3 1293 00619 4140

THESIS

LIBRARY
Michigan State
University

This is to certify that the

thesis entitled

Evaluation of Evapotranspiration, Yield, and Water Use Efficiency As Affected by Row Spacing in Soybeans (Glycine max L. Merr.) And by Irrigation Level In Corn (Zea mays L.)

presented by

Dale A. Magnuson

has been accepted towards fulfillment of the requirements for

Master of Science degree in Crop and Soil Sciences

Maurice L. Vitosh
Major professor

Date 12-13-84

O-7639

MSU is an Affirmative Action/Equal Opportunity Institution

MSU
LIBRARIES

RETURNING MATERIALS:
Place in book drop to remove this checkout from your record. FINES will be charged if book is returned after the date stamped below.

EVALUATION OF EVAPOTRANSPIRATION, YIELD, AND WATER USE EFFICIENCY AS AFFECTED BY ROW SPACING IN SOYBEANS (GLYCINE MAX L. MERR.) AND BY IRRIGATION LEVEL IN CORN (ZEA MAYS L.)

By

Dale Allan Magnusson

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Crop and Soil Science

1984

334-392X

ABSTRACT

EVALUATION OF EVAPOTRANSPIRATION, YIELD, AND WATER USE EFFICIENCY AS AFFECTED BY ROW SPACING IN SOYBEANS (*GLYCINE MAX* L. MERR.) AND BY IRRIGATION LEVEL IN CORN (*ZEA MAYS* L.)

By

DALE ALLAN MAGNUSSON

Corn and soybean evapotranspiration rates, yields, and water use efficiencies were evaluated under various treatment situations. Soybeans were planted in three row spacings (25, 51, and 76 cm) and at three seeding rates. Three corn hybrids (DeKalb 587, Pioneer 3572, and Pioneer 3707) were irrigated at decreasing levels using a line source sprinkler system. In 1984 evapotranspiration rates predicted by an empirical formula were compared to rates obtained from neutron probe measurements.

Soybean yields tended to increase when row spacings increased and populations decreased or when row spacings decreased and populations increased. There was no significant difference in yield due to row spacing or plant population. Water use efficiency was only significantly different at the .10 level between the 51 and 76 cm rows at the high population treatment.

Grain yields of all three corn hybrids were significantly affected by irrigation level. The highest water use efficiencies were always located near the lower irrigation treatments for both grain and stover. Evapotranspiration rates predicted from the empirical formula were very close to neutron probe calculated rates once canopy coverage was complete.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Maurice L. Vitosh for his assistance and guidance in this project and my education. His availability and readiness to assist me in any area is sincerely appreciated. I would also like to thank Dr. Raymond J. Kunze, Dr. Theodore L. Loudon and Dr. James J. Kells for the time and suggestions they contributed as members of my guidance committee.

I especially appreciate John Dahl for his personal assistance in the classroom and the field. The time, labor, and encouragement Dallas Hyde has given to me these past two years has been invaluable and is greatly appreciated.

Appreciation is also expressed to Matt Thompson, Ben Darling, and Bob Every for their assistance in the field.

Finally, I would like to thank my wife Sherrie for her personal support and sacrifice which enabled me to complete this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Literature Review

Evapotranspiration

Water constitutes the most limiting resource for crop production in the world. Irrigation accounts for the largest consumptive use of water today. Since 1939 the number of hectares irrigated in the United States has approximately tripled (Jensen, 1980). In 1980, 161,190 hectares of cropland were irrigated in Michigan. This amounts to 328.9 million cubic meters of water for irrigation in Michigan alone (Vitosh et al., 1982). On the basis of water use of this magnitude, it is appropriate that evapotranspiration is perhaps the most intensely studied subject in micrometeorology.

Evapotranspiration (ET) has been defined as "the combined process by which water is transferred from the earth's surface to the atmosphere; evaporation of liquid or solid water plus transpiration of liquid water through plant tissues expressed as the latent heat transfer per unit area or its equivalent depth per unit area" (Burman et al., 1980).

The two componets of ET, evaporation and transpiration are dynamic in their contribution to ET. Both of these are affected by the crop's developmental stage. Early in the growing season

ET is mostly evaporation from a bare soil. Even though evaporation proceeds at a potential rate when the soil is saturated, a fully cropped surface is more effective in transmitting water to the atmosphere than a bare soil (Veihmeyer, 1955). As the crop matures and achieves 100 percent ground coverage most of the ET is due to transpiration. The ET rate is dependent upon many plant, soil, and climatic factors. When water is readily available and the crop's vegetative cover is complete, ET is primarily dependent on incoming solar radiation.

In their four year study of corn's ET rates, Doss et al. (1962) reported that the water requirement was lowest from planting to the time the plants were 18 inches high. Evapotranspiration rates increased considerably during the 18-inch height to tasseling period. The maximum ET rate was reached between tasseling and late dough stage. From the late dough stage until maturity the water requirement decreased and approximated the ET rate achieved during the 18-inch height to tasseling period.

The ramifications of being able to accurately predict the daily or seasonal ET rates of a specific crop for irrigation scheduling purposes are important and will be covered in another section.

Potential Evapotranspiration

The concept of potential evapotranspiration (ETp) is an attempt to describe the maximum rate at which water, if nonlimiting, would be removed from the soil and plant surface.

Mathematically, Van Bavel (1966) described it as the ET that occurs when the vapor pressure at the evaporating surface is at the saturation point. Actual ET will generally be a fraction of ETp, depending upon such factors as plant canopy coverage, soil moisture, and root distribution. Evapotranspiration from a well watered crop will approach ETp during the active growing season if complete canopy coverage is achieved (Hillel and Guron, 1973).

Penman (1956) defined ETp as "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water." Although this original definition is a useful standard of reference for comparing ET values obtained from different regions and methods, certain ambiguities exist. The uncertainty of what is meant by "short green crop" has given rise to a new term called reference evapotranspiration (ETr).

Reference Evapotranspiration

This term is becoming increasingly popular. There are two definitions that are commonly used. Jensen et al.(1971) defined ETr as "the upperlimit or maximum evapotranspiration that occurs under given climatic conditions with a field having a well watered agricultural crop with an aerodynamically rough surface, such as alfalfa medicago sativa L.), with 30 to 50 centimeters of top growth." Doorenbos and Pruitt (1977) defined it as " the rate of evapotranspiration from an extensive surface of 8 to 15 centimeters, green grass cover of uniform height, actively growing, completely shading the ground and not short of water."

Considering these two definitions, the term "reference" specifies ETp from either a crop of grass or alfalfa. One reference crop is not necessarily better than the other, but there are certain terms that are specific for each crop and must be properly used in the calculation of ETr.

Crop Coefficients

A relationship exists between ETr and the ET of other crops. By simultaneously measuring ETr and the ET of a particular crop and setting them in terms of a unitless ratio, a crop coefficient (Kc) can be calculated. Originally, ETp was used in this definition (Jensen, 1974), but recently ETr has been consistently used. The equation usually appears as such:

$$Kc=ETc/ETr$$

Where ETc is the ET of the particular crop chosen. By using ETr instead of ETp, consistency between grass or alfalfa related ETr is guaranteed.

The Kc is affected by soil moisture availability, percent canopy coverage, and physiological development (Burman et al., 1983). Doorenbos and Pruitt (1977) suggested that humidity, harvesting operations, length of growing season, and other factors may also influence Kc. Since the Kc changes with time, a crop curve can be developed. This curve reflects the change in ET rates by the crop during the growing season. Doorenbos and Pruitt (1977) divided the growing season of field and vegetable crops into four stages: initial, crop development, midseason, and late season. They then constructed crop curves for the four stages. It is recommended that local data be used for determining dates for the different growth stages.

Water Use Efficiency

Efficiency describes a measure of the output obtainable from a given input. In relating this to water use and crop yield, the efficiency will vary depending on the nature of inputs and outputs used. Viets (1962) defined crop water use efficiency as the amount of dry matter produced per unit volume of water taken up by the crop from the soil. This in effect is the reciprocal of the transpiration ratio originally defined as the mass of water transpired per unit mass of dry weight produced (Briggs and Shantz, 1921). Strong correlation has been shown between cumulative seasonal dry matter (Y) and cumulative seasonal transpiration (T) when yields are transpiration limited (de Witt), 1958; Arkley, 1963). This relationship is usually linear in nature. It normally begins near the origin and rises linearly toward the point where maximum yield (Ymax) and maximum transpiration (Tmax) intersect. If adequate soil moisture levels are maintained by rainfall and/or irrigation, the attained Tmax should equal the potential seasonal transpiration (Stegman et al., 1980).

Since there is a close correlation between transpiration and ET, Y vs cumulative ET also plots as a linear or curvilinear relationship. This relationship has been shown to pass through or very near the origin for established perennial crops (Schofield, 1945; Stewart and Hogan, 1969). In newly planted crops the relationship tends to pass to the right of the origin because soil evaporation takes place before the new plants begin accumulating measurable dry matter (Hanks et al., 1969; Neghassi et al., 1975).

A greater generalization of yield functions may be achieved by plotting the ratio of Y/Ymax with either T/Tmax or ET/ETmax. The relationship between relative dry matter (Y/Ymax) and relative transpiration (T/Tmax) is the most consistent and has a correlation of very near 1:1 (de Witt, 1958). Thus if all other conditions are consistent and Ymax and Tmax levels have been accurately estimated for a given crop-soil-climate setting, the dry matter yield can be estimated for lesser T levels.

As Affected by Row Spacing and Plant Population in Soybeans

In the past quater century a vast amount of research has been conducted on the effect of plant population and row spacing on soybean yields (Weber et al., 1966; Lehman and Lambert, 1960; Cooper, 1977). Recently, considerable interest has arisen concerning the effect row spacing has on water use efficiency and crop yield. There is evidence which indicates narrow row spacing produces higher yields than wide row spacing in soybeans (Reicosky et al., 1982; Peters and Johnson, 1960; Mason et al., 1980). This yield increase is attributed to the development of a canopy that provides complete ground cover in narrow rows by the time rapid podfill occurs (Taylor, 1980; Shibles and Weber 1965).

Canopies that provide complete ground cover intercept more solar radiation, thus increasing photosynthetic activity.

However, during dry years this could be a disadvantage. If other factors are equal, the increased early season exposure of leaves to full sunlight increases soil water useage. This leaves less water available for the critical podfilling stage (Taylor, 1980). Reicosky et al. (1982) were unable to verify Taylor's results completely. They found that narrow row spacings seemed to increase ET values for irrigated plots but not for nonirrigated plots. Timmons et al. (1967) evaluated water use efficiency for soybeans using 20, 61, and 102 cm row spacings and plant populations ranging from 247,000 to 865,000 plants per hectare. They found the highest water use efficiencies were generally obtained at the lower plant populations in 20 cm rows, although statistically the differences were not significant. They also found that yields generally increased as population and row spacing decreased. Yield differences due to population were significant only at the 10 percent level in 1964, but differences due to row spacings were significant at the 10 percent level in 1964 and at the 5 percent level in 1965. This is consistent with Cooper's (1977) research which shows soybean yields being influenced more by row spacings than by plant populations.

As Affected by Irrigation Levels in Corn

In terms of total dry matter production, corn is an efficient user of water. It is also, potentially, the highest yielding grain crop among cereals. For maximum production in Michigan 48 to 51 cm of water per growing season are required (Vitosh et al., 1982).

Grain yield is highly influenced by the amount and frequency of precipitation. Moisture deficits during the flowering stage (tassel to silk) results in the greatest decrease in grain yield (Robins and Domingo, 1953; Howe and Rhoades, 1955; Salter and Goode, 1967). Stresses during the vegetative and/or grain filling stages have a lesser effect on grain yields (Doorenbos and Kassam, 1979). Generally, yields will not be reduced as long as the available soil water level in the root zone is not depleted below 50 percent (Doorenbos and Kassam, 1979; Hagan and Stewart, 1972; Taylor, 1965).

However, extremely warm temperatures can decrease yields even when the available soil water is 50 percent or above. Stegman and Aflatouni (1978) found that when leaf water potentials fell below -12.5 bars on several successive days, yield reductions were likely. Thus indicating that when temperatures rise the available soil water percentage must also be increased to prevent yield reductions (Stegman et al., 1976).

Temporarily subjecting plants to stress during their growing season may reduce production. Whereas, maintaining a relatively moist root zone to satisfy the plants optimum water requirements can increase production, even disproportionately to the increase in water used. Hillel and Guron (1973) conducted water use efficiency studies on corn over a five year period. Evapotranspiration estimates were made using a weighing lysimeter. During 1970, the wettest treatment received 1.1 times the estimated ET rate and the driest treatment received 0.4 times the estimated ET rate. The wettest treatment consumed 1.5 times as much water as the driest treatment, yet it produced over four times the dry matter and 10 times the grain. Intermediate results were also obtained from intermediate treatments. Hanks et al. (1969) found similar results using grain sorghum. They eliminated runoff and percolation below 90 cm by using lysimeters. This allowed approximately 10 cm of additional water to be available to the crop. The additional water doubled yields but ET was only increased by 50 percent.

Maintaining a relatively moist root zone permits the crop to transpire at a rate approaching the climatically induced potential ET. This prevents the occurrence of even temporary moisture stress in the plant. However, keeping the soil moist throughout the growing season increases the likelihood of water losses due to deep percolation and runoff. This is especially true when ET rates are low. Downward flow of soil water increases as ET rates decrease (Miller and Aarstad, 1971). Conversely, plants use significant amounts of water at high ET rates that would otherwise be lost as deep drainage. Therefore, careful attention should be given to early or late season irrigations in order to minimize deep drainage losses and maximize water use efficiency.

Approaches To Irrigation Scheduling

Irrigation scheduling has become increasingly necessary due to ever increasing demands on the limited water supply. Campbell and Campbell (1983) simplify the concept of irrigation scheduling by stating "proper scheduling of irrigation requires the answers to two questions: When should the water be turned on, and when should it be turned off?" The attempt to answer these two questions has led to three basic approaches to irrigation scheduling which are based upon: (1) soil moisture measurements, (2) evapotranspiration models, and (3) plant stress.

Soil Moisture Measurements

This is probably the oldest and most popular of the three approaches. Many people schedule irrigations simply based upon the feel of the soil. However, newer methods of monitoring the soil's moisture continue to gain acceptance. Most of these methods can be used to collect information for some type of water balance.

Water Balance Technique

A water balance is basically a detailed statement of the law of conservation of mass. The water content of a given soil volume cannot increase without outside additions and it does not decrease except by evapotranspiration to the atmosphere or deep drainage into a lower profile (Hillel, 1982). This technique is useful for estimating soil moisture levels as well as ET rates. A water balance equation for estimating ET would usually appear in a form similar to the following:

$$ET=P+I-Q-D-SM$$

Where P is precipitation by rain, I is irrigation, Q is runoff, D is deep drainage, and SM is the change in soil moisture content. Normally Q and D are considered to be negligible but this may not always be the case if rainfall and/or irrigation are excessive. Weighing lysimeters provide the most direct and efficient method for calculating the field water balance (Tanner, 1967), but they are unavailable in most areas. Having an understanding of field capacity, permanent wilting point, and available water is important when using the water balance technique.

There has been considerable debate and discussion concerning field capacity. It was first defined by Veihmeyer and Hendrickson (1949). Basically, field capacity is the presumed soil water content at which internal drainage allegedly ceases (Hillel, 1982). It is the upper limit of the amount of water a specific soil can store or hold while drainage losses are negligible. A generally accepted rule of thumb for determining when drainage virtually ceases is two or three days after a saturating rain or irrigation.

At the other end of the spectrum is the permanent wilting point. This can be defined as the soil moisture content at which a plant wilts and will not revive (Skaggs et al., 1981). Richards and Weaver (1944) found that the permanent wilting point was closely correlated to the soil moisture content at -15 bars tension.

The difference between permanent wilting point and field capacity is the available water capacity. At field capacity the available water content would be 100 percent. Many farmers irrigate when the available water has been depleted to a predetermined minimum amount. For corn it is recommended that water be applied when the available water content approximates 50 percent (Hagan and Stewart, 1972; Taylor, 1965).

Methods of Measuring Soil Moisture

Gravimetric Sampling

The gravimetric method is probably the most reliable for determining soil water content. This gives a direct determination of the water content, but it is very time consuming and laborious. Numerous samples must be taken in a field at any one time to give a representative estimate. The samples must be weighed and then dried at a temperature of 105 to 110 degrees centigrade. Usually 24 hours is a sufficient drying period. After drying, the samples are reweighed and the percent moisture by weight is determined. Multiplying the sample's bulk density by its percent moisture by weight will give the percent moisture by volume. If the field capacity and permanent wilting point are known, the available water content can easily be determined from the percent moisture by volume. This method is usually only used by researchers because of its tedious nature.

Neutron Scattering

The neutron meter, first developed in the 1950's (Belcher et al., 1950), directly measures the soil water content on a volume basis. Its main advantages over the gravimetric method are that it is faster, easier, repeatable at the same location, able to measure a larger volume, and nondestructive of the soil fraction it measures. The main disadvantages are the health hazards associated with exposure to neutron and gamma radiation, the difficulty of measuring surface zone soil moisture, and the high initial investment of the instrument.

This method has been widely used for soil moisture measurements, though mainly as a research instrument. Recently however, it has increasingly been used for irrigation scheduling (Campbell and Campbell, 1983). It consists of a probe which is lowered into the soil via an access tube and a ratemeter which monitors the flux of slow neutrons scattered by the soil. The probe contains a source of fast neutrons and a dectector of slow neutrons. The source of fast neutrons is obtained by mixing a radioactive emitter of alpha particles (helium nuclei) with beryllium. A mixture of americium or radium with beryllium is the usual source (Hillel, 1982). As the fast neutrons travel from the source into the soil, they collide with various atomic nuclei. Repeated collisions with atomic nuclei of low atomic weight (i.e., hydrogen) slows the neutrons. When the neutrons are slowed to about 2.7 km/sec they are said to be thermalized and are called slow neutrons. In the soil, hydrogen thermalizes the neutrons more effectively than any other element because it is the only element of low atomic weight present in appreciable amounts (Visvalingam and Tandy, 1972). If the soil is saturated, thus containing an appreciable concentration of hydrogen, the fast neutrons are thermalized quickly before they travel very far from the source. As the thermalized neutrons continue to elastically collide with nuclei present in the soil, a number of the now slowed neutrons return to the probe where they are counted by the detector. The number that are counted will be proportional to the density of the neutrons thermalized, and approximately linearly related to the soil moisture content. When a thermalized neutron encounters the detector an electrical pulse is created on a charged wire. The number of pulses over a given time interval is counted by a scaler or indicated by a ratemeter.

The moisture content is the main factor in considering the effective volume of soil being measured. When using the radium-beryllium source in a dry soil the volume measured is a sphere of about 50 cm diameter or more but only about 15 cm in a wet soil (de Vries and King, 1961; Van Bavel, 1961). Measurements near the soil surface are not as accurate because fast neutrons can escape into the atmosphere (Skaggs et al., 1981).

Tensiometers

Tensiometers are probably the most commonly used instrument for irrigation scheduling today. Because they are easy to use and are relatively inexpensive as compared to the neutron probe, these instruments have gained considerable popularity among irrigators. Although tensiometers measure soil moisture potential rather than soil moisture content they can be useful for the water balance approach. Soil moisture potential can be converted into percent water by volume by an experimentally determined soil moisture characteristic curve (Richards, 1949; Chides, 1940).

Each soil has a unique soil moisture characteristic curve. Since the determination of these curves is time consuming and tedious, most irrigators use tensiometers strictly for measuring soil moisture potential.

Basing irrigations according to moisture potential is useful because it reflects the plants response to moisture stress better than soil water content (Haise and Hagan, 1967). Irrigations are usually scheduled when a predetermined moisture potential is reached. Richards and March (1961) proposed that by using tensiometers at two or more depths proper amounts of water could be applied. They suggested plotting the daily tensiometer readings on a graph in order to follow the downward water movement. If the deeper tensiometers readings indicated that no water penetrated to their depth after one or two days, more water could be applied during the next irrigation. Even though their method of estimating irrigation amounts is less accurate than the water balance technique, it can be extremely useful when soil water content is not being measured.

The main limitations of tensiometers are they measure only a small volume of the soil and are useful at moisture tensions between 0-0.8 bar. The first limitation can be partially overcome by using a number of tensiometers (Dylla et al., 1981). The second is not as severe as it may first appear. Although the tension range of 0-0.8 bar is only a small part of the total range of tension in which a plant can remove water, estimated to be 0-15 bar, the tensiometer is very useful. In many agricultural soils the tensiometer range accounts for more than 50 percent of the soil water available to plants (Hillel, 1982).

Evapotranspiration Models

The main objective of irrigation is to supply plants with sufficient water to maximize yield and quality of the harvested parts (Haise and Hagan, 1967). The knowledge of a specific crop's water requirements at various stages of its life cycle can be used to schedule both the timing and amount of irrigations. Doorenbos (1977) defined crop water requirement as "the depth of water needed to meet the water loss through evapotranspiration (ETcrop) of a disease free crop, growing in large fields under nonrestricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment."

Numerous models requiring meteorological data for predicting ET have arisen in the past 35 years. These models are all empirical to various extents (Burman et al., 1981). The simplest models require only day length, a crop factor, and average air temperature. Those which require daily radiation, temperature, vapor pressure, and wind data are generally more accurate, especially when measurements are for periods of one week of less.

Obtaining ET estimates from weather data is relatively easy compared to calculating ET values from changes in soil moisture. Evapotranspiration estimates can be predicted several days in advance if proper weather information is available. These advantages, plus the adaptation of some models to microcomputer programs (Crouch et al., 1981; Burman et al., 1983), have made this approach to irrigation scheduling very appealing. The two models discussed in the following section (or some form of them) were used in this experiment.

Evaporation Pans

Most agricultural weather stations utilize evaporation pans for estimating evaporation. Although there are many types, the U.S. Class A pan is the most widely used. It is 121 cm in diameter and 25.5 cm deep. The pan is usually made of galvanized steel or Monel metal. It is placed on a level wooden platform with the bottom of the pan being approximately 15 cm above the ground. Water is replenished to maintain the water level between 5 to 7.5 cm below the rim.

Because pan evaporation (Epan) is influenced by many factors which affect ET (i.e., wind, radiation, humidity, and air temperature), data from pans have been correlated with ET for many years (Penman 1948; Rijtema, 1959). Pan evaporation can be related to ETr by an empirically derived coefficient (Kp). The equation appears as follows:

$$ETr = Epan * Kp$$

Many factors such as, height and type of surrounding crops, the use of a screen over the pan, and pan color can modify Kp. Pruitt and Angus (1961) found the cumulative evaporation from a Class A weather pan to be 135 cm from June through December when it was located in a large grass field. However, when the pan was sited in a dry fallow field evaporation for the same period was 175 cm. Doorenbos and Pruitt (1977) listed several Kp values for the Class A pan. The different values reflect the influence of various surroundings, wind speeds, and humidity. On the basis of these factors it is recommended that each pan be calibrated to it's specific locale (Tanner, 1967).

The main disadvantage of the pan is the relatively long time periods required to obtain reasonable estimates. Generally, 10 days is the shortest period for which pan estimates can safely be correlated to ETr (Rijtema, 1959; Pruitt and Angus, 1961). With careful siting and use, ETr estimates within 10 percent accuracy are be possible.

Penman Method

The Penman method, first introduced in 1948 (Penman, 1948), estimated evaporation from a free water source. By use of an empirical coefficient which varied with the season, potential ET was derived from evaporation estimates. This was the first of several equations which combined energy balance and a mass transfer or aerodynamic term for estimating ET. The equation for ETp short grass is as follows:

$$ETp = S/S+P \quad (Rn-G) + P/S+P \quad 15.36\ (1+0.0062\ V)\ (es-ed)$$

Where ETp is in $cal/cm^2/day$; S is the slope of the saturation vapor pressure curve in $mb/^{\circ}C$ at mean air temperature; P is the psychrometric constant in $mb/^{\circ}C$; Rn is the net radiant energy available at the surface in $cal/cm^2/day$; G is the energy into the soil in $cal/cm^2/day$; V is the average wind velocity in km/day at 2 meter height; es is the mean vapor pressure in mb (recorded at minimum and maximum daily air temperatures); and ed is the saturated vapor pressure at mean dew point temperature in mb.

Doorenbos and Pruitt (1977) were able to summarize specific procedures and guidelines for predicting crop water requirements for a wide range of crops, conditions, and availability of associated information by using a slightly adjusted Penman equation.

Often some modified version of Penman's equation is used due to lack of complete climatic information. Although these modified versions may be extremely useful, some degree of accuracy may be forfeited by using them. If all the required data is available, reliable estimates as short as one day are possible (Burman et al., 1981).

Plant Measurements

The third and final approach to irrigation scheduling is based upon plant or crop measurements. In this approach the plant "signals" when irrigations should begin. By measuring various plant parameters, plant water stress can be detected. Ideally the plant should signal when to irrigate and the soil should indicate how much water to apply (Teare et al., 1974; Geiser et al., 1982). Although irrigation scheduling based upon plant measurements is relatively new, its potential for future use appears promising. Based on a review of recent literature, plant water potential and canopy temperatures seem to be the most popular plant indicators in irrigation scheduling research.

Plant Water Potential

Scholander et al. (1965) first described how plant water potential could be determined by measuring the negative hydrostatic xylem sap pressure with a pressure chamber. Hiller and Clark (1971) tested several plant measurements and determined that plant water potential was the best indicator of water stress. They developed a stress day index (SDI) by multiplying a plant stress factor with a crop susceptibility factor. An inverse linear relationship between yield and seasonal SDI was obtained for several crops. Their concepts of stress measurements were expanded by Stegman et al. (1976), who found that leaf xylem pressure was best correlated with prevailing air temperature and available soil moisture. They noted when xylem pressure exceeded -12 and -10 bars in corn and potatoes respectively, the stomata began to close. They assumed the plant's physiological functions were affected when stomata closure began (Hsiao, 1973), thus reducing yields. Therefore, their critical leaf xylem levels were determined by when the stomata began to close. By combining this approach to irrigation scheduling with soil moisture measurements, a substantial savings of water without yield reduction was indicated in their simulated test.

Canopy Temperatures

The use of canopy temperatures to indicate plant water stress is based upon the assumption that the leaves are cooled below the temperature of the surrounding air by evaporation of transpired water (Jackson, 1983). When water is limited, transpiration is reduced and leaf temperatures increase (Ehrler, 1973; Sandhu and Horton,1978; Sumayao et al., 1980). Although the concept of using canopy temperatures to indicate plant stress is not new, the application of this methods to irrigation scheduling is fairly recent.

Idso et al. (1977) and Jackson et al. (1977) suggested the difference between the temperature of a plant canopy and the surrounding air (Tc-Ta) could be an indicator of water status in wheat. Jackson et al. (1977) presented a method for determining the timing and amounts of irrigations. Assuming that vapor pressure, net radiation, and wind would be mainly manifested in the canopy temperature, they defined stress degree day (SDD) as Tc-Ta. In their experiment, canopy temperatures were measured daily between 1330 and 1400 hours. Water depletion was measured with a neutron moisture meter and all positive values of SDD were summed. They concluded that irrigations should begin when or before SDD reached a value of 10.

The amount of water to apply was estimated from the following equation:

$$ET=Rn-0.064(Tc-Ta)$$

where ET is the evapotranspiration in cm/day of the specific crop; and Rn is net radiation. This equation was found to describe ET for periods of one week or more, but not for individual days.

Herman and Duke (1978) compared temperature differences between a well watered corn plot and an adjoining treatment plot. They noted that temperature differences greater than 1.5 °C were closely related to yield reductions.

Clawson and Blad (1982) defined the canopy temperature variability (CTV) as the range in temperatures of six readings taken from any one plot. The CTV was less than 0.7 °C in a fully irrigated reference plot. Canopy temperatures and CTV increased as water stress was incurred. Irrigation was initiated when CTV exceeded 0.7 °C. In comparison, the fully irrigated plot was irrigated weekly to refill the soil to field capacity as determined by neutron meter measurements. The CTV treatment received 45 percent less water than the fully irrigated plot, yet yield differences between the two were not significant.

Geiser et al. (1982) found similar results when scheduling irrigations according to resistance blocks, checkbook method, and canopy-air difference. The checkbook and resistance methods required 39 and 18 percent, respectively, more water than the canopy-air difference. Yields were not significantly different between the three methods.

In comparing canopy temperature with plant water potential, the former may be a better indicator of plant water stress (Jackson, 1983), especially during the early stages of stress. If so, canopy temperature measurements may have a greater future potential for irrigation scheduling.

Line Source Design For Irrigation Experiments

The line source irrigation system as described by Hanks et al. (1976) has been an effective method for evaluating various water application rates on crops. This system minimizes the experimental land area needed and provides a continuous variation of irrigation treatments ranging from excessive to no water. The water application gradient produced by moving perpendicular away from the line source has made the system popular, especially for water management experiments (Garrity et al., 1982; Hang and Miller, 1983; Miller and Hang, 1980; O'neill et al., 1983; Sorensen et al., 1980).

The actual design is a variation of Fox's (1973) continuous function experimental design. Fox applied increasing amounts of nitrogen to each plant down the row. Since the incremental change between each treatment was small, boarder rows were eliminated. Bauder et al. (1975) incorporated water treatments at right angles to the nitrogen levels. By using a trickle irrigation system they effectively controlled the amount of water applied. However, the trickle system was expensive, required considerable manhours to set up and operate, and required thorough filtering of the water.

Hanks et al. (1976) adapted the design further by using a line source sprinkler system. This design used a single line of closely placed sprinklers placed down the center of a plot. The plants closest to the line source received the highest application of water, while those furthest from the source received the least. They recommended the sprinkler spacings be between 10-25 percent of the wetted area in order to keep the application rate as uniform as possible parallel to the line source. The individual sprinklers should give a triangular shaped profile when operated in low winds at the desired pressure. The plot width is determined by the wetted diameter of the sprinklers. Two replications are produced, one on either side of the line source.

Several limitations of the line source system which should be considered before using this design are as follows (Hanks, 1976):

(1) The effect wind has on the sprinkling patterns. Even low winds can significantly alter the pattern.

(2) On any given plot all irrigation treatments must be applied at the same time and frequency.

(3) Ponding or runoff may be a problem due to the high rate of application.

(4) Since wind alters the distribution pattern it is advisable to measure water application data across the plot. This may be a problem with taller crops.

Possibly the biggest limitations of the line source design has been the statistical analysis. Hanks et al. (1980) suggested that statistical test were not available to compare irrigation levels with yields. The problem is that irrigation levels are applied systematically rather than randomly. Recently, Johnson et al. (1983) showed how multivariate methods could be used to obtain an appropriate statistical test for the line source and other nonrandomized experiments.

A greater understanding of the statistical analysis together with the advantages previously mentioned should continue to make the line source system a popular experimental design.

CHAPTER 2

EFFECT OF ROW SPACING ON EVAPOTRANSPIRATION, YIELD, AND WATER USE EFFICIENCY OF SOYBEANS

INTRODUCTION

In 1983 a study was conducted to evaluate yield and water use efficiency of soybeans planted at three different row spacings. Results in other parts of the country indicate that narrow rows generally produce higher yields than wide rows (Reicosky et al., 1982; Cooper, 1977), especially in wet years (Taylor, 1980). Since, very little information exists on how row spacing affects water use efficiency in soybeans, it became a logical objective of this study.

MATERIALS AND METHODS

Climate, Location and Soil

This study was conducted in 1983 at the Michigan State Soils Research Farm located at East Lansing Michigan. This area has a temperate climate and receives an average of 75.79 cm of rain and 100.08 cm of snow per year. Approximately 61 percent or 46.23 cm of the annual rainfall comes between April and September. The average temperature in the summer is 20.5 degrees centigrade, and the average daily maximum temperature is 26.8 degrees centigrade. The prevailing wind is from the southwest. Relative humidity averages 62 percent at midafternoon, and the percentage of possible sunshine is 68 percent in the summer (USDA Soil Survey of Ingham County, 1979). East Lansing is located between the 42nd and 43rd degree latitude and 84th and 85th degree longitude.

The soil of the research plot is mostly a Metea loamy sand, with some instances of Riddles sandy loam. Metea is a loamy, mixed, mesic Arenic Hapludalfs with approximately 127 cm of loamy sand covering a clay loam till. Riddles is a fine-loamy, mixed, mesic Typic Hapludalfs, with approximately 64 cm of sandy loam covering a clay loam or sandy clay loam till. Both soils are typically well drained. The available water capacity for the first 61 cm is 3.42 cm and 2.28 cm for the Riddles and Metea soils, respectively.

Experimental Design and Management Practices

In 1983, a study was established to evaluate how row spacing and plant population affect yield and water use efficiency of soybeans. The experimental design was a randomized complete block with four replications. Corsoy 79 was planted in row spacings of 25, 51, and 76 cm. Three seeding rates (309,000, 432,500, and 556,000 plants/ha) were attempted using the same drill setting. Nonviable seed was mixed with viable seed to obtain the desired seeding rate. The seed was killed by placing it in an oven for four days at 93 degrees centigrade.

In the spring the plots were moldboard plowed, disked, and then field cultivated. Corn was grown on this site in 1982. A broadcast application of 336 kg/ha of 6-24-24 and 336 kg/ha of 0-0-60 was applied preplant and incorporated. Alachlor (2.24 kg a.i./ha) and linuron (0.84 kg a.i./ha) were applied before planting for weed control. The soybeans were planted on May 27 and emerged June 7. The plots were hand weeded during the growing season to maintain a weed free environment.

The irrigation system consisted of two parallel solid set lines 16.4 meters apart running perpendicular to the treatment plots. On each line the risers were 10.2 meters apart and 1.02 meters high.

On October 20 an area of 40.9 square meters was mechanically harvested from each plot. All grain yields were adjusted to 13 percent moisture.

Soil Moisture Measurements and Water Management

Tensiometers were installed in the high population treatment of the 25 and 76 cm rows. They were placed directly in the rows 30.5 cm deep and read three times a week. Irrigations were scheduled to maintain the average of the eight tensiometers below 50 cb.

A neutron probe (Troxler Nuclear Moisture Gauge, Model 3222) was also used in monitoring the soil moisture. An aluminum access tube 1.02 meters long was placed in one row of the high population treatment at all three row spacings. Readings were taken at the 30.5 and 61 cm depths in each replicaton. Equal weight was given to each reading. The 30.5 cm reading was used as the estimate of soil moisture from 0-30.5 centimeters. Readings at shallower depths may give inaccurate measurements because of fast neutrons escaping through the soil surface. The 61 cm reading was used as the soil moisture estimate of the 30.5-61 cm profile. Evapotranspiration estimates were made throughout the season from this data using a water balance equation (see page 48).

Rainfall for the growing season was 35.86 cm and an addition 11.75 cm was added by irrigation. Class A pan evaporation data were collected and compared to the neutron probe ET estimates.

Statistical Analysis

Analysis of variance was performed using a Cyber 750 computer and a microcomputer statistical program (MSTAT). Statistical procedures used were those described by Steel and Torrie (1980).

RESULTS AND DISCUSSION

Growing Conditions for 1983

Growing conditions for 1983 were very close to normal. A cool wet spring delayed planting. Precipitation for June was 2.9 cm above average, but precipitation from July 1 to August 31 was 3.8 cm below normal. The average temperature for the growing season was slightly above normal. May was the only month which had an average monthly temperature below normal. Climatological data for 1983 is shown in Table 2-1.

Effect of Row Spacing and Plant Population on Yield and Growth

Soybean yields for 1983 are presented in Table 2-2. In general, yields increased when row spacings increased and populations were decreased or when populations were increased and row spacings decreased. However, there was no significant difference in yield due to row spacing or plant population. Hicks et al. (1969) reported similar results.

The desired seeding rate of 46 seeds per meter could not be achieved even at the highest drill setting. Actual seeding rates were approximately 30 percent less than desired. Stand counts taken one week after emergence indicated the populations were 50 percent lower than those originally planned (Table 2-3). The 25 cm rows had an early season stand count 23 percent lower than the 51 cm rows and 25 percent lower than the 76 cm rows. Cool wet weather coupled with surface crusting of the soil may have

Table 2-1. Climitological data for Soils Research Farm, East Lansing, Mi. from May 1 to September 30, 1983.

Month	Average Temperature (centigrade)	Precipitation (cm)		
		Rain	Irr.	Total
May	11.3	11.9	0.0	11.9
June	19.5	13.6	0.0	13.6
July	23.5	5.1	7.0	12.1
Aug.	22.4	6.3	4.8	11.1
Sept.	16.9	9.6	0.0	9.6
Totals		46.5	11.8	58.3

Table 2-2. Effect of plant population and row spacing on the yield of Corsoy 79 soybeans.

Row Spacing (cm)	Seeding Rate			LSD (.05)
	Low	Medium	High	
	-----------------kg/ha[1]-----------------			
25	2891.7	3053.1	3093.5	(NS)
51	3180.9	3228.0	3080.0	(NS)
76	3342.3	3147.3	2797.6	(NS)
LSD (0.5)	(NS)	(NS)	(NS)	

1 Adjusted to 13 percent moisture.

Table 2-3. Plant populations taken one week after emergence.

Row Spacing (cm)	Plant Population Level		
	Low	Medium	High
	----------------plants/ha----------------		
25	140,465	211,502	255,903
51	166,296	249,849	333,400
76	182,441	270,702	339,590
LSD (.05)	25,992	25,992	25,992

caused delayed and sporadic emergence. The wider rows may have had an advantage in breaking through the crusted soil because they had more seeds per foot than the 25 cm rows. Although no counts were taken later in the season, the final stands appeared to improve. The 25 cm row spacing treatment was significantly lower than the other two during the early emergence measurement.

As expected, the soybeans in the 25 cm row spacing achieved complete canopy coverage first. The soybeans in the 76 cm row spacing were visably the tallest. Lodging seemed to be accelerated due to irrigations.

Effect of Row Spacing on Water Use

Tensiometer readings taken at the 25 and 76 cm row spacings are shown in Figure 2-1. Evapotranspiration calculations, determined from neutron probe readings (Figures 2-2 and 2-3), are shown in Table 2-4. Water use and ET data were only collected at the high plant population level. The seasonal average daily ET rates were almost identical for all three row spacings. Pan evaporation data is listed for comparison with soil calculated ET. Figure 2-4 gives a visual comparison of ET rates and pan evaporation for each period. Table 2-5 lists the total water used between June 29 and September 9 for each of the row spacings. There was no significant difference in the amount of water used due to row spacings. The percentage each treatment was of pan evaporation is also shown.

Water use efficiency was determined by dividing the grain

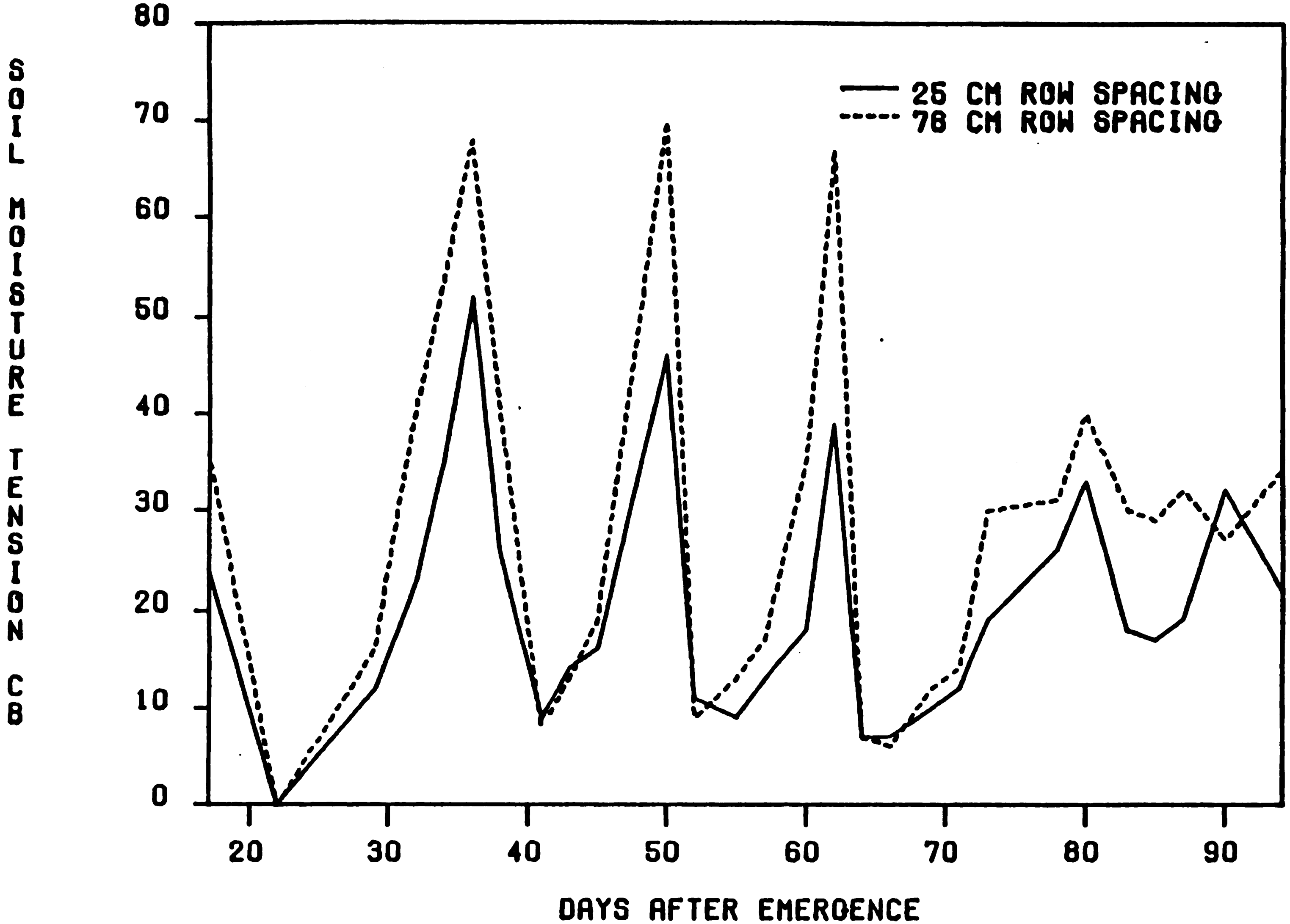

Figure 2-1. Tensiometer readings at the narrow and wide row spacings.

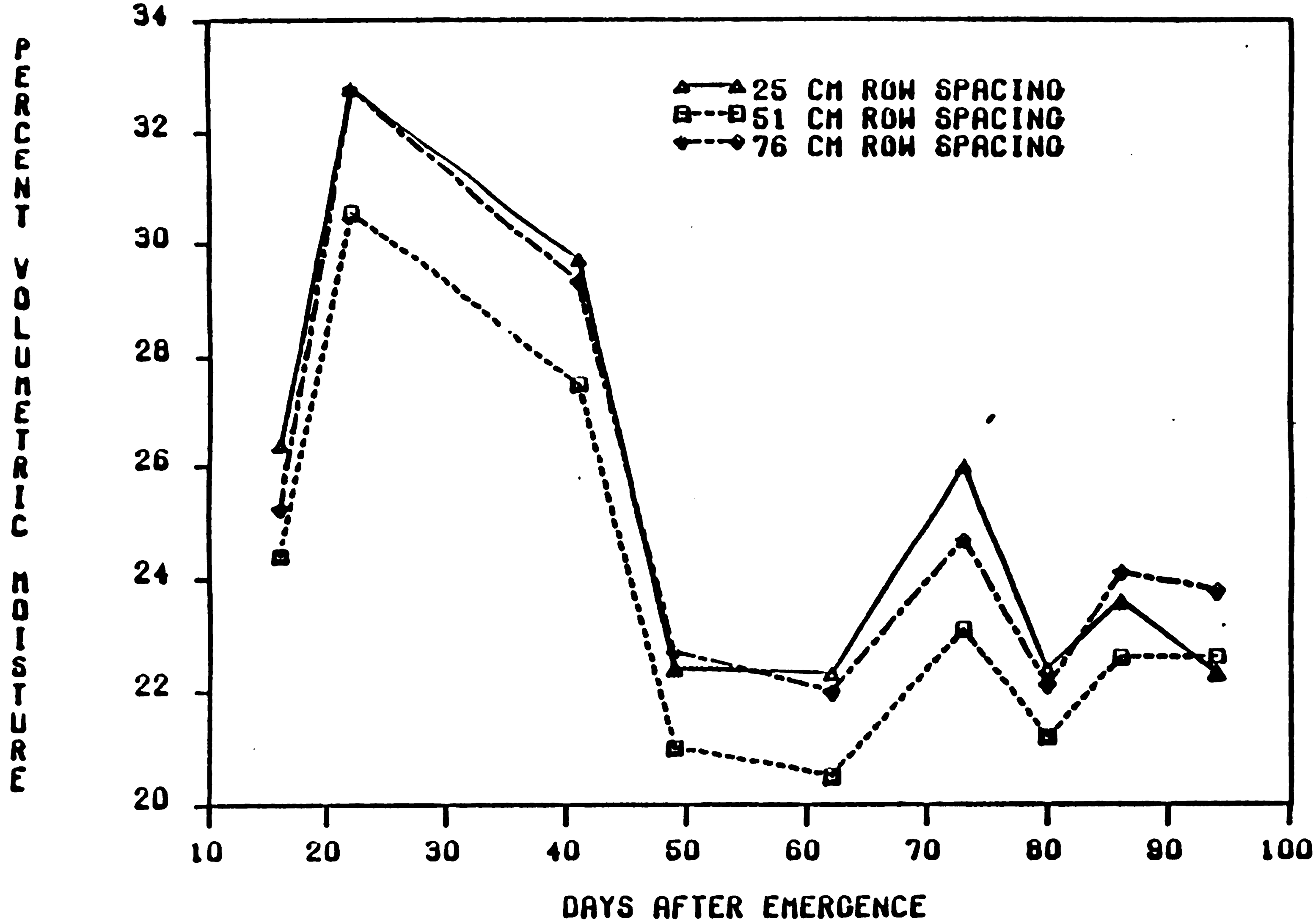

Figure 2-2. Neutron probe readings taken at the 30.5 cm depth.

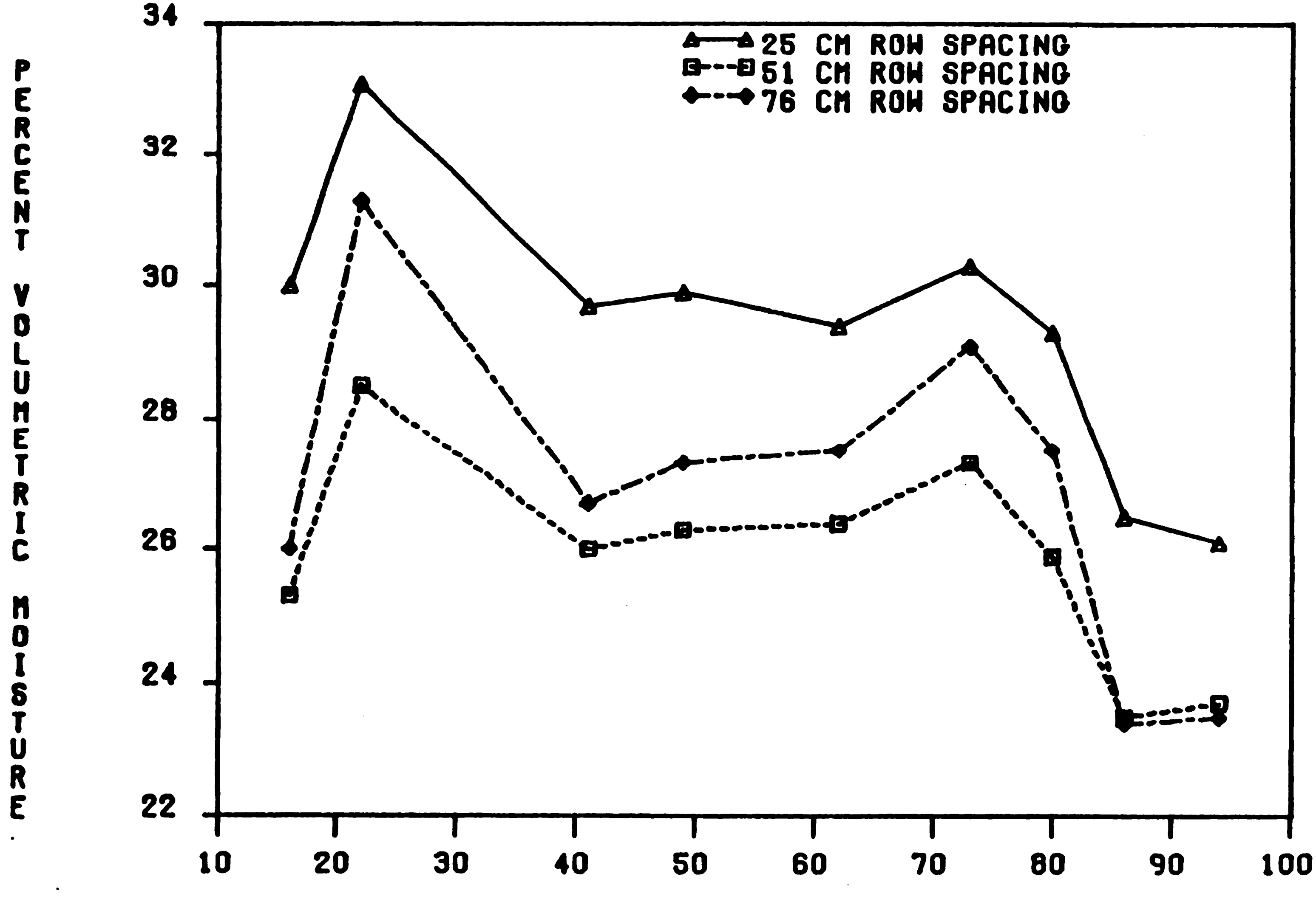

Figure 2-3. Neutron probe readings taken at the 61 cm depth.

Table 2-4. Average daily evapotranspiration rates as calculated from neutron probe measurements.

Time Period		Row Spacings (cm)			
Date	DAE[1]	25	51	76	Pan Evaporation
		----------cm of water----------			
6/29 - 7/18	22 - 41	.49	.47	.51	.68
7/18 - 7/26	41 - 49	.47	.44	.43	.70
7/26 - 8/8	49 - 62	.37	.36	.37	.54
8/8 - 8/19	62 - 73	.43	.46	.44	.52
8/19 - 8/26	73 - 80	.49	.43	.47	.48
8/26 - 9/1	80 - 86	.56	.53	.59	.49
9/1 - 9/9	86 - 94	.32	.24	.26	.60
Average		.44	.42	.44	.59

[1] Days after emergence.

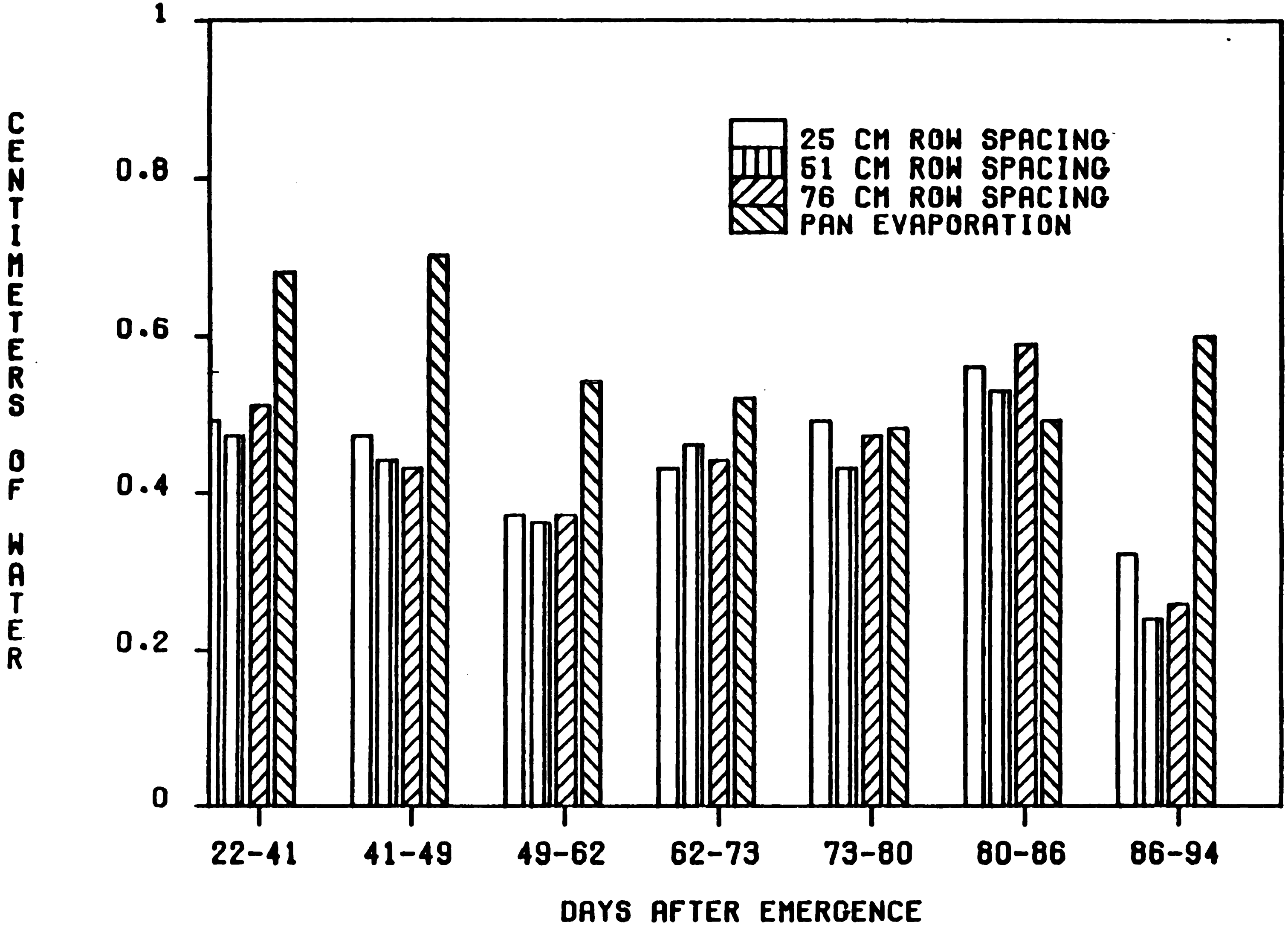

Figure 2-4. A comparison of evapotranspiration rates and Class A Pan evaporation.

Table 2-5. Effect of row spacing on water use effeciency at the high plant population.

Row Spacing (cm)	Total Water Use from 6/29 - 9/9	Percent of Pan	Yield	Water Use Efficiency[1]
	---cm---		kg/ha	kg/cm
25	31.8	74.7	3093.5	98.0
51	30.4	71.4	3080.0	101.3
76	31.6	74.2	2797.6	88.3
LSD (.05)	(NS)		(NS)	(NS)

[1] Water use efficiency was calculated by dividing the yield by the amount of water used between 6/29 and 9/9 as determined by calculations from neutron probe measurements.

yield by the ET accumulated between June 29 and September 9. There was a significant difference in water use efficiency between the 51 and 76 cm row spacings at the .10 level of significance but not at the .05 level. The 51 cm rows produced 101.3 kg/ha for each cm of water used, while the 76 cm rows produced only 88.3 kg/ha per cm of water. There was no significant difference in water use efficiency between the 25 cm row spacing treatment and the other two at either the .10 or .05 level of significance.

SUMMARY AND CONCLUSIONS

Soybean yields in 1983 were generally not affected by row spacing or plant population. This is somewhat surprising because the majority of research conducted in this area has shown narrow rows generally yield greater than wide rows (Reicosky et al., 1982; Peters and Johnson, 1960; Taylor, 1980).

The water use efficiency was significantly different only at the .10 significance level between the 51 and 76 cm row spacing treatments. The wide row spacing had the lowest water use efficiency of the three treatments.

Water use efficiency as well as yield may have been limited due to lower than expected plant populations. This is especially true at the narrow row spacing. The early season stand counts of the 51 and 76 cm rows were 23 and 25 percent higher, respectively, than the 25 cm rows.

The narrow rows achieved complete canopy coverage first. The soybeans in the 76 cm rows were the tallest. There was considerable lodging of all treatments, which is not uncommon with Corsoy 79 when irrigated.

A greater consistancy in plant population would have been helpful in evaluating yields and water use efficiencies, particularly with the narrow row spacing treatment. It also would have been beneficial to collect and compare water use data at the lower plant population levels, especially since the highest yields were obtained there.

CHAPTER 3

EFFECT OF IRRIGATION LEVEL ON YIELD AND WATER USE EFFICIENCY OF THREE CORN HYBRIDS

INTRODUCTION

In 1984 a study was conducted to evaluate how water use efficiency and yield are affected by irrigation levels. Three corn hybrids (DeKalb 587, Pioneer 3572, and Pioneer 3707) were used in this experiment. Evapotranspiration, precipitation, and yield were measured and compared at five irrigation levels.

An empirical formula for calculating ET, presently being used in an irrigation scheduling program at Michigan State University, was compared to ET estimates made from neutron probe readings and Class A pan data.

MATERIALS AND METHODS

Climate, Location and Soil

This study was conducted in 1984 at the Michigan State Soils Research Farm, located in East Lansing Michigan. The climate and location of this area was previously discussed in Chapter 2.

The predominate soil of the experimental area is Metea loamy sand (Loamy, mixed, mesic Arenic Hapludalfs), although there are some minor intrusions of Spinks loamy sand (Sandy, mixed, mesic Psammentic Hapludalfs). Both soils are well-drained with good permeability. Metea soils have more silt and clay in the lower part of the subsoil and substratum. The available water capacity for the first 91.5 cm is 8.94 cm for Metea soils and 7.16 cm for Spinks soils. Permeability is moderately rapid to rapid in the Spinks soils. In the Metea soil the permeability is very rapid in the upper part but only moderate to slow in the lower part.

Experimental Design and Management Practices

The experimental area was divided into three ranges of equal size (Figure 3-1). Each range was 30.5 by 30.5 meters. A single irrigation line ran through the middle of each range parallel to the rows. The risers on the line were 3.05 meters apart and 3.05 meters high. The ranges were quartered by dividing each one perpendicular to the irrigation line. Each range consisted of four quarters 15.25 by 15.25 meters. Each quarter was considered

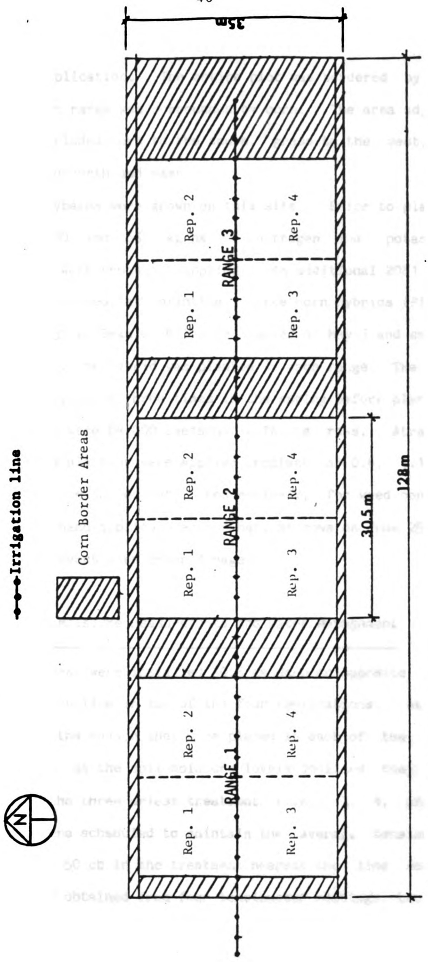

Figure 3-1. Plot layout.

to be one replication. The entire plot was bordered by mown grass and each range was surrounded by corn. The area adjacent to the plot included corn to the south, grass to the west, and soybeans to the north and east.

In 1983 soybeans were grown on this site. Prior to planting in 1984, 1500 and 652 kg/ha of nitrogen and potassium, respectively, were broadcast applied. An additional 2081 kg/ha of 5-20-20 was banded at planting. Three corn hybrids (Pioneer 3707, Pioneer 3572, Dekalb 587) were planted on May 3 and emerged on May 14. Only one hybrid was planted in each range. The plots were field cultivated three times in the spring before planting. Planting rates were 84,000 seeds/ha in 76 cm rows. Atrazine, cyanazine, and alachlor were applied preplant at 0.6, 1.1, and 2.8 kg/ha (active ingredient), respectively, for weed control. Carbofuran was hand applied over the harvest rows on June 25 and on July 9 to prevent corn borer damage.

Soil Moisture Measurements and Water Management

Tensiometers were installed 30.5 cm deep on opposite sides of the irrigation line in two of the four replications. At the beginning of the season they were placed in each of the five treatments but as the soil moisture levels declined they were removed from the three driest treatments (i.e., 3, 4, and 5). Irrigations were scheduled to maintain the average tensiometer reading below 50 cb in the treatment nearest the line source. The average was obtained from four tensiometer readings, two from each replication. All ranges were irrigated at the same time because the design of the line source in this experiment did not allow for each range to be irrigated separately. Therefore, irrigations were not begun until the wettest range reached soil moisture tensions of 50 cb.

A neutron moisture meter was also used to monitor soil moisture. Aluminum access tubes 1.22 meters long were placed in the same rows of each treatment as the tensiometers. Beginning on June 18, readings were taken at depths of 30.5, 61, and 91.5 cm. The 30.5 cm reading was used as an estimate of soil moisture in the 0-30.5 cm profile. The soil moisture in the 30.5-61 cm profile was estimated from the 61 cm reading, and the 91.5 cm reading estimated soil moisture in the 61-91.5 cm profile. Data from the neutron probe readings were used in a water balance equation for estimating ET. The equation was as follows:

$$ET=(SM1-SM2)+(R+I)$$

where SM1 is the soil moisture content at the beginning of the period; SM2 is the soil moisture content at the end of the period; R is the amount of rain that fell during the period; and I is the amount of irrigation applied during the period.

The neutron probe was used to follow changes in the soil moisture rather than absolute content. Therefore, the calibration curve determined by the manufacturer was considered to be appropriate and was used rather than a field calibrated curve. A Troxler Nuclear Moisture Gauge, model 3222 was used until August 23. Beginning On August 23, a Campbell Pacific Nuclear, model 503A was used for the remainder of the season due to mechanical failure of the first probe.

Irrigation amounts were measured in rain gauges, maintained at canopy height throughout the season, and considered 100 percent effective. The gauges were placed in each of the first four treatments on both sides of the line source. The driest treatment received no precipitation from irrigation so no gauges were placed there. Every access tube in the first four treatments had a rain gauge near it, and irrigation amounts for estimating ET from neutron probe data were collected individually from them. Since the irrigation amounts varied slightly along the irrigation line from range to range, this was felt to be more accurate than using an average of all the ranges when estimating ET. Between May 14 (emergence date) and September 6 (115 days) 26.11 cm of rain fell and another 22.37 cm was added through irrigation at the wettest treatment.

An empirical formula for predicting ET was compared to ET estimates made from the neutron probe data and Class A pan evaporation data. The formula is based on a modified Penman equation and requires daily inputs of average daily temperature and precipitation. Thornthwaite (1948) noted that when adjustments were made for variations in day length, mean air temperature and ETp were closely related. Schleusener and Kruse (1963) proposed an empirical equation relating average daily temperatures, average daily percent of annual daylight hours, and field measurements of ET. The formula used in this study is based around Schleusener's and Kruse's work and is as follows:

$$Up=(0.0259Tp)Pp-0.4128$$

where Up is the average daily water use rate in inches for the period between irrigations; Tp is the average of mean daily temperatures for the period between irrigations, degrees F. (Mean of maximum and minimum daily temperatures); and Pp is the average daily percent of total annual daylight hours for the period between irrigations.

Average daily percent of total annual daylight hours was obtained from a table of published values (USDA, Soil Conservation Service, 1970). By using the percent daylight hours instead of measured net radiation, ET estimates for any given mean temperature would be the same regardless of any cloud cover which might occur. This could cause serious errors in ET estimates for short periods, but because monthly averages of net radiation are fairly constant from year to year, accuracy increases as the length of the period measured increases.

Statistical Analysis

Statistical analysis was performed using a microcomputer statistical program (MSTAT). Statistical procedures used are those given by Steel and Torrie (1980). Unfortunately, the multivariate method, described by Johnson et al. (1983), for obtaining an appropriate statistical test for the line source experiment could not be used because irrigation level was the only variable in this experiment.

RESULTS AND DISCUSSION

Growing Conditions for 1984

Rainfall was below normal for the 1984 growing season. June and July were especially dry. Precipitation was 10.77 cm below average from June 1 to July 31. Although rainfall was above average for May, August, and September, it was either not enough to carry the crop through the dry period or it came to late in the season to prevent yield reduction. Temperatures were very close to normal with June being a little warmer than average (National Oceanic and Atmospheric Administration). Wet and cool conditions in May slightly delayed planting and emergence. Climitological data for the growing season is presented in Table 3-1 and 3-2.

Evapotranspiration Estimates

Evapotranspiration estimates were made from three different methods. The first was a soil water balance approach using a neutron probe. The second method was a computerized irrigation scheduling program based on the previously described empirical equation. The third and was a Class A weather pan.

Evapotranspiration values calculated from the neutron probe data early and late in the season were very close to what would be expected (Table 3-3 and Figures 3-2, 3-3, and 3-4). Values in the middle of the season were not as predictable. On July 10 and August 3 high intensity rains occurred resulting in runoff from the plots. On July 30 it was discovered that

Table 3-1. Climitological data for Soils Research Farm, East Lansing, Mi. from May 1 to September 30, 1984.

Month	Average Temperature (centigrade)	Precipitation (cm)		
		Rain	Irr.	Total
May	11.4	12.3	0.0	12.3
June	20.9	0.7	3.9	4.6
July	20.9	4.2	12.2	16.4
Aug.	22.2	10.5	6.3	16.8
Sept.	15.3	8.1	0.0	8.1
Totals		35.8	22.4	58.2

Table 3-2. Accumulated precipitation and evapotranspiration measurements from May 14 and June 18, respectively, until September 6, 1984 at five irrigation levels for Ranges 1, 2, and 3.

Trt.	Irrigation Level	Precipitation			Evapotranspiration[1]		
		Irr.	Rain	Total	Range 1	Range 2	Range 3
		cm					
1	100 %	22.37	26.11	48.48	46.57	44.87	47.92
2	81 %	18.08	26.11	44.19	45.06	42.16	45.95
3	58 %	12.89	26.11	39.00	41.22	37.44	40.86
4	25 %	5.55	26.11	31.66	36.91	32.73	35.26
5	0 %	0.00	26.11	26.11	30.75	27.98	31.09

[1] Calculated from neutron probe measurements.

Table 3-3. A comparison of ET estimates from neutron probe measurements and an empirical formula with Class pan evaporation data for Ranges 1, 2, and 3.

Time Period			Range			Empirical Formula	Class A Pan Evap.
Period	Date	DAE[1]	1	2	3		
			-------average ET/day in cm--------				
1	6/18-6/27	35-44	.51	.51	.41	.50	.74
2	6/28-7/4	45-51	.51	.53	.53	.54	.63
3	7/5-7/11	52-58	.69	.18	.74	.56	.60
4	7/12-7/18	59-65	.20	.43	.28	.58	.70
5	7/19-7/25	66-72	.74	.89	.79	.56	.69
6	7/26-8/1	73-79	.51	.48	.46	.48	.60
7	8/2-8/9	80-87	.71	.51	1.12	.57	.48
8	8/10-8/22	88-100	.94	.99	.74	.47	.60
9	8/23-8/29	101-107	.41	.43	.53	.37	.52
10	8/30-9/6	108-115	.25	.33	.31	.29	.44
Total ET for Entire Period			46.57	44.87	47.92	39.33	48.30

[1] Days after emergence.

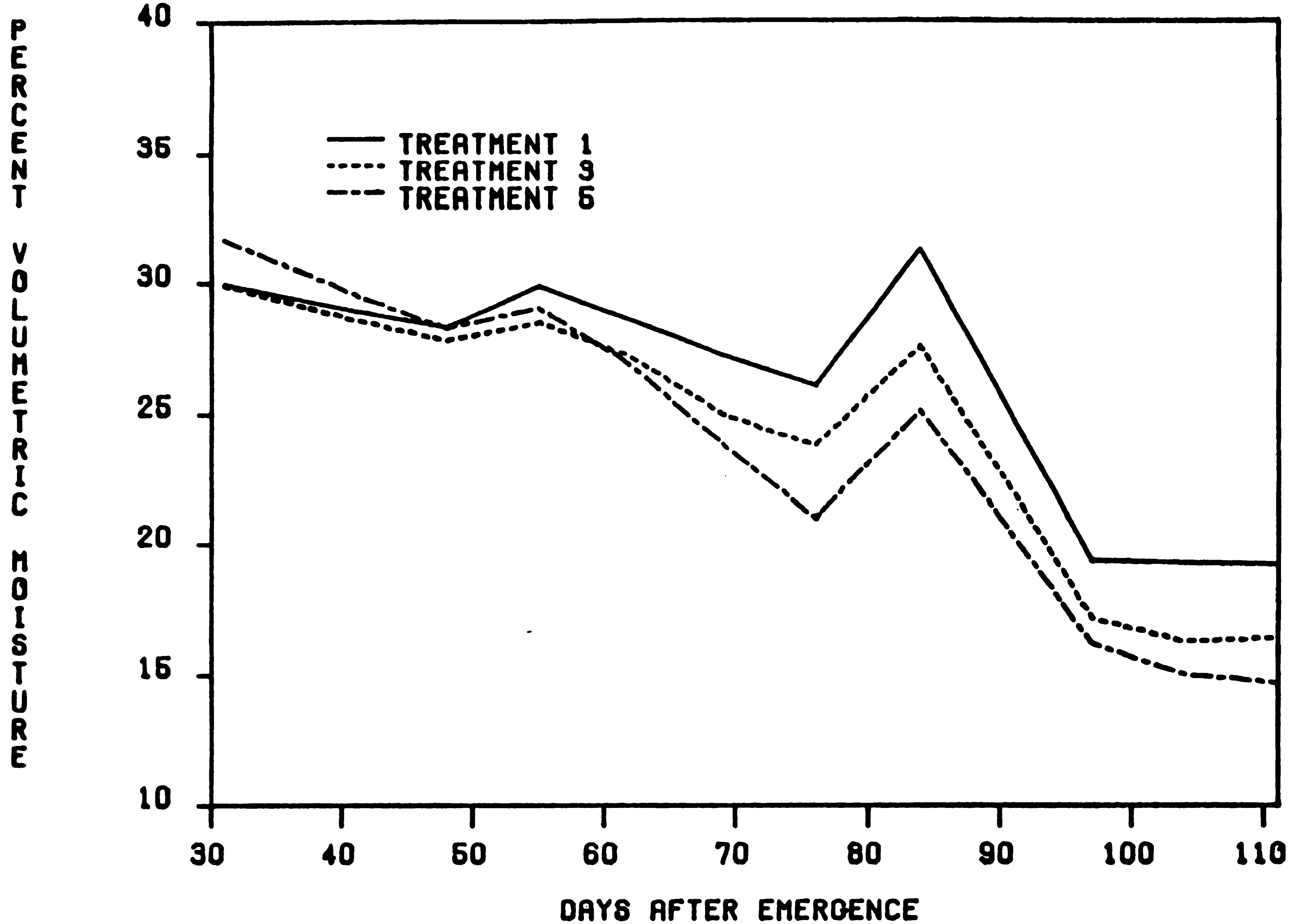

Figure 3-2. Neutron probe readings averaged from 30.5, 61, and 91.5 cm depths (Range 1).

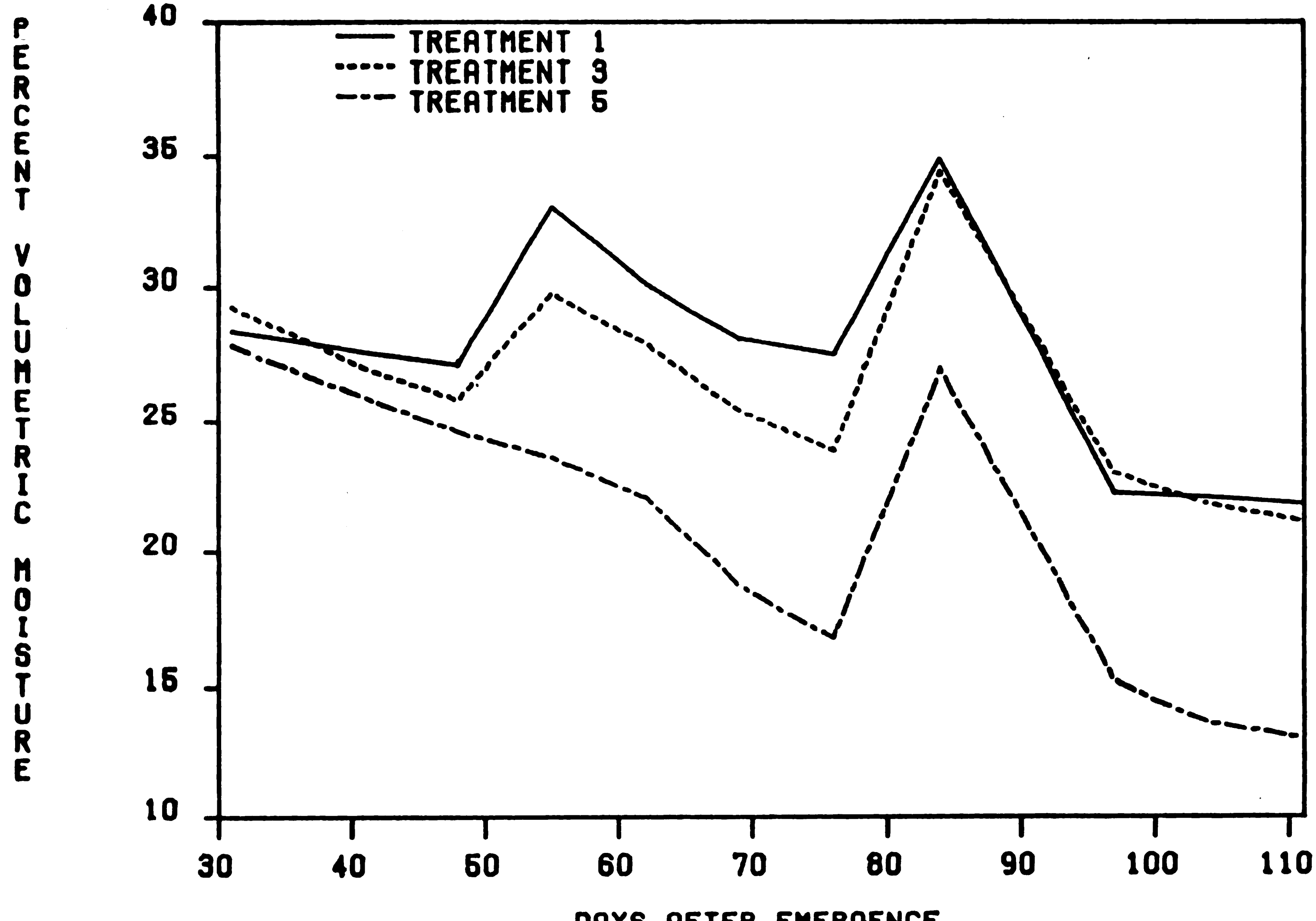

Figure 3-3. Neutron probe readings averaged from 30.5, 61, and 91.5 cm depths (Range 2).

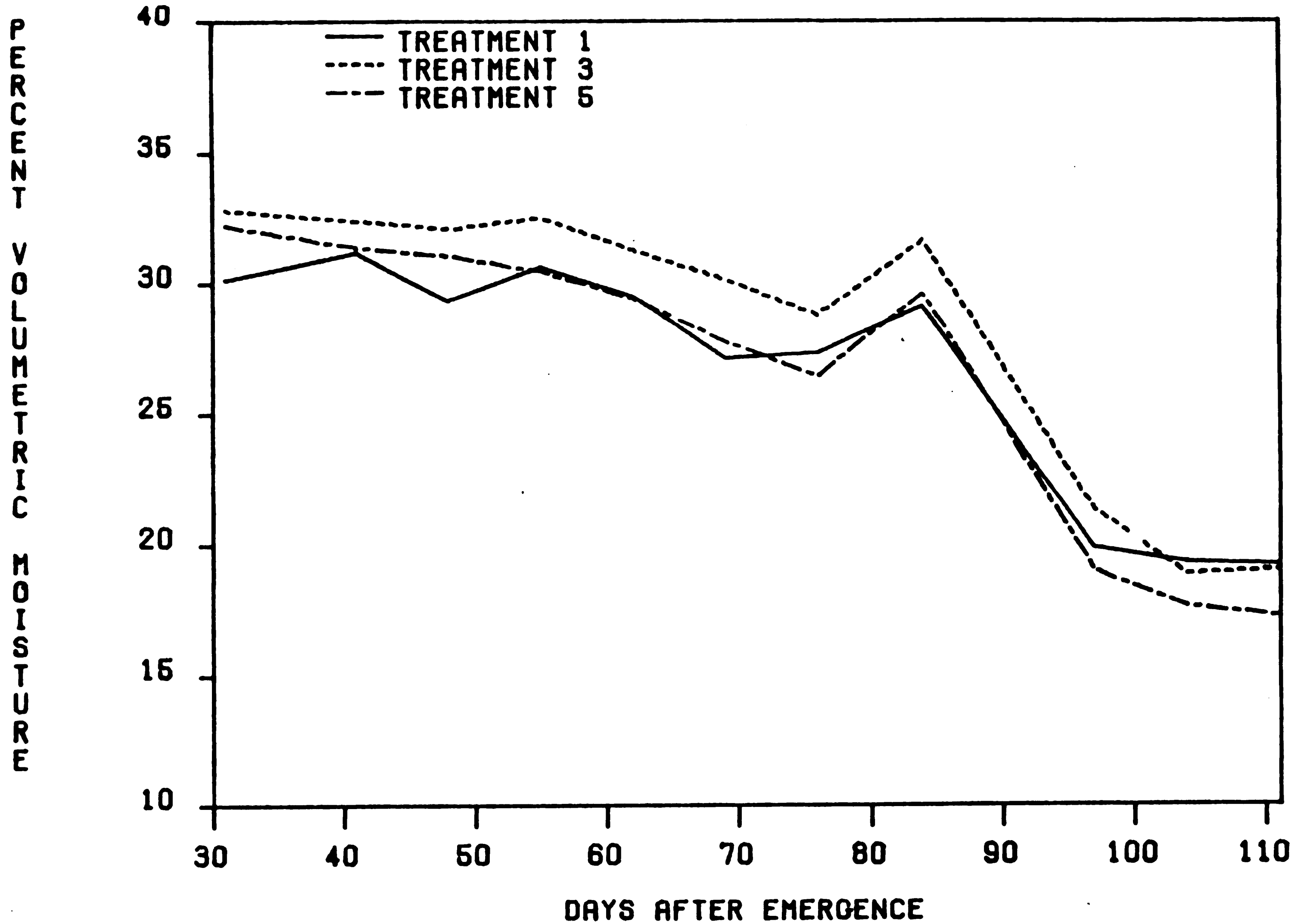

Figure 3-4. Neutron probe readings averaged from 30.5, 61, and 91.5 cm depths (Range 3).

water had run off Range 1 onto Range 2. This can be attested to by the low ET values for Range 2 in period 3 (Table 3-3). This low value indicates there was more moisture in the soil than would be expected due to the precipitation alone. Small channels and dikes were formed with the soil between the ranges to prevent further runoff from one range going onto another range. A comparison of the ranges' ET values in period 7 , which included a heavy rainfall on August 3, revealed that the channels were only partially effective. The low and high values for periods 4 and 5, respectively, are difficult to explain. Neither rainfall nor irrigation appeared to be excessive during either period. The high ET values in period 5 would indicate that moisture was depleted from the soil profile faster than would be expected from ET alone. The obvious possibilities of runoff and/or deep percolation can not be ruled out completely. Judging from the changes in moisture levels at the 91.5 cm depth, it appears deep percolation may have occurred. The low ET values in period 4 are the most difficult to explain. These low values suggest that more moisture than actually recorded was added to the plots. Underground lateral water movement from the surrounding area appears to be the best explanation. The slope and topography of this area as well as the 3.00 cm of rain received on July 10 would support this hypothesis. This would help account for the deep percolation in the following period. If this was true, the water moved into the plots during period 4 resulting in lower calculated ET values than expected. Deep percolation of this water occurred during period 5 resulting in higher calculated ET values than expected.

Starting on August 23 another neutron moisture meter was used due to mechanical problems with the first meter. This explains the high ET values obtained in period 8.

There were five periods (1, 2, 6, 9, and 10) when runoff, deep percolation or underground lateral water movement were believed to be nonexistent. During these periods, ET values predicted by the empirical formula were close to those obtained from neutron probe measurements.

Total ET for the period measured as determined by the empirical formula was 81 percent of pan evaporation. This was very close to what would be expected after multiplying pan evaporation by a pan coefficient.

Effect of Irrigation Levels on Yield and Water Use Efficiency

Yields for the three corn hybrids are reported in Tables 3-4, 3-5, and 3-6. The percentage of irrigation as well as the total precipitation (rain + irrigation) each treatment received in relation to the wettest treatment is shown.

Each range was treated as a separate experiment, therefore no comparisons were made between the three hybrids. A truly valid estimate of error was not possible because irrigation treatments were not randomized, however, for the purposes of obtaining some estimate of significance difference due to irrigation levels the experiment was treated as a randomized complete block design. Certain trends are obvious but levels of significance may not be as trustworthy as where randomization is

Table 3-4. Effect of irrigation level on yield and water use efficiency of grain and stover with DeKalb 587 (Range 1).

Trt.	Irr. Level	Total Precipitation Level	Yield		Water Use Efficiency	
			Grain[1]	Stover[2]	Grain	Stover
			------kg/ha-----		----kg/cm----	
1	100 %	100 %	10,496	5,642	216	116
2	81 %	91 %	11,188	6,327	258	143
3	58 %	80 %	10,351	4,892	266	126
4	25 %	65 %	9,274	4,770	293	151
5	0 %	54 %	7,251	4,091	278	157
LSD (.05)			(977)	(1,031)	(30)	(29)

[1] Adjusted to 15.5 % moisture

[2] Adjusted to 0.0 % moisture.

Table 3-5. Effect of irrigation level on yield and water use efficiency of grain and stover with Pioneer 3572 (Range 2).

Trt.	Irr. Level	Total Precipitation Level	Yield		Water Use Efficiency	
			Grain[1]	Stover[2]	Grain	Stover
			------kg/ha-----		------kg/cm-----	
1	100 %	100 %	11,540	7,270	238	150
2	81 %	91 %	11,961	6,248	271	141
3	58 %	80 %	11,616	6,464	298	166
4	25 %	65 %	10,446	6,473	330	205
5	0 %	54 %	7,875	4,894	302	188
LSD (.05)			(1,379)	(NS)	(42)	(NS)

[1] Adjusted to 15.5 % moisture.

[2] Adjusted to 0.0 % moisture.

Table 3-6. Effect of irrigation level on yield and water use efficiency of grain and stover with Pioneer 3707 (Range 3).

Trt.	Irr. Level	Total Precipitation Level	Yield		Water Use Efficiency	
			Grain[1]	Stover[2]	Grain	Stover
			------kg/ha-----		------kg/cm-----	
1	100 %	100 %	11,988	6,491	247	134
2	81 %	91 %	11,228	6,837	254	155
3	58 %	80 %	10,557	5,853	271	150
4	25 %	65 %	8,843	4,896	280	155
5	0 %	54 %	6,376	4,184	244	160
LSD (.05)			(1,201)	(1,104)	(NS)	(NS)

[1] Adjusted to 15.5 % moisture.

[2] Adjusted to 0.0 % moisture.

possible.

The highest grain yields were obtained at treatment 2 for DeKalb 587 and Pioneer 3572. This would imply that treatment 1 received more precipitation than was required for maximum yields. In Range 3 Pioneer 3707 had the highest grain yield at treatment 1. This was also the driest range according to tensiometer readings (Figure 3-5). Treatment 5 produced the lowest yields for both grain and stover in all three varieties. The trends in yields for grain and stover can be seen in Figures 3-6, 3-7, and 3-8. Grain yields were significantly different in each hybrid and stover yields were significantly different in all hybrids except Pioneer 3572. The lack of significant differences in stover yield with Pioneer 3572 may be attributed to water running onto the range earlier in the season, thus reducing the treatment effect.

Water use efficiency was calculated by dividing the yield by the amount of total precipitation received from May 14 until September 6 (Tables 3-4, 3-5, and 3-6). The highest water use efficiency for grain was achieved with treatment 4 in every hybrid. Pioneer 3707 was the only hybrid where grain water use efficiency was not significantly affected by irrigation levels.

The lowest water use efficiency for stover was always found in either treatment 1 or 2. Whereas, the highest efficiencies tended to be in the driest treatments (i.e., 4 or 5). Only DeKalb 587 had any significant difference in stover water use efficiency.

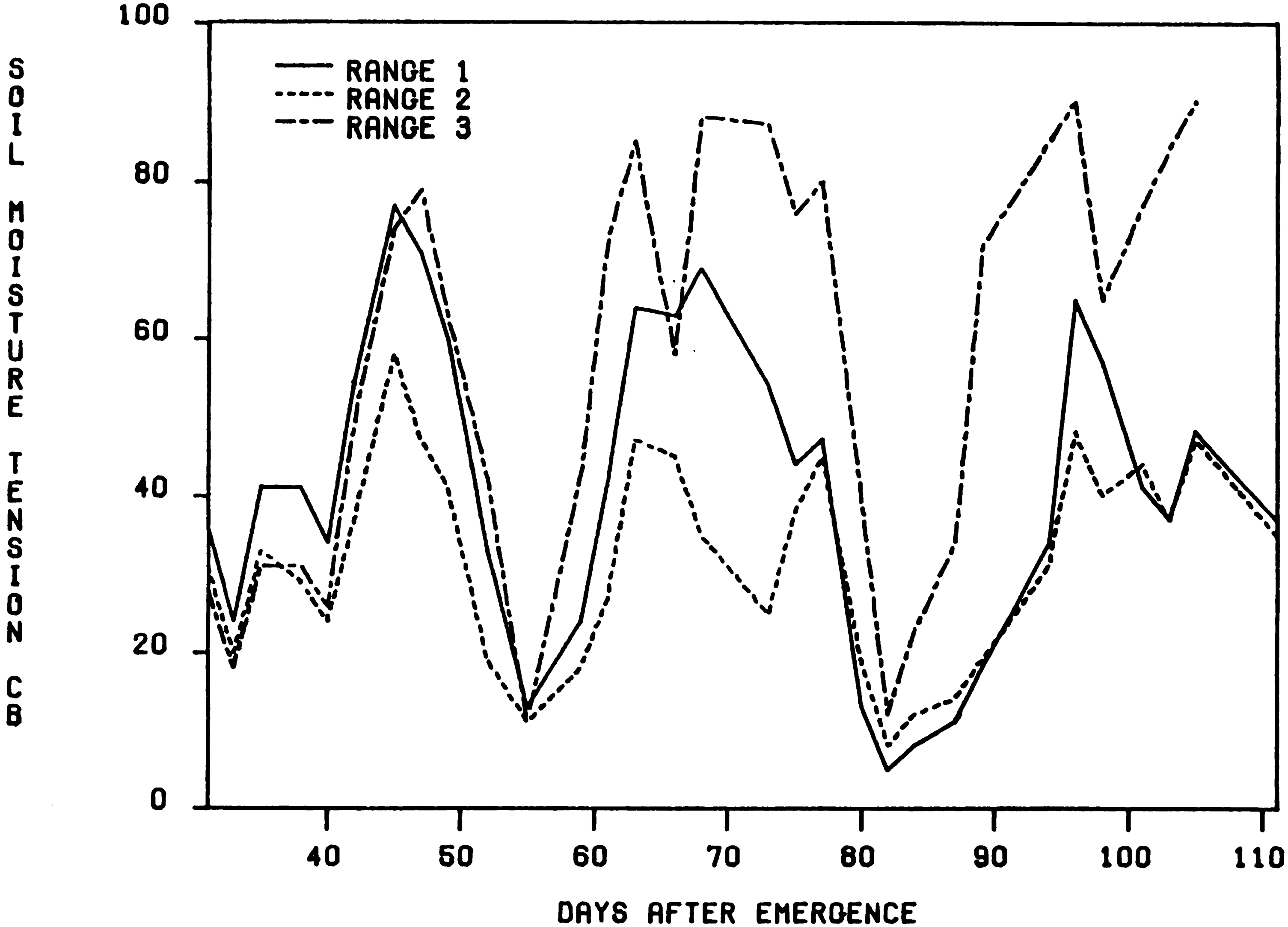

Figure 3-5. Tensiometer readings at treatment 1 for Ranges 1, 2, and 3.

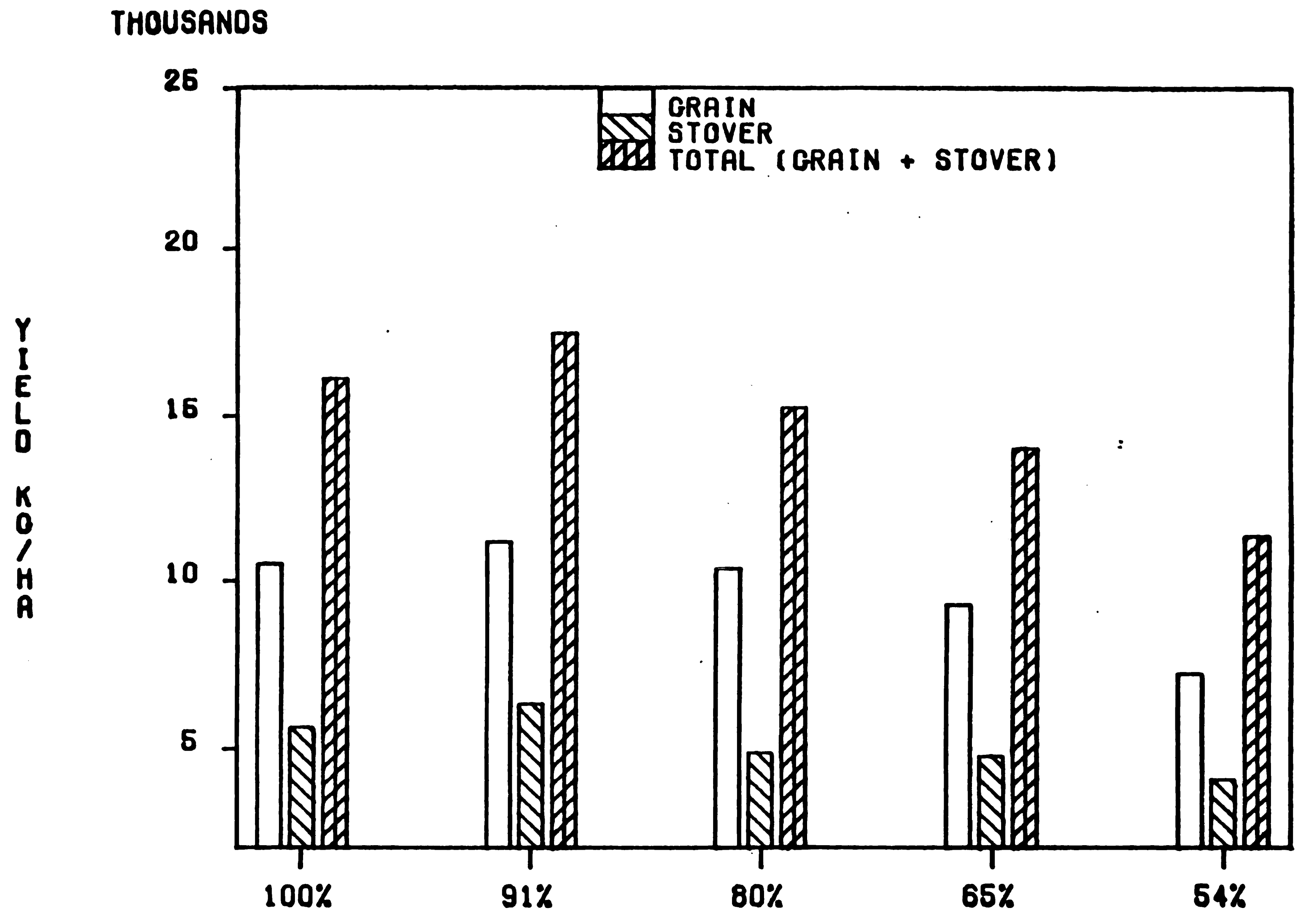

Figure 3-6. Effect of precipitation levels on grain and stover yields with DeKalb 587 (Range 1).

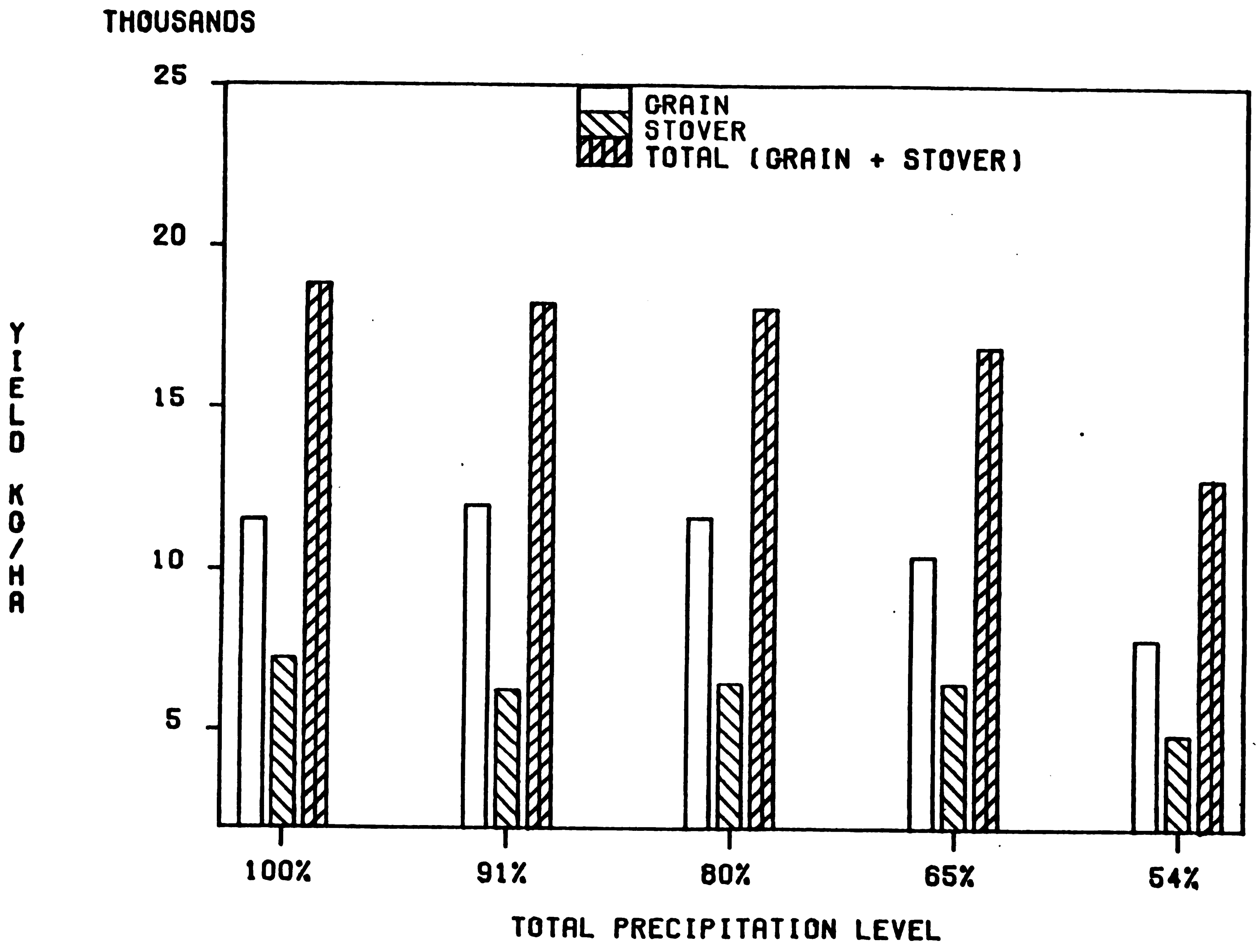

Figure 3-7. Effect of precipitation levels on grain and stover yields with Pioneer 3572 (Range 2).

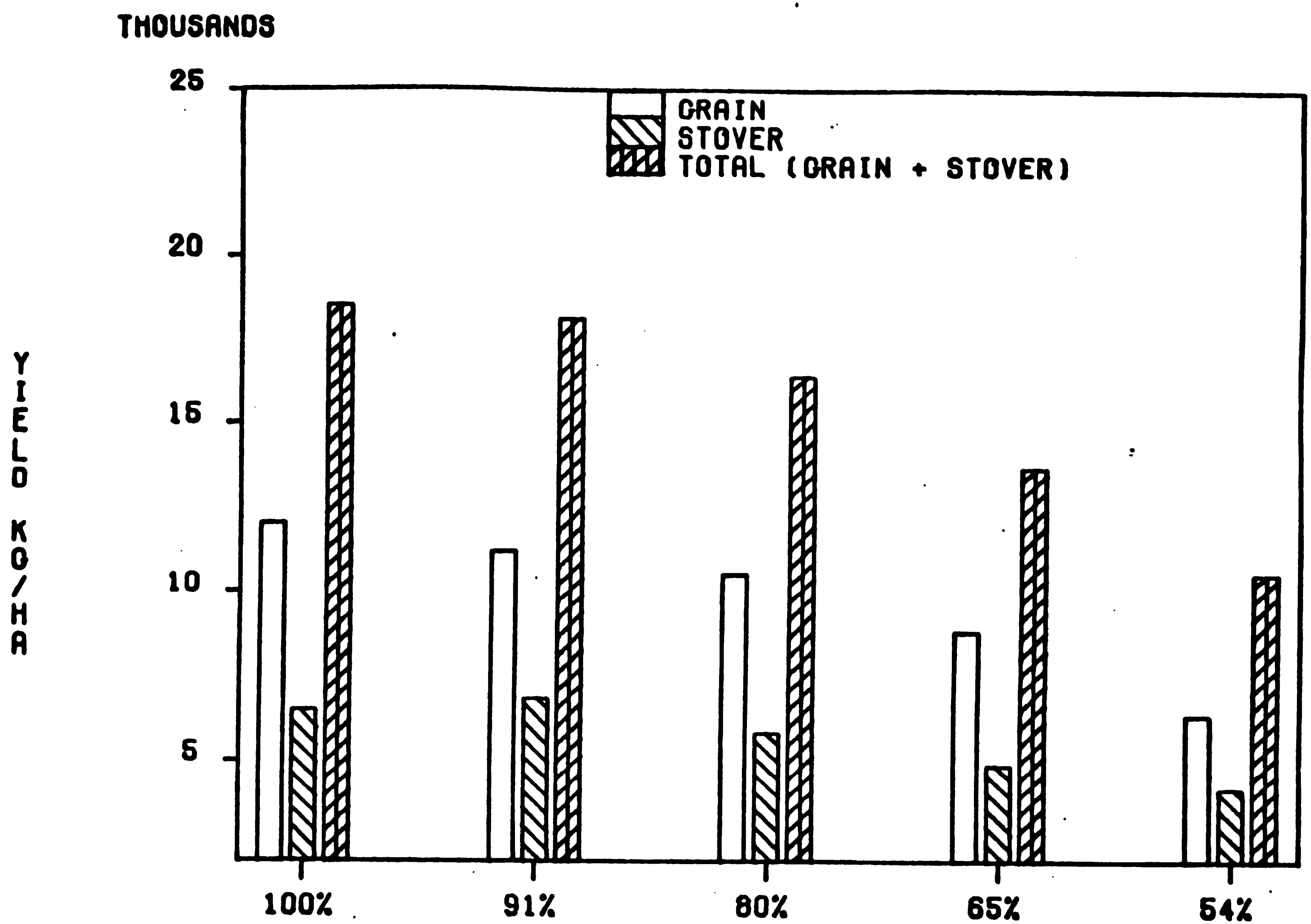

Figure 3-8. Effect of precipitation levels on grain and stover yields with Pioneer 3707 (Range 3).

These trends appear to indicate that water use efficiency increased as water was applied up to a point. After that point, the efficiencies began to decline. The highest water use efficiencies for grain and stover were consistently located in or around treatment 4. In this study treatment 4 received approximately 65 percent of the total precipitation of treatment 1. Trends in water use efficiencies can be seen in Figures 3-9, 3-10, and 3-11. A comparison of how each treatment related to the 1st treatment in the amount of precipitation received, water used, and grain and stover produced for all three hybrids is shown in Table 3-7.

Grain moisture, percent barren stalks, and plant populations are shown in Tables 3-8, 3-9, and 3-10. There was no significant difference in plant populations for any of the hybrids. Pioneer 3572 was the only hybrid which had a significant difference in percent barren stalks, and grain moisture was significantly different only with Pioneer 3707.

Table 3-11 shows an economic return to various irrigation levels for grain. The net return per ha was highest at treatment 2 for Dekalb 587 and Pioneer 3572. Pioneer 3707 had the highest net return per ha at treatment 1. The most profitable irrigation level was always found at the highest grain yield. This was in contrast to water use efficiency where the most efficient level tended to be near the lower irrigation levels and lower grain yields.

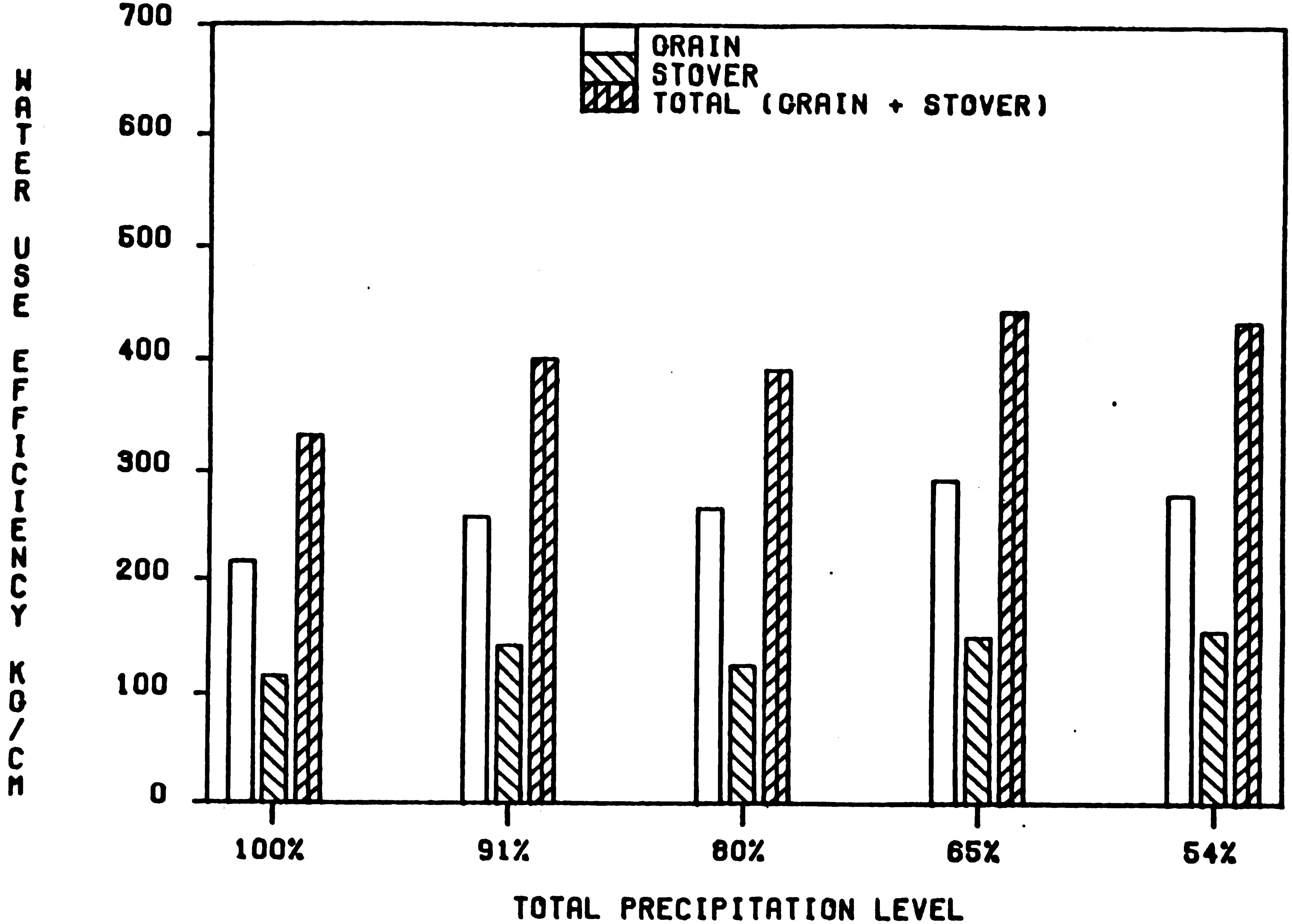

Figure 3-9. Effect of precipitation levels on water use efficiency of grain and stover with DeKalb 587 (Range 1).

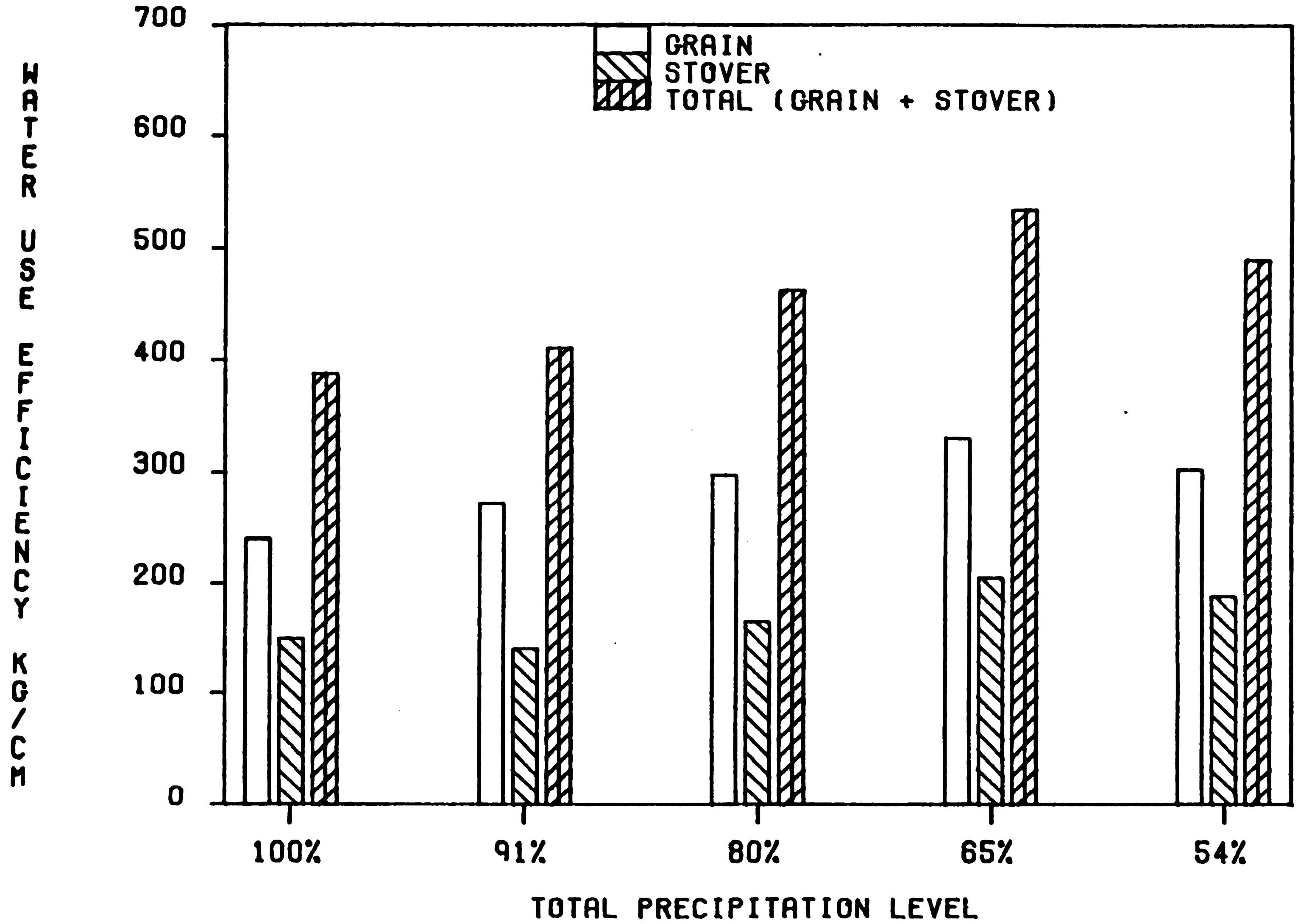

Figure 3-10. Effect of precipitation levels on water use efficiency of grain and stover with Pioneer 3572 (Range 2).

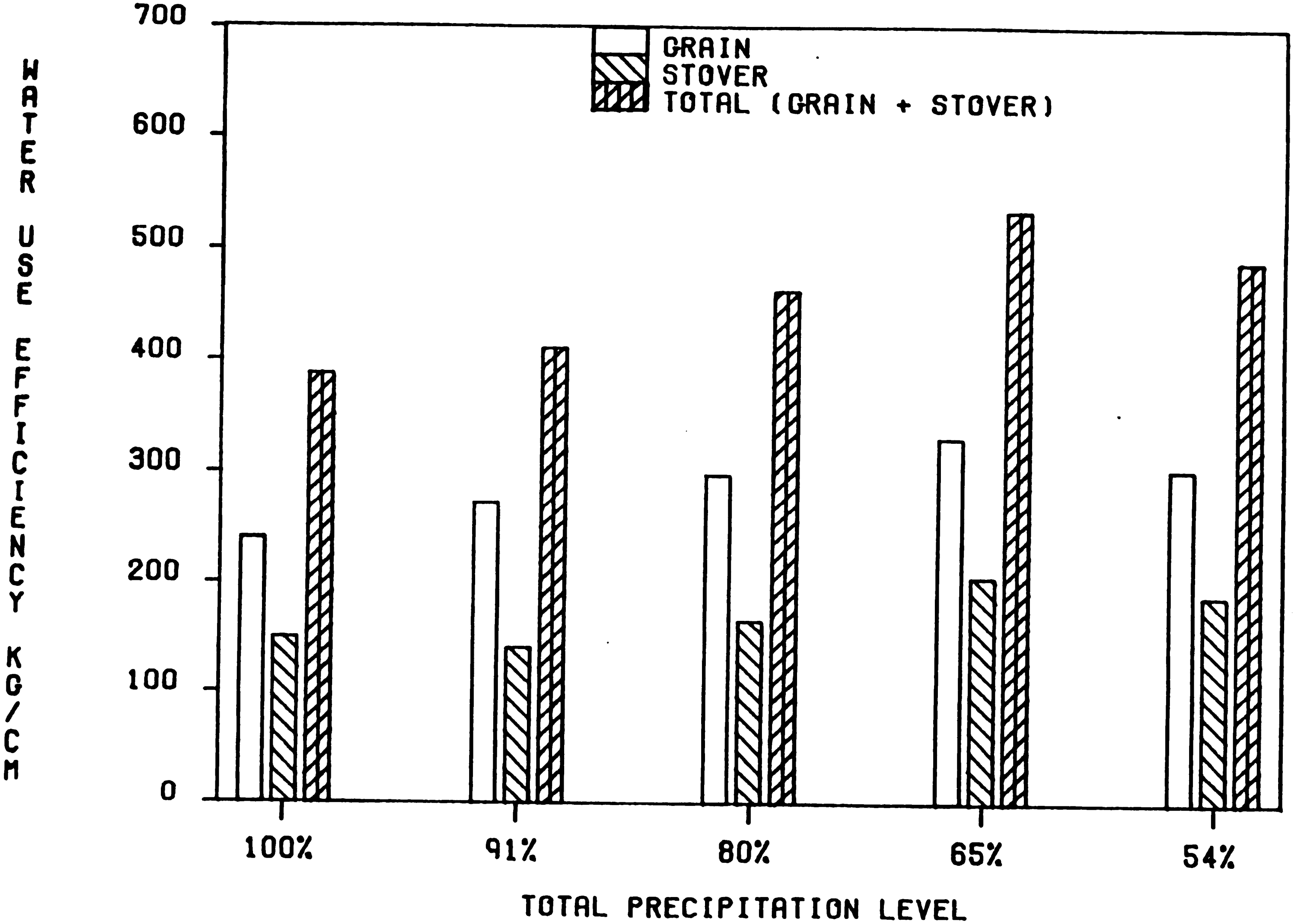

Figure 3-10. Effect of precipitation levels on water use efficiency of grain and stover with Pioneer 3572 (Range 2).

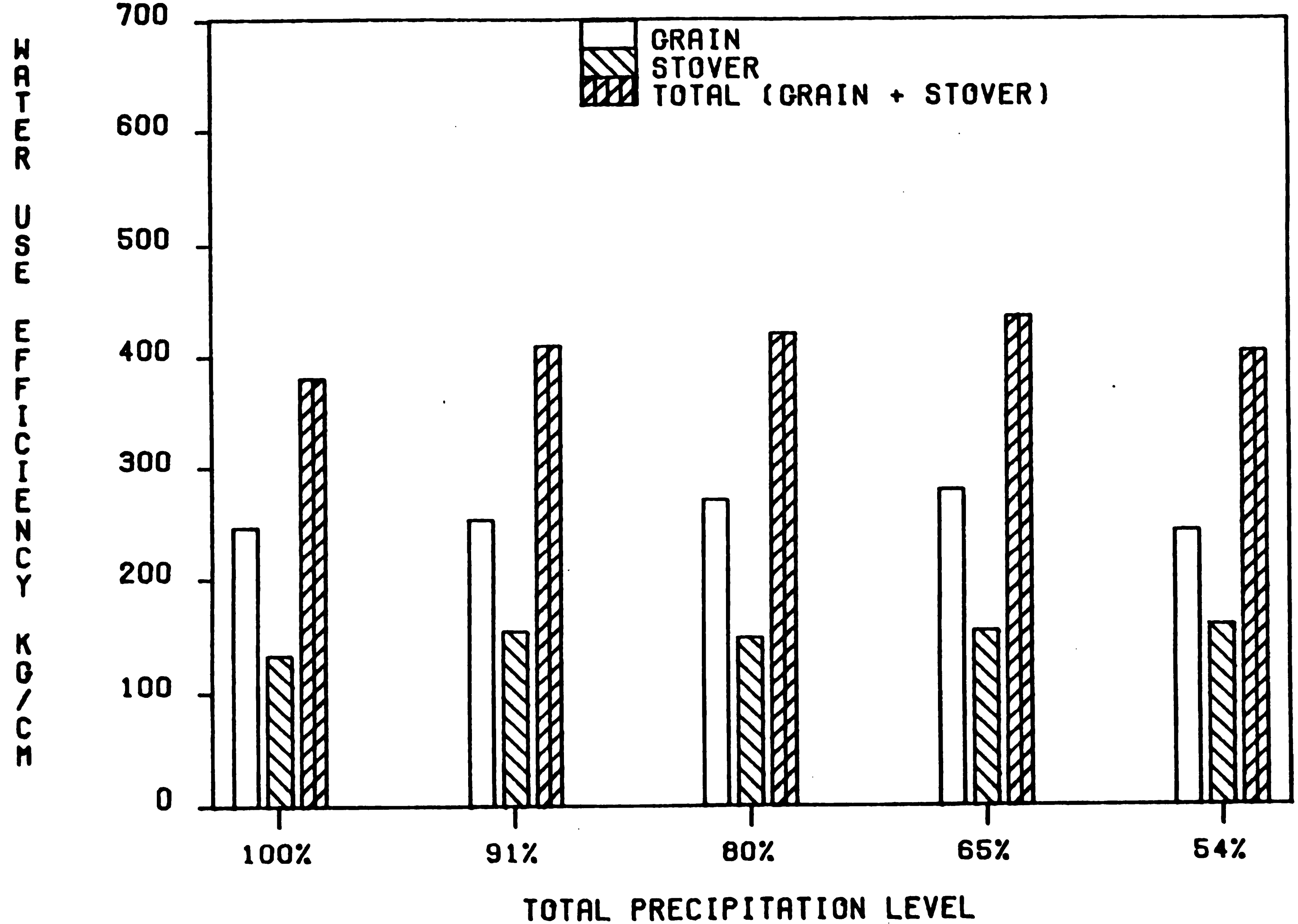

Figure 3-11. Effect of precipitation levels on water use efficiency of grain and stover with Pioneer 3707 (Range 3).

Table 3-7. A percentagewise comparison of each treatment as related to the 1st treatment in the amount of moisture received, water used, and grain and stover produced for all three Ranges.

Variety	Treatment	Total Precipitation Level	ET	Grain	Stover
		-----------% of 1st treatment-------------			
	1	100	100	100	100
	2	91	97	107	113
DeKalb 587	3	80	89	99	89
	4	65	79	88	86
	5	54	66	69	73
	1	100	100	100	100
	2	91	94	104	88
Pioneer 3572	3	80	83	101	92
	4	65	73	91	92
	5	54	62	68	69
	1	100	100	100	100
	2	91	96	94	105
Pioneer 3707	3	80	85	88	91
	4	65	74	74	76
	5	54	65	53	64

Table 3-8. Effect of irrigation level on grain moisture and barren stalks with DeKalb 587 (Range 1).

Trt.	Irr. Level	Total Precipitation Level	Grain Moisture	Barren Stalks	Plant Population
			---------%	----------	(plants/ha)
1	100 %	100 %	37.0	1.3	70,827
2	81 %	91 %	34.8	1.0	72,443
3	58 %	80 %	35.3	0.5	68,459
4	25 %	65 %	35.3	2.5	69,319
5	0 %	54 %	37.0	1.8	67,490
LSD (.05)			(NS)	(NS)	(NS)

Table 3-9. Effect of irrigation level on grain moisture and barren stalks with Pioneer 3572 (Range 2).

Trt.	Irr. Level	Total Precipitation Level	Grain Moisture	Barren Stalks	Plant Population
			---------%	----------	(plants/ha)
1	100 %	100 %	35.3	2.3	74,165
2	81 %	91 %	33.0	0.8	72,010
3	58 %	80 %	33.0	2.0	75,135
4	25 %	65 %	33.0	1.5	74,486
5	0 %	54 %	33.3	7.0	73,948
LSD (.05)			(NS)	(3.5)	(NS)

Table 3-10. Effect of irrigation level on grain moisture and barren stalks with Pioneer 3707 (Range 3).

Trt.	Irr. Level	Total Precipitation Level	Grain Moisture	Barren Stalks	Plant Population
			---------%	---------	(plants/ha)
1	100 %	100 %	31.5	1.8	80,306
2	81 %	91 %	30.8	2.3	80,726
3	58 %	80 %	30.5	3.8	80,837
4	25 %	65 %	31.3	4.5	80,948
5	0 %	54 %	37.5	3.5	80.521
LSD (.05)			(3.9)	(NS)	(NS)

Table 3-11. Economic net return to various irrigation levels for grain yield of three corn hybrids.

Irrigation		Net Return to Irrigation		
Level	Amount	DeKalb 587	Pioneer 3572	Pioneer 3707
	--cm--		\$/ha[1]	
100 %	22.37	273	323	553
81 %	18.08	376	394	484
58 %	12.89	302	378	430
25 %	5.55	211	276	264
0 %	0.00	---	---	---

[1] Calculations are based on 11.79 per quintal of corn and \$4.86 per ha cm of water.

SUMMARY AND CONCLUSIONS

All three corn hybrids responded to irrigation. The highest grain yields were obtained at treatment 2 for DeKalb 587 and Pioneer 3572, whereas Pioneer 3707 had the highest yield at treatment 1. The highest stover yields were found at treatment 1 for Pioneer 3572 and Pioneer 3707 and at treatment 2 for DeKalb 587. When considering grain yields, it appears that Range 1 and 2 (DeKalb 587 and Pioneer 3572 respectively) received excessive water under treatment 1. Stover yields from Range 1 would also indicate this.

The highest water use efficiencies were located around treatment 4 for both grain and stover. Water use efficiencies tended to decrease as irrigation amounts increased above the treatment 4 level.

Once canopy coverage was established ET estimates from the empirical formula agreed closely with those calculated from the neutron probe, when runoff was not a factor.

According to tensiometer readings, Range 3 was the driest range throughout most of the season. It is hard to determine if Range 3 was under irrigated at treatment 1 since it was here that the highest yields were obtained. The data does imply that corn grown on a Metea loamy sand in a climate similar to Michigan's can withstand soil moisture depletions above 50 cb without significant yield reductions. Exactly how far above 50 cb and for how long cannot be concluded from this study. However, once the soil moisture depletions begin to exceed the tensiometer range (0-.80 bar), such as in treatments 3, 4, and 5, yield reductions are likely.

The irrigation level that gives the best water use efficiency is not always the most economical for the grower. Net return to irrigation was greatest where grain yield was highest in every hybrid. The profitability of various irrigation levels is dynamic and is related to the prices of water and grain. This should be kept in mind when calculating economic return.

List of References

LIST OF REFERENCES

1. Arkley, R.J. 1963. Relationships between plant growth and transpiration. Hilgardia. 24:559-584.

2. Bauder, J.W., R.J. Hanks, and D.W. James. 1975. Crop production function determinization as influenced by irrigation and nitrogen fertilization using a contiouous variable design. Agron. J. 39:1187-1192.

3. Belcher, D.J., T.R. Cuykendall, and S. Sack II. 1950. The measurements of soil moisture and density by neutron and gamma-ray scattering. Civil Aero. Adm. Tech. Dev. Report 127, Washington D.C.

4. Briggs, L.J., and H.L. Shantz. 1921. The relative wilting coefficient for different plants. Bot. Gaz. 53:229-235.

5. Burman, R.D., R.H. Cuenca, and A. Weiss. 1983. Techniques for estimating irrigation water requirements; In: Advances in Irrigation. Vol. 2. D. Hillel, ed., Academic Press New York, New York. pp. 335-394.

6. ________, P.R. Nixon, J.L. Wright, and W.O. Pruitt. 1981. Water requirements; In: Design and Operation of Farm Irrigation Systems. ASAE Monograph No. 3, M.E. Jensen, ed., pp. 189-232.

7. ________, J.L. Wright. P.R. Nixon, and R.W. Hill. 1980. Irrigation management, water requirements and water balance; In: Irrigation Challenges of the 80's. Proc. of the Am. Soc. Ag. Eng. pp. 141-153.

8. Campbell, G.S., and M.D. Campbell. 1983. Irrigation scheduling using soil moisture; In: Advances in Irrigation. Vol. 1., Hillel, ed., pp. 25-42.

9. Childes, E.C. 1940. The use of soil moisture characteristics in soil studies. Soil Sci. 50:239-252.

10. Clawson, K.L., and B.L. Blad. 1982. Infrared thermomerty for scheduling irrigation of corn. Agron. J. 74:311-316.

11. Cooper, R.L. 1977. Response of soybean cultivars to narrow rows and planting rates under weed-free conditions. Agron. J. 69:30-34.

12. Crouch, C.E., W.E. Hart, G.D. Jardins, R.J. Brase. 1981. Desk top data systems for irrigation scheduling; In: Irrigation Scheduling for Water and Energy Conservation in the 80's. Proc. of the Am. Soc. of Ag. Eng. pp.27-35.

13. de Vries, J. and K.M. King. 1961. Note on the volume of influence of a neutron surface moisture probe. Can. J. Soil Sci. 41:253-257.

14. de Witt, C.T. 1958. Transpiration and crop yield. Verslag Van Landbouwk. Danderzock. 40. 64. 88 pp.

15. Dorenbos, J. and A.H. Kassam. 1979. Yield response to water. Irrig. and Drain. Paper 33, FAO. United Nations, Rome, Italy.

16. ______, and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements. FAO Irrig. and Drain. Paper No. 24, 144 pp.

17. ______. 1977. Guidelines for predicting crop water requirements. FAO Irrig. and Drain. Paper No. 24, (rev) 156 pp.

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

19. Dylla, A.S., H. Shull, D.R. Timmons. 1981. Number of sensors for efficient irrigation of a shallow soil. Irrigation News, Technical Feature. Published by the Irrigation Association.

20. Ehrler, W.L. 1973. Cotton leaf temperatures as related to soil water depletion and meteorlogical factors. Agron. J. 65:404-409.

21. Fox, R.L. 1973. Agronomic investigations using continuous function experimental design - nitrogen fertilization of sweet corn. Agron. J. 65:454-456.

22. Garrity, D.P., D.G. Watts, C.Y. Sullivan, and J.R. Gilley. 1982. Moisture deficits and grain sorghum performance: Effect of genotype and limited irrigation strategy. Agron. J. 74:808-814.

23. Geiser, K.M., D.C. Slack, E.R. Allred, K.W. Stange. 1982. Irrigation scheduling using crop canopy-air temperature difference. TRANSACTIONS of the ASAE. 25, 689-694.

24. Hagan, R.M., and I.J. Stewart. 1972. Water deficits - irrigation design and programing. Proc. of ASCE, Irrig. and Drain. Div. 98 (IR2):215-237.

25. Haise, H.R. and R.M. Hagan. 1967. Soil, plant, and evaporative measurements as criteria for scheduling irrigation; In: Irrigation of Agricultural Lands. Monograph No. 11, Am. Soc. Agron., Madison, Wisconsin. pp. 577-604.

26. Hang, A.N., and D.E. Miller. 1983. Wheat development as affected by deficit, high frequency sprinkler irrigation. Agron. J. 75:234-239.

27. Hanks, R.J., D.V. Sisson, R.L. Hurst, and K.G. Hubbard. 1980. Statistical analysis of results from irrigation experiments using the line source sprinkler system. Soil Sci. Soc. Am. J. 44:886-888.

28. ______, J. Keller, V.P. Rasmussen, and G.D. Wilson. 1976. Line source sprinkler for continuous variable irrigation crop production studies. Soil Sci. Soc. Am. J. 40:426-429.

29. ______, H.R. Gardner and R.L. Florian. 1969. Plant growth-evapotranspiration relations for several crops in central Great Plains. Agron.J. 61:30-34.

30. Heermann, D.J., and H.R. Duke. 1978. Evaluation of crop water stress under limited irrigation. Paper. Am. Soc. Agric. Eng. 78-2556:1-12.

31. Hicks, D.R., J.W. Pendleton, R.L. Bernard, and T.J. Johnston. 1969. Response of soybean plant types to planting patterns. Agron. J. 61:290-293.

32. Hillel, D. 1982. Introduction to Soil Physics. Academic Press, New York, pp. 288-303.

33. ______, and Y. Guron. 1973. Relation between evaportranspiration rate and maize yield. Water Resour. Res. 9:743-749.

34. Hiller, 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

35. Howe, O.W., and H.F. Rhoaes. 1955. Irrigation practice for corn production in relation to stage of plant development. Soil Sci. Soc. Am. Proc. 19:94.

36. Hsiao, T.C. 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24:519-517.

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

38. Jackson, R.D. 1983. Canopy temperatures and crop water stress; In: Advances in Irrigation. Vol.1., D. Hillel ed., Academic Press, New York. pp. 43-85.

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

40. Jensen, M.E. 1980. Introduction; In: Design and Operation of Farm Irrigation Systems. M.E. Jensen ed., Monograph No. 3, Am. Soc. Agric Eng., St. Joseph, Michigan. pp. 5-11.

41. ______. ed., 1974. Consumptive use of water and irrigation water requirements. ASCE, New York. Report of the irrigation water requirements committee. 215 pp.

42. ______, J.L. Wright, and B.J. Pratt. 1971. Estimating soil moisture depletion from climate, crop and soil data. TRANSACTIONS of the ASAE 14(5):954-959.

43. Johnson, D.E., U.N. Chaudhuri, and E.T. Kanemasu. 1983. Statistical analysis of line source sprinkler experiments and other nonrandomized experiments using multivariate methods. Soil Sci. Soc. Am. J. 47:309-312.

44. Lehman, W.F. and J.W. Lambert. 1960. Effects of spacing of soybean plants between and within rows on yield and it's components. Agron. J. 52:84-86.

45. Mason, W.K., H.M. Taylor, A.P. Bennie, H.R. Rowse, D.C. Reicosky, Y. Jung, A.A. Righes, R.L. Yang, T.C. Kasper, and J.A. Stone. 1980. Soybean row spacing and soil water supply: Their effect on growth, development, water relations, and mineral uptake. Adv. in Agric. Tech. Sci. and Educ. Admn. USDA. Published by Agric. Research. 59 pp.

46. Miller, D.E., and A.N. Hang. 1980. Deficit, high-frequency irrigation of sugar beets with the line source technique. Soil Sci. Am. J. 44:1295-1298.

47. ______, and J.S. Aarstad. 1971. Available water as related to evapotranspiration rates and deep drainage. Soil Sci. Soc. Am. Proc. 35:131-134.

48. National Oceanic and Atmospheric Administration. 1983. Local Climatological Data: Annual summary with comparative data, 1983, Lansing, Michigan. U.S. Department of Asheville, North Carolina.

49. Neghassi, H., D.F. Heermann, and D.E. Smika. 1975. Wheat yield models with limited water. TRANSACTIONS of the ASAE 18:549-557.

50. O'Neill, M.K., W. Hofmann, A.K. Dobrenz, and V. Marcarrian. 1983. Drought response of sorghum hybrids under a sprinkler irrigation gradient system. Agron. J. 75:102-107.

51. Penman, H.L. 1956. Evaporation: An introductory survey. Netherlands J. Agric Sci. 1:9-29, 151-153.

52. ______. 1948. Natural evaporation from open water, bare soil and grass. Proc Roy. Soc. London, Ser. A. 193:120-146.

53. Peters, D.B., and L.C. Johnson. 1960. Soil moisture use by soybeans. Agron. J. 52:687-689.

54. Pruitt, W.O., and D.E. Angus. 1961. Comparisons of evapotranspiration with solar and net radiation and evaporation from water surfaces. First Ann. Rep. USAEPG Contract DA-36-039-SC-80334, 1961. University of California, Davis. pp. 74-107.

55. Reicosky, D.C., H.R. Rowse, W.K. Mason, and H.M. Taylor. 1982. Effect of irrigation and row spacing on soybean water use. Agron. J. 74:958-964.

56. Richards, L.A., and A.W. March. 1961. Irrigation based on soil suction measurements. Soil Sci. Proc. 24:65-69.

57. ______. 1949. Methods of measuring soil moisture tension Soil Sci. 68:95-112.

58. ______, and L.R. Weaver. 1944. Fifteen atmosphere pressure as related to the permanent wilting percentage. Soil Sci. 56:331-339.

59. Rijtema, P.E. 1959. Calculation methods of potential evapotranspiration. Inst. Land Water Manage. Res. Tech. Bull. No. 7. Wageningen, Netherlands. 10 pp.

60. Robins, J.S., and G.E. Domingo. 1953. Some effects of severe soil moisture stress deficits at specific growth stages in corn. Agron. J. 45:618.

61. Salter, P.J., and J.E. Gooed. 1967. Crop responses to water at different stages of growth. Commonwealth Agr. Bur., Farnham Royal, Bucks, England, 246 pp.

62. Sandhu, B.S., and M.L. Horton. 1978. Temperature response of oats to water stress in the field. Agric. Meteorol. 19:329-336.

63. Schleusener, P.E. and E.G. Kruse. 1963. Empirical formula for computing water needs of row crops. TRANSACTIONS of the ASAE. Vol.6, No. 2:140-122.

64. Scholander, P.F., H.T. Hammel, E.D. Bradstreet, and E.A. Hemmimgsen. 1965. Sap pressure in vascular plants. Sci. 148:339-346.

65. Scofield, C.S. 1945. The water requirement of alfalfa. USDA Cir. No. 735.

66. Shibles, R.M., and C.R. Weber. 1965. Leaf area solar radiation interception and dry matter accumulation by soybeans. Crop Sci. 5:575-578.

67. Skaggs, R.W., D.E. Miller, and R.H. Brooks. 1981. Soil water; <u>In:</u> Design and Operation of Farm Irrigation Systems. ASAE Monograph No. 3, Jensen, ed., pp. 182-232.

68. Sorensen, V.M., R.J. Hanks, and R.L. Cartee. 1980. Cultivation during early season and irrigation influences on corn production. Agron. J. 72:266-270.

69. Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics: a biometrical approach. Second edition. MaGraw-Hill, New York.

70. Stegman, E.C., R.J. Hanks, J.T. Musick, and D.G. Watts. 1980. Irrigation water management - adequate or limited; <u>In:</u> Irrigation, Challenges of the 80's. pp. 115-165.

71. ______, J.T. Musick, and J.I. Stewart. 1980. Irrigation water management; In: Design and Operation of Farm Irrigation Systems. ASAE Monograph No. 3, Jensen, ed., pp. 763-817.

72. ______, and M. Aflatouni. 1978. Corn yield response to water stress management. ASAE Paper # 78-2558 St. Joseph, Michigan.

73. ______, L.H. Schiele, and A. Bauer. 1976. Plant water stress criteria for irrigation scheduling. TRANSACTIONS of the ASAE 19:850-855.

74. Stewart, B.A., and R.M. Hagan. 1969. Predicting effects of water shortage on crop yield. Proc. Am. Soc. Civ. Eng., J. Irrig. and Drain. Div. 95 (IR1)91-104.

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

76. Tanner, C.B. 1967. Measurement of evapotranspiration; In: Irrigation of Agricultural Lands. Monograph No. 11., Am. Soc. Agron., Madison, Wisconsin. pp. 534-574.

77. Taylor, H.M. 1980. Soybean growth and yield as affected by row spacing and by seasonal water supply. Agron. J. 72:543-547.

78. Taylor, S.A. 1965. Managing irrigation water on the farm. TRANSACTIONS of the ASAE 8(3):433-435.

79. Teare, I.D., E.T. Kanemasu, W.L. Powers, and R.L. Stone. 1974. Physiological indicators of water stress. Evaporation Laboratory, Kansas Agricultural Experimental Station, Manahattan, 24 pp.

80. Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. Geographical Review 38:54-94.

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

82. U.S. Department of Agriculture. 1979. Soil Survey of Ingham County, Michigan. Soil Conservation Serv., Mich. Agric. Expt. Station. East Lansing, Michigan. 142 pp.

83. U.S. Department of Agriculture. 1970. Irrigation water requirements. Soil Conservation Serv., Tech. Release No. 21, 83 pp.

84. Van Bavel, C.H.M. 1961. Neutron measurements of surface soil moisture. J. Geophys. Res. 66:4193-4198.

85. ______. 1966. Potential evapotranspiration: the combination concept and its experimental verification. Water Resources Res., 2(3):455-467.

86. Veihmeyer, F.J. 1955. Evaporation from soils and transpiration. Trans. Am. Geophys. Union, 19:612-619.

87. ______, and A.H. Hendrickson. 1949. Methods of measuring field capacity and wilting percentages of soils. Soil Sci. 68:75-94.

88. Viets, F.G., Jr. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:228-261.

89. Visvalingam, M., and J.D. Tandy. 1972. The neutron method for measuring soil moisture content - A review. Journal of Soil Sci., Vol. 23, No. 4, pp. 499-511.

90. Vitosh, M.L., R.J. Kunze, E.H. Kidder, G.D. Schwab, F.J. Henningsen, and E.A. Netherton. 1982. Irrigation water demand for agriculture in Michigan. In: Impact Evaluation of Increased Water Use By Agriculture in Michigan. J.F. Bartholic ed., Research Report, No. 449 AES, Michigan State Univ. East Lansing, Michigan.

91. Weber, C.R., R.M. Shibles, and D.E. Byth. 1966. Effect of plant populations and row spacings on soybean development and production. Agron. J. 58:99-102.

MICHIGAN STATE UNIV. LIBRARIES
31293006194140

MICHIGAN STATE UNIV. LIBRARIES
31293006194140