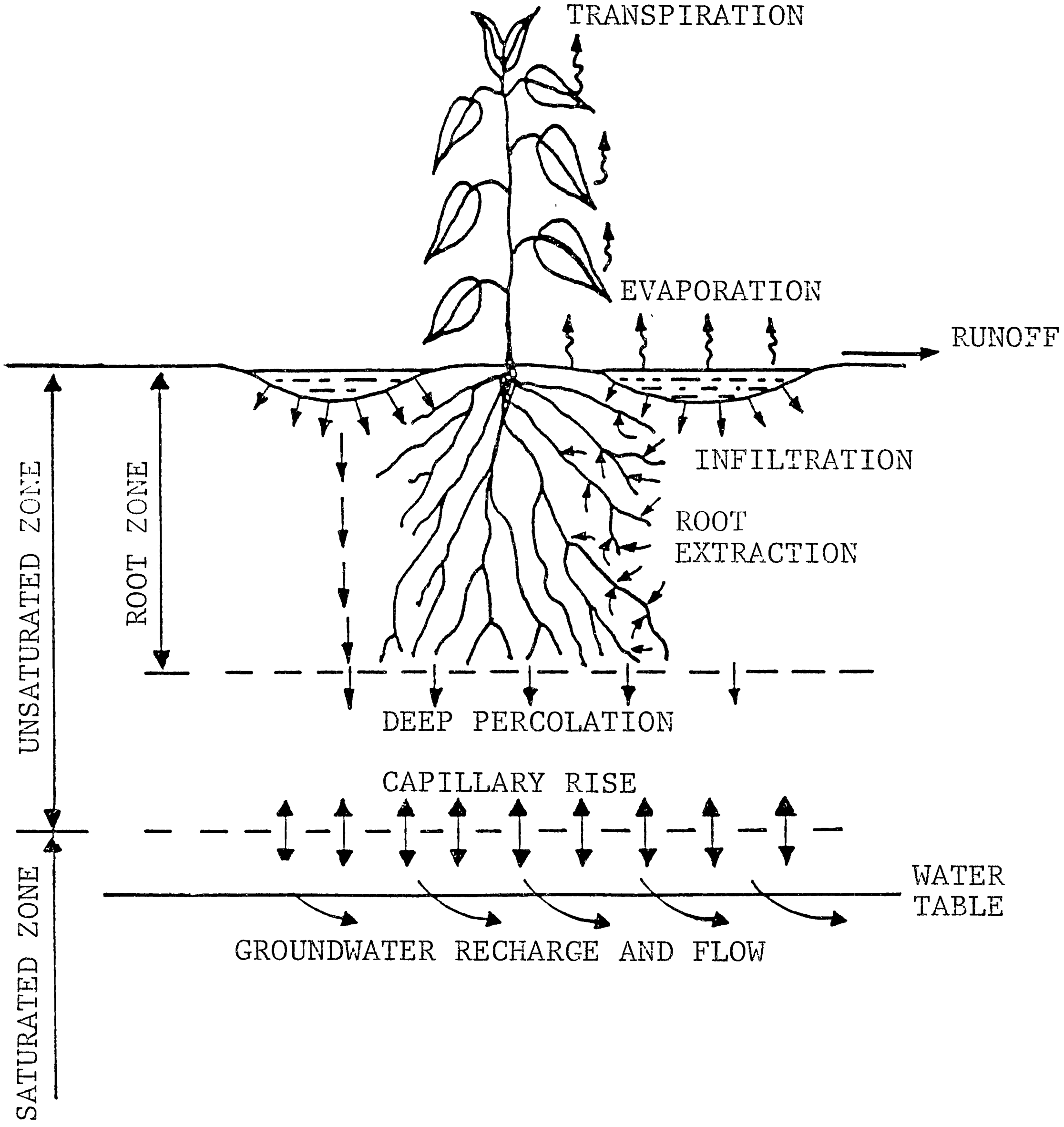

Figure 2. Water balance schematic of the rooting zone (After Hillel, 1982).

can't be created or destroyed, but simply changes from one location or state to another. Stated in more familiar terms, the equation accounts for all water entering into (rainfall + irrigation + capillary rise) or removed from (ET + deep percolation) the rooting zone or lost as surface runoff.

Precipitation, irrigation, and surface runoff terms in equation (2.1) tend to be discrete, while ET, deep percolation, capillary rise, and the change in total soil moisture are of a continuous nature (Rose, 1966). Terms on the right side of the equation may be measured directly or determined indirectly by formulas, and then actual ET calculated. Precipitation and sprinkler irrigation depths may be measured with a simple raingage, whereas surface irrigation depths may be calculated by knowing the rate, duration, and area of application. The runoff term may be quantified by integrating a hydrograph that describes the runoff characteristics of the watershed. Deep percolation, capillary rise, and the change in total soil moisture may be determined by periodically monitoring soil moisture tension with tensiometers and the water content with a neutron probe or other technique.

Evapotranspiration Estimation in Irrigation Scheduling

Well-watered, mature stands of alfalfa (Jensen et al., 1970) or grass (Doorenbos and Pruitt, 1977) are typically used as reference crops when measuring ET. Reference crop

ET (sometimes called potential evapotranspiration) may be defined as

> '. . . the evaporation from an extended surface of a short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water. Potential evapotranspiration cannot exceed free water evaporation under the same weather conditions. (Rosenburg, 1974, p. 172)'

In this study alfalfa was selected as the reference crop because it

> . . . has an extensive rooting system that minimizes the effects of decreasing soil water on ET; it provides a dense cover crop; it has a low leaf resistance to the diffusion of water vapor; and it is an aerodynamically rough crop (Wright and Jensen, 1972, p. 194).

By monitoring pertinent climatic variables in conjunction with field measurements of reference crop ET, weather-based ET estimating equations may be calibrated and incorporated into scheduling programs.

From calibrated ET estimating equations ET rates for well-watered crops may be found by multiplying by an appropriate crop coefficient. The value of the coefficient will vary depending upon the type of crop and its stage of physiological development. Representative values for each phase of development are determined initially by dividing measured well-watered crop ET rates by corresponding measured reference crop ETs (Wright, 1981).

If the available soil moisture limits plant growth, ET rates will be retarded. This reduction may be accounted for by multiplying the well-watered ET rate by a soil moisture adjustment factor. The details of this procedure and the use of crop coefficients are discussed in more length in the chapter entitled Methods and Procedures.

Once a reference ET estimating equation is calibrated and crop coefficients and soil moisture adjustment factors are known, irrigations may be scheduled by a computerized program, or by employing a "checkbook" type manual accounting method (Lundstrom et al., 1981). If irrigations are scheduled via computer, the weather-based estimating equation and all other relationships should become an integral part of the program. Regardless of the scheduling method selected, irrigations are usually called for when the available moisture reaches some predetermined lower limit. A standard threshold deficit of 50% available moisture is typically used (Doorenbos and Kassam, 1979).

The foregoing discussion outlined a sequence of events beginning with the measurement of reference crop ET, continuing with the calibration of weather-based ET equations, crop coefficients, and the soil moisture adjustment factor, and ending with its application at the farm level in terms of irrigation scheduling. The weakest link in this chain of events, as stated previously, centers around the calibration of weather-based ET estimating equations. To estimate reference crop ET, various theoretical and empirical formulas have been developed. Hill et al. (1983) note that there are "more than 50 methods and variations advanced for the theoretical estimation of ET". The advantage of developing a weather-based equation vis-a-vis using equation (2.1) to find reference ET may be realized in terms of reduced data acquisition and analysis costs. Once calibrated, the estimation equation may be incorporated into an irrigation scheduling software package and disseminated to county extension agents, competent consulting services of the private sector, and adept farmers.

The following discussion reviews the estimating equations used in this study and assumes the use of an alfalfa reference crop unless otherwise specified. The four methods evaluated were selected on the basis of their widespread use in related research, and the ease with which their various inputs could be monitored with the instrumentation on hand. Also, several of the other methods were eliminated because they use a grass reference crop. The Blaney-Criddle method was not included in this study because the minimum suggested time increment between ET estimates is one month (Hill et al., 1983). Durations of this length are not conducive to achieving the refinement and precision desired in a scheduling program.

Modified-Penman

The Penman equation (Penman, 1948) combines energy balance and aerodynamic terms into one equation for predicting reference crop ET; thus it is classified as a combination equation (Jensen, 1973). A simplified version of the original formula was developed for alfalfa and is given below:

$$E_{tr} = [d / (d + g)] (R_n + G) + [g / (d + g)] 15.36 W_f (e_a - e_d) \tag{2.2}$$

where

E_{tr} = Alfalfa based reference ET (cal/cm^2-d)

d = Slope of the vapor pressure-temperature curve (mb/°C)

g = Psychrometric "constant" (mb/°C)

R_n = Net radiation [positive towards the soil surface (cal/cm^2-d)]

G = Soil heat flux [positive towards the soil surface (cal/cm^2-d)]

15.36 = Constant of proportionality (cal/cm^2-d-mb)

W_f = Dimensionless wind function

e_a = Saturation vapor pressure at the mean daily air temperature (mb)

e_d = Saturation vapor pressure at the mean daily dew point temperature (mb)

$e_a - e_d$ = Mean daily vapor pressure deficit (mb)

Regardless of the form selected, the following quantities depend upon the weather and not the type of reference crop: incoming solar radiation, vapor pressure, the slope of the vapor pressure-temperature curve, and the psychrometric "constant". Conversely, net radiation and soil heat flux inputs are dependent upon the type of reference crop selected (Burman et al., 1980).

The utility of the modified-Penman ET equation in irrigation scheduling studies is evidenced by its prolific usage in related research. For example, Wright and Jensen

(1978) used the equation to determine reference ET for the USDA-ARS Computerized Irrigation Scheduling Program. Other examples of its use include research by Cope (1980), Elliott (1984), Hulsman (1984), and Norman and Campbell (1983).

Alternate forms of the equation have been presented by researchers investigating reference crop ET. Wright and Jensen (1972) calibrated the modified-Penman equation for Kimberly, Idaho by defining the regression coefficients of the wind function as a function of the calendar date. Allen and Wright (1984) used the same equation to compare results with measured reference ET from two weighing lysimeters.

On an international level, the Penman equation has been used to predict reference crop ET for grasses. Kristensen (1979) and Hansen (1980) both calibrated the equation using measured ET rates from well-watered plots of grass in Norway.

Priestley-Taylor

The many climatic inputs required to solve the modified-Penman equation often prompt researchers to resort to simpler estimating equations like the Priestley-Taylor formula (Priestley and Taylor, 1972):

$$E_{tr} = C\,[d\;/\;(d + g)]\;(R_n + G) \qquad (2.3)$$

where

C = Locally calibrated constant

A comparison between equations (2.2) and (2.3) reveals the Priestley-Taylor formula to be similar to the modified-

Penman equation but without an aerodynamic term. The formula is classified as a combination method (Hill, 1983), even though no advective term is included in the equation. The formula was originally calibrated from lysimeter data in humid and subhumid regions. It was primarily designed to determine reference crop ET for vegetation grown under nonadvective conditions. Advective conditions may be assumed when latent energy is greater than (R_n + G) (Jury and Tanner, 1975). In their original work Priestley and Taylor (1972) analyzed data from 11 sites (under non-advective conditions) and found C to be 1.26. Typically the value of C will fall between 1.26 and 1.35 (Hill et al., 1983). To adjust for periods of advection, Jury and Tanner (1975) developed a formula to predict C from the saturation vapor pressure at screen height, and the long-term mean saturation deficit for a period when advection was low. However, Kanemasu et al. (1976) found this approach to grossly underestimate ET.

Shouse et al. (1980) in Riverside, California selected the modified-Penman equation over the Priestley-Taylor. They found a single calibration of the Priestley-Taylor equation insufficient to describe the extreme changes in sensible heat advection from year to year. Watts and Goltz (1985) determined actual ET for irrigated potatoes in Maine during 1984 using a water balance approach. Priestley-Taylor ET was estimated by employing an additional factor to account for the soil water matric potential at 200 mm

(Goltz, 1980). In comparing actual with predicted ET, Watts and Goltz found a favorable similarity.

The Priestley-Taylor equation has also been used to predict reference ET for grass. Pochop et al. (1985) estimated monthly reference ET for Pawnee grasslands from 1972 through 1975 using the modified-Penman and Priestley-Taylor formulas. They found the Penman estimates of ET averaging 14 percent lower than lysimeter measurements. Using the Priestley-Taylor formula with C = 1.28, estimates averaged 20 percent lower than measured ET.

The Priestley-Taylor equation, like the modified-Penman, has had world-wide applications. Gunston and Batchelor (1983) analyzed mean monthly climatic data from 30 tropical stations situated between 25°N and 25°S latitude. In comparing the Priestley-Taylor and Penman methods of estimating reference ET it was found that both gave good approximations during those months when monthly rainfall exceeded monthly ET. The results were so encouraging that they concluded,

> . . . the Priestley-Taylor PE equation offers a satisfactory alternative to the Penman ET equation for estimating potential evapotranspiration (PET) in humid tropical climates (p. 65).

Green et al. (1984) in New Zealand compared reference crop ET measured with a weighing lysimeter to daily estimates using the Priestley-Taylor formula. Priestley-Taylor ET was reported to exceed measured reference ET by only 7% during a 30 day rain-free period.

Jensen-Haise

Jensen and Haise (1963) evaluated a 35-year compilation of 3,000 ET observations from soil moisture and lysimeter data in the Western United States. From approximately 100 observations of alfalfa reference crop ET, a linear relationship expressing reference ET was found.

After a few alterations the Jensen-Haise equation took on its current "modified" form (Jensen et al., 1970) and is classified as a radiation method (Jensen, 1973).

$$E_{tr} = C_t \ (T - T_x) \ R_s \qquad (2.4)$$

where

$C_1 = 38 - (2\ E\ /\ 305)$

$C_H = 50\ mb/(e_2 - e_1)$

$C_t = 1\ /\ (C_1 + 7.3C_H)$

e_1 = Saturation vapor pressure of water in mb at the mean minimum air temperature for the warmest month of the year

e_2 = Saturation vapor pressure of water in mb at the mean maximum air temperature for the warmest month of the year

E = Elevation above sea level (m)

R_s = Incoming short wave solar radiation (cal/cm^2-d)

T = Mean daily temperature (^oC)

$T_x = -2.5 - 0.14(e_2 - e_1) - (E\ /\ 550)$

Hill et al. (1983) compiled data on alfalfa and corn water use and yield from 18 sites in 17 western states. After multiplying E_{tr} in equation (2.4) by the elevation correction factor:

$$CF = 1.653 - (0.1640\ E/1000) \qquad (2.5)$$

where

CF = Correction factor

E = Elevation above sea level (ft)

their findings confirmed those of Jensen and Haise (1963) with the statement that the Jensen-Haise equation

> . . . was the most applicable ET method used at all alfalfa and corn sites included in this study with the exception of Grand Junction, followed closely by KMPEN [modified-Penman] (Hill et al., 1983, p. 3-46).

As with most weather-based equations, one form of the equation may work exceptionally well in one climatic zone and perform poorly in another. Rosenburg (1974) compared the original and modified Jensen-Haise methods with lysimetric measurements of ET from well-watered soybeans in Mead, Nebraska. In this case the modified version was reported to have underestimated actual ET much more seriously than the original version.

The Jensen-Haise formula has also had international applications. Work by Salih and Sendil (1984) in Saudi Arabia found the equation useful in predicting reference crop ET under very arid conditions. Al-Nakshabandi (1983) in Kuwait also found the formula helpful in arid climates. In comparing the modified-Penman and modified Jensen-Haise methods, he found a high degree of correlation ($r = 0.97$) and recommended the use of Jensen-Haise over Penman due to its simplicity.

Evaporation Pan

Perhaps the simplest and most universal reference ET estimating equation is the evaporation pan formula:

$$E_{tr} = K_p \, E_p \tag{2.6}$$

where

E_{tr} = Alfalfa based reference ET (mm/d)

E_p = Pan evaporation (mm/d)

K_p = Dimensionless pan coefficient

Before estimating reference crop ET from pan data, it is necessary to calibrate the dimensionless pan coefficient (K_p) from measured ET reference data. The calibration is accomplished normally by regressing measured reference crop ET on measured pan evaporation.

Values of K_p are dependent upon the size of pan, the type and density of vegetation surrounding the pan, the reference crop and climatic factors. Typical values of K_p for a U.S. Weather Bureau Class A Pan range from 0.6 to 1.0 (Hill et al., 1983).

Multiplying pan evaporation by a coefficient to account for all factors affecting a complex, dynamic phenomenon like reference crop ET inevitably introduces estimating errors. Shouse et al. (1980), in comparing the pan method in Riverside, California with the Priestley-Taylor and modified-Penman equations, found the method to yield the poorest results when either weekly or seasonal estimates were considered.

In arid areas pans may seriously underestimate reference ET. This is primarily due to high advective conditions and the aerodynamically "rough" surface of crops. The roughness of the crop allows more sensible heat to be withdrawn from passing air (Rosenburg, 1974), thus accelerating the conversion to latent energy. An aerodynamically "rough" surface stands in contrast to the evaporation pan which confines an aerodynamically "smooth" body of water.

The evaporation pan has perhaps its greatest utility in humid regions, i.e., areas of low sensible heat advection. Rosenburg and Powers (1970), working with soybeans in Mead, Nebraska, reported that pan estimates of ET were lower than lysimetric measurements of actual ET during periods of high sensible heat advection. In contrast, ET pan measurements over-predicted the ET of the same crop during periods of low sensible heat advection.

In spite of its shortcomings, the pan method persists as a viable alternative for estimating reference crop ET. Sands et al. (1984) used pan evaporation data to estimate reference ET in a modified version of the SPAW model for water budgeting (Saxton et al., 1974). Dugas and Ainsworth (1983) used the evaporation pan, Priestley-Taylor and Penman equations to determine reference ET in Texas. In comparing total annual reference ET they found Penman estimates similar to those measured by the evaporation pan. They then proceeded to evaluate data from 16 National Weather Service evaporation pans and constructed average daily pan evaporation maps for the entire state.

A pragmatic approach towards reducing the cost of on-site estimates of crop ET using evaporation data was described by Westesen and Hanson (1981). By substituting a No. 1 wash tub for an evaporation pan, the capital investment cost was reduced from $500 to $10. Their research indicated that reference crop ET estimates using a No. 1 wash tub were compatible with estimates using a Weather Bureau Class A evaporation pan. Inexpensive innovations like this appeal to farmers because of the possibility of enhancing water use efficiency at a minimal cost.

Infrared Thermometry Use in Irrigation Scheduling

Background

Most irrigation scheduling methods use soil, weather, or plant based criteria to determine the appropriate timing of an irrigation event. With soil-based methods irrigations are initiated when measured available soil moisture falls below a minimum percentage. Weather-based methods also use a minimum soil moisture percentage but moisture levels are estimated by monitoring climatic variables which affect the hydrologic balance of the rhizosphere. Weather-based methods were described in more detail in the previous section.

Since the main objective in scheduling an irrigation is to meet crop water needs, a direct, plant-based measurement of crop water stress is perhaps the best criterion to use for decision making (Geiser et al., 1982). Plant-based assessment of crop water stress has traditionally focused upon the measurement of leaf water content or leaf water potential. Although these indicators may be considered superior in comparison to other means of determining crop water stress, they ". . . are time consuming and require numerous measurements in order to characterize a field" (Jackson, 1982, p. 44).

Plant-based methods of scheduling irrigations have also been hampered by a lack of pertinent crop information. For example, Hiler and Clark (1971) and Hiler et al. (1974) developed the stress day index (SDI) method for scheduling irrigations. The SDI was determined using the following equation:

$$SDI = \sum_{i=1}^{n} (SD_i)(CS_i) \qquad (2.7)$$

where

CS = Susceptibility of crop yield to a given water deficit

i = Growth stage

n = Number of growth stages considered

SD = Duration and degree of plant water deficit

The acceptance and utilization of the SDI concept has been hindered by an "incomplete definition of yield susceptibilities as complete functions of water stress indicators" (Stegman, 1983, p. 2).

Significant strides have recently been made with plant-based irrigation scheduling using canopy temperature measurements. Past attempts at using foliage temperatures for scheduling purposes had a measurable degree of success, but required laborious efforts to implant thermocouples into plant tissue (Ehrler, 1973). Portable infrared (IR) thermometers such as the Telatemp Model AG-42[1] and Everest Model 112 Agri-Ther[2] have obviated the need for contact temperature methods, and allowed the rapid, integrated measurement of crop canopy temperature (Pinter, 1982; Jackson, 1982). Since physical contact with the crop is not required, the possibility of heat flow errors (often associated with "contact" type thermometers) is also eliminated.

Infrared Thermometry and the Effects of Azimuth Angle, Viewing Angle, and Shading on Canopy Temperature

Infrared radiation is electromagnetic radiation in the wavelength interval from about 0.75 mc to approximately 1000 mc (Everest Interscience, 1984). Infrared thermometers measure the radiation emitted by an object and then relate emitted radiation to a surface temperature. Because plant tissue does not radiate as a perfect blackbody, the radiation measurements must be adjusted accordingly. Emissivity correction factors for plant tissue have been

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[1] Telatemp Corp., Fullerton, CA.
[2] Everest Interscience, Tustin, CA.

measured in the range of 0.971 to 0.976 (Fuchs and Tanner, 1966; Blad and Rosenburg, 1976), and for field research an emissivity value of 0.98 is typically used (Everest Interscience, 1984). Once radiation measurements are adjusted for emissivity, surface temperatures may then be accurately determined.

Three factors should be considered when monitoring canopy temperature: azimuth angle, viewing angle, and shading. Azimuth angle is usually defined as the clockwise angle measure from the local meridian, and ranges from 0° to 360°. Fuchs et al. (1967) reported that the azimuth angle of the sun and row direction have a small effect on measured canopy temperature. More recently, Clawson and Blad (1982) measured corn temperature with an IR thermometer and reported negligible directional effects. However Nielsen et al. (1984), measuring the canopy temperature of soybeans from the four cardinal directions (N,S,E,W) and at varying azimuth angles relative to the sun, had some conflicting conclusions. Redefining the azimuth angle to be 0° with the sun positioned directly behind the observer's back, canopy temperature was observed to decrease linearly as the azimuth angle increased from 0° to 110°. Canopy temperatures taken at azimuth angles greater than 110° remained fairly constant (approximately 0.3°C below the average of the four cardinal temperature readings). They concluded that an average canopy temperature could be best approximated by viewing the canopy from various azimuth angles. The study also supported the hypothesis that average canopy temperature may be measured using only one reading, i.e., if the azimuth angle were greater than 110°.

Recent studies have demonstrated the dependency of canopy temperature upon the IR thermometer viewing angle. Hatfield (1979) measured the canopy temperature of wheat in the nadir position (i.e. directly above the point of measurement) and at 45° from nadir in the four cardinal directions. Errors from the inclusion of soil surface temperature with canopy temperature were found most troublesome in the nadir position, prior to complete canopy coverage. Kimes et al. (1980) reported similar findings with soybeans. Errors may also be introduced if viewing angles are within 30° of the nadir position. Jackson et al. (1979) found that the apparent temperature of sunlit cotton (Gossypium hirsutum L.) leaves rose for viewing angles less than 30° from the nadir position.

To accurately assess crop canopy temperature, IR viewing angles should be great enough, with respect to the nadir position, to eliminate any integration of soil temperature and yet acute enough to avoid the integration of horizon sky temperature. Normally viewing angles ranging from 60 to 75 degrees suffice. Howell et al. (1984) found a viewing angle between 60 and 70 degrees from the nadir position adequate for measuring the foliage temperature of cotton. Pinter and Reginato (1982), also working with cotton, found a viewing angle ranging between 65 and 75 degrees to be sufficient.

A strong correlation between incoming solar radiation and foliage temperature has been documented for cotton (Wiegand and Namken, 1966; Wiegand and Swanson, 1973) and for sorghum (Stone et al., 1975). Complementary studies have demonstrated the dependency of canopy temperature upon the degree of shading. Kimes (1981) reported maximum canopy temperature measurements when viewing sunlit leaves and minimum temperatures when viewing shaded leaves. Fuchs et al. (1967) reported a difference of 3° C between the canopy temperatures of sunlit and shaded soybean leaves. Thus only leaves subjected to full sunlight should be monitored when assaying water stress from canopy temperature.

Canopy Temperature Scheduling Methods

There are three methods commonly employed for scheduling irrigations from canopy temperature measurements. The first method (Wiegand and Namken, 1966) assumes a positive canopy minus air temperature differential (T_c - T_a) to be indicative of water stress and the need to commence irrigating. Further refinements and improvements using the T_c - T_a stress concept are discussed in the next section. The second method (Fuchs and Tanner, 1966) schedules an irrigation whenever the difference between the canopy temperature of a stressed and non-stressed (well-watered) crop exceeds a threshold value. The third method (Aston and van Bavel, 1972) schedules irrigations whenever the range of canopy temperature readings exceeds a threshold value.

Canopy - Air Temperature Differential. Canopy minus air temperature methods (T_c - T_a) assume that transpired water evaporating from leaves will cool the crop canopy below ambient air temperature. Canopy temperature is dependent upon the radiant energy absorbed by the leaf, the rate of evaporative cooling, and the rate of sensible heat exchange (Ehrler and van Bavel, 1967). As a plant begins experiencing water stress, stomatal resistance to vapor diffusion increases (Salisbury and Ross, 1978). This causes a reduction in transpiration and a shift from the removal of the heat load via evaporative cooling to dissipation via convection and thermal reradiation (Hall, 1982; Keener and Kircher, 1983). This was confirmed by Hatfield (1981) who reported increasing stomatal resistance in proportion to rising leaf temperature. It is the rise in thermal reradiation that accounts for an increase in canopy temperature under stress (Kirkham, 1983).

A good correlation between T_c - T_a and traditional indicators of physiological drought stress has been established. Ehrler et al. (1978a) and Carlson et al. (1972) reported a negative correlation between T_c - T_a and both leaf water content and leaf water potential. Ehrler et al. (1978b) also measured diurnal fluctuations of plant water potential concurrently with canopy temperatures and found maximum stresses occurring near solar noon. Work by Blad et al. (1981) supported their conclusion that 1400 hr was the best time of day to monitor crop water stress and canopy temperature.

Building upon the work of Wiegand and Namken (1966), Idso et al. (1977) and Jackson et al. (1977) developed the Stress Degree Day (SDD) method for scheduling irrigations. The SDD may be expressed by the following formula:

$$SDD = \sum_{i=1}^{n} (T_c - T_a) \qquad (2.8)$$

where

i = Incremental date

n = Number of days for which $T_c - T_a$ is positive

SDD = Stress Degree Day

T_c = Canopy temperature at solar noon (°C)

T_a = Ambient temperature at solar noon (°C)

If $T_c - T_a$ is negative, SDD is assumed zero for computational purposes. All positive SDDs measured since the last irrigation are summed and irrigation initiated if the sum exceeds a management-determined threshold value. Jackson et al. (1977) used a threshold value of 10 for wheat, which also corresponded to the removal of 65% of all extractable water from the upper one meter of soil.

From a physiological standpoint, correlations between leaf water potential and the SDD have been found by Ehrler et al. (1978a) working with wheat and Hatfield (1981) working with sorghum.

A central and perhaps erroneous assumption of the SDD method is that water stress is present only when the SDD is greater than zero. The validity of this supposition is dubious because the stress-nonstress threshold is dependent upon the prevailing psychrometric conditions (Jackson, 1982). In an arid area, where air temperatures may exceed well-watered canopy temperatures by more than 10° C (Jackson, 1982), Gardner et al. (1981a) found the temperature of stressed corn to fall below ambient air temperature during much of the study period. In contrast, Jackson (1982) reported that, under conditions of high humidity, well-watered leaf temperatures will tend to be near or exceed that of ambient air. For example, Sumayao et al. (1980) found leaf temperatures of well-watered corn and sorghum to be warmer than air when ambient air temperature was greater than 33° C. Idso et al. (1981b) argued that this phenomenon was dependent upon the vapor pressure deficit (VPD) at the time of measurement. The dependency of $T_c - T_a$ on psychrometric conditions was also noted by Carlson et al. (1972) and Ehrler (1973), who found an inverse linear relationship between $T_c - T_a$ and VPD. In Manhattan, Kansas, Kirkham et al. (1983) measured the temperature of ambient air and an alfalfa canopy under seven watering treatments during the 1980 and 1981 growing seasons. One year was significantly drier than the other (157 mm and 471 mm of precipitation, respectively). They reported that canopy temperatures during the dry year were generally cooler than those observed during the wet year. Regardless of the year considered, canopy temperatures were observed to cool in proportion to the rise in VPD, thus demonstrating the dependency of the SDD upon psychrometric conditions.

To rectify this problem, Idso et al. (1981c) developed a plant water stress index (PWSI) that normalized the SDD with respect to prevailing ambient air VPD. In order to determine the PWSI, an upper and lower baseline, representing maximum and minimum possible $T_c - T_a$'s over a range of VPDs common to the area, must first be plotted (Fig. 3). The upper baseline represents the relationship between $T_c - T_a$ and the VPD for a crop subjected to water stresses inducing near metabolic collapse. The upper baseline plots as a straight line because $T_c - T_a$ is independent of the VPD at stress levels nearing metabolic collapse. Idso et al. (1981a) developed an empirical procedure using the ambient air temperature to predict the position of the stressed baseline. A second, lower baseline describes the linear relationship between $T_c - T_a$ and the VPD for a well-watered crop transpiring at the potential or energy-limiting rate (Idso et al., 1980, 1981a, 1981b, 1981c). With the establishment of an upper and lower baseline, the PWSI may then be determined for any $T_c - T_a$ and VPD. For example, the PWSI for an observation falling at point P (Fig. 3) may be calculated by dividing the vertical distance from P to the lower baseline by the vertical distance between the upper and lower baselines corresponding to the VPD at T_a. A PWSI of 1 indicates total

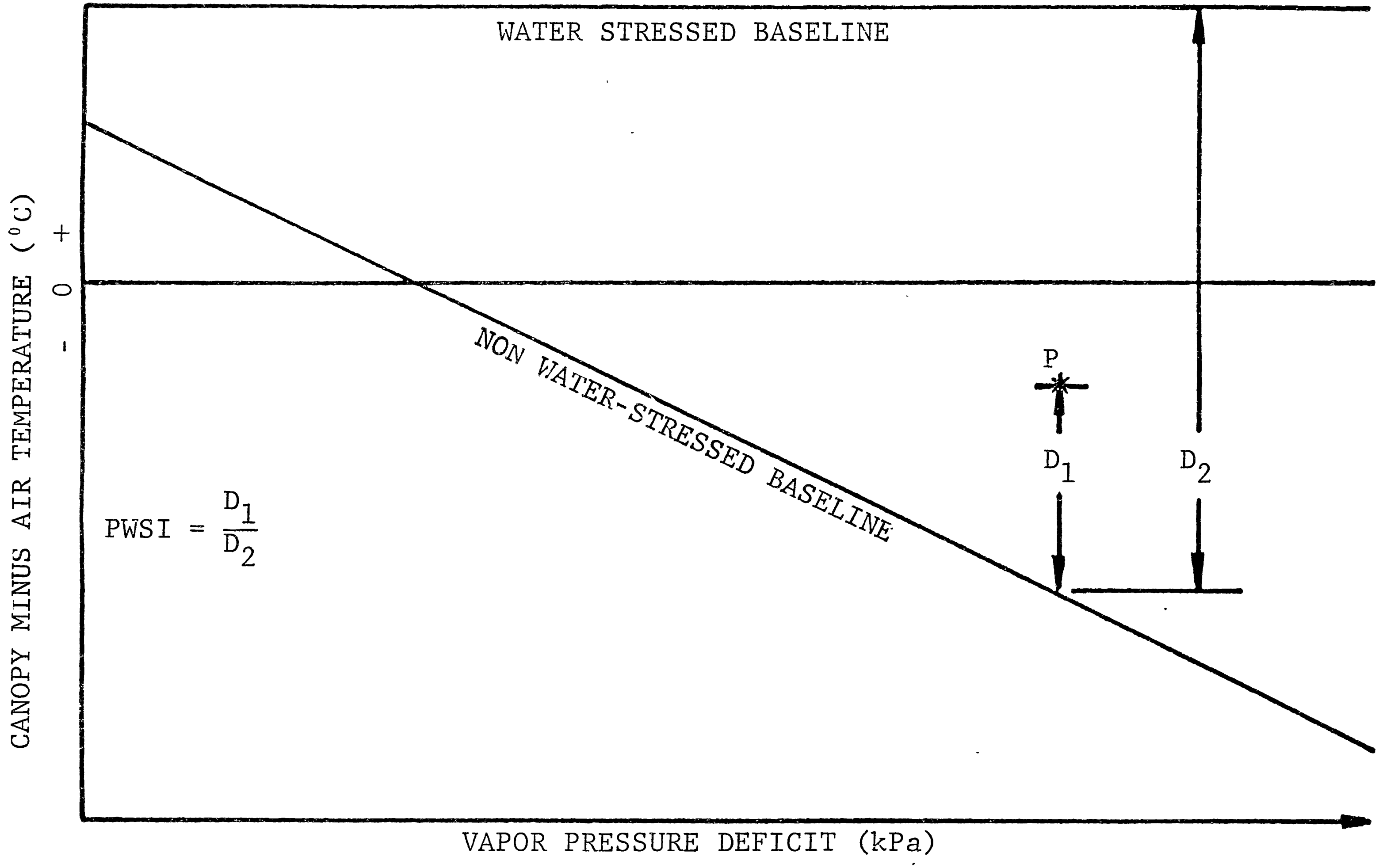

Figure 3. Graphical representation of the plant water stress index (PWSI). (After Idso et al., 1981a)

stress and a PWSI of 0 implies no stress. Idso (1982) determined well-watered baselines for 26 crop species located in Arizona, Kansas, Minnesota, and North Dakota. Baselines of some crops shifted significantly in moving from vegetative to reproductive stages. Baselines of crops subjected to shading fell sharply below those under full sunlight, thus demonstrating the dependency of the PWSI on net radiation.

When IR temperatures are supplemented with additional meteorological information, a more accurate assessment of crop stress is possible. Geiser et al. (1982) developed an irrigation scheduling model using $T_c - T_a$ and found by step-wise regression techniques that net radiation and humidity have a significant effect upon $T_c - T_a$. Geiser et al. (1982) and Slack et al. (1981) reported that the inclusion of net radiation enhanced their ability to predict crop stress. They concluded that radiation should be monitored in addition to leaf temperature. Idso et al. (1981c) and Jackson and Pinter (1981) also emphasized the need for supplemental net radiation measurements, especially for humid environments. O'Toole and Hatfield (1983), in determining the upper $T_c - T_a$ baseline, found the term to be sensitive to wind speed. To compensate for wind effects, they suggested that a correction factor be utilized.

To account for net radiation and aerodynamic factors, Jackson (1982) suggested using a crop water stress index (CWSI) given by the following formula:

$$CWSI = 1 - (E / E_p) \tag{2.9}$$

where

$$\frac{E}{E_p} = \frac{d + g^*}{d + g(1 + r_c/r_a)}$$

so

$$CWSI = \frac{g(1 + r_c/r_a) - g^*}{d + g(1 + r_c/r_a)}$$

where

$$g^* = g(1 + r_{cp}/r_a)$$

$$\frac{r_c}{r_a} = \frac{g\ r_a R_n/(pc_p) - (T_c - T_a)(d+g) - (e_{A*} - e_A)}{g[(T_c - T_a) - r_a R_n/(pc_p)]}$$

and

c_p = Heat capacity of air (J/kg-°C)

CWSI = Crop water stress index

d = Slope of the saturated vapor pressure-temperature curve (Pa/°C)

e_A = Saturated vapor pressure of air (Pa)

e_{A*} = Vapor pressure of air (Pa)

g = Psychrometric constant (Pa/°C)

p = Density of air (kg/m^3)

r_c = Canopy resistance (sec/m)

r_a = Aerodynamic resistance (sec/m)

r_{cp} = Canopy resistance at potential evapotranspiration (sec/m)

R_n = Net radiation (W/m^2)

T_c = Canopy temperature (°C)

T_a = Air temperature (°C)

The theory behind the CWSI was developed by Monteith and Szeicz (1962).

Keener and Kircher (1983) evaluated the SDD, PWSI, and

CWSI scheduling methods to assess drought stress in humid regions. They concluded that the variability of VPD in humid regions requires the inclusion of a VPD term in T_c - T_a based drought indexes. There was some indication that the inclusion of net radiation could be advantageous as well.

Although the CWSI may predict physiological drought stress more accurately than either the SDD or PWSI methods, it does have definite drawbacks. Jackson and Pinter (1981) plotted the CWSI of wheat with time and found CWSI to decline to a minimum value 2 to 3 days after an irrigation. They suggested that the recovery period, the changing root zone, and senescence could raise doubts about the validity of using one-time-a-day temperature measurements. Perhaps the greatest hindrances to the general acceptance of the CWSI method are the instrumentation, monitoring, and computational costs involved.

Stressed - Well-Watered Plot Temperatures. Irrigations may also be scheduled when the canopy temperature of a stressed plot exceeds that of a well-watered crop by some threshold value (a well-watered plot is used as a reference to compensate for the environmental effects of VPD, wind, and T_a). Gardner et al. (1981b) defined the difference between a stressed and well-watered canopy as the temperature stress day (TSD).

The TSD method has been used by researchers for a number of years. Tanner (1963) was one of the first to use

IR thermometry for monitoring the canopy temperatures of well-watered and stressed crops. Early work by Clark and Hiler (1973) showed leaf temperatures of well-watered peas to be 2-3° cooler than stressed ones and suggested the differential be used to schedule irrigations. Heermann and Duke (1978) reported that a significant reduction in corn yield could be expected if the TSD were allowed to exceed 1.5° C. Clawson and Blad (1980) began irrigating when TSD plots became 1° C and 3° C warmer than well-watered plots. Later Clawson and Blad (1982) successfully scheduled irrigations using a TSD of 1° C on corn near Tryon, Nebraska.

Canopy Temperature Variability. The range in canopy temperature may also be used to determine the scheduling of an irrigation, but is not commonly employed in comparison to other IR based methods. Aston and van Bavel (1972) suggested that the heterogeneity of soils would naturally result in a heterogeneity of measured canopy temperatures. They hypothesized that the canopy temperature variability (CTV) would become more pronounced as a crop experienced higher levels of water stress. They then proposed that irrigations be scheduled whenever a threshold CTV was exceeded. Research by Blad et al. (1981) and Gardner et al. (1981a) favorably demonstrated the utility of the CTV method for irrigation scheduling. Clawson and Blad (1982) successfully used this method on corn by employing a CTV of 0.7° C.

To evaluate the utility of the infrared and ET estimating methods for application in the Panhandle region, field experiments were conducted in 1984 and 1985 near Goodwell, Oklahoma. A description of the region and the procedures used to collect the data are given in the following section.

CHAPTER III

METHODS AND PROCEDURES

Site Description

The Oklahoma Panhandle is an eastwardly sloping plateau that descends from an elevation of 1520 m (4980 ft) along the northwest edge of Cimarron County to 610 m (1990 ft) along the eastern boundary of Beaver County (Hart et al., 1976). The three Panhandle counties of Beaver, Texas and Cimarron lie along an east-west line at approximately 37 degrees north latitude and between 100 and 103 degrees west longitude. The semi-arid climate of the region supports the production of irrigated alfalfa and grain sorghum during a six month growing season. It is during this period (May - October) that most of the region's 400 to 500 mm (16 to 20 in) of annual precipitation falls (Harris, 1981). Later in the fall, winter wheat is planted, vernalized over the winter, and then harvested the next spring. The progressive accumulation of rainfall and winter snowmelt in the root zone normally forms a reservoir sufficient to meet the water needs of dryland wheat up to maturity.

Many meters below the surface of the Panhandle lie the extensive waters of the Ogallala. The formation may be delineated into three basins by the Arkansas River in southwestern Kansas and the Canadian River in the Texas Panhandle. The central basin of the formation underlies 16,000 km^2 (6300 mi^2) of land in Oklahoma and encompasses all or parts of Beaver, Beckham, Cimarron, Dewey, Ellis, Harper, Roger Mills, Woods, Woodward, and Texas Counties. In the Panhandle alone, the aquifer thickness ranges up to 200 m (700 ft) (Oklahoma Water Resources Board, 1983). The spatial variation is due to the irregular surface over which the Ogallala was deposited thousands of years ago (Oklahoma Water Resources Board, 1984). The local composition of the strata varies from thin limestone, lenses of gravel, and interbedded sands, to siltstone, clay, and caliche (Lamerand, 1971).

Approximately 2450 high-capacity wells have been drilled in the Panhandle area with flow rates ranging from 30 L/s to 60 L/s (500 to 1000 gpm) (Oklahoma Water Resources Board, 1984). Well concentration is densest in areas north of Goodwell, south of Guymon, and in the northwest corner of Texas County. In Cimarron County, high concentrations are found near Felt and Boise City (Oklahoma Water Resources Board, 1984). The withdrawals from these and other well-fields dwarf the 8 mm (0.3 in) of annual natural recharge (Sharples, 1969). Thus hydrologists modeling the formation usually consider the Ogallala as a closed system, with only water removal by wells and movement within the aquifer affecting water levels (Chowning, 1973).

Field research was conducted at the Panhandle Research

Station near Goodwell, Oklahoma. The 13.5 ha (33 ac) station lies at an elevation of 1005 m (3297 ft) and is located at 36.6° N. latitude and 101.5° W. longitude. With the exception of alfalfa, all field data were collected from research plots located on the station grounds. Alfalfa plots were located 10 km (6 mi) northwest of the station and situated within a 53 ha (130 ac) field of mature, irrigated alfalfa. Richfield clay loam was the predominant soil type at both locations. A dense layer of caliche was found in the alfalfa plots at a depth of approximately 1 m (3 ft).

Experimental Design

Four crops were selected for both the ET and infrared temperature studies: alfalfa, corn (TE 6996), sorghum (Pioneer 8501), and soybeans [OKSOY (Calland)]. All annual crops were planted in 100 m (330 ft) rows in 1984 (Fig. 4). Corn and soybeans were planted in 700 mm (28 in) wide rows and plants were spaced 200 mm (8 in) and 60 mm (2.5 in) apart, respectively. Sorghum was planted on 1.4 m (56 in) beds with two rows per bed and plants were spaced 50 mm (2 in) apart. In 1984 corn was planted on May 4, sorghum on June 4, and soybeans on May 10. Corresponding emergence dates were May 13, June 7, and May 20. Design populations were 64,000 plants/ha (26,000 plants/ac), 160,000 plants/ha (65,000 plants/ac), and 185,000 plants/ha (75,000 plants/acre), respectively.

In 1985 identical varieties were used and corn was

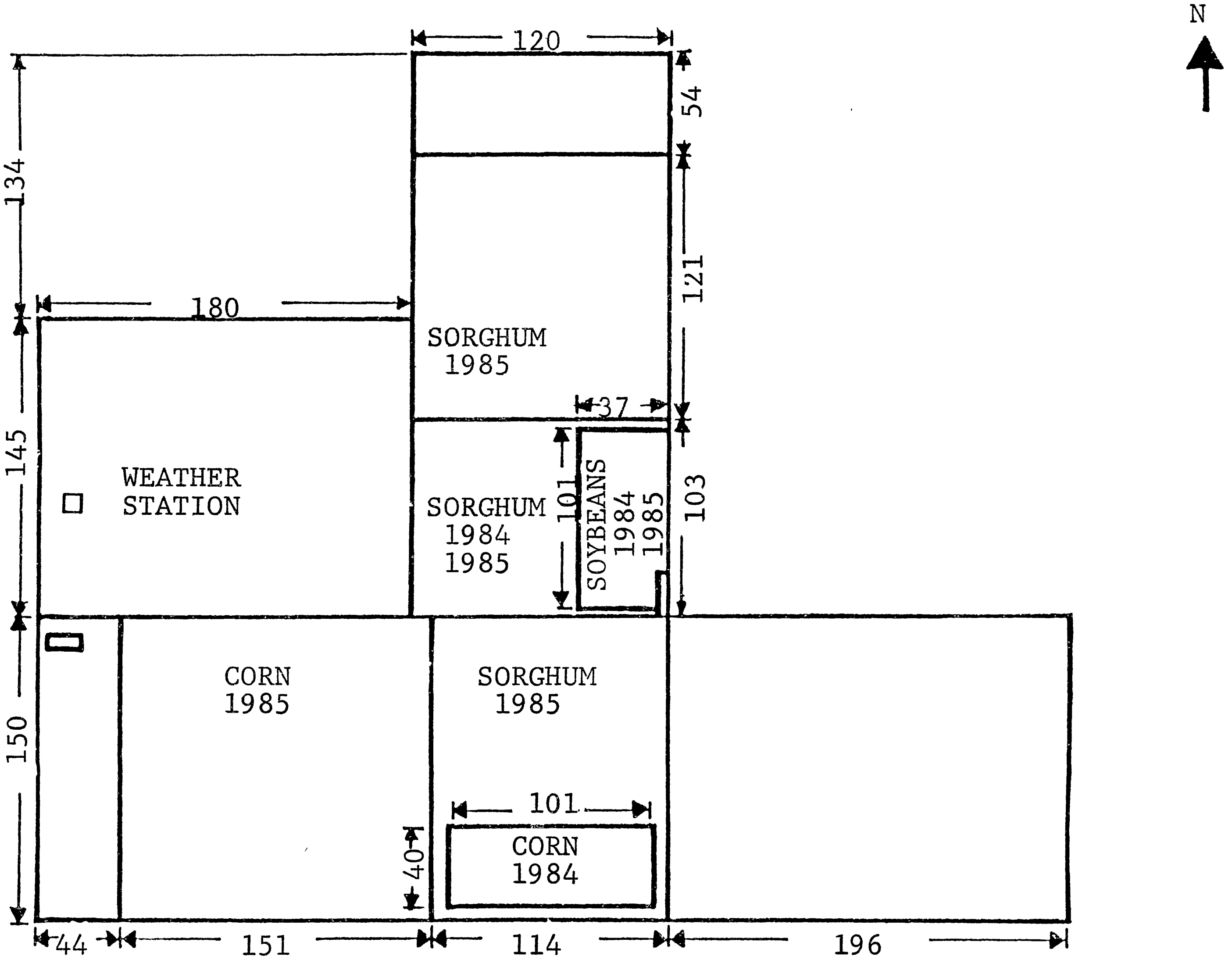

Figure 4. Panhandle Research Station (dimensions in m).

planted on May 16, sorghum on May 17 and 18, and soybeans on May 28. Corresponding emergence dates were May 20, May 23, and June 7. Plant and row spacings as well as design plant populations were the same as those used in 1984. Corn rows were extended in 1985 from 100 m (330 ft) to 150 m (500 ft).

A randomized complete block statistical design was used to guide the layout of experimental plots. The cultural practice of the region is to irrigate within a 7 to 15 day interval (Reeves, 1985). In this study, a 7 day allocation interval was found to be the most practical time span for normal irrigation treatments. During the 1984 season semi-weekly (well-watered) and weekly (normal) irrigation treatments were applied to all crops. During the 1985 season, row crops were subjected to well-watered, normal, and bi-weekly (stressed) irrigation treatments. If crop stress did not appear to be pronounced near the end of a stressed treatment irrigation interval, applications were delayed an additional week. Alfalfa plots received only well-watered and normal watering treatments in both years.

The alfalfa study was located on private land, thus only a small area could be allotted to each plot. The well-watered alfalfa plot measured 2.7 m x 5.0 m (9 ft x 16 ft) and was bordered with 150 mm (6 in) galvanized flashboard to retain supplemental irrigation water supplied from a watering tank. The normal irrigation treatment had approximately the same plot dimensions.

Field Data

Weather

Meteorological data were monitored at the Panhandle Research Station with a Campbell Scientific CR21 Micrologger[1] and associated sensors (Fig. 5). The Micrologger was programmed to scan all sensors listed in Table 1 every minute, with the exception of the psychrometer and rain gage. Wet and dry bulb temperatures were monitored on an hourly basis and totalized rainfall was monitored every fifteen minutes. Two output tables were stored in the Micrologger's memory. One table was composed of hourly averages of ambient air temperature, wind speed and direction; hourly total solar radiation; and hourly psychrometric temperature readings. The second table was a 24 hour compilation of average ambient air temperature, wind speed and direction; maximum and minimum ambient air temperature; and total solar radiation and rainfall.

Readings were stored in the working memory of the Micrologger and were also routed to a thermal printer every hour. A 24 hour summary of hourly readings was also stored in the working memory and routed to the printer at the end of every day. When the memory capacity of the Micrologger was reached, hourly and daily data were then transmitted to cassette tape for permanent storage. At the end of each irrigation season the information stored on cassette was

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[1] Campbell Scientific, Logan, Utah

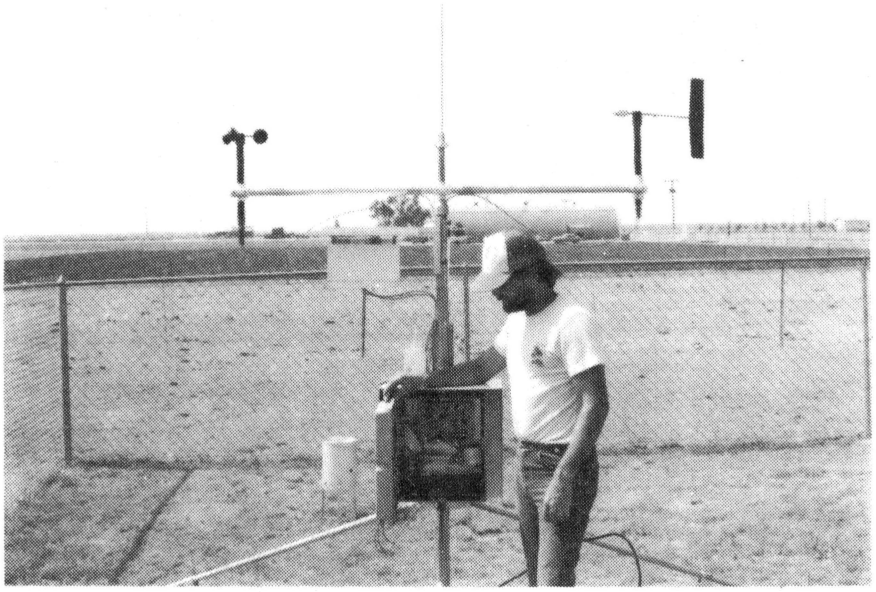

Figure 5. Microprocessor based weather station.

TABLE 1.

CAMPBELL SCIENTIFIC CR21 MICROLOGGER INSTRUMENTATION

Variable	Sensor	Model
Ambient temperature	Thermister	101
Rainfall	Sierra-Misco rain gage	RG2501
Solar radiation	Li-Cor silicon pyranometer	LI-200SZC
Wet and dry bulb temperature	Delta-T Devices ventilated psychrometer	WVU-21
Wind direction	Met-One wind direction sensor	024A
Wind speed	Met-One wind speed sensor	014A

decoded and transmitted to Oklahoma State University's IBM 3081K computer for analysis.

In 1984 the weather station began monitoring on May 28 and ended on October 15. In 1985 the weather station began monitoring on June 12 and ended on October 8. From June 13 to July 2 the Micrologger was accidentally left in a non-recording mode and the data were not stored.

In addition to the meteorological parameters monitored by the Micrologger sensors, other pertinent variables were measured as well. Within the the immediate vicinity of the weather station was located a U.S. Weather Bureau Class A Evaporation Pan. The pan was constructed of galvanized steel with a diameter of 1.21 m (4 ft) and a depth of 250 mm (10 in). The bottom of the pan was elevated approximately 150 mm (6 in) above ground level on wooden slats. Water in the pan was maintained between 50 mm (2 in) and 75 mm (3 in) below the lip. Pan evaporation was measured daily with a vernier hook gage located in a stilling well. The pan was not covered by a screen nor surrounded by actively growing vegetation.

To quantify the depth of precipitation falling on alfalfa plots, two rain gages were installed. One gage was open to collect rainfall or irrigation water from a passing center pivot line. The other gage was also open, but direct interception of water was blocked by a plate located 50 mm (2 in) above the orifice. The blocked rain gage was topped daily to 25 mm (1 in) and any evaporative losses were recorded. Actual precipitation was calculated by adding the depth in the open gage to the time-weighted depth of water lost in the blocked gage.

Soil Moisture

In order to calculate crop ET it was first necessary to monitor the amount of water held in the soil profile. To facilitate the monitoring process, three 60 mm (2.5 in) diameter steel access tubes were installed in each treatment. The galvanized tubing was first inserted to a depth of 1 m (3 ft) with a tractor-mounted hydraulic ram. A sledge hammer was then employed to drive the tube into the soil until only the top 150 mm (6 in) was exposed. During installation the bulk of cut soil within the tube was removed with a hand auger. In the final stage of installation, any soil adhering inside the tube wall was removed with a cylindrical wire brush. Each tube was then capped with a #9 laboratory rubber stopper to prevent the entrance of precipitation.

In 1984, three 1.50 m (5.0 ft) tubes were installed approximately 30 m (100 ft) apart down crop rows. In 1985, three 1.95 m (6.4 ft) sections of pipe were used and spaced about the same distance apart. Access tubes that were installed to a depth of 1.37 m (4.5 ft) in alfalfa plots during the 1984 season were left undisturbed for reuse in the 1985 season.

Volumetric water content (VWC) is defined as the volume of water stored in the profile per unit volume of soil. By knowing the VWC in conjunction with the total depth of soil, the total water content may be determined and employed in equation (2.1). The VWC was monitored during the 1984 and 1985 irrigation seasons with a 3220 series Troxler[1] neutron probe. Measurements were taken at 150 mm (6 in) increments down the soil profile. Maximum depths of 1.20 m (3.9 ft) and 1.80 m (5.9 ft) were monitored in row crops during the 1984 and 1985 seasons, respectively.

Whenever the VWC was monitored, the following operating sequence was followed:

1. Turn the neutron probe instrument switches to the "On" and "Slow" positions and allow 10 minutes for equilibration purposes.

2. Set the instrument upon an access tube, switch dials to "Standard Count" and "Slow". Depress the "Start" button, and after four minutes a Standard Count will be displayed for recording.

3. Repeat step 2 but set switch to "Fast" for a one minute count.

4. Lower the probe 150 mm (6 in), switch to "Measured Count", and depress the "Start" button. After 15 seconds a "Measured Count" will be displayed for recording.

5. Repeat step 4 until the probe may be lowered no more.

6. Retract the cable and move to the next access tube and repeat steps 3 through 6.

7. Once all tubes have been read, repeat step 2.

8. Turn the instrument off and plug in the unit's battery charger.

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[1] Troxler International, LTD., Research Triangle Park, North Carolina

At the end of each season neutron scatter data were converted to VWCs via a calibrated linear equation. Volumetric water contents were then converted to total water contents for calculating the dS term in equation (2.1).

To accurately approximate crop ET it was also necessary to monitor water movement in plots where access tubes did not extend below 1.20 m (3.9 ft). This was accomplished by measuring the soil moisture tension (negative pressure potential) with tensiometers set to depths of 1.20 m (3.9 ft) and 1.50 m (4.9 ft). By relating soil moisture tension and gravitational head to a fixed datum, the total head and its gradient were determined. By comparing the total heads at the two depths, the direction of water movement was ascertained. To quantify the rate of water movement Darcy's equation was employed.

Soil moisture tension was monitored in all treatments during the 1984 season, and only in alfalfa plots in 1985. In 1985 row crop access tubes were installed 600 mm (2.0 ft) deeper in the hopes that the soil water would be relatively static (at least at the 1.80 m depth). This was necessary to better account for water movement in the region and to eliminate the need for tensiometers. Longer access tubes could not be installed in alfalfa plots but were also not needed because of a relatively impenetrable and impermeable layer of caliche.

In 1984 two sets of tensiometers were installed at alternating depths of 1.20 m (3.9 ft) and 1.50 m (4.9 ft) within each treatment. Tensiometers and access tubes were aligned parallel to crop rows and uniformly spaced 0.5 m (1.5 ft) apart (Fig. 6). A soil auger, rubber mallet, and an aluminum anvil cap were required for the installation process. All but the last 50 mm (2 in) of soil was removed from the tensiometer site hole with an auger slightly larger in diameter than the tensiometer cup. Next, an auger with a diameter slightly smaller than the tensiometer cup was employed to remove the final 50 mm (2 in) of soil from the site hole. Prior to insertion, the entire surface of the tensiometer was doused with water to decrease resistance during insertion, and to enhance the soil-to-surface contact of the ceramic cup. The tube was then inserted by hand and driven in the last 50 mm (2 in) by fixing the anvil cap over the tensiometer column and striking the anvil with a rubber mallet. Nylon tubing was used to connect the tensiometer to a mercury reservoir and quick drying epoxy cement was used to make the tensiometer-to-tubing connection.

After installation, tensiometers were filled for the next three days with boiled, distilled water until a near equilibrium was attained between the tensiometer's porous, ceramic cup and the surrounding soil moisture regime. Once equilibrium was approached, the following procedures were implemented five days a week for data acquisition:

1. Observe and record the manometer level above the mercury reservoir.

Figure 6. Tensiometer installation

2. Examine spaghetti tubing for air pockets. If entrained air is greater than 25 mm (1 in) in length, then purge the tube by proceeding with steps 3 through 5.
3. Uncork tensiometer and fill the ear syringe with boiled, distilled water.
4. Insert the syringe into the tensiometer and fill until all entrained air is purged from the system.
5. Repeat steps 2 through 4 until all manometers are purged.
6. Cork all tensiometers immediately.

Stage of Growth

Growth stages of all crops were monitored between three and five times a week in 1984. In 1985 the growth stages of corn and soybeans were infrequently monitored while sorghum was monitored between four and five times a week. Three to five plants were sampled from each treatment and growth stages were classified according to the physical descriptions given in Tables 2, 3, and 4. Alfalfa fluctuated between vegetative and reproductive stages of development due to the periodic cutting of buds and blooms. Throughout both irrigation seasons, alfalfa plots were never trimmed shorter than 300 mm (12 in), and in 1985 only the blooms were cut to prevent seed set.

Canopy Temperature

Crop canopy and canopy-minus-air (T_c - T_a) temperatures were monitored with a hand-held Telatemp infrared thermometer, Model AG42. Three precautions were taken to

TABLE 2.

GROWTH STAGES OF CORN[1]

Growth Stage Description	Stage #
Emergence	0.0
2-3 leaves	0.5
4-6 leaves	1.0
8-10 leaves	2.0
12-14 leaves	3.0
16 leaves	4.0
Silks emerging, pollen shedding	5.0
Plant pollinated, silks green to brown	5.5
Brown silk, cob full size, kernels in blister stage	6.0
Kernels in "soft dough"	7.0
Few kernels with "dents"	8.0
All kernels fully dented ("hard dough")	9.0
Physiological maturity	10.0

[1](Bottrell, 1979)

TABLE 3.

GROWTH STAGES OF SORGHUM[1]

Growth Stage Description	Stage #
Emergence	0.0
3 leaf	1.0
5 leaf	2.0
7-10 leaf	3.0
Flag leaf visible in whorl	4.0
Boot stage	5.0
Half-bloom	6.0
Soft-dough	7.0
Hard-dough	8.0
Physiological maturity	9.0

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[1] (Vanderlip, 1972)

TABLE 4.

GROWTH STAGES OF SOYBEANS[1]

Growth Stage Description	Stage #
Emergence	V1
Cotyledon	VC
First-node	V1
Second-node	V2
Third-node	V3
.	.
.	.
Nth-node	V(N)
Beginning bloom	R1
Full bloom	R2
Beginning pod	R3
Full pod	R4
Beginning seed	R5
Full seed	R6
Beginning maturity	R7
Full maturity	R8

[1] (Fehr and Caviness, 1977)

insure the reliability and repeatability of temperature measurements. First, canopy temperatures were not monitored until crop foliage was full enough to minimize ground temperature interference. Second, readings were taken between 1 PM and 3 PM with the sun behind the observer's back, and then only during cloudless periods spanning at least the duration of each measurement. Thirdly, markers were set in the field so that the same locations were monitored each day.

Initially the thermometer was turned on and allowed to equilibrate for ten minutes. Then canopy temperature was monitored by pointing the hand-held thermometer at an oblique angle toward foliage 6 meters (20 ft) away. To monitor the temperature atop maturing corn, a ladder was employed. Immediately after canopy temperature was read, a trigger on the thermometer was depressed and canopy-minus-air temperature was displayed and recorded.

For all four crops infrared thermometer readings were replicated three times per treatment during the 1984 season and six times per treatment during the 1985 season. Replicates were increased during the 1985 season to refine variability estimates. Additional infrared readings from a dryland treatment were incorporated into the sorghum study during the 1985 season. Temperatures were monitored on 24, 18, 20, and 20 separate dates for alfalfa, corn, sorghum, and soybeans, respectively in 1984. In 1985 temperatures were sampled on 23, 16, 23, and 13 dates for the same crops, respectively.

Measured Evapotranspiration (Water Balance)

The calibration of alfalfa reference crop ET equations and crop ET predictions are dependent upon accurate measurements of ET at the field level. Measured ET for this study was derived from the basic water balance formula:

$$ET = I + P - RO - DP - dS \qquad (2.1)$$

Alfalfa

Deep percolation in alfalfa plots was retarded due to a subhorizon of caliche. An analysis of the tensiometer data revealed only minimal water movement in this region for most of the season, thus the DP term of equation (2.1) could be eliminated during these periods. Runoff was assumed negligible in both alfalfa plots due to the flat terrain of the area and the moderate permeability of the A and B soil horizons. After dispensing with these terms equation (2.1) took the form:

$$ET = I + P - dS \qquad (3.1)$$

During periods when DP equalled or exceeded 1 mm/d equation (2.1) became:

$$ET = I + P - DP - dS \qquad (3.2)$$

On the well-watered plot, the depth applied with the watering tank was estimated by dividing the volume of water applied by the plot area. Surface water applied to the plot was confined by a flashboard dike until infiltrated.

Row Crops

Measured ETs for row crops were calculated for periods void of irrigation events, effectively eliminating the "I" term in equation (2.1). This was unavoidable because the depth of irrigation at each access tube could not be precisely measured. Based upon field observations during and after rainfall events, the RO term was set to zero. Incorporating these modifications into the basic water balance equation, equation (2.1) was rewritten as:

$$ET = P - DP - dS \tag{3.3}$$

In 1985 access tubes were set deep enough to eliminate the need for tensiometers and the DP term in equation (3.3). Thus, in 1985 and for periods of negligible DP in 1984, equation (3.3) was modified to:

$$ET = P - dS \tag{3.4}$$

To determine if DP was greater than or equal to 1 mm/d for any given set of tensiometer readings, it was first necessary to calculate the total head:

$$h = D + s - 12.6H + Z \tag{3.5}$$

where

h = Total head (mm of water)

D = Tensiometer depth below the soil surface (mm)

s = Height of mercury reservoir above the soil surface (mm)

12.6 = Specific gravity of mercury minus one

H = Manometer level above the mercury reservoir (mm)

Z = Gravitational head above a fixed datum (mm)

The flux rate and direction were determined from the equation for flow under unsaturated conditions:

$$DP = -K(VWC)\ dh/dL \qquad (3.6)$$

where

$K(VWC)$ = Hydraulic conductivity (mm/d) for a specific VWC

dh/dL = Gradient in total head (mm/mm)

The dh/dL term was always the difference between the average total heads at 1.50 m and 1.20 m divided by 300 mm.

To predict the hydraulic conductivity of Richfield clay loam under unsaturated conditions, an empirical equation developed by J. M. Davidson and reported by Stone (1985) was employed:

$$K(VWC) = 3.069\text{x}10^{-7} \exp(48.174VWC) \qquad (3.7)$$

where VWC has units of mm^3/mm^3.

The following empirical relationships were also reported by Stone (1985) for Richfield clay loam:

$$VWC_{1.20\ m} = 0.4188 + 0.001153X + 3.1\text{x}10^{-6}\ X^2 \qquad (3.8)$$

$$VWC_{1.50\ m} = 0.3933 + 0.00087X + 2.4\text{x}10^{-6}\ X^2 \qquad (3.9)$$

where

X = Pressure head of soil water (cm of Hg)

To find the lower limits of equations (3.8) and (3.9), both equations were differentiated with respect to X and set equal to zero. The resulting pressure heads were -186 cm and -181 cm for equations (3.8) and (3.9), respectively. The VWC for pressure heads below these values was not calculated because values would erroneously increase due to the quadratic form of the equations.

Equations (3.8) and (3.9) were solved using the pressure heads for each depth. The lower of the two VWC values was then substituted into equation (3.7) to find K(VWC). Finally, K(VWC) was substituted into equation (3.6) to find DP.

The storage term in equations (3.3) and (3.4) was quantified by determining the temporal variation of total soil moisture between irrigations. During periods when neither a rainfall or irrigation event occurred, and when water movement below the root zone was negligible, a drop in the total soil moisture was assumed to be a measure of actual crop ET.

Predicted Evapotranspiration

Weather-Based Equations

Modified-Penman. A combination equation for predicting reference crop ET on a daily basis was presented by Penman (1948). The equation was later modified and is given in one of its current forms by Burman et al. (1980):

$$E_{tr} = [d / (d + g)] (R_n + G) + [g / (d + g)] 15.36 W_f (e_a - e_d) \tag{2.2}$$

To convert E_{tr} from cal/cm^2-d to mm/d, E_{tr} was divided by the average latent heat of vaporization (in cal/cm^3) and then multiplied by 10 for unit conversion (mm/cm).

A linear expression relating the latent heat of vaporization to mean daily temperature was found by Brunt (1952) to be:

$$L = 595 - 0.51\ T \qquad (3.10)$$

where

L = Latent heat of vaporization (cal/g)

T = Mean daily temperature (°C) (average of 24 hourly readings)

The slope of the vapor pressure-temperature curve was approximated by employing an expression developed by Bosen (1960):

$$d = 2.00\ (0.00738\ T + 0.8072)^7 - 0.00116 \qquad (3.11)$$

The psychrometric constant was calculated from an expression developed by Brunt (1952):

$$g = 0.386\ P / L \qquad (3.12)$$

where

P = Average station barometric pressure (mb)

and the specific heat of air at constant pressure was assumed equal to 0.242 cal/g-°C.

The value of P is usually assumed constant for a given location, and may be approximated by a linear relationship given by Burman et al. (1980):

$$P = 1013 - 0.1055\ E \qquad (3.13)$$

where

E = Elevation above sea level (m)

Net radiation was not measured at the Panhandle station; however incoming short wave solar radiation was measured continuously at the site. Net radiation may be derived from solar radiation by an expression given by Burman et al. (1980):

$$R_n = (1-A)\ R_s - R_b \tag{3.14}$$

where

A = Fraction of incoming short wave radiation which is reflected (albedo)

R_s = Incoming short wave solar radiation (cal/cm^2-d)

R_b = Net outgoing long wave radiation (cal/cm^2-d)

The albedo of most commercial irrigated crops was reported by Merva (1975) to be 0.23. Net outgoing long wave radiation was approximated with the following expression given by Burman et al. (1980):

$$R_b = [(a\ R_s\ /\ R_{so}) + b]\ R_{bo} \tag{3.15}$$

where

a, b = Empirical coefficients

R_{so} = Clear day solar radiation (cal/cm^2-d)

R_{bo} = Net outgoing long wave radiation on a clear day (cal/cm^2-d)

The coefficients a and b of equation (3.15) were assigned values of 1.2 and -0.2 after Jensen (1973).

A relationship between clear sky solar radiation and the calendar day was found by fitting a quadratic equation to five extreme daily solar radiation readings for 1984 and 1985.

Net outgoing long wave radiation for a clear day was determined by an expression given by Burman et al. (1980):

$$R_{bo} = (a_1 + b_1\ e_d^{0.5})\ 11.71 \times 10^{-8}\ T_k^4 \qquad (3.16)$$

where

a_1, b_1 = Empirical coefficients

e_d = Saturation vapor pressure at mean dew point temperature (mb)

11.71×10^{-8} = Stefan-Boltzmann constant (cal/cm^2-d-$^\circ$K)

T_k = Average daily air temperature ($^\circ$K)

The soil heat flux (G) in equation (2.2) was assumed negligible for daily E_{tr} calculations.

The saturation vapor pressure at any temperature was determined from an expression given by Bosen (1960):

$$e_{si} = 33.8639\ [(0.00738\ T_i + 0.8072)^8 - 0.000019\ |1.8\ T_i + 48| + 0.001316] \qquad (3.17)$$

where

e_{si} = Hourly saturation vapor pressure (mb)

T_i = Hourly temperature ($^\circ$C)

The saturation vapor pressure for mean daily air temperature was determined by substituting 24 hourly dry bulb temperature readings into equation (3.17), summing to find total e_s, and dividing by 24 (from Cuenca and Nicholson, 1982), i.e.:

$$e_a = \left(\sum_{i=1}^{24} e_{si} \right) / 24 \qquad (3.18)$$

The saturation vapor pressure at mean daily dew point temperature was calculated from the following expression:

$$e_d = \sum_{i=1}^{24} [e_{wi} - g\ (T_i - T_{wi})]\ /\ 24 \qquad (3.19)$$

where

e_{wi} = Hourly saturation vapor pressure at wet bulb temperature (mb)

T_i = Hourly dry bulb temperature (°C)

T_{wi} = Hourly wet bulb temperature (°C)

The mean daily vapor pressure deficit for equation (2.2) was calculated by simply subtracting e_d from e_a.

The wind function may be expressed by the linear equation:

$$W_f = a_w + b_w\ U_z \qquad (3.20)$$

where

a_w, b_w = Regression coefficients

U_z = Daily wind travel at a height of 2 m (km/d)

In order to calibrate equation (2.2) (i.e., determine values of a_w and b_w), it was necessary to rearrange the equation and solve for W_f where:

$$W_f = \frac{E_{tr} - [d\ /\ (d + g)]\ R_n}{15.36\ [g\ /\ (d + g)](e_a - e_d)} \qquad (3.21)$$

Values of E_{tr}, $[d\ /\ (d + g)]$, R_n, $[g + (d + g)]$, and $(e_a - e_d)$ were averaged for 4 and 5 day periods and average W_fs calculated. The values of a_w and b_w were then found by regressing W_f on U_z.

Priestley-Taylor. The following version of the Priestley-Taylor method of calculating alfalfa reference crop ET was used:

$$E_{tr} = a_{PT} + b_{PT} [d / (d + g)](R_n + G) \qquad (3.22)$$

where

a_{PT}, b_{PT} = Regression coefficients

To account for more of the variability associated with the data, equation (2.3) was not forced through zero thus allowing an intercept (a_{PT}) and slope (b_{PT}) term to be approximated. Net radiation (R_n) was determined using equation (3.14) and soil heat flux (G) was again assumed negligible. The values of a_{PT} and b_{PT} were quantified by regressing 4 and 5 day averages of alfalfa reference E_{tr} on the average value of $[d / (d + g)]\ R_n$.

<u>Modified Jensen-Haise.</u> Another method of predicting E_{tr} for a well-watered alfalfa reference crop was developed by Jensen and Haise (1963). Since its inception, the formula has been modified and is presented in its current form (Burman et al., 1980):

$$E_{tr} = C_t\ (T - T_x)\ R_s \qquad (2.4)$$

Long term temperature averages were compiled from 33 years of minimum and maximum temperatures for the month of July. Four and five day averages of mean daily temperature and total solar radiation were used to determine E_{tr}.

<u>Pan Evaporation Method.</u> A U.S. Weather Bureau Class A Pan was used to measure pan evaporation in the equation:

$$E_{tr} = a_p + b_p E_p \qquad (3.23)$$

where

E_{tr} = Alfalfa based reference ET (mm/d)

E_p = Pan evaporation (mm/d)

a_p, b_p = Regression coefficients

To account for more of the variability associated with the data, equation (2.6) was not forced through zero, but an intercept (a_p) and slope term (b_p) were found by regressing E_{tr} on E_p using 4 and 5 day averages.

Crop Coefficients

Crop coefficients for corn, grain sorghum, and soybeans were referenced to a well-watered plot of alfalfa in this study, and were calculated using the following expression:

$$K_c = E_t / E_{tr} \qquad (3.24)$$

where

K_c = dimensionless crop coefficient for a particular well-watered crop at a particular growth stage

E_t = ET of a well-watered crop (mm/d)

Soil Moisture Adjustment

Under normal field conditions, it is rare that crops escape from periods of soil moisture stress. When the water available to plant roots is restricted, evaporative flux rates may also be reduced. To adjust K_c for stressed conditions the following formula may be employed (Burman et al., 1980):

$$K_c = K_{cb} K_a + K_s \qquad (3.25)$$

where

K_{cb} = daily basal ET crop coefficient

K_a = A coefficient dependent upon available soil moisture

K_s = A coefficient to allow for increased evaporation from the soil surface occurring after a rain or irrigation.

An accurate determination of K_s' is dependent upon a precise measurement of ET. The resolution needed to measure K_s would require the use of weighing lysimeters. Due to costs and other factors, lysimeters were not used and K_s could not be incorporated into equation (3.25). In recognition of enhanced ET rates from wet soil surfaces, measured ET rates were not calculated until 24 hours had elapsed after a rainfall or irrigation event.

Values of K_c were based upon the assumption that increased evaporation from a wet soil surface was minimal, but soil-water availability was not limiting, i.e., $K_c = K_{cb}$ with $K_a = 1$ and $K_s = 0$ (Burman et al., 1980). Crop coefficients were determined by dividing the ET of a well-watered crop by the measured ET of well-watered alfalfa. To normalize K_c between years and to facilitate the development of a mathematical equation for predicting K_c, crop coefficients were expressed as a function of the number of days after crop emergence.

Infrared Estimates of Crop Water Stress

In this study, three avenues of predicting crop water stress from $T_c - T_a$ differentials and canopy temperatures were explored. First, non water-stressed baselines were determined by regressing $T_c - T_a$ values from well-watered crops with VPD. Vapor pressure deficits were calculated from hourly psychrometer readings recorded by the CR21 Micrologger. To better define a possible correlation between $T_c - T_a$ and VPD, data was pooled between treatments and years if comparison testing revealed no statistical differences between the regression equations. Second, the level of soil moisture in the rooting zone was predicted by regressing the volumetric water content (VWC) with the temperature stress day (TSD). By defining this relationship relative to the field capacity and the wilting point, an observer could estimate the percent of available soil moisture (AM) in a very short time without soil probing. Thirdly, canopy temperature variability (CTV) was regressed with AM to determine the degree of correlation. If a meaningful relationship were established, irrigations could then be scheduled based on only a few minutes of canopy temperature readings.

CHAPTER IV

RESULTS AND DISCUSSION

Measured Evapotranspiration (Water Balance)

Alfalfa

The collection of pertinent data for determining measured ET rates began on June 7 and ended September 21, 1984. A second season of data collection began the next year on June 14 and ended September 5. Measured ET rates for both years are given in Table 5. Normally alfalfa soil moisture readings were taken on Mondays and Thursdays with tank irrigations following the Monday measurements. Thus E_{tr} was calculated for periods beginning on Thursday and ending on Monday.

Cumulative rainfall collected at the alfalfa site in 1984 measured 140 mm (5.5 in) (Table 6). During the study period the well-watered plot received 720 mm (28 in) and the normal plot 520 mm (20 in) of supplemental irrigation water. Daily accumulations of rainfall and irrigation never exceeded 55 mm (2.2 in) and 38 mm (1.5 in) in well-watered and normal plots, respectively. A privately owned center pivot system applied 33 mm (1.3 in) of water to both plots on roughly a five day interval. This was in addition to weekly water tank applications of 28 mm (1.1 in) on well-

TABLE 5.

SUMMARY OF MEASURED WELL-WATERED ET RATES FOR 1984 AND 1985

		Daily ET (mm)			
Year	Dates	Alfalfa	Corn	Sorghum	Soybeans
1984	6/14 - 6/17	11.2	6.4	5.3	6.7
	6/28 - 7/1	8.3	-	2.4	4.9
	7/12 - 7/15	10.4	10.6	7.1	10.1
	7/19 - 7/22	12.3	12.4	10.3	9.5
	7/26 - 7/30	10.4	6.4	4.5	6.8
	8/16 - 8/19	11.7	10.1	3.9	3.9
	8/23 - 8/26	11.6	7.6	-	1.8
1985	7/12 - 7/15	10.7	6.5	9.5	3.5
	8/8 - 8/11	7.6	5.1	5.4	8.1
	8/15 - 8/18	4.9	-	-	-
	8/22 - 8/25	7.8	6.8	5.2	6.1
	8/26 - 8/29	13.6	8.7	7.2	-
	8/30 - 9/2	13.7	-	2.1	10.0

TABLE 6.

VARIOUS WATER BALANCE PARAMETERS FOR 1984

			Total		Maximum			VWC	
			R	I	DP	CR	ET		
Crop	Trt[1]	Dates	(mm)	(mm)	(mm/d)	(mm/d)	(mm)	min	max
Alf	W	6/7- 9/21	140	720	5	2	12	0.27	0.37
Alf	N	6/7- 9/21	140	520	0	0	11	0.22	0.35
Corn	W	6/4- 9/4	133	310	6	0	12	0.29	0.37
Corn	N	6/4- 9/4	133	220	5	0	11	0.27	0.34
Sorg	W	6/14- 9/12	133	500	7	2	10	0.30	0.35
Sorg	N	6/14- 9/12	133	410	2	0	10	0.29	0.33
Soyb	W	6/6- 9/12	133	770	3	1	10	0.31	0.36
Soyb	N	6/6- 9/12	133	650	3	1	9	0.31	0.36

[1] W = Well-watered N = Normal

watered plots.

Measured ET rates for 1984 were determined using equations (3.1) and (3.2). Equation (3.2) was employed when the magnitude of the deep percolation (DP) or capillary rise (CR) equalled or exceeded 1 mm/d (0.04 in/d). Below 1.20 m (3.9 ft), an horizon of caliche retarded nearly all water movement. Consequently, DP was so low that equation (3.2) was used on only one occasion. The event followed a singular occurrence in which a tank watering, sprinkler irrigation, and rainfall fell on the same date. The day following DP was determined to be 5 mm/d (0.20 in/d).

Frequent irrigations and rainfalls kept the soil profile moist enough to maintain a flush stand of alfalfa throughout the season. During this period the volumetric water content (VWC) of the well-watered and normal plots never fell below 0.27 and 0.22, respectively. Evapotranspiration rates during the season reached a maximum of 12 mm/d (0.47 in/d) and 11 mm/d (0.43 in/d) in well-watered and normal plots, respectively. The difference between ET rates may be attributed to various factors including:

1. A reduction of stomatal resistances in the well-watered treatment, resulting in higher transpiration rates.
2. Wetter soil surface conditions in the well-watered plot, promoting accelerated evaporation.

Cumulative rainfall in 1985 was 41 mm (1.6 in) (Table 7). Daily depths of rainfall and irrigation during the 1985

TABLE 7.

VARIOUS WATER BALANCE PARAMETERS FOR 1985

			Total		Maximum			VWC	
Crop	Trt[1]	Dates	R (mm)	I (mm)	DP (mm/d)	CR (mm/d)	ET (mm)	min	max
Alf	W	6/14-9/5	41	610[2]	27	7	14	0.35	0.44
Alf	N	6/14-9/5	41	280[2]	18	0	14	0.26	0.44
Corn	W	6/17-9/5	34	480	0	0	9	0.30	0.34
Corn	N	6/17-9/5	34	360	0	0	8	0.28	0.33
Corn	S	6/17-9/5	34	280	0	0	7	0.24	0.32
Sorg	W	6/17-9/5	34	410	0	0	10	0.24	0.27
Sorg	N	6/17-9/5	34	350	0	0	9	0.24	0.28
Sorg	S	6/17-9/5	34	150	0	0	6	0.26	0.33
Soyb	W	6/17-9/5	34	580	0	0	10	0.30	0.33
Soyb	N	6/17-9/5	34	460	0	0	9	0.30	0.33
Soyb	S	6/17-9/5	34	200	0	0	7	0.28	0.34

[1] W = Well-watered N = Normal S = Stressed

[2] Depth is actually greater due to two unmeasured flooding events.

season never exceeded 51 mm (2.0 in) and 43 mm (1.7 in) in the well-watered and normal plots, respectively. Cumulative irrigation depths for the same period were 610 mm (24 in) for the well-watered plot, and 280 mm (11 in) for the normal plot. These depths do not include two ungauged flooding events which followed the stalling of the center pivot system near the research plots. When operating properly, the system applied 18 mm (0.7 in) on roughly a five day interval.

In 1985, a maximum DP rate of 27 mm/day (1.1 in/d) was recorded following the first flooding of alfalfa plots. Later in the season the system stalled a second time and reflooded research plots. The next day a maximum DP rate of 18 mm/d (0.71 in/d) was measured in the normal plot.

The adventitious flooding of alfalfa in 1985 raised the VWC contents in both plots to their highest recorded levels. A VWC of 0.44 was recorded for both well-watered and normal plots following the first and second flooding events.

Maximum ET rates in 1985 exceeded those recorded in 1984. From field data the higher 1985 rate could be partially explained by a higher average daily wind travel for the period of peak ET. Evapotranspiration peaked at 14 mm/d (0.55 in/d), which reflects the averaging of both plots. Because the normal rate exceeded the well-watered rate, the mean was calculated using both the normal and well-watered data.

Row Crops

Daily rainfall for row crops was measured with a recording rain gage located near the research site. Cumulative depths measured during the 1984 and 1985 seasons were 133 mm (5.2 in) and 34 mm (1.3 in), respectively. Irrigation water was conveyed to the site by gated pipe and flow rates were regulated by adjusting slide gates. Irrigation depths were not included in ET calculations because their spatial variability down the field could not be measured accurately.

Evapotranspiration rates for all row crops grown in 1984 were calculated by using either equation (3.3) or (3.4). The DP term in equation (3.3) was needed to account for water movement below 1.20 m (3.9 ft). In 1985 access tubes were installed to a depth of 1.80 m (5.9 ft) to eliminate the DP term and the need for equation (3.3). Equation (3.4) was then employed exclusively to calculate ET rates.

In 1985 the calculation of measured ET for well-watered row crops was complicated by an interspersion of irrigation events between soil moisture readings. Consequently, ET rates covering important physiological events such as florescence and pollination could not be determined accurately. Thus, maximum ET rates reported for row crops may not have covered periods of maximum water usage.

The physiological development of corn and soybeans was predicted by calculating the number of days after crop emergence and using 1984 growth data as a reference. Growth data from 1985 was also used, but a precise chronological delineation of the various vegetative and reproductive stages was obscured by the infrequency of visual observations. During the 1985 season a second study involving sorghum was conducted concurrently on the station. Stage of growth data from that study was merged with 1984 data and incorporated into the analysis.

Corn. Seasonal readings for 1984 began on June 4 and ended September 4. Well-watered plots were irrigated 11 times during this period with application depths averaging 28 mm (1.1 in). Deep percolation was only measurable between June 12 and 29. Within this period DP never exceeded 6 mm/d (0.24 in/d). During the same interval the highest VWC of the season was measured at 0.37. A maximum ET rate of 12 mm/d (0.47 in/d) was measured during the period of July 19-22. This period fell within the reproductive silking and pollen shedding stage of plant development (stage 5.0, Table 2).

The normally watered plot received eight irrigations averaging 28 mm (1.1 in) in 1984. Deep percolation was measurable on five occasions. The highest DP rate (5 mm/d) was measured on July 6. Capillary rise was always less than 1 mm/d (0.04 in/d) in both well-watered and normal plots. A maximum ET level of 11 mm/d (0.42 in/d) was measured between July 19-22. Corn plants were at the silking stage (5.0) of physiologic development during this time.

In 1985 the study period for corn began on June 17 and ended September 5. The frequency of irrigation was adjusted in 1985 to create a broader range of soil moisture regimes. Plots were watered 16, 9, and 4 times for well-watered, normal, and stressed treatments, respectively. Average application depths for each treatment were 70 mm (2.8 in), 40 mm (1.6 in), and 30 mm (1.2 in). Minimum VWCs corresponding to these treatments were 0.30, 0.28, and 0.24.

The highest recorded ET for well-watered (9 mm) and normal (8 mm) plots of corn occurred between August 26-29 and July 12-15, respectively. The stages of crop development during these periods were soft dough (7.0) and 16 leaf (4.0).

<u>Sorghum</u>. The first study period began on June 14 and ended September 12, 1984. Well-watered plots received 11 irrigations averaging 45 mm (1.8 in) each and normal plots received 10 irrigations averaging 41 mm (1.6 in) in depth. The maximum ET rate was 10 mm/d (0.39 in/d), with this value reflecting the averaging of well-watered and normal plots. Maximum ET rates were observed between July 19-22. The crop at this time was just beginning to boot (Stage 4.5, Table 3) In 1985 the study period for sorghum began on June 17 and ended September 5. In 1985 well-watered, normal, and stressed sorghum plots were watered 12, 9, and 4 times with average depths corresponding to 34 mm (1.3 in), 39 mm (1.5 in), and 37 mm (1.5 in). Stressed irrigation depths were not recorded, thus the average depth was estimated as the

average of well-watered and normal depths for those irrigation events. The maximum ET rate observed in well-watered plots was 10 mm/d (0.39 in/d). This observation was made between July 12-15 during the flag leaf stage (4.0). The maximum ET rate for the normal plot (9 mm/d) was also observed between July 12-15 during stage 4.0. A maximum ET rate of 6 mm/d (0.24 in/d) was observed in the stressed plot between July 12-15 as well. The stage of plant development during this period was 4.0.

The VWC of the stressed sorghum plot (0.33) exceeded the well-watered (0.27) and normal plots (0.28) on July 5. Prior to this date, all three treatments had received two watering treatments, thus a higher moisture content would not have been inconsistent at this point in time.

<u>Soybeans</u>. The first study began on June 6 and ended September 12, 1984. Well-watered plots were irrigated 11 times in 1984 with applications averaging 70 mm (2.8 in) in depth. The highest ET rate (10 mm/d) was observed between July 12-15. The growth stage during this period was full bloom (R2, Table 4). The normal plot was irrigated nine times with an average application depth of 72 mm (2.8 in). A maximum ET rate of 9 mm/d (0.35 in/d) was observed between July 19-22 for the normal treatment. The stage of crop development during this period fell between full bloom (R2) and beginning pod (R3).

In 1985 the study period for soybeans began on June 17 and ended September 5. In 1985 well-watered plots were irrigated 14 times with application depths averaging 41 mm (1.6 in). A maximum ET rate of 10 mm/d (0.39 in/d) was observed between August 30 and September 2. The stage of growth during this time was full seed (R6). Normal plots received 11 irrigations averaging 42 mm (1.7 in) per application. A maximum ET rate of 9 mm/d (0.33 in/d) was recorded between August 30 and September 2. The stage of growth corresponding to this period was R6. Stressed soybean plots received four irrigations averaging 49 mm (1.9 in) per application. A maximum ET rate of 7 mm/d (0.28 in/d) was observed between August 30 and September 2 during growth stage R6 of plant development.

Predicted Evapotranspiration

Weather-Based Equations

Measured alfalfa reference ET data suitable for calibration purposes were selected on the basis of fulfilling two requirements. First, only measured averages spanning minimum periods of four days were considered. It was felt that time intervals of this length minimized possible errors associated with shorter (1 or 2 day) sampling frequencies. Second, post-harvest measurements observed up to 10 days after a cutting were not used. Preliminary calculations of ET measured within these periods were abnormally high when adjusted by equation (4.1), and thus were rejected. Measured ET rates observed 11 to 20 days after cutting, however, were used and converted to reference values by dividing by the adjustment factor given below (Jensen et al., 1971):

$$AF = 0.5 + (N/40) \tag{4.1}$$

where

AF = Adjustment factor

N = Number of days after cutting

After the screening process, a total of 13 periods of measured alfalfa ET remained for calibrating weather-based equations (Table 5). Weather-based equations were calibrated using measured ET averages from one five-day and six four-day periods observed in 1984, and six four-day intervals observed in 1985. The single five day interval was used for calibration purposes but not for the crop coefficient analysis discussed later. The Jensen-Haise formula required only long term temperature averages, so alfalfa ET reference data were not needed. Occasionally ET rates from normal treatments exceeded well-watered rates. In such cases all were treated as well-watered replicates, and averaged with well-watered ET rates.

Modified-Penman. The calibration of the modified-Penman equation (equation 2.2) was dependent upon the determination of an envelope curve to estimate clear sky solar radiation in equation (3.15). The envelope curve was found by first plotting daily total incoming solar radiation with the 1984 and 1985 calendar date (Fig. 7.). Next, five extreme solar radiation values were selected from periods scattered as uniformly throughout the season as possible.

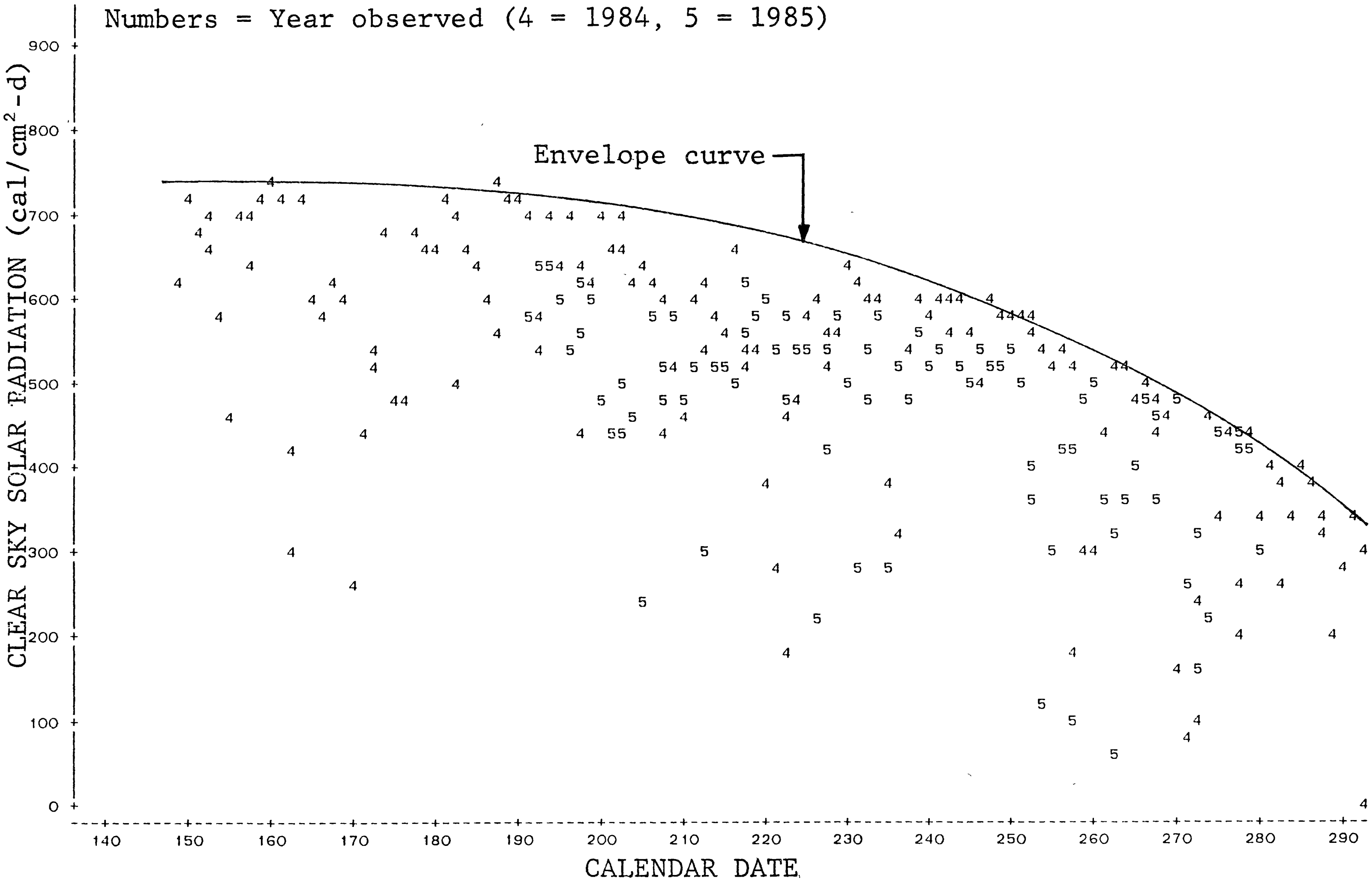

Figure 7. Clear sky solar radiation plotted with calendar date

A quadratic equation was then fitted to these five values to form the envelope curve:

$$R_{so} = 85.2 + 7.88(\text{Date}) - 0.0236(\text{Date})^2 \qquad (4.2)$$

where

R_{so} = Clear sky radiation (cal/cm^2-d)

Date = Calendar date

The model accounted for 99% percent of the variability associated with the five data points ($R^2 = 0.99$).

To find the wind function coefficients of equation (3.20), W_f was regressed on daily wind travel (U_z) (Fig. 8) where:

$$W_f = \frac{E_{tr} - [d \,/\, (d + g)]\, R_n}{15.36\, [g \,/\, (d + g)](e_a - e_d)} \qquad (3.21)$$

The values of E_{tr}, $d/(d + g)$, R_n, $[g / (d + g)]$, and $(e_a - e_d)$ in equation 3.21 were averaged over four or five day periods, depending upon the corresponding lengths of the E_{tr} intervals involved. By simple linear regression a_w and b_w of equation (3.20) were found to be -2.20 and 0.0206 (Table 8). Observed significance levels for the parameters were 0.57 and 0.057, respectively. The null hypothesis that the intercept is equal to zero could not be rejected at the 0.05 significance level. Using the same criterion, the null hypothesis that the slope is equal to zero could not be rejected either, although the slope parameter was bordering near the 0.05 significance level.

The modified-Penman model accounted for 29% of the variability associated with the data ($R^2 = 0.29$) and had a corresponding mean square error (MSE) of 3.48. By

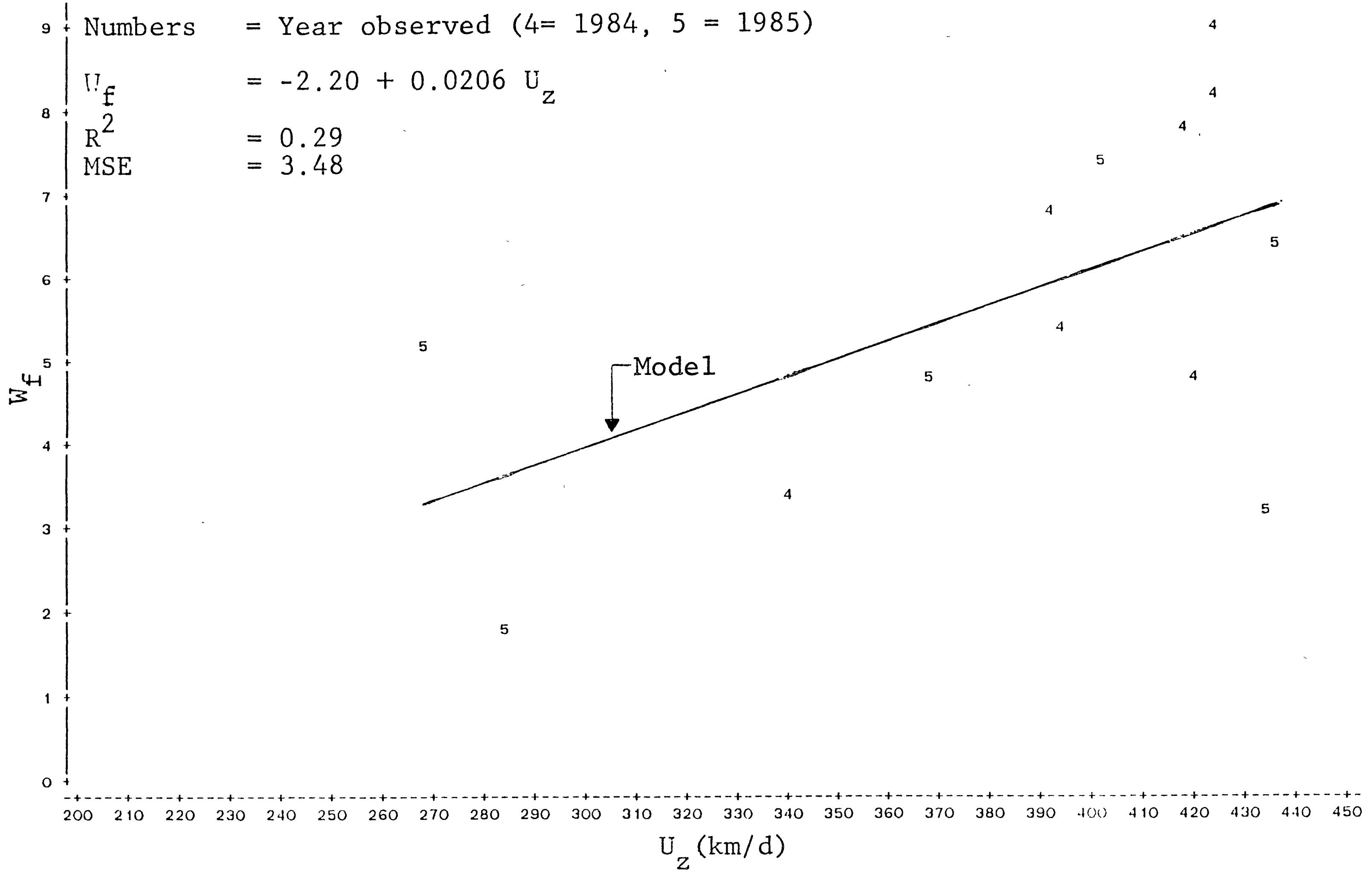

Figure 8. Model of modified-Penman wind function (W_f) with daily wind travel (U_z)

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TABLE 8.

REGRESSION AND STATISTICAL PARAMETERS FOR LINEAR MODELS OF PREDICTED REFERENCE ET WITH MEASURED REFERENCE ET

Estimating Equation	Independent Variable	Intercept Est.[1]	Intercept P>|T|[2]	Slope Est.	Slope P>|T|	R^2
Modified-Penman	U_z	-2.20	0.57	0.0206	0.057	0.29
Priestly-Taylor	PT	419	0.23	0.7705	0.598	0.03
Evapo pan	K_p	5.07	0.11	0.3971	0.099	0.23

[1] Est. = Estimate

[2] P>|T| = Probability of a greater T.

observation, the variability of W_f with U_z appears greatest at either end of the regression plot and narrowest near the middle (Fig. 8). Six out of seven observations for 1984 fell near the upper end of the graph. This would indicate that the daily wind travel observed in 1984 was generally higher than in 1985. Average observations of daily wind travel in 1985 appear to be more uniformly distributed than 1984 observations.

The ability of the calibrated modified-Penman equation to estimate measured ET may be visualized by referring to Fig. 9. Data used to calculate predicted values were the same data used in the calibration. Thus, for all weather-based equations prediction values were found by substituting measured values into prediction equations and solving. In comparing Figures 8 and 9, it appears that the variability of W_f with increasing U_z did not translate into a greater variability of predicted reference ET with actual reference ET. One explanation for this phenomenon would be that as reference ET increased the radiant energy term of equation (2.2) overshadowed the effects of the advective term.

<u>Priestley-Taylor</u>. The Priestley-Taylor formula (equation 3.22) was calibrated by regressing E_{tr} on PT where $PT = [d / (d + g)] R_n$. To better account for the variability associated with the data, the regression equation was not forced through zero (Fig. 10). Neither the intercept (OSL = 0.23) nor slope terms (OSL = 0.598) were significant at the 0.05 level. Therefore, Ho (the slope and

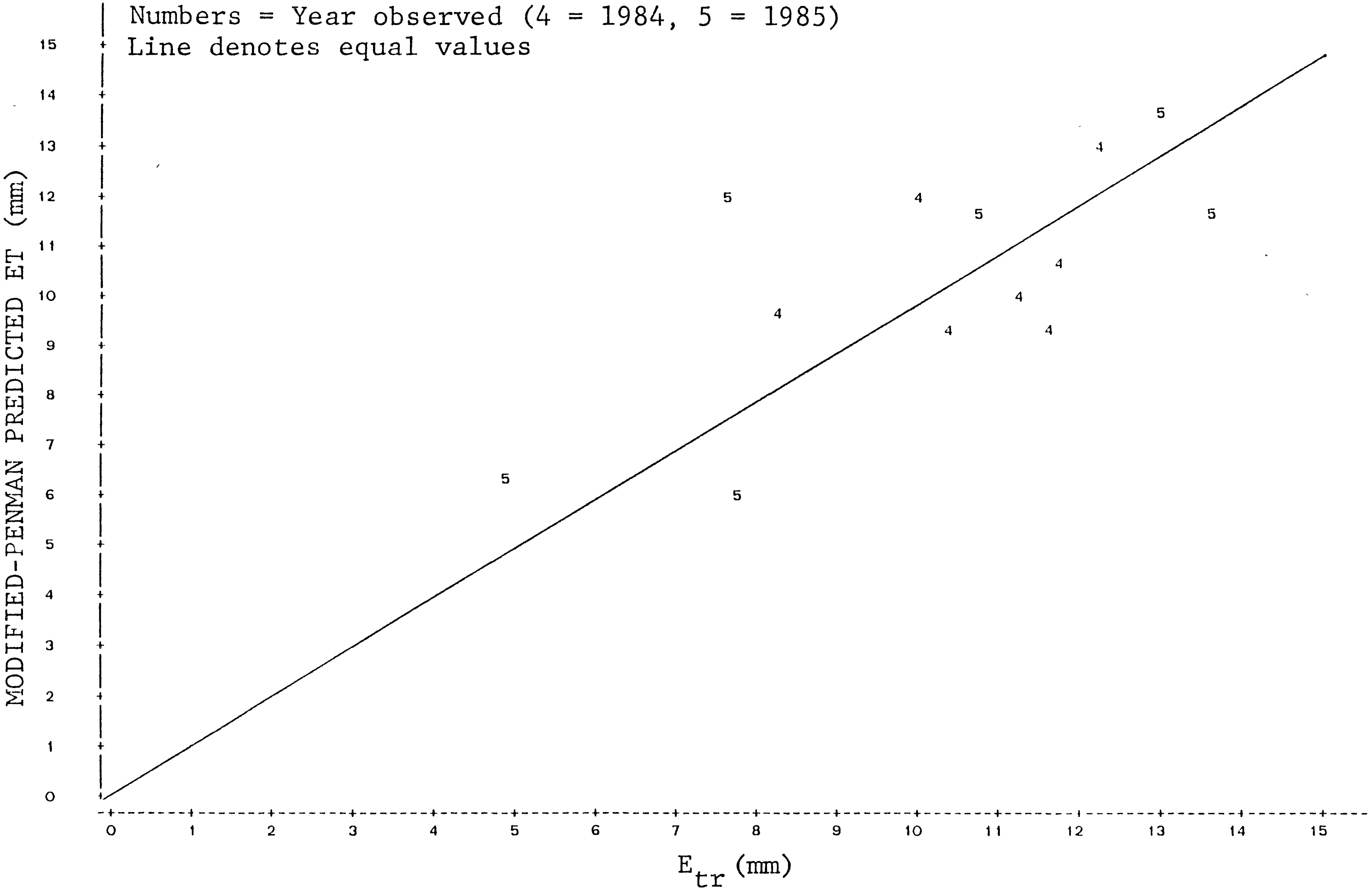

Figure 9. Plot of modified-Penman predicted ET with measured reference ET (E_{tr})

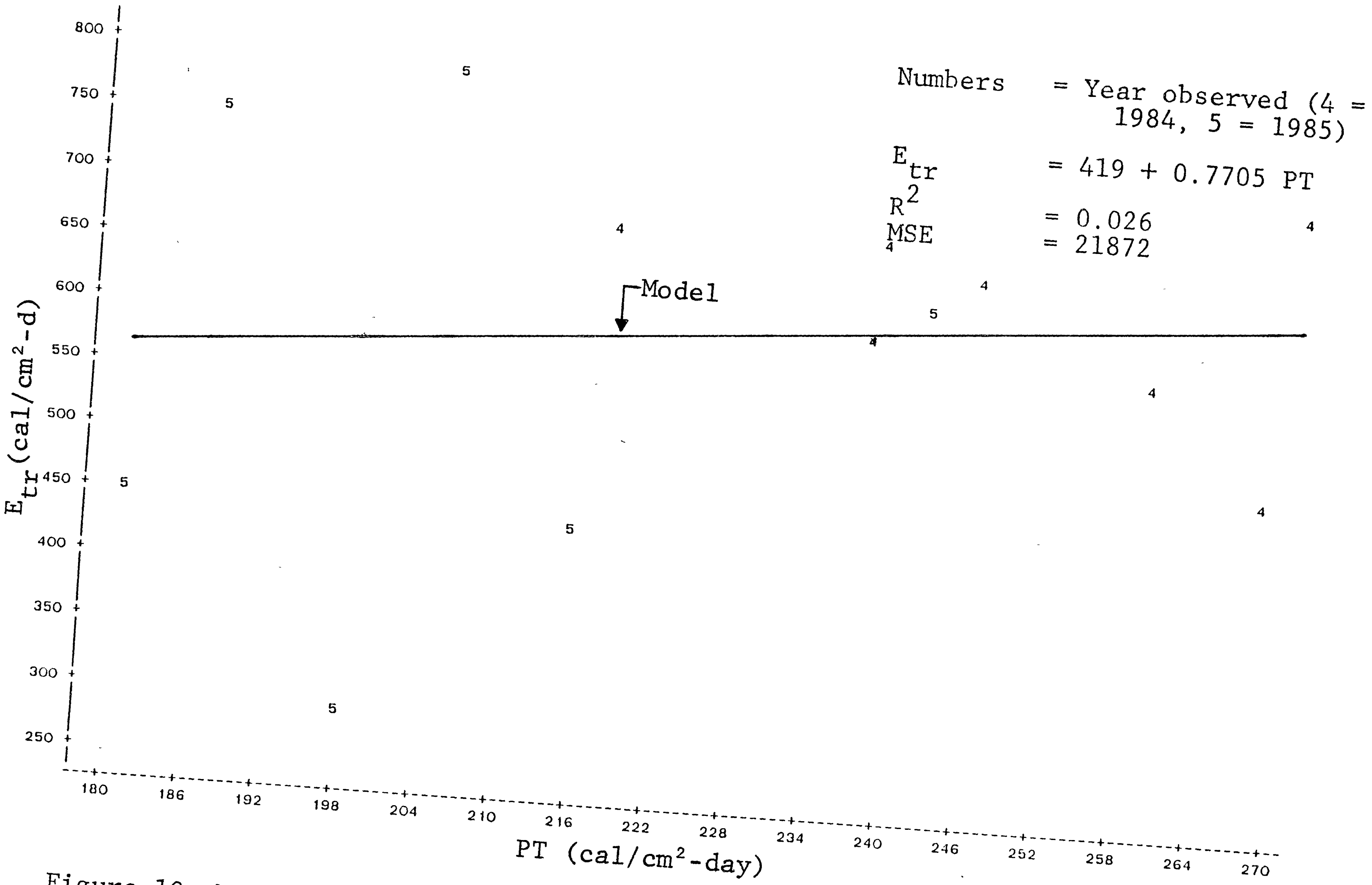

Figure 10. Model of measured reference ET (E_{tr}) with PT.

intercept are equal to zero) could not be rejected. Other statistical parameters associated with the model were: R^2 = 0.026 and MSE = 21872.

In light of the lack of statistical significance, measured reference and Priestley-Taylor predicted ET may be considered linearly independent. To better visualize this independence, refer to Fig. 11. Advective forces in the Priestley-Taylor equation are supposedly accounted for in the regression coefficients a_{PT} and b_{PT}. Because the coefficients are constant, the equation is unresponsive to fluctuations of U_z on a day to day or period to period basis. Therefore, in areas of high advection, the PT equation might be expected to perform poorly. The climate of the Oklahoma Panhandle is characterized by high advective forces, which could explain the poor relationship shown in Fig. 11.

<u>Jensen-Haise</u>. To calculate C_t and T_x for the Jensen-Haise equation (2.4), temperature data were extracted from 33 years of weather data observed between 1948 and 1981 at the Goodwell Research Station. July was ascertained to be the warmest month of the year with a mean maximum temperature of 34.1°C (93.3°F) and a mean minimum temperature of 18.2°C (64.8°F). Calculated values derived from these average temperatures were C_t = 0.0234 and T_x = -8.87.

To visualize how well the Jensen-Haise equation predicted measured ET, estimates using equation (2.4) were

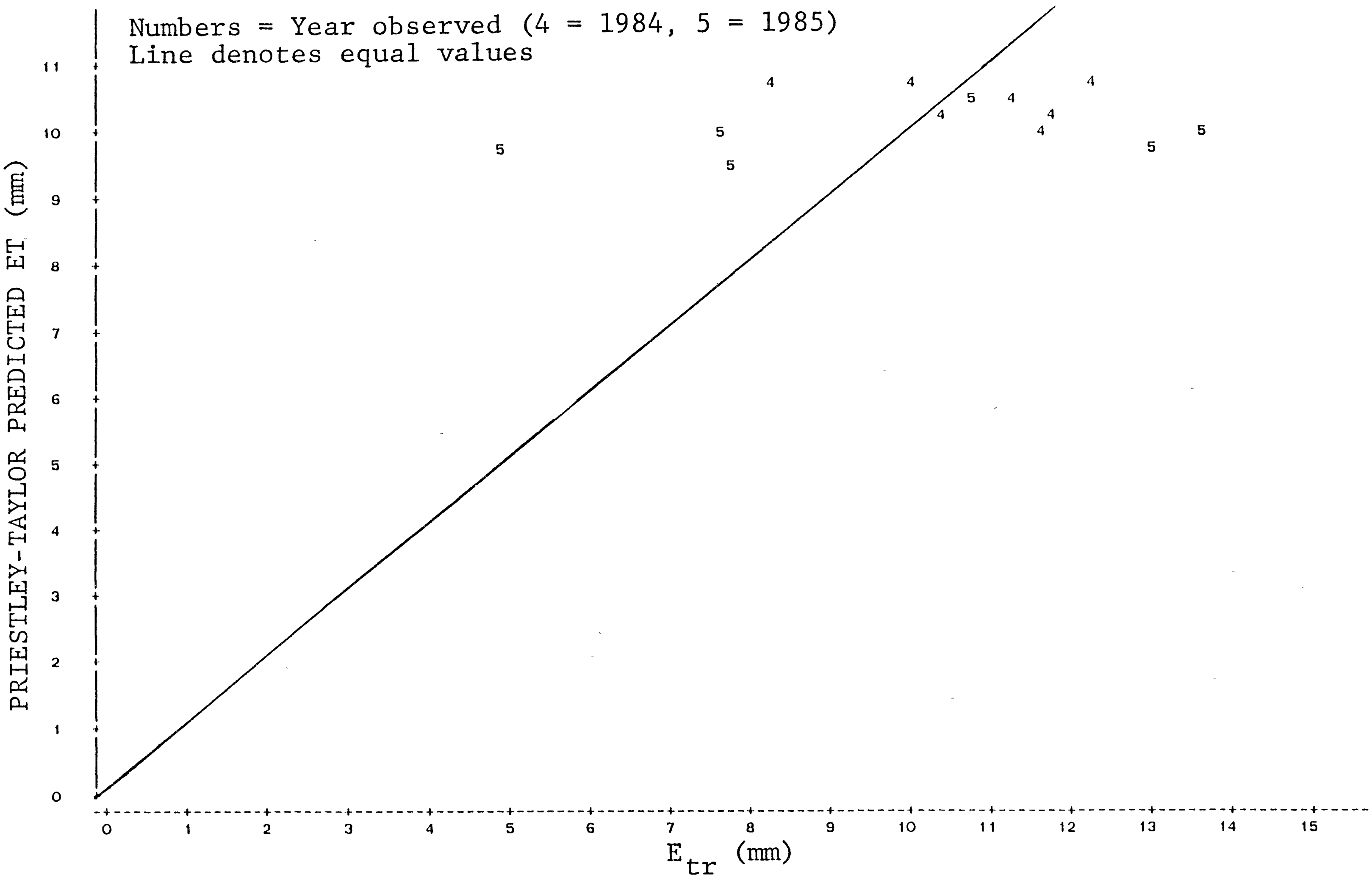
Numbers = Year observed (4 = 1984, 5 = 1985)
Line denotes equal values

Figure 11. Plot of Priestley-Taylor predicted ET with measured reference ET (E_{tr})

plotted with E_{tr} in Fig. 12. By observation the calibrated equation tended to underpredict actual ET whenever E_{tr} exceeded 9 mm/d (0.35 in/d).

Predictions of reference ET on a day to day basis are dependent upon daily averages of ambient air temperature and total solar radiation. Other factors such as advection are supposedly incorporated into the constants C_t and T_x. Since advection in the Oklahoma Panhandle is an important factor to be considered, and is not static, the poor fit shown in Fig. 12 is understandable.

Evaporation Pan. Measured reference ET for 1984 and 1985 was regressed on pan ET measured at the Goodwell Research Station (Fig. 13). It was assumed that climatic conditions prevailing at the alfalfa site were equivalent to those at the pan site.

To better account for the variability associated with the data, equation (2.6) was not forced through zero, thus allowing an intercept (5.07) and slope (0.40) to be approximated. Neither term was found to be significant at the 0.05 level (Table 8). If the significance level were changed to 0.10 however, the slope could be classified as significant. Other statistical parameters associated with the model were: $R^2 = 0.23$ and MSE = 5.16.

The pan does integrate many of the climatic factors known to affect reference ET, e.g., humidity, wind speed, solar radiation, etc. However, the pan was located 10 km (6 mi) from the reference plot which might have had a

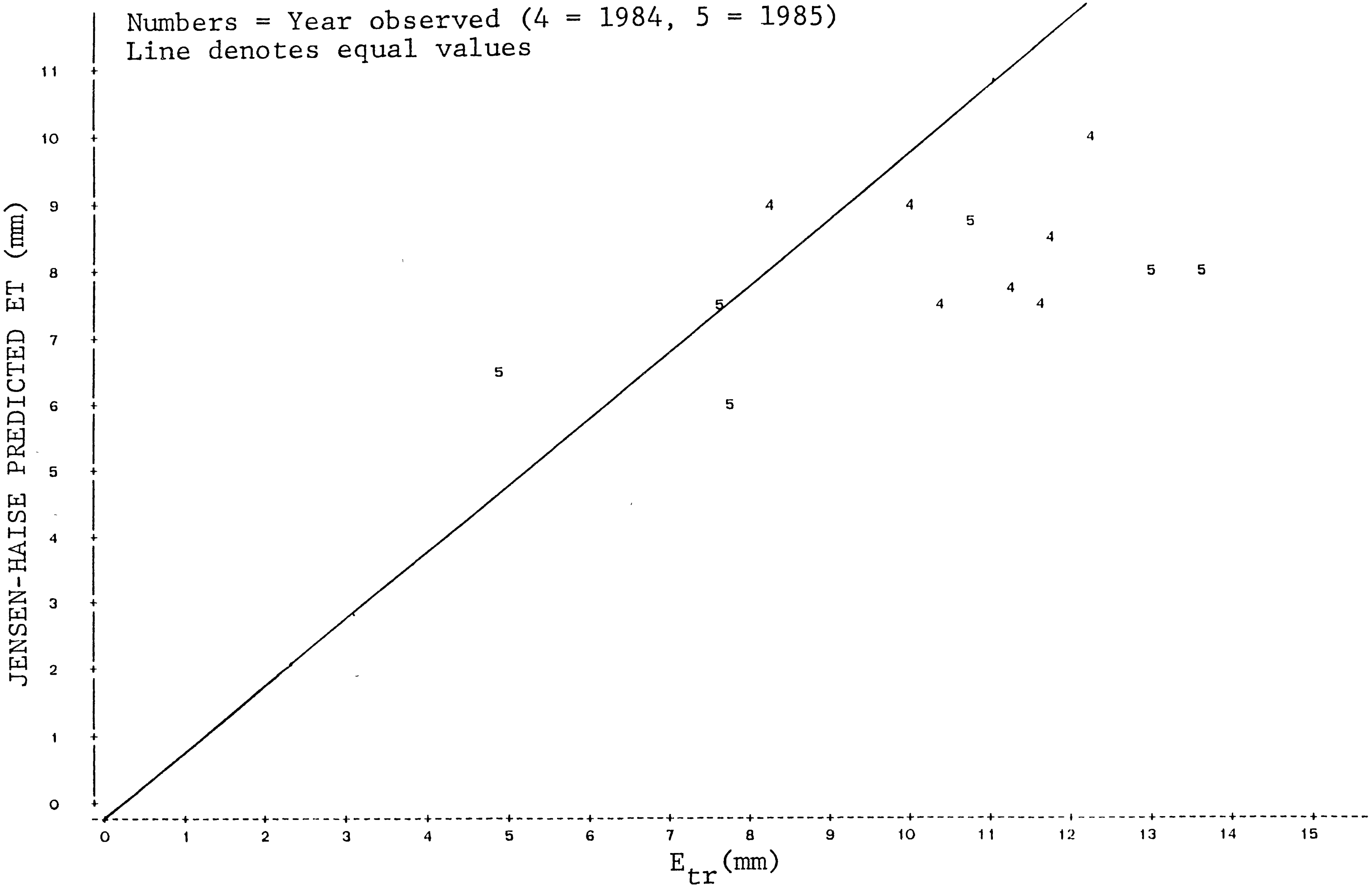

Figure 12. Plot of Jensen-Haise predicted ET with measured reference ET (E_{tr})

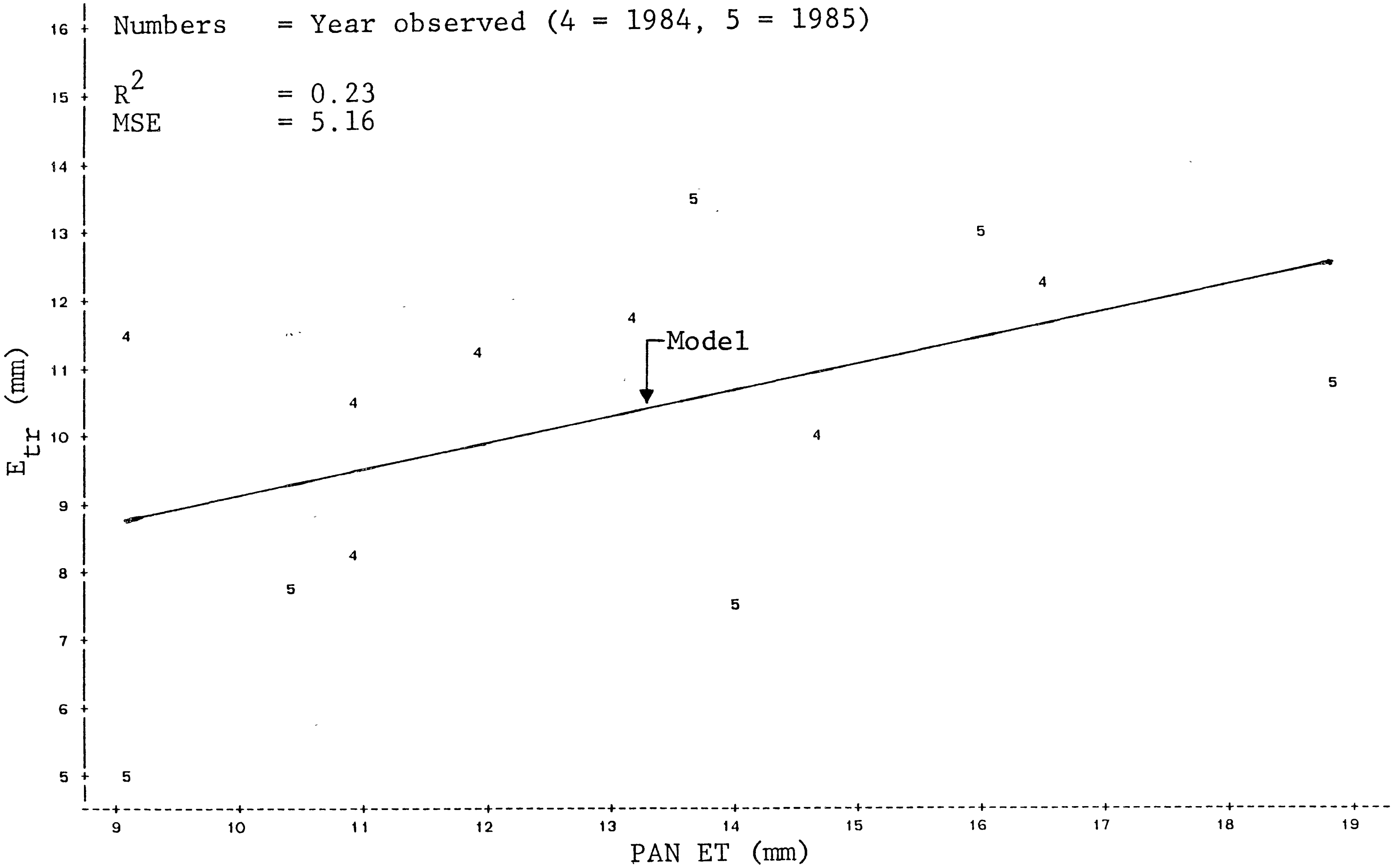

Figure 13. Model of measured reference ET (E_{tr}) with pan ET.

detrimental impact on a possible significant correlation. If the pan and reference crop were in closer proximity, a better relationship might have been established.

Crop Coefficients

To facilitate the prediction of row crop ET from alfalfa reference ET, crop coefficients (K_c) were calculated using equation (3.24). Reference and crop ETs used in the calculations were selected from values listed in Table 5. Occasionally measured crop ET rates from normal and stressed plots were higher than those observed in well-watered plots. In such cases, readings were treated as well-watered replicates and averaged with well-watered ET rates.

Identical row crop varieties were planted in 1984 and 1985, so the times between the various phases of physiological development were nearly equal. Capitalizing upon this fact the growth stages for each year were normalized by defining the stage as a function of the number of days after crop emergence (DAE) (see Phene et al., 1985). Growth stages of corn and soybeans were observed more frequently in 1984 than in 1985. Conversely, sorghum observations were more frequent in 1985 than in 1984. Thus pooled growth stage data relied more heavily upon these crop-year combinations with respect to DAE.

The values of K_c were first calculated and then plotted against DAE. Next, a subset of K_c values from scatterplots was judiciously selected and regressed on DAE (Table 9).

TABLE 9.

SUMMARY TABLE OF CROP COEFFICIENTS FOR 1984 AND 1985

Year	Dates	Corn		Sorghum		Soybeans	
		K_c	DAE	K_c	DAE	K_c	DAE
1984	6/14 - 6/17	0.57	33.5	0.47	8.5[1]	0.60	26.5[1]
	6/28 - 7/1	-	-	0.29	22.5	0.59	40.5
	7/12 - 7/15	1.02	61.5	0.68	36.5	0.97	54.5
	7/19 - 7/22	1.01	68.5	0.84	43.5	0.77	61.5[1]
	7/26 - 7/30	0.61	76.0[1]	0.44	51.0[1]	0.65	69.0[1]
	8/16 - 8/19	0.86	96.5	0.33	71.5[1]	0.33	89.5
	8/23 - 8/26	0.65	103.5	-	-	0.15	96.5
1985	7/12 - 7/15	0.60	54.5[1]	0.88	51.5	0.33	36.5
	8/8 - 8/11	0.67	81.5[1]	0.70	78.5	1.07	63.5
	8/22 - 8/25	0.88	95.5	0.67	92.5	0.79	77.5
	8/26 - 8/29	0.64	99.5	0.53	96.5	-	-
	8/30 - 9/2	-	-	0.15	100.5	0.73	85.5

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[1] Not used in K_c regression analysis

Data excluded from the analysis either had peculiarities associated with the timing or method of field data acquisition, or gross dissimilarities to curves reported in the literature (Phene et al., 1985). For example, K_c values for the period July 26-30, 1984, were rejected for all crops because reference crop observations were made immediately after a sprinkler irrigation, rather than allowing some time for redistribution.

Cubic equations were used to describe the relationship of K_c with DAE (Phene et al., 1985). It should be noted that model predictions given in Figures 15, 17, and 19 were found by substituting measured values (used in the calibration) into prediction equations and solving.

Corn. One five-day and nine four-day intervals of well-watered corn ET were merged with corresponding alfalfa reference ETs to calculate K_c values for those periods (Table 9). These values were then plotted against DAE in Fig. 14. Three of those values were ignored for the polynomial regression analysis that modeled K_c with DAE. One of those values corresponded to the five day interval previously discussed. The two remaining values were removed based on inconsistencies with the literature (Burman, 1980).

Statistical and regression parameters associated with the regression model are given in Table 10 and a plot of measured data with the model is given in Fig. 15. The coefficient of determination (R^2) was 0.92, but none of the regressor variables were significant at the 0.05 level.

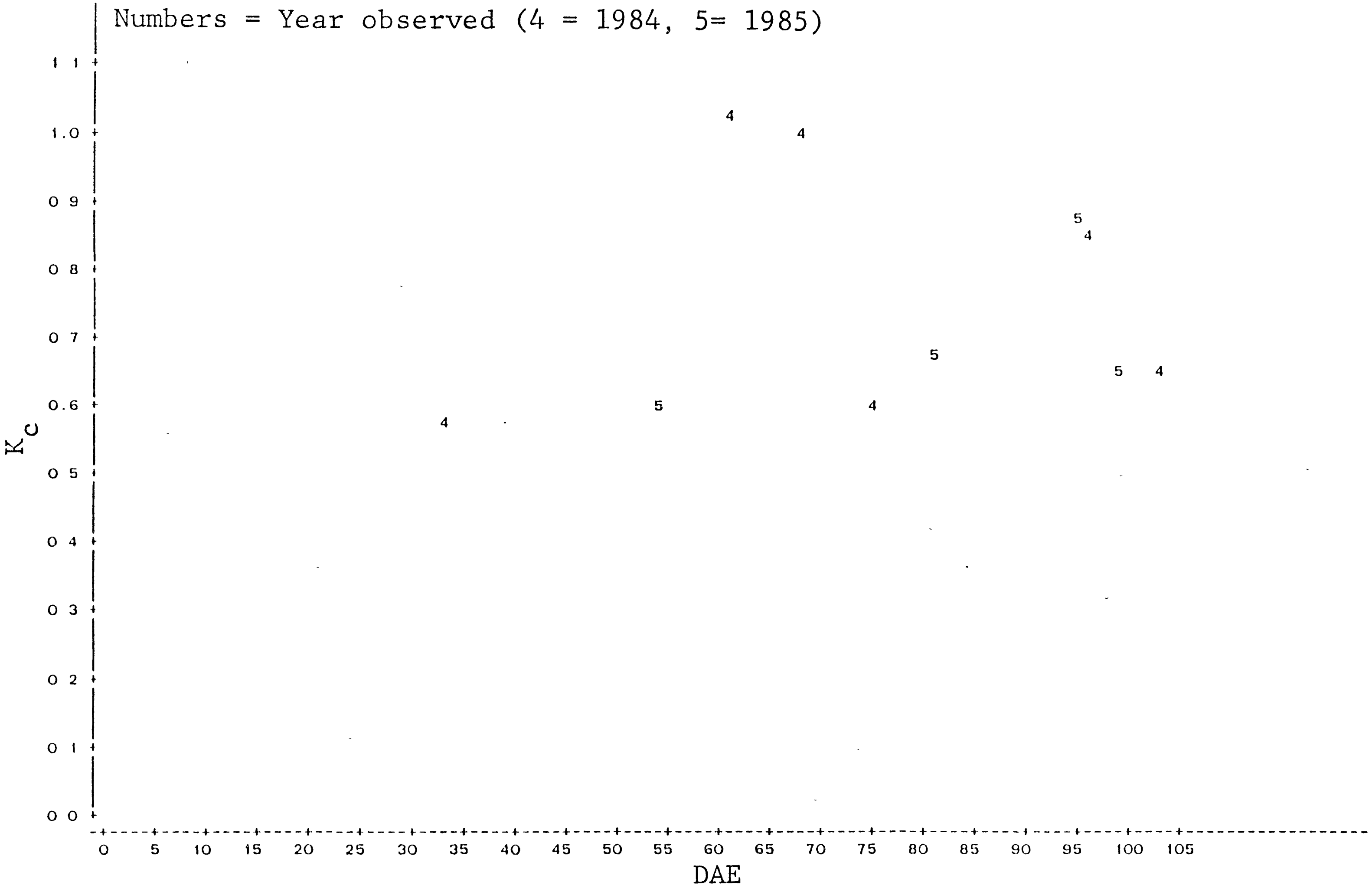

Figure 14. Corn crop coefficients (K_c) plotted with days after emergence (DAE)

TABLE 10.

REGRESSION AND STATISTICAL PARAMETERS FOR CUBIC MODELS OF CROP COEFFICIENTS (K_c) WITH THE NUMBER OF DAYS AFTER CROP EMERGENCE (DAE)

Crop	Intercept		DAE		DAE^2		DAE^3	
	Est.[1]	P>|T|[2]	Est.	P>|T|	Est.	P>|T|	Est.	P>|T|
Corn	.0699	.96	.00805	.91	3.18 E-4	.77	-3.33 E-6	.55
Sorg	-.595	.42	.0483	.29	-3.62 E-4	.64	-3.10 E-7	.94
Soyb	-3.81	.08	.176	.10	-1.90 E-3	.22	5.11 E-6	.48

[1] Est. = Estimate

[2] P>|T| = Probability of a greater T

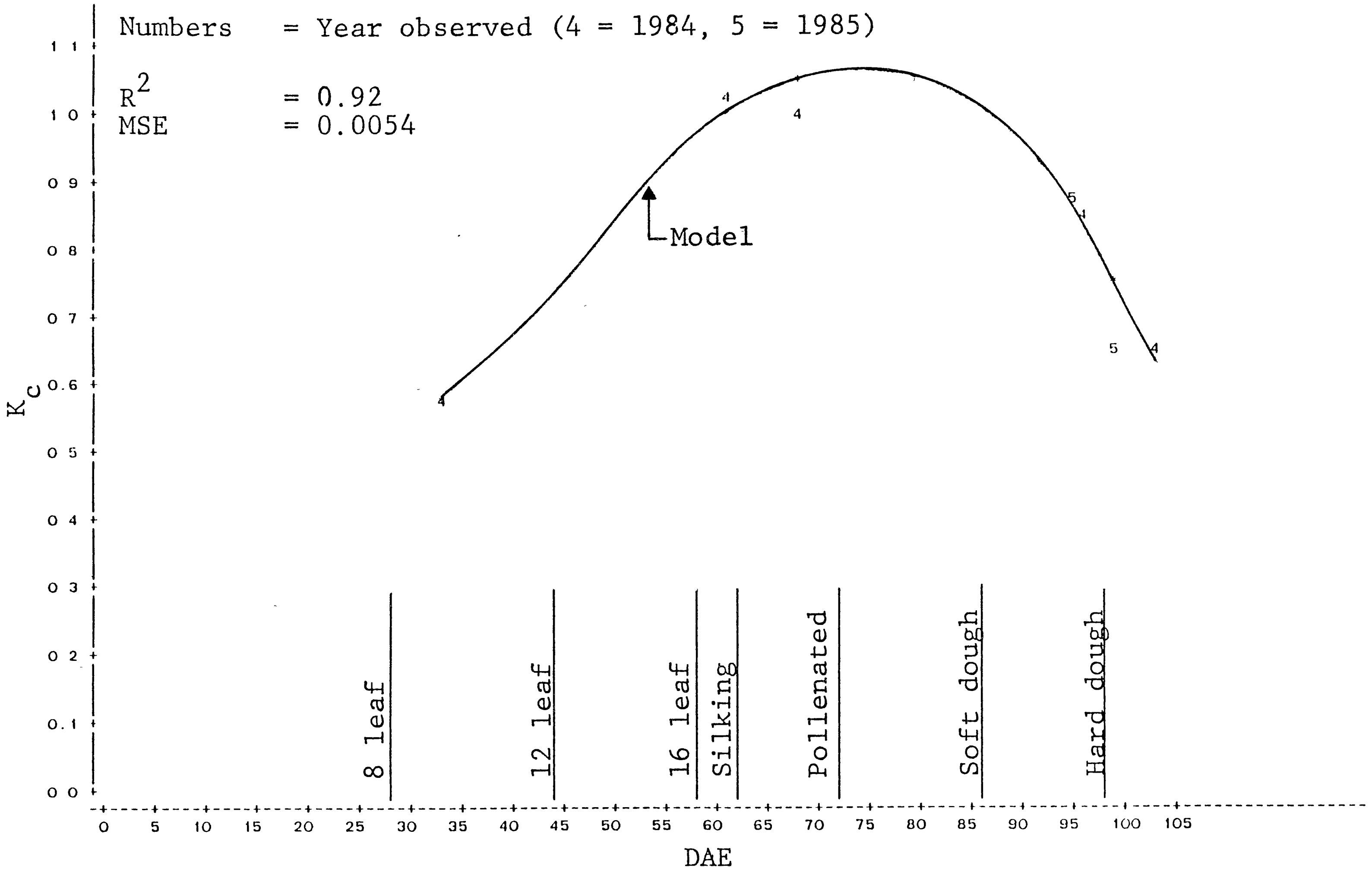

Figure 15. Model of corn crop coefficients (K_c) with days after emergence (DAE).

This would imply that a quadratic equation might suffice for the model, but since models reported in the literature (Burman et al., 1980; Wright, 1982) are cubic in form, a second order equation was not evaluated.

A maximum K_c of 1.06 on DAE = 74 was calculated from the model equation:

$$K_c = 0.0699 + .00805\ DAE + 3.18X10^{-4}\ DAE^2 - \quad (4.3)$$
$$- 3.33X10^{-6}\ DAE^3$$

The growth stage at this point was two days into the pollinated phase (5.5). In comparison, a measured peak K_c of 1.02 was observed between July 12-15, 1984. The growth stage during this period was between the 16 leaf (4.0) and pollen shedding (5.0) phases. Peak K_c was closely followed by a K_c of 1.01 observed between July 19-22, 1984. The growth stage during this period was between the pollen shedding (5.0) and pollinated (5.5) phases. Since these two observations were so close it would be difficult to conclude that maximum K_c will occur between the 16 leaf (4.0) and pollen shedding (5.0) phases. It would be more logical to assume from observed data and the model that maximum water usage will occur between phases 5.0 and 5.5 of crop development.

Sorghum. One five-day and ten four-day periods of measured, well-watered sorghum ET data were merged with alfalfa reference ET data to find values of K_c (Table 9). Calculated coefficients were then plotted with DAE in Fig. 16. Three of those values were ignored for the regression

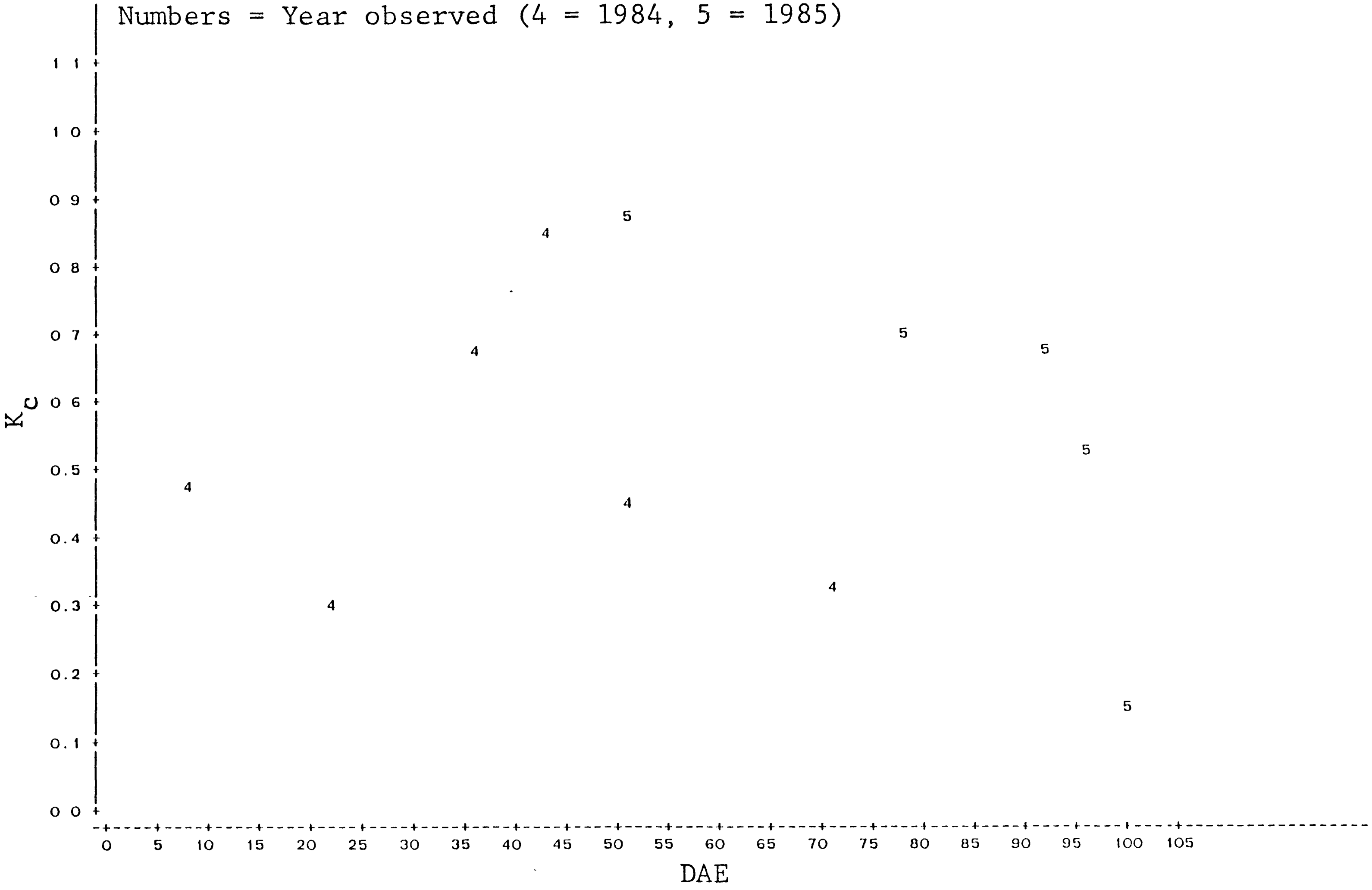

Figure 16. Sorghum crop coefficients (K_c) plotted with days after emergence (DAE).

fit of K_c with DAE (Fig. 17). One of those values corresponded to the five day interval previously discussed. Crop coefficients measured between June 14-17, 1984, were found to be abnormally high for both sorghum and soybeans and were ignored in the regression analysis. Up until June 20, 1984 starting and final standard counts for the neutron probe were measured in the 1 minute "normal" mode rather than the four minute "slow" mode. An unusually low standard count measured on June 14 resulted in an overestimation of soil water content, causing the removal of the June 14-17 period from the analysis.

The regression model calculated from the remaining data is given below:

$$K_c = -0.595 + 0.0483\ DAE - 3.62X10^{-4}\ DAE^2 - 3.10X10^{-7}\ DAE^3 \qquad (4.4)$$

The model described 85% of the variability associated with the data ($R^2 = 0.85$), however none of the regressor variables were significant at the 0.05 level.

A maximum K_c of 0.93 was calculated by equation (4.4) using a DAE of 62. On this date the crop was two days into the half bloom phase (6.0) of development. In comparison, the highest K_c level observed during the two year study was 0.88 and was observed between July 12-15 during the 7 to 10 leaf phase (3.0). Pertinent K_c data between the flag leaf (4.0) and soft-dough (7.0) stages were not available for the analysis, thus the observed maximum K_c should not be considered as absolute. It is probable that equation (4.4)

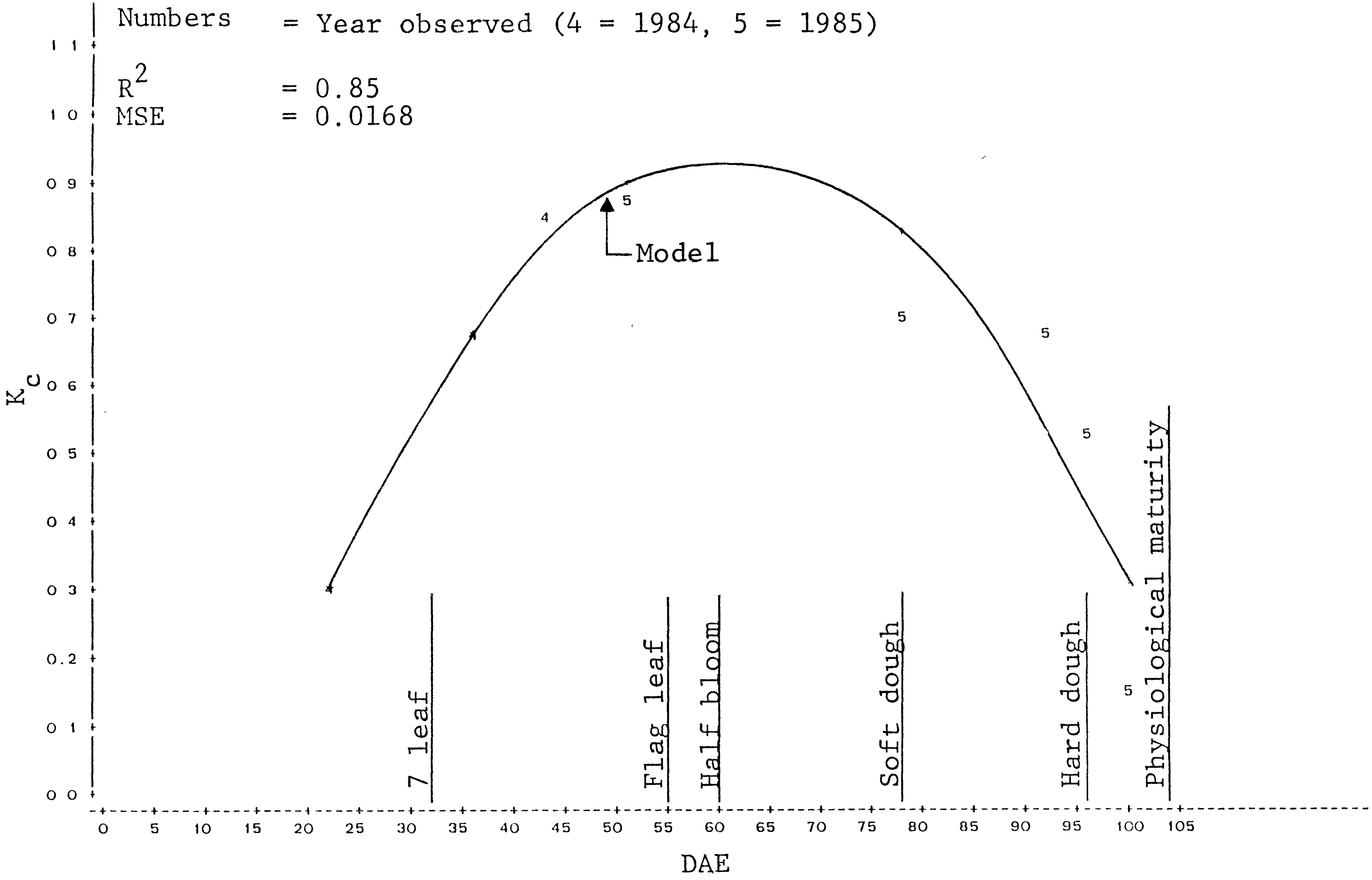

Figure 17. Model of sorghum crop coefficients (K_c) with days after emergence (DAE).

is a better predictor of maximum K_c. This assumption is borne out in the literature as well. For example, Spears and Coffey (1957) reported sorghum ETs to be their highest during the boot stage (5.0) of development.

Soybeans. One five-day and ten four-day periods of measured ET were merged with alfalfa reference ET to calculate K_c. Values of K_c and corresponding DAEs were then plotted in Fig. 18. Three points from the data set were removed (two corresponding to the same dates and for the same reasons as those stated in the sorghum analysis) and a regression analysis similar to ones previously described was performed. The resulting model was plotted with measured K_c in Fig. 19 using the formula below:

$$K_c = -3.81 + 0.176\ \text{DAE} - 1.90\text{X}10^{-3}\ \text{DAE}^2 + 5.11\text{X}10^{-6}\ \text{DAE}^3 \qquad (4.5)$$

The model accounted for 95% of the variability associated with the data ($R^2 = 0.95$) and yet none of the regressor terms were significant at the 0.05 level.

A peak K_c of 1.02 was calculated from equation (4.5) using a DAE of 62. The growth stage on this date was bordering between the full bloom (R2) and beginning pod (R3) phases of development. In comparison, peak K_c from observed data was 1.07. This was recorded between August 8-11, 1985, and corresponded to the R2 phase of crop development.

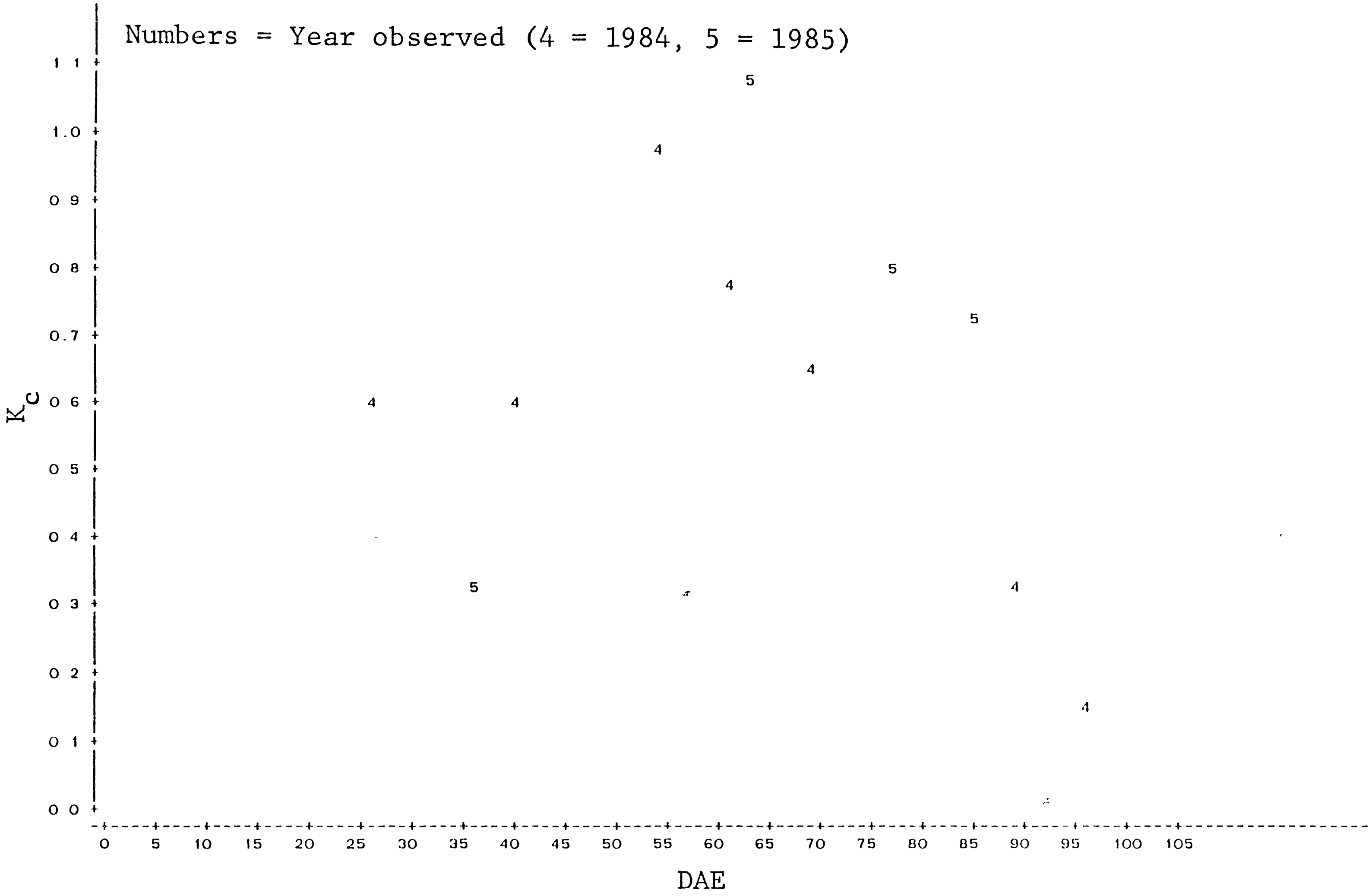

Figure 18. Soybean crop coefficients (K_c) plotted with days after emergence (DAE).

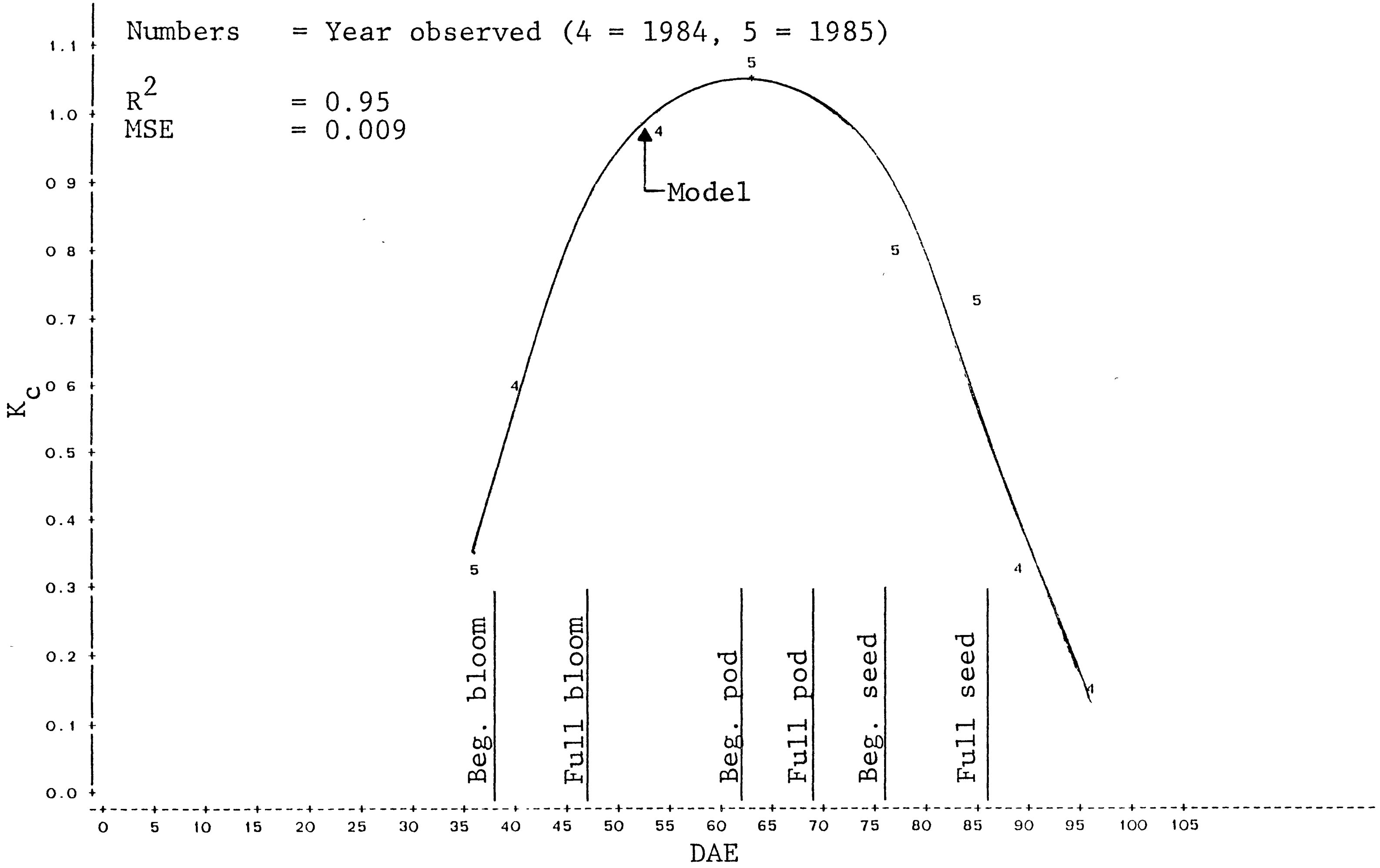

Figure 19. Model of soybean crop coefficients (K_c) with days after emergence (DAE)

Infrared Estimates of Crop Water Stress

Canopy - Air Temperature Method

Canopy minus ambient air temperature differentials were regressed with vapor pressure deficits (VPD) to find non water-stressed baselines for well-watered crops. Baselines representing each irrigation treatment were also calculated and compared within crops. Whenever baseline slopes and intercepts did not differ significantly at the 0.05 level, common slopes and intercepts were calculated.

For all hypothesis testing a type I mean square treatment (TRT) x date error term was used. Treatment x date interaction was used as the error term for testing irrigation differences because "dates" were considered as being replications of the irrigation treatments. When VPD x TRT was tested against error, the hypothesis being tested was that the slope of the linear regression fit to each treatment was the same (Tables 11, 12). The hypothesis could not be rejected regardless of the year or crop thus allowing a common slope for each crop to be calculated. Data were not pooled over years because the variability associated with the 1985 data was significantly higher (0.05 level) than the variability of the 1984 data.

A second evaluation tested the hypothesis that baseline slopes were equal to zero. The hypothesis could only be rejected (0.05 level) for corn and soybeans in 1984, and alfalfa and soybeans in 1985. Plots of $T_c - T_a$ with VPD for

TABLE 11.

1984 REGRESSION AND STATISTICAL PARAMETERS FOR LINEAR MODELS OF T_c - T_a with VPD

Crop	Source	PR>F[1]	I_0	I_1	S_0	S_1
Alf	VPDxTRT	.629				
	VPD	.888			0.0	0.0
	TRT	.001	0.533	-1.86		
Corn	VPDxTRT	.784				
	VPD	.001			-7.40	-7.40
	TRT	.427	0.98	0.98		
Sorg	VPDxTRT	.526				
	VPD	.361			0.0	0.0
	TRT	.690	-1.62	-1.62		
Soyb	VPDxTRT	.780				
	VPD	.004			2.20	2.20
	TRT	.545	-3.58	-3.58		

---

[1] PR>F = Probability of a greater F

I = Intercept S = Slope $_1$ = Well-watered $_0$ = Normal

TABLE 12.

1985 REGRESSION AND STATISTICAL PARAMETERS FOR LINEAR MODELS OF $T_c - T_a$ WITH VPD

Crop	Source	PR>F[1]	I_o	I_1	I_s	S_o	S_1	S_s
Alf	VPDxTRT	.896						
	VPD	.001				-1.3	-1.3	-1.3
	TRT	.476	2.6	2.6	2.6			
Corn	VPDxTRT	.542						
	VPD	.561				0.0	0.0	0.0
	TRT	.029	2.1	-.83	-2.2			
Sorg	VPDxTRT	.636						
	VPD	.711				0.0	0.0	0.0
	TRT	.017	1.73	0.63	-3.1			
					2.5*			-5.1*
Soyb	VPDxTRT	.727						
	VPD	.031				-5.1	-5.1	-5.1
	TRT	.004	.58	2.1	-1.4			

[1] PR>F = Probability of a greater F

I = Intercept S = Slope $_1$ = Well-watered $_o$ = Normal

$_s$ = Stressed * = Dryland

these treatments are given in Figures 20 - 23.

Finally the hypothesis that the intercepts of all baselines were equivalent was tested for each crop. Whenever the hypothesis was not rejected a common intercept was determined by averaging the intercepts of all baselines calculated for that crop.

Canopy-minus-air temperatures (T_c - T_a) for 1984 soybeans was, as expected, negatively correlated with VPD (Fig. 21) and was statistically significant. In contrast T_c - T_a from 1985 (Fig. 23) was positively correlated with VPD and was statistically significant. Other inconsistencies were noted with corn baselines. A plot of T_c - T_a versus VPD yielded a positive correlation (Fig. 20), whereas only negative correlations have been reported in the literature. Since non water-stressed baselines could not be precisely defined, a T_c - T_a method could not be recommended for irrigation scheduling purposes without further research.

Temperature Stress Day Method

A temperature stress day (TSD) is the difference in canopy temperatures between a non well-watered and well-watered crop (measured at solar noon on a clear day). In this study the TSD was calculated using average canopy temperature readings. It was theorized that if a relationship between the percentage of available moisture (AM) in the rooting zone and TSD could be established, one could then estimate AM in any field from only a few minutes

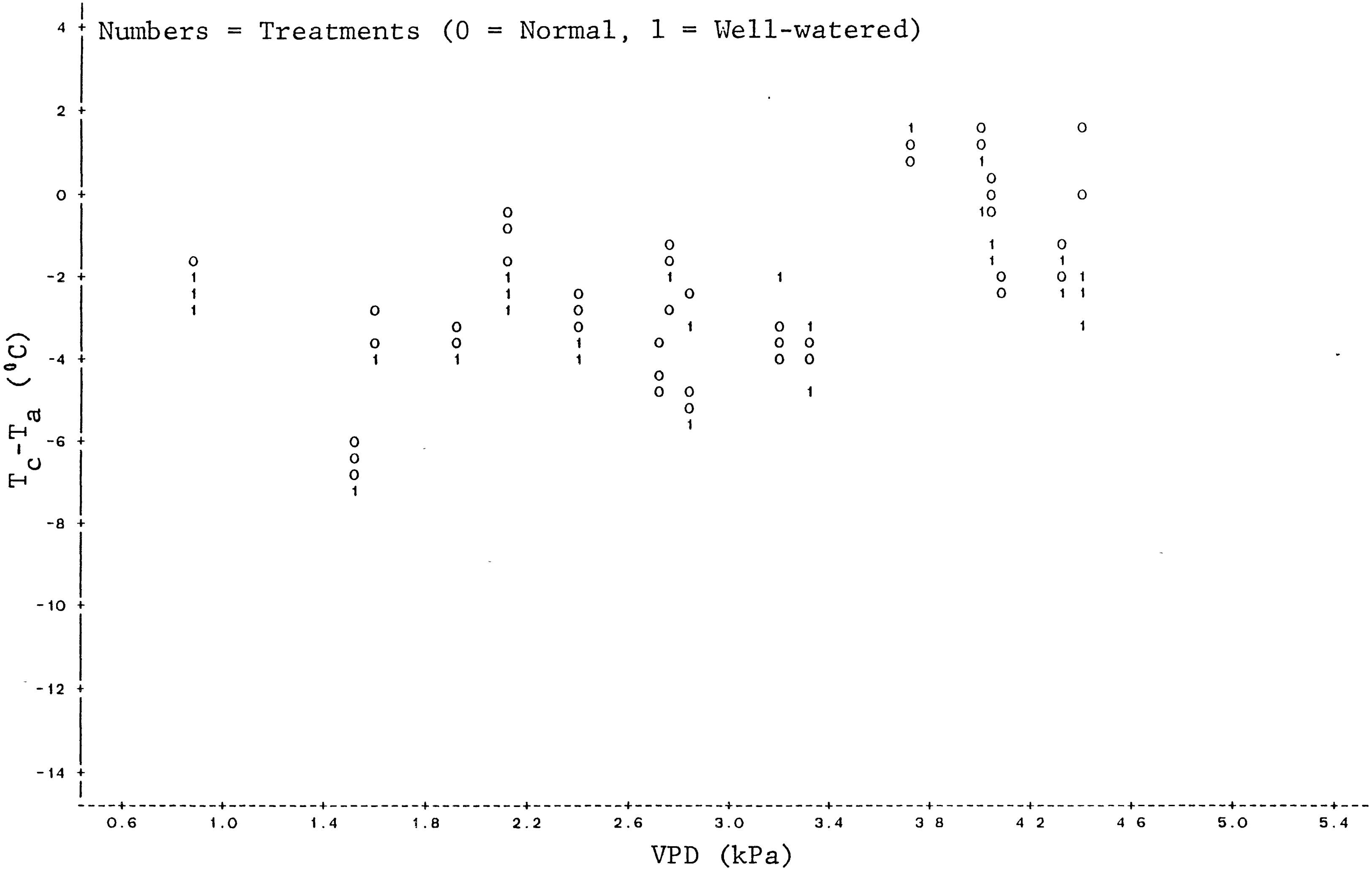

Figure 20. Canopy minus air temperature (T_c-T_a) plotted with vapor pressure deficit (VPD) for 1984 corn.

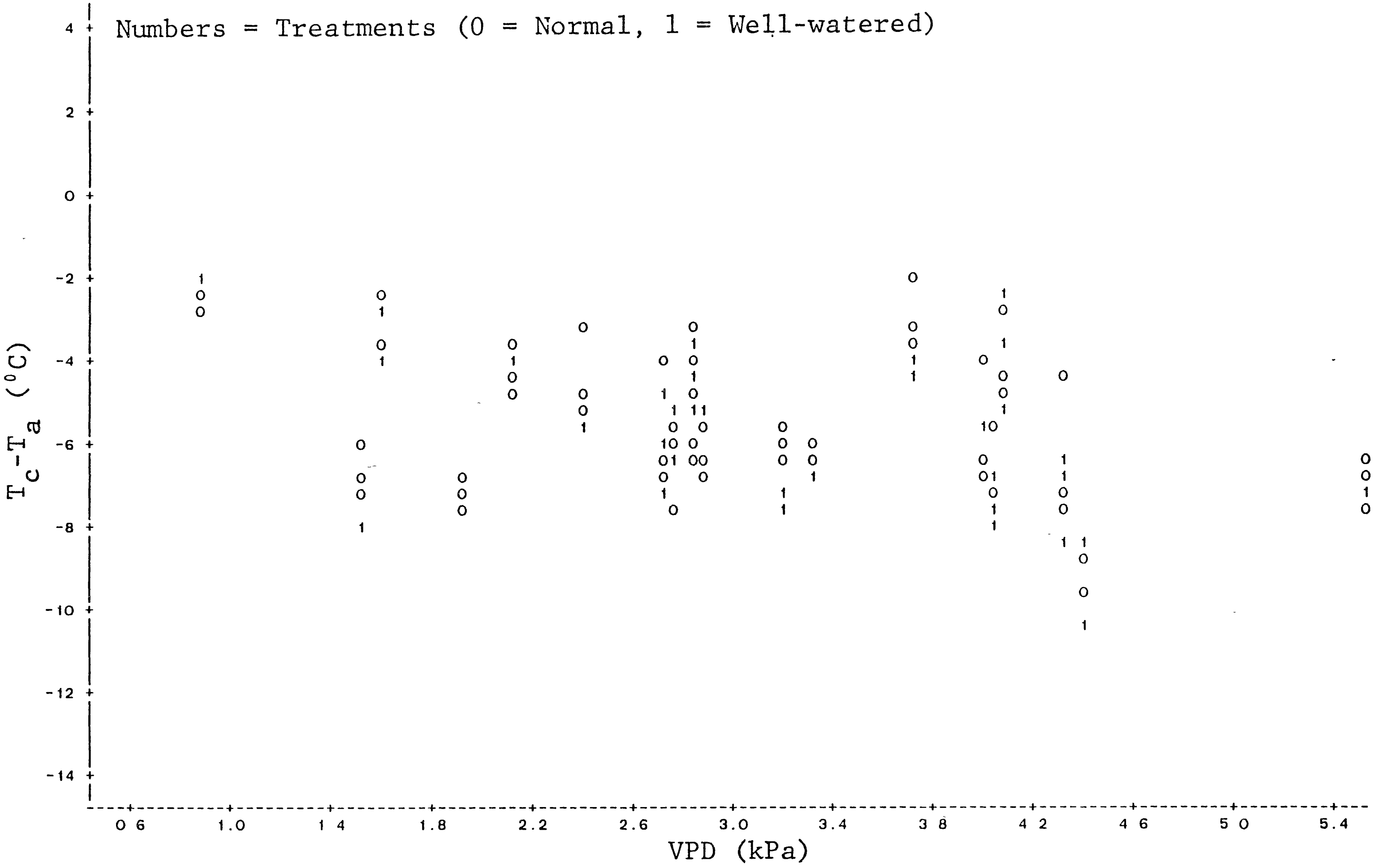

Figure 21. Canopy minus air temperature (T_c-T_a) plotted with vapor pressure deficit (VPD) for 1984 soybeans.

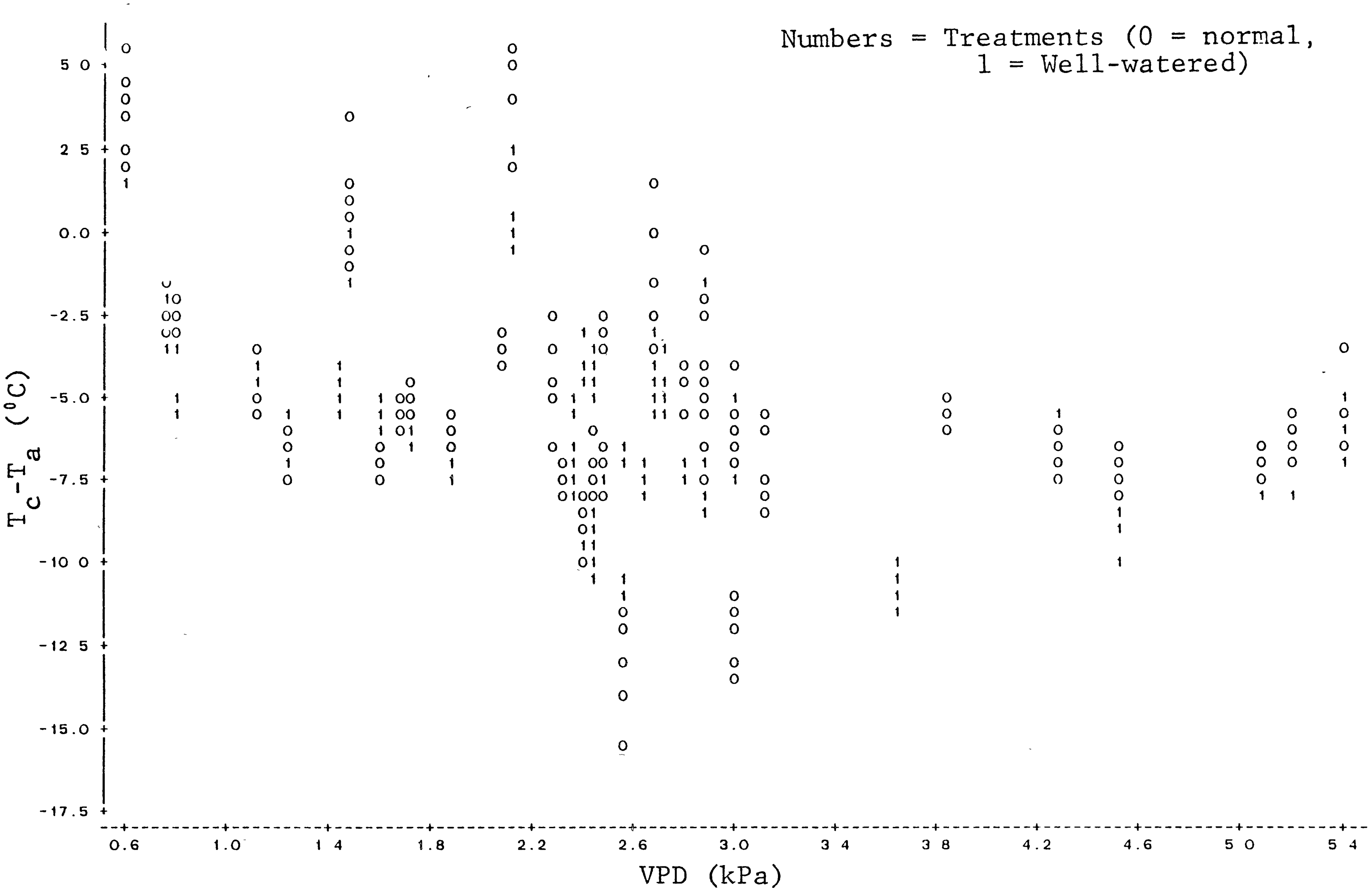

Figure 22. Canopy minus air temperature (T_c-T_a) plotted with vapor pressure deficit (VPD) for 1985 alfalfa.

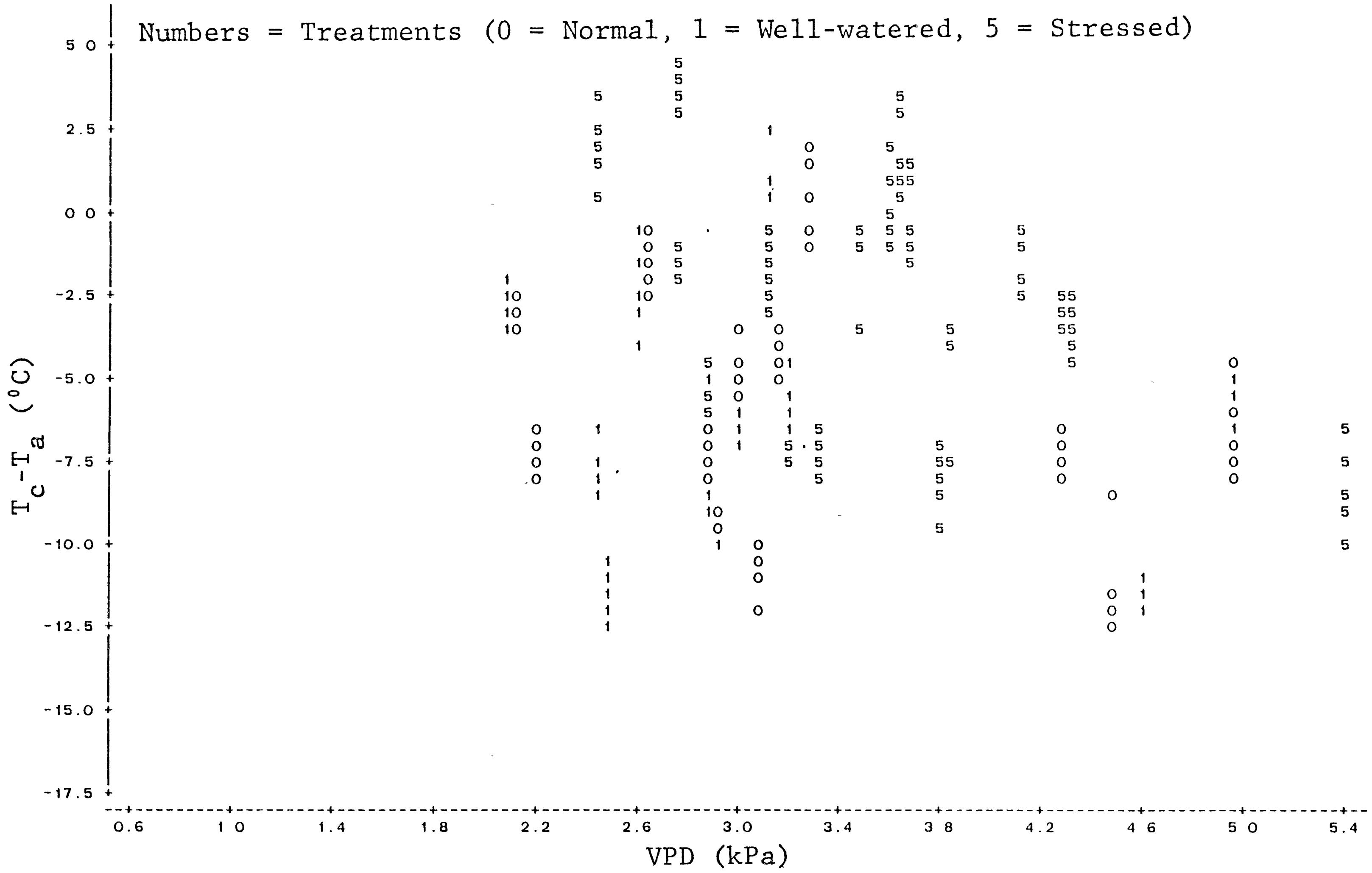

Figure 23. Canopy minus air temperature (T_c-T_a) plotted with vapor pressure deficit (VPD) for 1985 soybeans.

of canopy temperature readings. To find a possible relationship, AMs were calculated by first employing equations (3.8) and (3.9) to determine the volumetric water content (VWC) at field capacity (-1/3 bar). Values of 0.39 and 0.37, corresponding to 1.20 m (3.9 ft) and 1.50 mm (4.9 ft) depths, were calculated and then averaged (0.38) to approximate the VWC of the entire profile at field capacity. A wilting point VWC of 0.11 was then calculated from field data reported by Stone (1985), and AM determined by the following expression:

$$AM = 100\,(VWC - 0.11)/(0.27) \qquad (4.6)$$

where

AM = Percent available moisture

VWC = Volumetric water content

0.11 = VWC at the wilting point (-15 bars)

0.27 = VWC at field capacity (-1/3 bar) minus VWC at the wilting point

Negative linear relationships were found when AM from 1984 and 1985 were plotted against TSD. Regressions of AM with TSD yielded the following expressions:

$$AM_{Alf} = 92.5 - 9.78(TSD) \qquad (4.7)$$

$$AM_{Corn} = 74.3 - 5.50(TSD) \qquad (4.8)$$

$$AM_{Soyb} = 81.5 - 1.62(TSD) \qquad (4.9)$$

Statistical parameters associated with the data are given in Table 13, and plots of measured AM with predicted AM are given in Figures 24 - 26. An equation and plot of AM with TSD for sorghum is not given because of the weak relationship found (Table 13). Model predictions of AM with

TABLE 13.

REGRESSION AND STATISTICAL PARAMETERS FOR LINEAR MODELS OF AM WITH TSD

Crop	a_{TSD}	P>|T|[1]	b_{TSD}	P>|T|	MSE	R^2
Alfalfa	92.54	0.000	-9.78	0.000	219	0.60
Corn	74.31	0.000	-5.50	0.000	30.8	0.72
Sorghum	66.00	0.000	1.37	0.240	101	0.05
Soybeans	81.54	0.000	-1.62	0.000	18.6	0.64

[1] P>|T| = Probability of a greater T

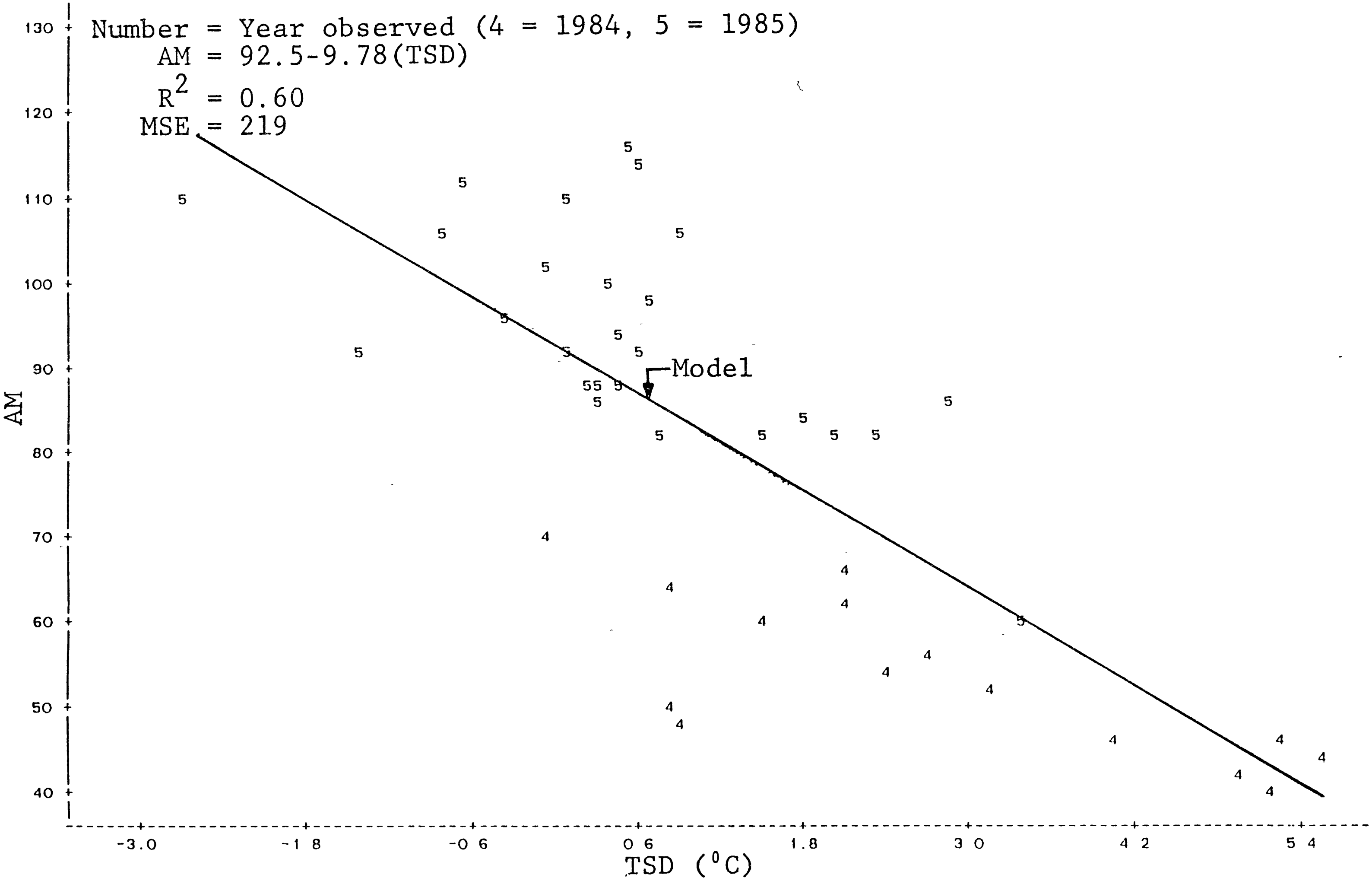

Figure 24. Percent of available moisture (AM) plotted with temperature stress day (TSD) for 1984 and 1985 alfalfa.

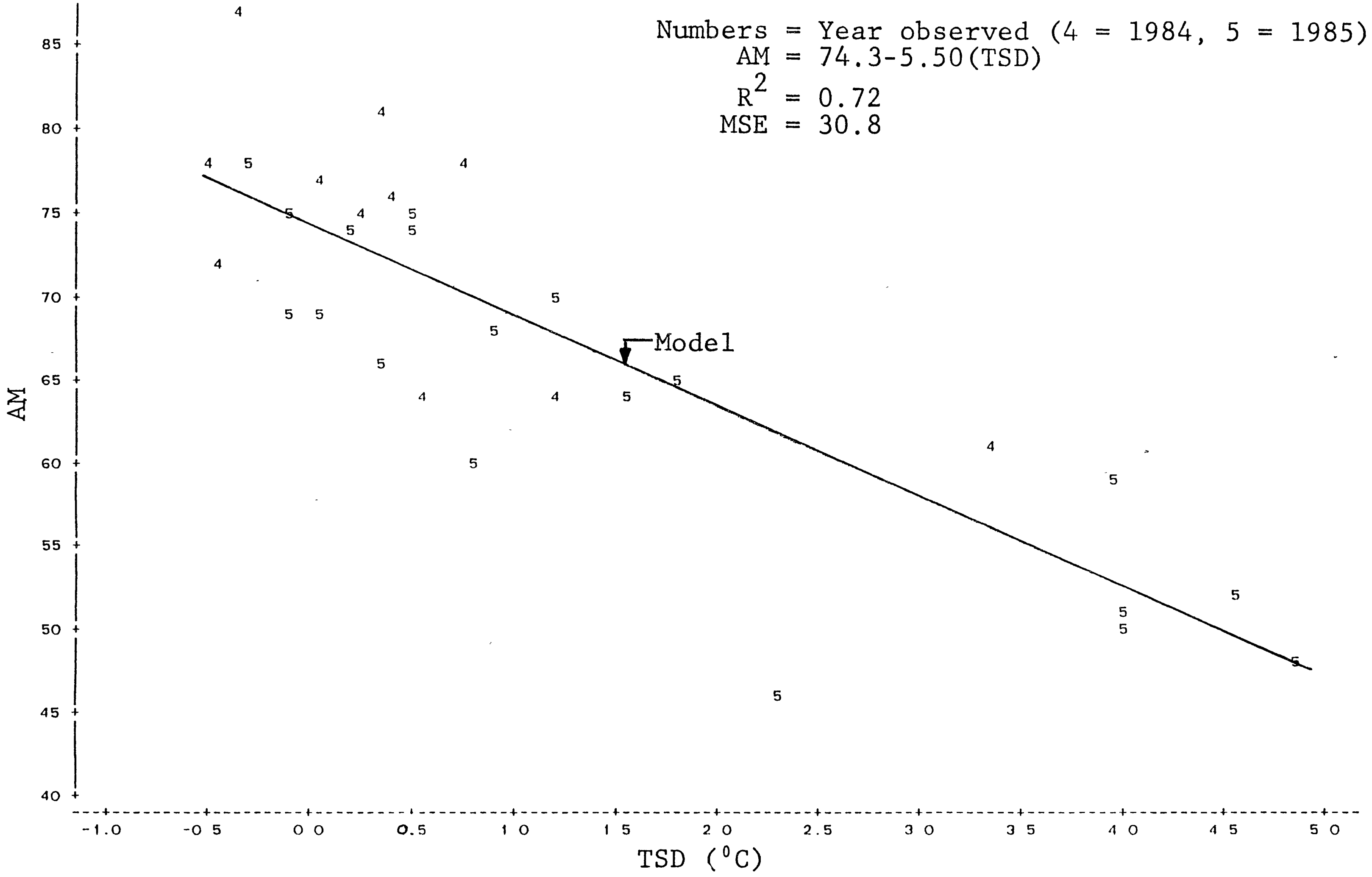

Figure 25. Percent of available moisture (AM) plotted with temperature stress day (TSD) for 1984 and 1985 corn.

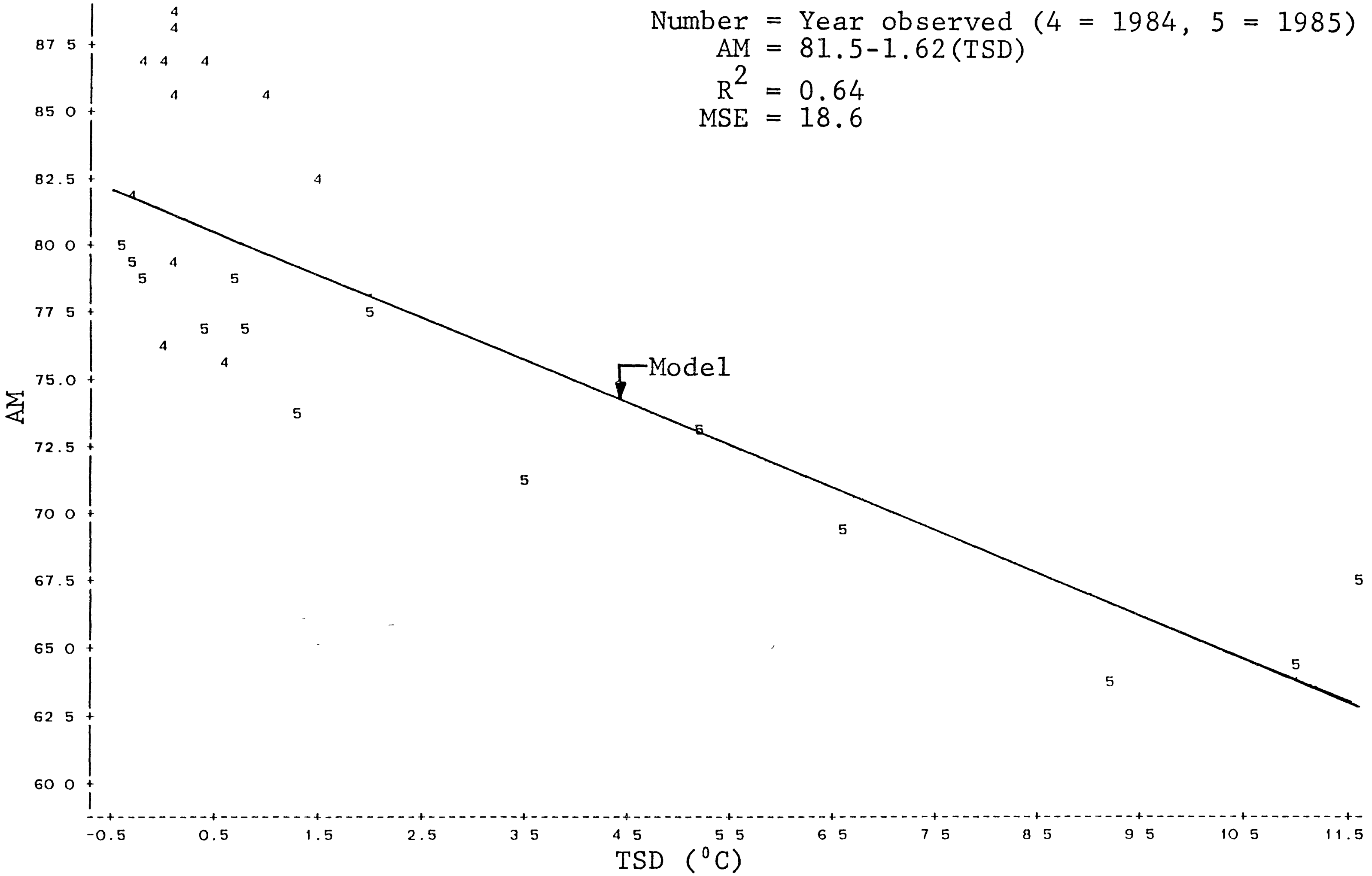

Figure 26. Percent of available moisture (AM) plotted with temperature stress day (TSD) for 1984 and 1985 soybeans.

TSD plotted in the figures were determined by substituting measured values (used for calibration) into prediction equations.

The variability of AM appears to increase as TSD decreases (Fig. 24 - 26). This would not present a problem in predicting AM from TSD since most irrigations would be scheduled in the region of lower variability, i.e., 50% available moisture.

The calculated available moisture percentages appear to be higher than those generally associated with stress-induced yield reductions. Yield differences between treatments were found (indicating significant water stress) and a check of the neutron data seemed to suggest that a value of 0.27 for the VWC at field capacity is too low. Thus, it is recommended that equations (3.8) and (3.9) be checked by additional soil sampling and testing. If AM values have in fact been overestimated, the relationships between AM and TSD are still valid, but the ordinate will need to be rescaled.

Based upon the regression and statistical parameters given in Table 13 and the regression plots shown in Figures 24 - 26, the prediction of AM from TSD data appears to be a viable scheduling criterion to follow for alfalfa, corn, and soybeans. To implement the TSD scheduling method, a well-watered portion of the field would have to be monitored in conjunction with the remainder of the field. With a center pivot system the well-watered plot might be situated nearest the center pivot, or whatever area receives the greatest depth of applied water. With a surface irrigation system a depression in the field where water tends to accumulate (but not to harmful levels) could serve as a well-watered IR reference plot.

In the case of sorghum, there appears to be no dependent relationship similar to those found for the other crops. The TSD method is designed to register only temperature differences due to watering treatments since climatic factors affecting each treatment are the same. The only exception would be if plots were not sufficiently stressed. In that case AM would show virtually no dependency on the TSD and yields for each treatment would be statistically equivalent (Johnson, 1986). This was not the case with sorghum. A comparison of treatment yields for both 1984 and 1985 demonstrated that sorghum was stressed enough to reduce yields significantly (Table 14). Thus it may be concluded that the TSD method should not be used for sorghum irrigation scheduling. It should also be noted that the statistical equivalence of soybean yields for 1984 and corn for 1984 and 1985 reinforced the notion that normal plots could be treated as well-watered replicates.

Canopy Temperature Variability Method

A third method of predicting crop water stress from infrared thermometer data involved the measurement of canopy temperature variability (CTV), where CTV is the difference

TABLE 14.

A COMPARISON OF ROW CROP YIELDS FOR 1984 AND 1985

Year	Crop	Yield (kg/ha)		
		Well-watered	Normal	Stressed
1984	Corn	13200 A	13600 A	-
	Sorghum	8560 A	8020 B	-
	Soybeans	3860 A	4340 A	-
1985	Corn	9350 A	8530 A	3820 B
	Sorghum	7270 A	6850 AB	5300 B
	Soybeans	3440 A	2980 B	1800 C

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[1] Treatment means with the same letter are not significantly different at the 95% level of probability according to Duncan's New Multiple Range Test.

between maximum and minimum daily canopy temperature readings observed at solar noon. These values were plotted with AM to see if a meaningful relationship could be established. Only a scatterplot of the sorghum data appeared to merit further investigation. A negative exponential relationship was used to fit the data. To calculate regression coefficients the following transformation was used:

$$\ln(AM) = \ln a_{(CTV)} - b_{CTV}(CTV) \qquad (4.10)$$

The natural log of AM was then regressed on CTV and a summary of those results is given in Table 15.

By transforming the regression equation back to exponential form, AM within the rooting zone could then be predicted by the following formula:

$$AM = 75.5 \exp(-0.0638CTV) \qquad (4.11)$$

A plot of the field data and predicted AM is given in Fig. 27. Model predictions given in Fig. 27 were found by substituting measured values into prediction equations and solving for AM. The AM in 1984 was generally higher than levels measured in 1985. When plotted with CTV, data clustered above the 70 percent available moisture level (Fig. 27). In 1985 CTV values covered a broader range as AM decreased. This was probably due to higher stress levels, but may also have resulted from increasing the number of replications from three in 1984 to six in 1985.

In another test, average temperatures for each treatment were compared by crops to see if yields differed

TABLE 15.

REGRESSION AND STATISTICAL PARAMETERS FOR A LINEAR MODEL OF LN(AM) WITH CTV

Crop	$\ln(a_{CTV})$	P>|T|[1]	b_{CTV}	P>|T|	MSE	R^2
Sorghum	4.324	0.000	0.0638	0.000	0.0163	0.41

[1] Probability of a greater T

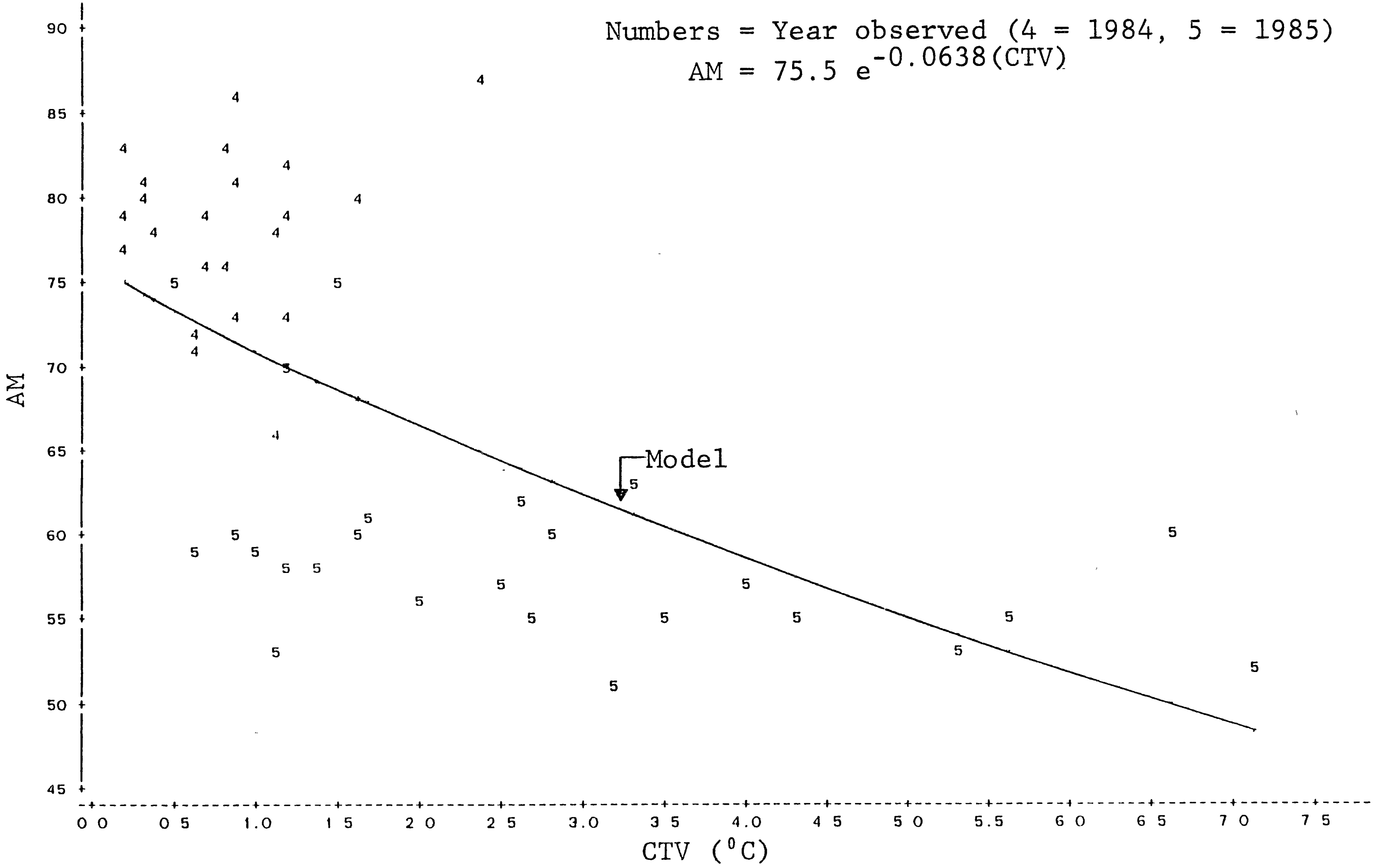

Figure 27. Percent of available moisture (AM) plotted with canopy temperature variability (CTV) for 1984 and 1985 sorghum.

significantly for significant changes in average canopy temperature (Table 16). With the exception of sorghum, temperature and yield differences nearly always coincided (Table 14). This would reinforce the idea that water stress in sorghum may be determined best by the CTV method and not the TSD method.

The unusual behavior of sorghum may be related to its water saving characteristics. Sorghum's drought resistant characteristics are recognized by Panhandle farmers, and for this reason it is often preferred over other summer crops. Its ability to withstand an arid environment may be partially evidenced by a higher average canopy temperature due to reduced canopy stomatal conductance (Johnson, 1986). This was supported by 1984 and 1985 field data (Table 17). Average seasonal canopy temperatures were statistically compared by treatments using the Duncan's New Multiple Range Test. The analysis indicated that corn and sorghum canopy temperature levels were significantly higher than those measured for soybeans in 1984 and for alfalfa in 1985. Both corn and sorghum are C_4 plants, whereas alfalfa and soybeans are C_3 plants. Higher canopy temperatures could have been due to this physiological difference (Johnson, 1986). In 1985 the average canopy temperature of sorghum was significantly higher than all other crops. A higher canopy temperature is indicative of a crop's preference to dissipate radiant energy through sensible heat loss rather than latently via transpiration. This would support the

TABLE 16.

A COMPARISON OF CANOPY TEMPERATURES FOR 1984 AND 1985 (°C)

Year	Crop	Temperature[1]		
		Well-watered	Normal	Stressed
1984	Alfalfa	26.4 B	29.1 A	-
	Corn	30.4 A	30.9 A	-
	Sorghum	29.9 A	30.0 A	-
	Soybeans	26.8 A	27.0 A	-
1985	Alfalfa	27.5 A	27.9 A	-
	Corn	29.8 B	29.8 B	32.1 A
	Sorghum	33.3 A	33.0 A	34.1 A
	Soybeans	28.4 B	28.6 B	33.8 A

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[1] Treatment means with the same letter are not significantly different at the 95% level of probability according to Duncan's New Multiple Range Test.

TABLE 17.

A COMPARISON OF AVERAGE CROP CANOPY TEMPERATURES (°C)[1] FOR 1984 AND 1985 IRRIGATION TREATMENTS

Year	Treatment	Alfalfa	Corn	Sorghum	Soybeans
1984	Well-watered	26.4 B	30.4 A	29.9 A	26.8 B
	Normal	29.1 A	30.9 A	30.0 A	27.0 B
1985	Well-watered	27.5 C	29.8 B	33.3 A	28.4 BC
	Normal	27.9 C	29.8 B	33.0 A	28.6 BC
	Stressed	-	32.1 A	34.1 A	33.8 A

[1] Treatment temperature means with the same letter are not significantly different at the 95% level of probability according to Duncan's New Multiple Range Test.

idea that sorghum is more drought resistant than the other cultivars studied.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Over twenty percent of all irrigated cropland in the U.S. is dependent upon the groundwater reserves of the Ogallala aquifer. Since 1954 annual withdrawal rates have exceeded recharge, and in many areas economic exhaustion of the aquifer has already occurred. Unless corrective countermeasures are expedited, it is estimated that the Ogallala's economic life will expire early in the next century (High Plains Study Council, 1982).

In the hope of conserving remaining reserves this project was begun at the Panhandle Research Station near Goodwell, Oklahoma. As a first step in improving current irrigation scheduling practices evapotranspiration (ET) rates for alfalfa, corn, grain sorghum, and soybeans were calculated for four and five day periods in 1984 and 1985 using a water balance formula. Reference crop ET was estimated by monitoring the pertinent meteorological parameters and then calibrating the modified-Penman, Priestley-Taylor, Jensen-Haise, and evaporation pan equations. Crop coefficients (K_c) were calculated for the three row crops and equations were developed for predicting

K_c based upon the number of days after crop emergence. In addition, infrared thermometry was utilized to monitor canopy temperatures and canopy-air temperature differences for the four crops. These data were used to predict non water-stressed baselines and available soil moisture.

Conclusions

Calculated ET rates using the water balance formula compared favorably with rates given in the literature. Of the four weather-based equations tested, the modified-Penman predicted alfalfa reference ET best. Regression coefficients calculated for the modified-Penman wind function were $a_w = -2.20$ and $b_w = 0.0206$. If the proper meteorological inputs are available, it is suggested that the modified-Penman equation be used to predict alfalfa reference ET in the Oklahoma Panhandle region. A second best approximation would be to employ the evaporation pan formula.

Crop coefficients (K_c) were calculated by dividing measured crop ET by measured alfalfa reference ET. An equation for each crop species is given below (DAE is the number of days after crop emergence):

Corn:

$$K_c = 0.0699 + 0.00805\ \mathrm{DAE} + 3.18\mathrm{X}10^{-4}\ \mathrm{DAE}^2 - 3.33\mathrm{X}10^{-6}\ \mathrm{DAE}^3 \qquad (4.3)$$

Sorghum:

$$K_c = -0.595 + 0.0483\ DAE - 3.62X10^{-4}\ DAE^2 - 3.10X10^{-7}\ DAE^3 \qquad (4.4)$$

Soybeans:

$$K_c = -3.81 + 0.176\ DAE - 1.90X10^{-3}\ DAE^2 + 5.11X10^{-6}\ DAE^3 \qquad (4.5)$$

Irrigation scheduling using infrared temperature data is a viable option for one to consider when irrigating in the Panhandle. Although the canopy-minus-air temperature method failed, scheduling using the temperature stress day (TSD) and canopy temperature variability (CTV) methods showed promise. By calculating the canopy temperature differential between a stressed or normally watered crop and one that was well-watered (TSD method), the percent of available moisture remaining in the root zone (AM) was predicted using the following formulas:

Alfalfa:

$$AM = 92.5 - 9.78(TSD) \qquad (4.7)$$

Corn:

$$AM = 74.3 - 5.50(TSD) \qquad (4.8)$$

Soybeans:

$$AM = 81.5 - 1.62(TSD) \qquad (4.9)$$

The canopy temperature of sorghum did not respond to changes in AM in the same manner as the other crops. Instead AM was predicted more accurately using the difference between maximum and minimum daily canopy temperatures (CTV method). The formula used to describe the relationship is given below:

$$AM = 75.51 \exp(-0.06381CTV) \tag{4.10}$$

Recommendations

For future studies it is suggested that the modified-Penman equation be used to calculate alfalfa reference crop ET. A second best approximation might be obtained using the evaporation pan equation. Further calibration of both these equations would be desirable. Neither the Jensen-Haise nor Priestley-Taylor equations are recommended for predicting alfalfa reference ET in the Oklahoma Panhandle region.

If similar research plots are used in the future, it is suggested that the soil water content be monitored on Mondays and Wednesdays, with irrigations following Monday readings. This would allow a five day interval to be measured and thus meet the minimum time intervals suggested for the Jensen-Haise and pan methods (Hill et al., 1983). It is also suggested that neutron access tubes be installed to a depth of 1.80 m (5.9 ft). This would eliminate the need for tensiometers and better account for the available water held in the rhizosphere.

When irrigating alfalfa, corn, and soybeans based upon infrared estimates of canopy temperature, the TSD method should be employed. For irrigated sorghum, the CTV method is recommended. It is also recommended that equations (3.8) and (3.9) and the AM at wilting point be verified from additional field data. If the equations are accurate, it is recommended that the range of AM's be extended for future studies (below 50%).

With the development of the formulas above, a possible direction for future irrigation scheduling research has been established. The next logical step would be to implement an irrigation scheduling study based upon those formulas and refine ET and AM predictions from more field data. Ultimately the verification of this research by additional field testing and the implementation of the results could lead to the conservation of limited groundwater reserves.

LITERATURE CITED

Allen, R. G. and J. L. Wright. 1984. Variation within measured and estimated consumptive use requirements. Proceedings of the 1983 Irrigation Specialty Conference. ASCE Jackson, WY. July 21-23, 1983. ASCE, New York, NY. 10017. pp. 1-12.

Al-Nakshabandi, G. A. 1983. The potential evapotranspiration of short grass (Cynodon dactylon) as related to the estimated potential evapotranspiration and evaporation from meteorological data in the coastal region of Kuwait. J. of Arid Environments. Safat, Kuwait. 6(1):33-38.

Aston, A. R., and C. H. M. van Bavel. 1972. Soil surface water depletion and leaf temperature. ASA Agron. J. ASA, Madison, WI. 53711. 64:388-373.

Bekure, S. 1971. An economic analysis of the intertemporal allocation of ground water in the central Ogallala formation. Ph.D. Thesis. Oklahoma State Univ., Stillwater, OK. Diss. Abstr. Int. 72-21844. 145 p.

Blad, B. L., B. R. Gardner, D. G. Watts, and N. J. Rosenburg. 1981. Remote sensing of crop moisture status. Remote Sens. Q. 3:4-20.

Blad, B. J. and N. J. Rosenburg. 1976. Evaluation of resistance transport evapotranspiration models requiring canopy temperature data. ASA Agron. J. ASA, Madison, WI. 53711. 68:764-769

Bosen, J. F., 1960. A formula for approximation of the saturation vapor pressure over water. Monthly Weather Rev, 88(8):275-276.

Bottrell, D. G. 1979. Guidelines for integrated control of maize pests. FAO plant production and protection paper 18. p. 32.

Brunt, D. 1952. Physical and dynamical meteorology. 2nd ed, University Press, Cambridge, UK. 428 p.

Burman. R. D., P. R. Nixon, J. L. Wright, and W. O. Pruitt. 1980. Water requirements. In Design and Operation of Farm Irrigation Systems. M. E. Jensen (ed.) ASAE Monograph 3. ASAE, St. Joseph, MI. 49085. pp. 189-232.

Carlson, R. E., O. N. Yarger, and R. H. Shaw. 1972. Environmental influence on the leaf temperatures of two soybean varieties grown under controlled irrigation. ASA Agron. J. ASA, Madison, WI. 53711. 64:224-229.

Chowning, J. T., 1973. A multilayer aquifer model of the Ogallala formation in Oklahoma. (Unpub. M.S. Thesis, Library, Oklahoma State University, Stillwater, OK.)

Clark, R. N., and E. A. Hiler. 1973. Plant measurements as indicators of crop water deficit. Crop Sci. 13:466-469.

Clawson, K. L., and B. L. Blad. 1980. Irrigation scheduling utilizing infrared thermometry. Presented at the 1980 Annual Meetings of American Society of Agronomy. Crop Sci. Soc. of Amer. and Soil Sci. Sci. Soc. of Amer. Detroit, MI. December 1980.

Clawson, K. L. and B. L. Blad. 1982. Infrared thermometry for scheduling irrigation of corn. ASA Agron. J. ASA, Madison, WI. 53711. 74(2): 311-316.

Cope, F. 1980. Calculating when to apply water. Soil and Water. U.K. 8(1):8-12.

Cuenca, R. H., and M. T. Nicholson. 1982. Applications of the Penman equation wind function. ASCE J. Irrig. Drain. Div. IR1. ASCE, New York, NY. 10017. pp. 13-23.

Day, K. S. and R. J. Brase. 1985. Practical techniques for calibrating ET modeling parameters. From Advances in Irrigation. In Proceedings of the National Conference on Advances in Evapotranspiration. ASAE, St. Joseph, MI. 49085. pp. 224-230.

Doorenbos, J. and Kassam, A.H. 1979. Yield response to water. Irrig. Drain. Pap. 33, FAO, Rome.

Doorenbos, J., and W. O. Pruitt. 1977. Guidelines for predicting crop water requirements. FAO Irrig. and Drain. Paper 24 (rev.), FAO, Rome.

Dugas, W. A. and C. G. Ainsworth. 1983. Agroclimatic atlas of Texas. In Potential evapotranspiration. Texas Agric. Expt. Station Bulletin MP 1543. College Station, TX.

Ehrler, W. L. 1973. Cotton leaf temperatures as related to soil water depletion and meteorological factors. ASA Agron. J. ASA Madison, WI. 53711. 65:404-409.

Ehrler, W. L., S. B. Idso, R. D. Jackson, and R. J. Reginato. 1978a. Wheat canopy temperature: Relation to plant water potential. ASA Agron. J. ASA, Madison, WI. 53711. 70:251-256.

Ehrler, W. L., S. B. Idso, R. D. Jackson, and R. J. Reginato. 1978b. Diurnal changes in plant water potential and canopy temperature of wheat as affected by drought. ASA Agron. J. ASA, Madison, WI. 53711. 70: 999-1004.

Ehrler, W. L., and C. H. M. van Bavel. 1967. Sorghum foliage response to changes in soil water content. ASA Agron. J. ASA, Madison, WI. 59:404-409.

Elliott, R. L., 1984. Cropping strategies under irrigation in the Oklahoma panhandle. ASAE Paper No. SWR-83-301. ASAE, St. Joseph, MI. 49085.

Everest Interscience. 1984. Non-contact infrared thermometry. Tustin, CA. 1984.

Fehr, W. R. and C. E. Caviness. 1977. Stages of soybean development. Cooperative Extension Service, Iowa State University, Ames, Iowa. Special report 80.

Fuchs, M., E. T. Kanemasu, J. P. Kerr, and C. B. Tanner. 1967. Effect of viewing angle on canopy temperature measurements with infrared thermometers. ASA Agron. J. ASA, Madison, WI. 53711. 59:494-496.

Fuchs, M. and C. B. Tanner. 1966. Infrared thermometry of vegetation. ASA Agron. J. ASA, Madison, WI. 53711. 58: 597-601.

Gardner, B. R., B. L. Blad, and D. G. Watts. 1981a. Plant and air temperatures in differentially irrigated corn. Agric. Meteorol. 25:207-217.

Gardner, B. R., B. L. Blad, D. G. Watts, and D. P. Garrity. 1981b. Relationships between crop temperature, grain yield, evapotranspiration and phenological development in two hybrids of moisture stressed sorghum. Irrig. Sci. 2:213-224.

Gieser, K. M., D.C. Slack, E. R. Allerd, and K. W. Starge. 1982. Irrigation scheduling using crop canopy-air temperature difference. Transactions of the ASAE 25:689-694.

Goltz, S. M. 1980. Evapotranspiration from vegetative surfaces in Maine. Tech. Bull. 97. Me. Life Sci. and Agr. Exp. Sta., Orono, ME.

Green, A. E., B. E. Clothier, J. P. Kerr, D. R. Scotter. 1984. Evapotranspiration from pasture: A comparison of lysimeter and Bowen ratio measurements with Priestley-Taylor estimates. New Zealand Journal of Agricultural Research. New Zealand. 27(3):321-327.

Green, D. E. 1979. Panhandle pioneer: Henry C. Hitch, his ranch and his family. University of Oklahoma Press, Norman, OK.

Gunston, H. and C. H. Batchelor. 1983. A comparison of Priestley-Taylor and Penman methods for estimating reference crop ET in tropical countries. Agricultural Water Management. UK 6(1):65-77.

Hall, W. A. 1982. Technology assessment of irrigation scheduling and crop response. OWRT, USDI, Washington, D.C. OWRT Project No. C-00179-T.

Hansen, V. 1980. On the problem of estimating daily rates of potential evapotranspiration. Meldinger fra Norges Landbrukshogskole 59(15).

Harris, T. R. 1981. Analysis of irrigation scheduling for grain sorghum in the Oklahoma Panhandle. (Unpub. Ph.D. Thesis. Oklahoma State Univ., Stillwater, OK. Diss. Abstr. Int. 81-23839. 257 p.

Hart, D. L., Jr., G. L. Hoffman and R. L. Goemaat. 1976. Geohydrology of Oklahoma Panhandle, Beaver, Cimarron, and Texas counties. Water Resources Investigation. USGS, pp. 25-75.

Hatfield, J. L. 1979. Canopy temperatures: The usefulness and reliability of remote measurements. ASA Agron. J. ASA, Madison WI. 53711. 71:889-892.

Hatfield, J. L. 1981. Irrigation scheduling with thermal infrared and spectral remote sensing inputs. From Irrigation Scheduling for Water and Energy Conservation in the 80's. In Proceeding of the Irrigation Scheduling Conference. ASAE, St. Joseph, MI 49085. pp. 10-17.

Heermann, D. F. and H. R. Duke. 1978. Evaluation of crop water stress under limited irrigation. ASAE Paper No. 78-2556, pp. 1-12.

High Plains Associates, Inc.: Camp Dresser and McKee Inc., Black and Veach, and Arthur D. Little, Inc. 1982. Six-state High Plains Ogallala regional study. Summary, Austin, TX.

High Plains Study Council. 1982. A summary of the Ogallala aquifer regional study, with recommendations to the Secretary of Commerce and Congress. Austin, TX. 61 p.

Hiler, E. A. and R. N. Clark. 1971. Stress day index to characterize effects of water stress on crop yields. Transactions of the ASAE 14:757-761.

Hiler, E. A., T. A. Howell, R. B. Lewis, and R. P. Boos. 1974. Irrigation timing by the stress day index method. Transactions of the ASAE 17:393-398.

Hill, R. W., E. L. Johns and D. K. Frevert. 1983. Comparisons of equations used for estimating agricultural crop evapotranspiration with field research. USBR, Eng. Rsch. Cnt., Denver, CO.

Hillel, D. 1982. Introduction to soil physics. Academic Press, New York, NY. 364 p.

Howell, T. A., J. L. Hatfield, H. Yamada, and K. R. Davis. 1984. Evaluation of cotton canopy temperature to detect crop water stress. Transactions of the ASAE. 27:84-88.

Hulsman, R. B. 1984. Achieving water-use efficiency. The Johnson Drillers Journal, Third quarter, pp. 4-5.

Idso, S. B. 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agric. Meteorol. 27:59-70.

Idso, S. B., R. D. Jackson, P.J. Pinter, Jr., R. J. Reginato, and J. L. Hatfield. 1981a. Normalizing the stress degree day for environmental variability. Agric. Meteorol. 24:45-55.

Idso, S. B., R. D. Jackson, and R. J. Reginato. 1977. Remote sensing of crop yields. Science 196:19-25.

Idso, S. B., R. J. Reginato, J. L. Hatfield, G. K. Walker, R. D. Jackson, and P. J. Pinter, Jr. 1980. A generalization of the stress-degree-day concept of yield prediction to accommodate a diversity of crops. Agric. Meteorol. 21:202-211.

Idso, S. B., R. J. Reginato, R. D. Jackson, and P. J. Pinter, Jr., 1981b. Foliage and air temperatures: Evidence for a dynamic "equivalence point." Agric. Meteorol. 24:223-226.

Idso, S. B., R. J. Reginato, D. C. Reicosky, and J. L. Hatfield. 1981c. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. ASA Agron. J. ASA, Madison, WI. 53711. 73:826-830.

Jackson, R. D. 1982. Canopy temperature and crop water stress. Advances in Irrigation. Academic Press, New York, NY. 1:43-85.

Jackson, R. D., and P. J. Pinter, Jr. 1981. Detection of water stress in wheat by measurement of reflected solar and emitted thermal IR radiation. Int. Colloq. Spectral Signatures Objects Remote Sens. pp. 399-496.

Jackson, R. D., R. J. Reginato, and S. B. Idso. 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Resour. Res. 13:651-656.

Jackson, R. D., R. J. Reginato, P. J. Pinter, Jr. , and S. B. Idso. 1979. Plant canopy information extraction from composite scene reflectance of row crops. Appl. Opt. 18:3775-3782.

Jensen, M.E. 1969. Scheduling irrigations with computers. Journal of Soil and Water Conservation. 24:193-195.

Jensen, M. E. (Ed.). 1973. Consumptive use of water and irrigation water requirements. Rep. Tech. Com. on Irrig. Water Requirements. ASCE J. Irrig. Drain. Div. ASCE, New York, NY. 10017. 215 p.

Jensen, M. E. and H. R. Haise. 1963. Estimating evapotranspiration from solar radiation. Proceedings of the ASCE J. Irrig. Drain. Div. ASCE, New York, NY 10017. 89:15-41.

Jensen, M.E., D.C.N. Robb, and C.E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. ASCE J. Irrig. Drain. Div. ASCE, New York, NY. 11017. 96:25-28.

Jensen, M. E., J. L. Wright, and B. J. Pratt. 1971. Estimating soil moisture depletion from climate, crop and soil data. Transactions of the ASAE 14(6):954-959.

Johnson, R. C. Personal interview. Stillwater, Oklahoma. April 24, 1986.

Jury, W. A., and C. B. Tanner. 1975. Advection modification of the Priestley and Taylor evapotranspiration formula. ASA Agron. J. ASA, Madison, WI. 53711. 67:840-842.

Kanemasu, E. T., L. R. Stone, and W. L. Powers. 1976. Evapotranspiration model tested for soybean and sorghum. ASA Agron. J. ASA, Madison, WI. 53711. 68:569-572.

Keener, M. E. and P. L. Kircher. 1983. The use of canopy temperature as an indicator of drought stress in humid regions. Agric. Meteorol. 28:339-349.

Kimes, D. S. 1981. Azimuthal radiometric temperature measurements of wheat canopies. Appl. Opt. 20:1119-1121.

Kimes, D. S., S. B. Idso, P. J. Pinter, Jr., R. D. Jackson, and R. J. Reginato. 1980. Complexities of nadir-looking radiometric temperature measurements of plant canopies. Appl. Opt. 19:2162-2168.

Kirkham, M. B., D. E. Johnson, Jr., E. T. Kanemasu, and L. R. Stone. 1983. Canopy temperature and growth of differentially irrigated alfalfa. Agric. Meteorol. 29: 235-246.

Kraenziel, C. F. 1955. The Great Plains in Transition. University of Oklahoma Press, Norman, OK.

Kristensen, K. J. 1979. A comparison of some methods for estimation of potential evapotranspiration. Nordic Hydrology 10(4):239-250.

Lamerand, T. J. 1971. Applications of a management model to the Ogallala groundwater aquifer of the Oklahoma Panhandle. (Unpub. M.S. Thesis, Library, Oklahoma State University, Stillwater, OK.)

Lundstrom, D. R., E. C. Stegman, and H. D. Werner. 1981. Irrigation scheduling by the checkbook method. From Irrigation Scheduling for Water and Energy Conservation in the 80's. In Proceeding of the Irrigation Scheduling Conference. ASAE, St. Joseph, MI 49085. pp. 187-193.

Mapp, H. P., 1975. Simulated soil water and atmospheric stress-crop yield relationships for economic analysis. Oklahoma State University, Stillwater, OK. Tech. Bul. T-140.

Merva, G. E. 1975. Physioengineering principles. AVI Publishing Co., Westport, CT.

Monteith, J. L., and G. Szeicz. 1962. Radiative temperature in the heat balance of natural surfaces. Q. J. R. Meteorol. Soc. 88:496-507.

Nielsen, D. C., K. L. Clawson, and B. L. Blad. 1984. Effect of solar azimuth and infrared thermometer view direction on measured soybean canopy temperature. ASA Agron. J. ASA, Madison, WI. 53711. (76):607-610.

Norman, J. M., and G. Campbell. 1983. Application of a plant-environment model to problems in irrigation. From Advances in Irrigation. Academic Press, New York, NY. 2:155-188.

Oklahoma Water Resources Board. 1983. State-level research results for the six-state High Plains Ogallala aquifer area study. University of Oklahoma Press, Norman, OK. Publication 113.

Oklahoma Water Resources Board. 1984. Oklahoma's water atlas. University of Oklahoma Press, Norman, OK. Publication 120. 186 p.

O'Toole, J. C., and J. L. Hatfield. 1983. Effect of wind on the crop water stress index derived by infrared thermometry. ASA Agron. J. ASA, Madison, WI. 53711. 75: 811-817.

Penman, H. L. 1948. Natural evaporation from open water, bare soil, and grass. Proc. Roy. Soc. London. 193:120-145.

Phene, C. J., D. W. Meek, and K.R. Davis. 1985. Real time crop evapotranspiration and determination of crop coefficients. From Advances in Irrigation. In Proceedings of the National Conference on Advances in Evapotranspiration. ASAE, St. Joseph, MI 49085. pp. 122-129.

Pinter, P. J., Jr. 1982. Remote sensing of microclimatic stress. Biometeorology in integrated pest management. J. L. Hatfield and I. J. Thomas (eds.). Academic Press, New York, NY. pp. 101-145.

Pinter, P. J., Jr. and R. J. Reginato. 1982. A thermal infrared technique for monitoring cotton water stress and scheduling irrigations. Transactions of the ASAE 25:1651-1655.

Pochop, L. O., F. M. Smith, and R.E. Smith. 1985. Evapotranspiration estimates for the Pawnee grasslands. From Advances in Irrigation. In Proceedings of the National Conference on Advances in Evapotranspiration. ASAE, St. Joseph, MI 49085. pp. 262-267.

Postel, S. 1985. Beyond Africa: The larger global water threat. Engineering Times, Nat. Soc. Prof. Engr. 7(2): 1.

Priestley, C. H. B. and R. H. Taylor. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Non. Weath. Rev. 100:81-92.

Reeves, H. 1985. Personal Interview. Stillwater, Oklahoma, December 11, 1985.

Rose, C. W. 1966. Agricultural physics. Pergamon International Library. New York, NY. 230 p.

Rosenburg, N. J. 1974. Microclimate-The biological environment. Wiley (Interscience), New York. 315 p.

Rosenburg, N. J. and W. Powers. 1970. Potential for ET and its manipulation in the Plains region. Proc. of the symposium on ET in the Great Plains. Agricultural Council Pub. No. 50:275-300.

Salih, A. M. and U. Sendil. 1984. Evapotranspiration under extremely arid climates. J. of Irrigation and Drainage Engr. Rhiyadh, Saudi Arabia. 110(3):289-303.

Salisbury, F. B., and C. W. Ross. 1978. Plant physiology 2nd. Ed. Wadsworth Publishing Co. Inc. Belmont, CA. 422 p.

Sands, G., I. D. Moore, and R. C. Warner. 1984. A computer model for irrigation planning and management. ASAE Paper No. 84-2605. ASAE, St. Joseph, MI. 49085

Saxton, K. E., H. P. Johnson, and R. W. Shaw. 1974. Modeling evapotranspiration and soil moisture. Transactions ASAE 17:673-677.

Schwab, D. 1983. Irrigation survey. Oklahoma State University, Stillwater, OK. 25 p.

Sharples, J. A. 1969. The representative farm approach to estimation of supply response. Am. J. of Agr. Econ. 51(2).

Shearer, M. N. and J. Vomocil. 1981. Twenty-five years of modern irrigation scheduling promotional efforts. From Irrigation Scheduling for Water and Energy Conservation in the 80's. In Proceeding of the Irrigation Scheduling Conference. ASAE, St. Joseph, MI 49085. pp. 208-212.

Shouse, P., W. A. Jury, and L. H. Stolzy. 1980. Use of deterministic and empirical models to predict potential evapotranspiration in an advective environment. ASA Agron. J. ASA, Madison, WI. 53711. 72(6):994-998.

Slack, D. C., K. M. Geiser, K. W. Starge, and E. R. Allerd. 1981. Irrigation scheduling in subhumid areas with infrared thermometry. From Irrigation Scheduling for Water and Energy Conservation in the 80's. In Proceeding of the Irrigation Scheduling Conference. ASAE, St. Joseph, MI 49085. pp. 116-124.

Spears, B. R. and L. Coffey. 1957. Growing grain sorghums. Texas Agricultural Extension Service. Bulletin No. B-210.

Stegman, E. C. 1983. Irrigation scheduling: Applied timing criteria. Advances in Irrigation. Academic Press, New York, NY. 2:1-30.

Stegman, E. C. and D. A. Coe. 1984. Water balance irrigation scheduling based on Jensen-Haise equation: Software for Apple II, II+, and IIE computers. North Dakota Research Report Agri. Exp. Sta., North Dakota State University.

Stone, J. F. Personal interview. Stillwater, Oklahoma, August 22, 1985.

Stone, L. R., E. T. Kanemasu, and M. L. Horton. 1975. Grain sorghum canopy temperature as influenced by clouds. Remote Sensing Environ. 4:177-181.

Sumayao, C. R., E. T. Kanemasu, and T. W. Brakke. 1980. Using leaf temperature to assess evapotranspiration and advection. Agric. Meteorol. 22:153-166.

Tanner, C. B. 1963. Plant temperatures. ASA Agron. J. ASA, Madison, WI. 53711. 55:210-211.

US Army Corps of Engineers. 1982. Summary report, six-state High Plains Ogallala aquifer regional resources study. USACE, Southwestern Division. 104 p.

USDA Soil Conservation Service. 1964. Soil-plant-water relationships. National Engineering Handbook, Section 15, 1:52-60.

Vanderlip, R. L. 1972. How a sorghum plant develops. Kansas Agricultural Experiment Station, Manhattan, KS. Contribution No. 1203.

Watts, D. B. and S. M. Goltz. 1985. Potato evapotranspiration and yield under limiting and nonlimiting water conditions. From Advances in Irrigation. In Proceedings of the National Conference on Advances in Evapotranspiration. ASAE, St. Joseph, MI 49085. pp. 314-322.

Webb, W. P. 1931. The Great Plains. Grosset and Dunlap, New York, NY.

Westesen, G. and T. Hanson. 1981. Irrigation scheduling using wash tub evaporation pans. From Irrigation Scheduling for Water and Energy Conservation in the 80's. In Proceeding of the Irrigation Scheduling Conference. ASAE, St. Joseph, MI 49085. pp. 144-149.

Wiegand, C. L., and Namken. 1966. Influence of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. ASA Agron. J. ASA, Madison, WI. 53711. 58:582-586.

Wiegand, C. L., and W. A. Swanson. 1973. Time constants for thermal equilibrium of leaf, canopy, and soil surfaces with change in insolation. ASA Agron. J. ASA, Madison, WI. 53711. 65:722-724.

Wright, J. L. 1981. Crop coefficients for estimates of daily crop evapotranspiration. From Irrigation Scheduling for Water and Energy Conservation in the 80's. In Proceeding of the Irrigation Scheduling Conference. ASAE, St. Joseph, MI 49085. pp. 18-26.

Wright, J. L. 1982. New evapotranspiration crop coefficients. ASCE J. Irrig. Drain. Div. ASCE, New York, NY. 10017. 108(IR1):57-74.

Wright, J. L. and M. E. Jensen. 1972. Peak water requirements of crops in southern Idaho. ASCE J. Irrig. Drain. Div. ASCE, New York, NY. 10017. 98(IR2):193-201.

Wright, J. L., and M. E. Jensen. 1978. Development and evaluation of evapotranspiration models for irrigation scheduling. Transactions of the ASAE 21(1):88-96.

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